ABSTRACT

ALSHAREF, ABDULLAH FAHAD A. Leveraging Data Analytics to Improve Construction Operations and Occupational Safety. (Under the direction of Drs. Edward Jaselskis and Alex Albert).

Undoubtedly, there has been an exponential growth in the amount of data generated during all stages of construction projects (from project inception and planning to maintenance and demolition). However, massive amounts of data remained uncaptured and unexamined. As the engineering and construction industries are witnessing an unprecedented digital transformation, it becomes vital to leverage this data and turn it into valuable insights to solve numerous industry challenges. This dissertation focused on solving problems in five separate areas: (1) regulations, regulatory changes, and compliance, (2) occupational safety and health, (3) infrastructure management, (4) construction safety, and (5) disaster management.

The first study targeted the COVID-19 pandemic that has caused much disruption in the construction industry. The study objectives were achieved through conducting interviews with project managers, engineers, designers, and superintendents that represented different states and distinct industry sectors in the United States. The adverse effects, new opportunities, and risk mitigation measures that are being adopted in construction workplaces were reported in this study. The study's findings will guide industry stakeholders to continue maintaining a safe and productive work environment.

The second research study was inspired by the unacceptable numbers of construction workplace injuries. Additionally, the impacts of these injuries carry more effect if the sustained injury is classified as severe or serious. In order to assess, understand, and mitigate severe construction workplace injuries, over 11,000 severe construction injuries were obtained from the newly developed OSHA severe injury reporting program. The study comprehensively analyzed

the incidents’ attributes and assessed overrepresented attribute categories. The study's findings are expected to be practical for struggling construction organizations with high frequency and severity workplace injuries.

The third study investigated past incidents reports that involved driving license examiners. This community of workers plays a vital role in our society as they ensure only competent drivers drive on the roads. Despite their essential role in enhancing traffic safety and serving the public, they are nonetheless exposed to high levels of safety risk. This study empirically examined past incident reports that involved driver license examiners. Qualitative content analysis was performed on the incidents’ narratives to identify the fundamental attributes (e.g., event type, contributing factor, and injured body part) and their categories. The study provided deeper understandings of the safety incidents that driver license examiners experience which can inform the development of effective injury prevention policies and safety interventions.

The fourth study was mainly driven by how the construction industry is strongly regulated and these regulations are constantly subjected to changes and reevaluations. Such regulations typically influence capital projects' design, construction, and operation. The study's overarching goal was to evaluate the impact of regulations throughout the complete construction project lifecycle. The research methodology involved conducting an organizational survey to understand better how companies address regulations. The discoveries from the study can help organizations better understand the effect of regulations on building and operating projects and better plan for regulation compliance.

Lastly, the fifth study pertains to assessing the interruptions of utility facilities to transportation projects. Coordinating public transportation projects with other stakeholders is significantly challenging. This is especially true if the other stakeholder must accommodate its facility on the projects such as utilities. Construction organizations and departments of transportations are expected to consistently coordinate with utility providers regarding utility relocations during transportation projects. However, utilities typically conflict with the projects' performances and cause delays and cost claims. This study followed qualitative and quantitative research approaches to assess the impact of utilities on public transportation projects. Findings from this study are anticipated to benefit struggling transportations agencies with managing utilities on their construction projects.

Leveraging Data Analytics to Improve Construction Operations and Occupational Safety

by
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DEDICATION

This dissertation is dedicated to

My father and role model Fahad Alsharef, my mother and biggest supporter Norah Alghannam, my brother Badr, and my sisters Sarah and Fahdah. I am eternally grateful for your endless love, encouragement, and support;

and

My grandfathers Abdullah Alsharef and Abdulmohsin Alghannam. I am eternally grateful for your advice and words of wisdom that guided me through life.

BIOGRAPHY

Abdullah Alsharef was born and raised in Riyadh, Saudi Arabia. He earned his bachelor's degree in Civil Engineering at King Saud University (KSU) where he worked as a teaching assistant before joining North Carolina State University (NCSU) to pursue higher education degrees. At NCSU, Abdullah received his Master of Science in Civil Engineering where he investigated factors that affect letting date and designed construction expenditure forecasting and monitoring tools for transportation mega projects.

During his doctoral studies at NCSU, Abdullah was fortunate to be trained and advised by two of the top experts in the construction industry: Drs. Edward Jaselskis and Alex Albert. Under their supervision, Abdullah undertook various research studies that were funded by governmental agencies and private entities. The findings from these investigations have been published in various journals including Elsevier's Safety Science, ASCE Journal of Construction Engineering and Management, ASCE Journal of Management in Engineering, and others. Abdullah's research has also been recognized with various awards including the Best Paper Award at the Lean and Computing in Construction Congress and the second place for the best poster at the 2021 North Carolina Department of Transportation Research & Innovation Summit. Abdullah's research interests include construction safety management, payout curves prediction, and developing best practices in the construction industry.

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Chapter 1: Introduction

1.1. Motivation and Need

Large amounts of data are being generated on an ongoing basis in work-related settings (McKinsey & Company 2011). This data can often offer valuable insights on improving work operations and enhancing workplace efficiency. Unfortunately, much of this data largely remains unexamined to improve processes across domains (Bilal et al. 2019; Wickham and Grolemund 2016). This is particularly the case in industries such as the construction industry where there is a shortage of proficient personnel in both construction processes and the state-of-the-science data analytic approaches (Turner et al. 2021; Yan et al. 2020).

For example, in the construction industry, large amounts of textual data in the form of accident investigation reports often remain unleveraged to enhance workplace safety. Likewise, countless claim reports associated with undesirable outcomes including cost overruns and delays in workplaces remain unexamined during efforts that focus on improving workplace efficiency. These examples represent lost opportunities where data that is available has not been used to generate useful information, knowledge, and wisdom that are essential to inform strategic initiatives as per the data-information-knowledge-wisdom (DIKW) hierarchy model shown in Figure 1-1 (Ackoff 1989; Frické 2019).

To tackle these important issues, this dissertation's overarching objective is to leverage data analytical approaches to address some of the pressing challenges in the context of construction operations and occupational safety. Specifically, the following challenges are targeted in greater detail in the following chapters of this dissertation:

<u>Challenge 1:</u> *Qualitative investigation of the impacts of the Covid-19 pandemic on the United States construction industry.*

The COVID-19 pandemic has been the most significant global health crisis in decades. Apart from the unprecedented number of deaths and hospitalizations, the pandemic has resulted in economic slowdowns, widespread business disruptions, and significant hardships across nations. The pandemic has also had a significant impact on construction businesses and construction employees. There is a need to understand the challenges and management efforts that construction businesses and their workforce are employing to tackle the largely unexpected risks. Moreover, it will be valuable to document the adopted best practices across the industry to combat the effects of the pandemic. Accordingly, the first target area in this dissertation focuses on gathering qualitative data from construction professionals and performing a content analysis to identify adverse effects, new opportunities, and risk mitigation measures that are being implemented in construction workplaces. The data gathering and analysis effort will be useful as industry stakeholders continue maintaining a safe and productive work environment.

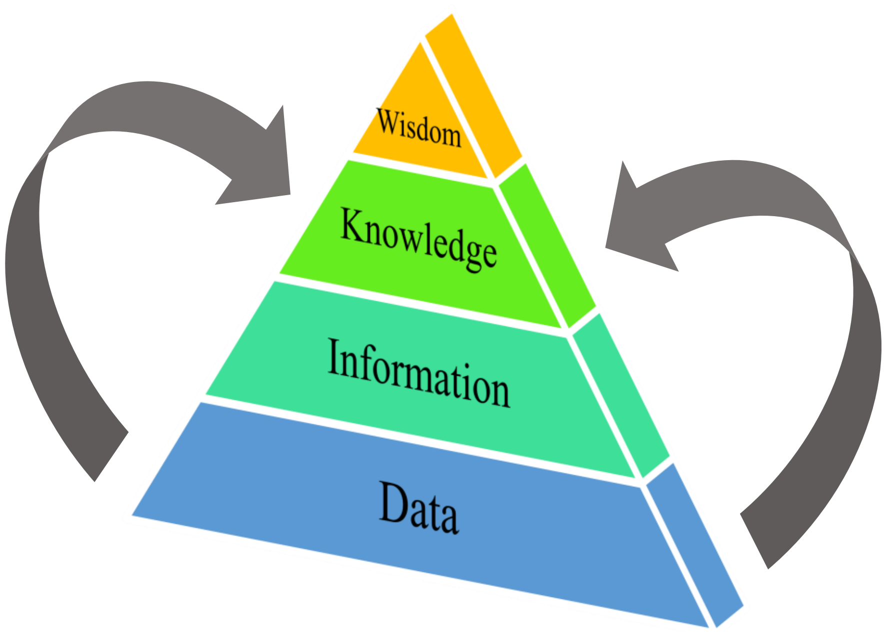

Figure 1-1: DIKW Model Hierarchy

<u>Challenge 2:</u> *Analyses of severe injury reports captured from the construction industry.*

Construction workplaces report a disproportionate number of workplace injuries. Estimates suggest that over 60,000 fatal and over a million non-fatal incidents are experienced every year from the global construction industry (Lingard 2013). These injuries result in much pain and distress among workers and are associated with costs that exceed billions of dollars in the United States (Hinze 2006). While much effort has been devoted to improving safety performance, large amounts of textual accident investigation reports that can offer insights into effective safety measures largely remain unexamined. One source of such data is the data gathered by the Occupational Safety and Health Administration (OSHA) as part of their severe injury reporting program since 2015 (OSHA 2015). This program captures severe work-related injuries that resulted in amputation, in-patient hospitalization, or loss of an eye. As part of the research effort, the severe construction injuries database is examined to extract incident precursors such as the source of the incident, incident outcome, nature of the injury, incident type, and others. Moreover, of the research effort aimed to examine if there are relationships between the various extracted attributes. For example, it will be examined whether or not a relationship exists between the trade focus of the injured worker and the experienced incident type. Such a deeper understanding of the incidents that workers experience in the construction industry is expected to offer valuable insights into how safety in construction workplaces can be enhanced.

<u>Challenge 3:</u> *Examining textual safety incident reports involving driver license examiners.*

Driver license examiners serve as the first line of defense against unsafe drivers and driving practices. Nonetheless, these examiners themselves are exposed to high levels of safety risk as they test new drivers – with limited driving proficiency and experience. A deeper understanding of the safety challenges that this community of workers experiences can inform the development of effective injury prevention policies and interventions. Towards achieving this goal, this research will present results from content analyses of safety incident reports maintained by the North Carolina Division of Motor Vehicles (NCDMV) that involved driver license examiners. More specifically, the content analysis will focus on extracting key incident attributes to identify high-priority problem areas that the driver license examiners experience and will seek to identify possible safety solutions that can address the safety incidents experienced by these examiners.

Challenge 4: *Assessing the impacts of regulatory changes on the construction industry*.

In recent years, a large number of regulatory changes that impact construction businesses and construction operations have been introduced. These changes can create much uncertainty across the project lifecycle including planning, design, execution, operation, and decommissioning stages. In fact, these regulatory changes can create significant disruptions as construction businesses strive the adapt to evolving regulations and statutory requirements. To better prepare construction organizations to tackle these evolving regulations, a data collection effort was conducted to gather details on how different construction organizations cope with these changes. This study's findings can help organizations better understand the effect of regulations on building and operating projects and better plan for regulation compliance.

Challenge 5: *Reducing claims and related outcomes during the construction of Transportation infrastructure projects.*

Undertaken projects by transportation agencies such as the construction of bridges and the expansion of highways often encounter utilities including pipelines, power lines, and telecommunication infrastructure during construction operations. In these circumstances, the transportation agencies and their contractors may have to temporality halt construction operations, notify various utility companies of the conflict, and request that the utilities be relocated to a different location. Unfortunately, when not efficiently handled, such interruptions can translate into significant cost overruns and project delays (Quiroga et al. 2019). In such circumstances, the contractor will submit construction claims to recover the cost and time associated with the experienced disruptions. Unfortunately, there has been a disproportionate number of such claims in projects that are being undertaken by the North Carolina Department of Transportation. To tackle this issue and reduce the number of claims and related outcomes, an analysis of the claims data that is maintained by the North Carolina Department of Transportation (NCDOT) will be presented. The objective of the effort is to unveil factors that contribute to such claims to identify relevant interventions and best practices to reduce any related risk.

1.2. Organization of the Dissertation

The following chapters provide an in-depth investigation of the five stated problems in the last section. Each chapter adheres to a typical article publication format with a distinct introduction, method, results, and discussions/conclusion (IMRaD) sections following the IMRaD structure (Swales and Feak 2004). Each chapter is intended to be submitted for potential publications in peer-reviewed journals. The title for each chapter in this dissertation is the title of the planned peer-reviewed article. Table 1-1 provides an overview of the following main chapters. The last chapter (not included in this document) is intended to be the dissertation's conclusion. The conclusion will include a summary, key research Contributions, and future research directions.

Table 1-1: Overview of the Dissertation's Main Chapters

Chapter	Title	Area	Data Source
2	Early Impacts of the COVID-19 Pandemic on the U.S Construction Industry	Disaster Management	Subject Matter Experts Interviews
3	Severe Injuries among Construction Workers	Occupational Safety	Governmental Open-source Database
4	Work-Related Safety Incidents among Driver License Examiners	Occupational Safety	Private Sector Database
5	Assessing the Impact of Regulatory Changes on Capital Projects in the United States	Regulations and Compliance	Organizational Surveys
6	Assessing Utilities-Related Claims on Transportation Projects	Infrastructure Management	Governmental Private Database

1.3. References

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Chapter 2: Early Impacts of the COVID-19 Pandemic on the U.S Construction Industry

Alsharef, A., Banerjee, S., Uddin, S. M., Albert, A., and Jaselskis, E. (2021). "Early Impacts of the COVID-19 Pandemic on the United States Construction Industry." *International Journal of Environmental Research and Public Health,* 18(4).

2.1. Abstract

The COVID-19 pandemic has been the largest global health crisis in decades. Apart from the unprecedented number of deaths and hospitalizations, the pandemic has resulted in economic slowdowns, widespread business disruptions, and significant hardships. This study focused on investigating the early impacts of the COVID-19 pandemic on the U.S. construction industry since the declaration of the national emergency on March 13, 2020. The study objectives were achieved through 34 telephone interviews with project managers, engineers, designers, and superintendents that represented different states and distinct industry sectors in the United States. The interviewees offered information on their experience with the pandemic including the general and adverse effects experienced, new opportunities created, and risk management efforts being undertaken. The reported adverse effects included significant delays on projects, inability to secure materials on time, reduction in productivity rates, material price escalations, and others. The new opportunities that were created included projects involving the fast-track construction of medical facilities, construction of residential buildings, transportation-related work, and opportunities to recruit skilled workers. The risk management measures that were widely adopted included measures to enhance safety and reduce other project risks. The safety measures adopted included requiring employees to wear cloth face masks, adoption of social distancing protocols, staggering of construction operations, offering COVID-19 related training, administering temperature checks prior to entry into the workplace, and others. Measures to manage other project risks included the formation of a task force team to review the evolving pandemic and offer recommendations,

advocating that construction businesses be deemed essential to combat delays, and taking advantage of government relief programs. The study findings will be useful to industry stakeholders interested in understanding the early impacts of the pandemic on the construction industry. Industry stakeholders may also build upon the reported findings and establish best practices for continued safe and productive operations.

2.2. Introduction and Study Motivation

The Coronavirus disease, also known as COVID-19, is caused by the virus named severe acute respiratory syndrome coronavirus 2 (i.e., SARS-CoV-2) (World Health Organization 2020a). The virus is confirmed as being transmitted from human-to-human and results in symptoms including fever, dry cough, fatigue, and shortness of breath (Centers for Disease Control and Prevention 2020). Since its first discovery by the World Health Organization (WHO) on December 31, 2019, the virus has spread to over 200 nations (World Health Organization 2020a). The WHO declared the crisis as first being a public health emergency of international concern on January 30, 2020 (World Health Organization 2020b). Later the crisis was declared as being a global health pandemic on March 11, 2020 (World Health Organization 2020c).

Given the rapid spread in the United States following the first detected case in January, a national emergency was declared on March 13, 2020 (White House 2020). Since then, the number of confirmed COVID-19 cases in the United States has continued to increase rapidly as can be seen in Figure 2-1 (The COVID Tracking Project 2020). As of January 3, 2020, over 20 Million confirmed cases and more than 350,000 deaths had been linked with the COVID-19 pandemic in the United States (The COVID Tracking Project 2020). Not surprisingly, the COVID-19 pandemic was identified as the leading cause of death in the United States in 2020 (Woolf et al. 2020).

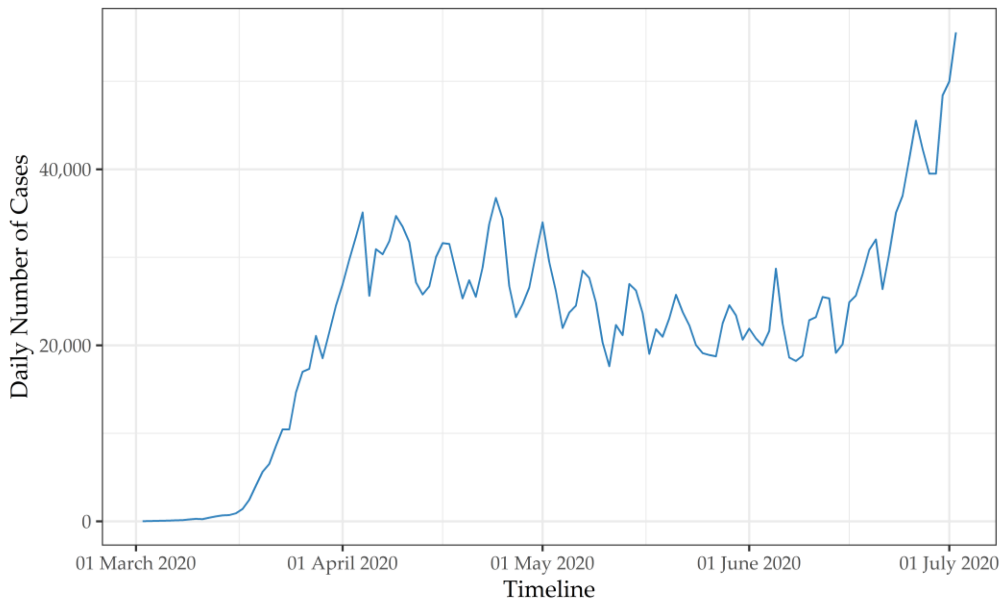

Figure 2-1: Daily Number of Confirmed COVD-19 Cases in the United States between March and July 2020 (i.e., Early impacts) as Reported by the COVID Tracking Project (The COVID Tracking Project 2020)

Apart from the widespread health crisis, the COVID-19 pandemic has resulted in a nationwide economic downturn. In fact, the National Bureau of Economic Research (NBER) announced that the United States has entered a recession phase in February – and called it the COVID-19 recession (Chodorow-Reich and Coglianese 2020; Gallant et al. 2020). Because of the economic downturn, the United States has experienced record-high unemployment rates. More specifically, from an unemployment rate of about 3.8% in February 2020, the unemployment rate peaked at roughly 14.7% in April 2020 (U.S. Bureau of Labor Statistics 2020). This corresponds to over 23 million individuals in the United States being unemployed – far exceeding the numbers experienced at any time during the Great Recession (i.e., 2007 to 2009) (U.S. Bureau of Labor Statistics 2020). The high unemployment rates resulted from the massive shrinkage in demand that has devastated industries including airlines, restaurants, manufacturing, and retail (Federal

Reserve System 2020; Goldman Sachs 2020; International Air Transport Association 2020). These unemployment rates have resulted in much financial distress among citizens; particularly among lower-income individuals and those that were unable to continue work (Pew Research Center 2020).

Like the other industries, the construction industry has also been impacted by the pandemic in a number of ways. For example, like other industries, the number of construction jobs available reduced following the pandemic onset – with the least number of jobs reported in April 2020 as shown in Figure 2-2 (U.S. Bureau of Labor Statistics 2021). These job losses are partly attributable to interruptions in work following work-related restrictions that were imposed to curb the virus-spread, shortage in PPE as they were prioritized for healthcare workers, and widespread market uncertainty. In addition, several construction projects were delayed and suspended; particularly in the oil-and-gas sector (e.g., West Loop Gas Pipeline, Liberty Pipeline, etc.), where the demand for oil dipped following travel restrictions (Pipeline & Gas Journal 2020; S&P Global 2020).

However, most importantly, a significant number of construction workers reportedly tested positive for COVID-19. In fact, a recent investigation from Los Angeles concluded that construction workers were reporting the highest number of positive cases; compared to workers in other industries including transportation, healthcare, and manufacturing (Allan-Blitz et al. 2020). Likewise, another study found evidence that construction workers are roughly five times more likely to be hospitalized as a result of COVID-19 than workers in other industries (Pasco et al. 2020). Several other state public departments have also highlighted the risk of COVID-19 infections particularly among the construction workforce (Bui et al. 2020; Michigan Department of Health and Human Services 2020; Washington State Department of Health 2020).

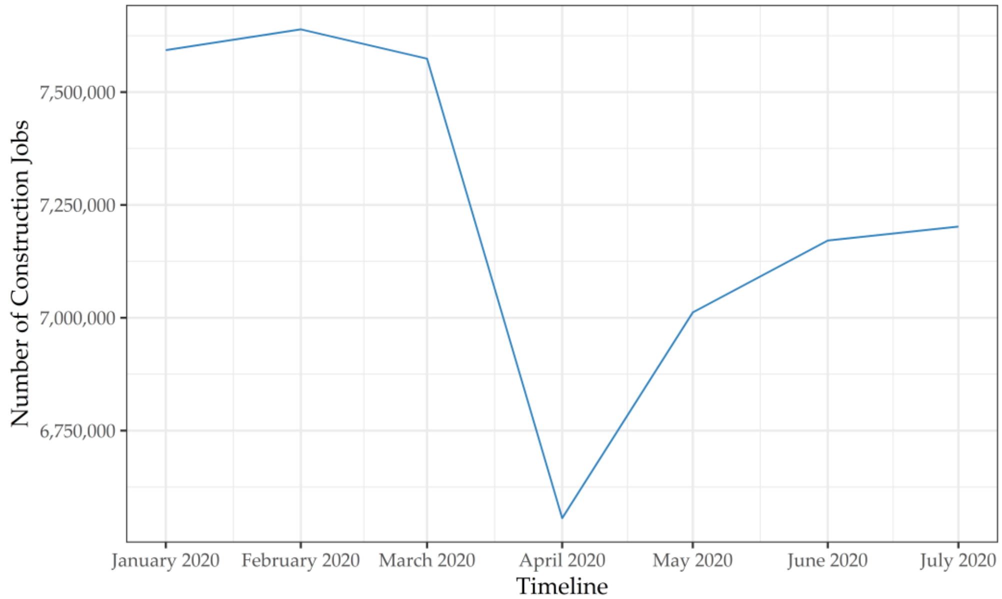

Figure 2-2: Construction Industry Employment Data between January and July, 2020 (i.e., Early Impacts) as Reported by the Bureau of Labor Statistics (BLS) (2021)

Although some preliminary surveillance data on the impacts of the COVID-19 pandemic in the context of the construction industry exists, there is much that remains unknown. Insights from industry stakeholders are particularly lacking in the broader literature. Accordingly, the reported effort focused on gathering information on the effect of the COVID-19 pandemic from the perspective of the construction workforce. The effort also focused on identifying new opportunities that may have been created and efforts that were undertaken to manage the challenges associated with the pandemic.

The findings are expected to be useful as the industry continues to combat the pandemic and grapple with preserving safety and maintaining productivity. The findings can also serve as a resource for the future if the industry encounters similar epidemics, pandemics, or emergencies.

2.3. Research Methods

To accomplish the research objectives, the research methods, as presented in Figure 2-3 was adopted. As can be seen, following a review of the limited and relevant research, a semi-structured interview template was developed. As per the template, after gathering information on the participant's background (i.e., professional role, workplace location, experience in no. of years, etc.), the responses to the following questions were targeted for solicitation:

- How has the COVID-19 pandemic affected the construction industry and the project/projects you are involved in (i.e., general and adverse impacts)?
- Have there been new opportunities for the construction industry as a result of the COVID-19 pandemic? If so, what are they?
- What efforts have been undertaken to manage the challenges associated with the COVID-19 pandemic in the context of the construction industry? Are there any related challenges that are being experienced?

As can be seen, the targeted questions covered three specific thematic areas that captured the impact of the pandemic on the industry. After the interview template was finalized, prospective Subject Matter Experts (SME) were identified through professional organizations including the Associated General Contractors of America (AGC), the Construction Specifications Institute (CSI), and personal contacts available to the research team. The effort resulted in the recruitment of 34 participants between April and May 2020 – which represented the data collection period to capture the early effects of the pandemic on the construction industry; following the declaration of the national emergency on March 13, 2020. Collectively, the participants possessed over 400 years of experience in the construction industry. Additional information on the background of the participants is presented in Table 2-1. It needs to be noted that certain participants were part of organizations that focused on multiple construction sectors and were involved in projects across multiple states. Accordingly, the total participant counts in the construction sector category and the state category exceeds the total number of participants (i.e., 34) to account for these overlaps. The presented percentage corresponds to the ratio between the count associated with each of the background information categories and the total number of participants (i.e., 34).

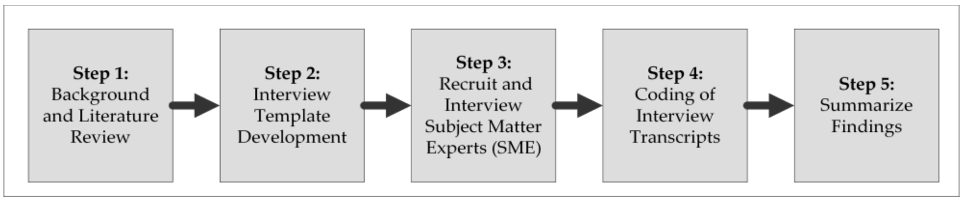

Figure 2-3: Adopted Research Process

The interviews were conducted via telephone to ensure the safety of the research team and the study participants. The responses of the study participants were transcribed as the conversations progressed. Follow-up questions and relevant examples were solicited for each of the questions to enhance the quality of the data and the insights gathered from the effort.

After the interviews were complete, the transcribed qualitative data was imported into the NVivo 10 software package for content analysis and coding. NVivo 10 offers powerful features, including the ability to search for keywords and iteratively select codes and subcodes (Bazeley and Jackson 2013). The interview transcripts were inductively and iteratively coded by the first three authors over multiple meetings until complete consensus was achieved. The codes used corresponded to the three themes that the study targeted and the subcodes were identified on an evolving and iterative basis as discussed above.

It is important to note that the codes and subcodes adopted were not necessarily mutually exclusive. Rather, the codes and subcodes were adopted to facilitate the presentation of the information gathered in a coherent manner for the purpose of the current article. The findings of the effort are summarized in the following sections.

Table 2-1: Summary of the Participants and their Organizations' Background Information

Construction Sector		
Construction Sector	**Count**	**Percentage (%)**
Commercial	23	67.65
Industrial	6	17.65
Infrastructure	9	26.47
Residential	11	32.35
Organization Type		
Construction Sector	**Count**	**Percentage (%)**
Contractor	25	73.53
Owner	7	20.59
Supplier	2	5.88
Job Role		
Role	**Count**	**Percentage (%)**
Project Manager/Engineer	26	76.47
Architect/Designer	6	17.65
Superintendent	2	5.88
Organization Size		
Size	**Count**	**Percentage (%)**
Less than 100	14	41.18
100–500	9	26.47
More than 500	11	32.35
Project Location (State)		
State	**Count**	**Percentage (%)**
Florida	9	26.47
Texas	5	14.70
Virginia	4	11.74
North Carolina	4	11.74
California	3	8.82
Arizona	2	5.88
New York	2	5.88
Illinois	1	2.94
South Carolina	1	2.94
Georgia	1	2.94
Kansas	1	2.94
Pennsylvania	1	2.94
Indiana	1	2.94
Washington	1	2.94
Arkansas	1	2.94
Washington, D.C.	1	2.94
New Jersey	1	2.94

2.4. Study Findings

The findings of the effort are organized on the basis of the three themes that the research targeted. However, as mentioned above, there was significant overlap in the content across the targeted areas. Therefore, the purpose of the division of the content in the following sections is only to present the gathered information in a digestible and coherent manner. Overall, the purpose of the organization is to offer a holistic understanding of the early impacts of the COVID-19 pandemic on the construction industry as captured from the interviews. Figure 2-4 summarizes the generated codes and subcodes under the three main themes (i.e., general and adverse impacts, new opportunities, and efforts to manage challenges).

2.4.1. General and Adverse Impacts of COVID-19 on the Construction Industry

2.4.1.1. Disparities across States on Whether Construction Operations are Essential or Non-Essential

In the first few months of the pandemic, stay-at-home or shelter-in-place orders were being enforced across several states to prevent the spread of the novel coronavirus. However, a few states did not require any such restrictions. In most states, construction businesses were deemed to be essential; however, a few states identified construction operations to be at least partly non-essential. Therefore, there were restrictions for construction operations in some states whereas there were no restrictions in other states. Among the states where construction operations were partly restricted, there was much variability in the degree of restrictions. Accordingly, there were many differences in how construction businesses were impacted across different states.

For example, some of the participants mentioned that there was little impact on their projects and that operations continued as normal; although a number of new safety measures were adopted. However, others mentioned that construction operations had completely ceased in their workplaces. A few participants shared that during the first few days, there was significant confusion on whether their business was deemed essential or non-essential due to the variability in the degree of restrictions across states. More specifically, it was unclear to the participants' employer whether they can continue operations. There was also much uncertainty on when construction operations will resume in several states where restrictions were in place. In other cases, the participants were concerned whether new restraints would be placed if COVID-19 cases increased in their communities.

In cases where construction operations were considered non-essential, one participant mentioned that the impacts are not limited to only construction businesses. The participant shared that upstream suppliers and the operations of several downstream facilities were also adversely impacted. In addition, the participant mentioned that several other industries that serve the construction industry such as manufacturing will also experience negative impacts.

A few of the participants believed that the restrictions were essential given the risk of the virus spread. Others believed that the economic and adverse impacts far exceeded the risk of the virus spread. One of the participants mentioned that several agencies were advocating for the reopening of construction businesses and to change the status of construction businesses as being essential.

2.4.1.2. Material Delivery Delays and Shortage of Material

Most of the participants reported experiencing or expecting delays in material delivery. These delays in material delivery were also, in turn, expected to delay overall project progress and cause significant schedule disruptions. The delays were particularly relevant when the supply chain involved material or raw material from overseas. For example, one of the project managers mentioned that several building elements were to be shipped from Europe; however, the manufacturing plants were non-operational in Europe due to the COVID-19 pandemic. Others mentioned similar supply chain disruptions involving material and raw material from China, Mexico, Canada, and other nations.

Even within the U.S., although construction was deemed as an essential business in a number of states, several upstream manufacturing units and trucking companies within the supply chain were deemed non-essential. Accordingly, some of these businesses had to halt operations in response to the pandemic. In another case, a vendor mentioned that material delivery delays can also occur because several truck drivers are hesitant to cross state lines due to fears of contracting the virus and the requirement of quarantining for 14 days as imposed by certain states.

Material shortage was also experienced as a result of the social distancing and quarantining requirements that resulted in a smaller workforce within supply chain organizations. In many cases, the study participants were unable to predict the amount of delays given the number of factors that can impact delivery time in a pandemic situation.

2.4.1.3. Delays in Inspections and Securing Permits

Significant delays in inspections and securing permits were also reported. For example, one of the interviewed contractors mentioned that as all parties transitioned to the new format of working, there were delays in completing inspections and the certification of work. More specifically, the contractor mentioned that the owner's representative in many cases was unable to stick to the initial timeframe to complete the certification of completed work. In many cases, several inspection-related meetings had to be canceled and postponed due to the challenges and restrictions of meeting in person.

The participants also shared that there were delays with securing permits from various governmental agencies. These delays were largely due to governmental agencies transitioning to working remotely from home and challenges associated with accessing the necessary information and documentation. In fact, in many cases, designers, architects, and project engineers mentioned that governmental agencies did not have an efficient and working system in place to make such a rapid transition. There were also discussions on the lack of sufficient technology-related support for these agencies as they grappled with making operational changes to the permitting process. In a few cases, the participants mentioned that the permitting processes were suspended temporarily until the governmental agencies were able to set up an online protocol for issuing the necessary permits.

2.4.1.4. Reduction in Efficiency and Productivity Rates

Productivity rates reportedly suffered across the construction industry. Much of the loss in productivity and efficiency was attributed to the new safety measures that were necessary to protect the workforce as the pandemic continued to progress. In fact, one of the project managers indicated that working safely was the top priority, and productivity took a backseat in the pandemic situation. Reduction in productivity rates also was attributed to shortages in the availability of PPE and the reduction in the number of workers to comply with the social distancing recommendations. In many cases, the participants also mentioned that workers choose to not report to work for a variety of reasons, which also impacted productivity and efficiency. Some of the reasons mentioned included quarantining requirements, caring for children as a result of school closure, and the fear of being infected at work and being carriers of the virus when around family. Recruitment and training of replacement workers also consumed substantial amounts of time.

The staggering of subcontractors in such a way so that they do not work alongside other subcontractors also was mentioned as affecting productivity rates. One of the participants mentioned that such staggering required significant revisions to the initially planned schedule and required much additional work and coordination. Inefficiencies in coordination along with the safety contingencies that were applied yielded lower productivity levels.

Cash flow challenges experienced by contractors and subcontractors were also mentioned as affecting productivity. Cash flow issues were particularly a problem due to escalating material prices and challenges that owners experienced with making timely payments to the contractors. Finally, as already discussed above, delays in material delivery, shortage on material availability, and delays with inspections and permitting were all also associated with productivity losses.

2.4.1.5. Suspension or Slowing of Ongoing Projects and Delay in the Start Date for New Projects

Given that the pandemic caused widespread economic downturns and uncertainties, owners, investors, and businesses were increasingly wary about investing in construction projects and operations. Therefore, a number of projects were canceled or temporally suspended. For example, one of the participants mentioned that several developers of commercial property, in particular, are increasingly waiting on the commitment from potential tenants before they can begin customized construction operations. However, the volume of potential tenants willing to make a commitment has significantly reduced as a result of the pandemic. In the same manner, one participant mentioned that with the plunge in the price of oil and the drop in the travel demand, a number of projects in the oil and gas sector have been suspended. The participant also mentioned that the budget devoted to oil and gas projects in the near future is expected to dramatically reduce.

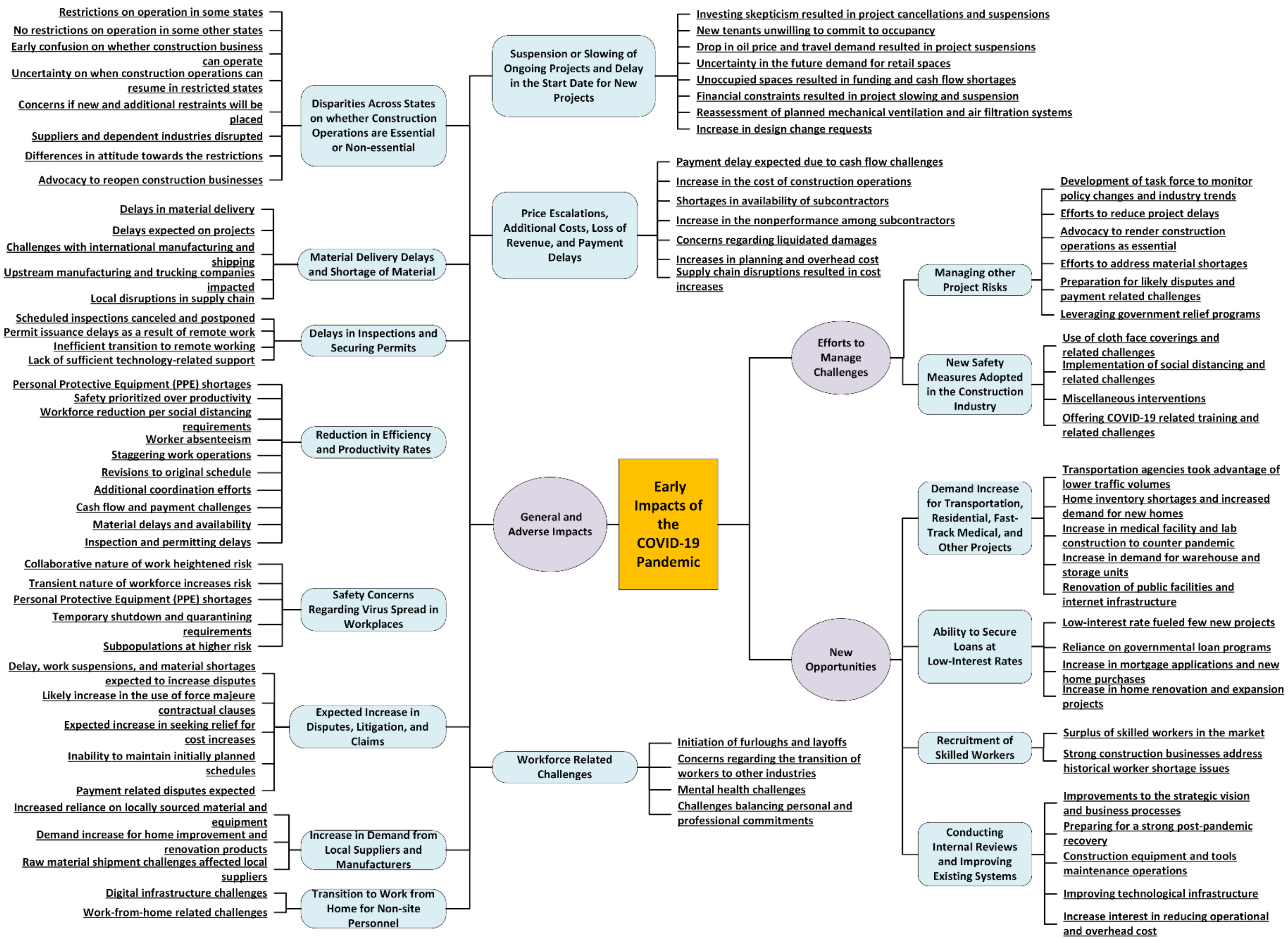

Figure 2-4: Themes, Generated Codes, and Subcodes from the Interviews

In many other cases, the study participants reported that several private owners are citing financial concerns with the broader market and requesting that construction operations be either slowed or stalled. According to one architect, with the increasing number of individuals working, shopping, and studying over the internet, the future of retail and commercial property remains uncertain. The participant also mentioned that it is unlikely for the demand in these sectors to rebound in the immediate future and hence it may not be financially prudent to make progress in many of the ongoing projects.

One of the owners asked the contractors to slow the completion of a student apartment since students were not expected to report to the college-town as classes were being taught online. Several of the owners experienced cash flow issues from existing properties and were unable to fund the completion of additional properties.

New construction projects were particularly impacted. One project engineer working for an industrial contractor reported that nearly 90% of the projects that were in the front-end loading (FEL) phase (i.e., pre-project planning) were put on hold. Moreover, several projects that were in the bidding stage were also canceled or postponed. One of the participants mentioned that fewer projects will be approved and funded as a result of the pandemic compared to previous years.

Another important reason for slowing down ongoing projects was the increase in requests to reassess the mechanical ventilation and air-filtration systems. One of the architects mentioned that owners were now concerned with whether the mechanical ventilation and air-filtration systems would adequately replace contaminated air with clean air. In several cases, owners requested upgrades to the initial design to offer superior occupancy safety. There were also concerns on whether design changes will need to be incorporated in a post-pandemic world in anticipation of future events.

2.4.1.6. Price Escalations, Additional Costs, Loss of Revenue, and Payment Delays

According to several of the participants, the supply chain disruptions resulted in an increase in the cost of construction materials. As discussed earlier, much of the disruption resulted from the closure and reduction in the capacity of manufacturing and processing facilities that are upstream in the supply chain. The increase in the cost of lumber, cement, and concrete products was particularly highlighted by a number of participants. Along with the increase in the cost of material, an increase in the cost of doing business was also reported. In many cases, the participants mentioned that this resulted in unexpected revenue and financial shocks at various points in the supply chain. In some cases, the participants mentioned that construction businesses may have to handle the extra costs themselves unless there is relief from the owners and other stakeholders as per the contractual agreement. This included the additional costs of managing safety, offering pandemic-related safety training, and securing the necessary personal protective equipment (PPE) to sufficiently protect the workforce.

An increase in costs was also experienced since fewer subcontractors were willing to work and travel during the pandemic. According to one of the project managers, subcontractors that had to cross state lines were particularly hesitant to work given that they preferred to stay in their city of residence and avoid the 14-day quarantining requirement imposed by some states. In such cases, subcontractors often had to be offered larger compensations and incentives which resulted in higher costs and potentially lower quality. An increase in the number of nonperformance among subcontractors was also reported to increase costs.

Several contractors also expressed concerns with respect to additional costs from liquidated damages. The contractor representatives mentioned that the delays caused in the projects can result in these additional liabilities and this can in turn impact the profit margins and the success of the projects.

Contractors were concerned that their staff will spend additional time on projects as a result of the experienced delays. This additional time was expected to translate into additional costs and overhead. Likewise, owners were concerned about the loss of revenue that was expected due to project delays and unoccupied retail and commercial properties. The participants were also concerned regarding the additional costs associated with the planning efforts that were necessary to transition successfully through the pandemic. Others alluded to the cost of shutting down projects and restarting the project as a major cost item that construction businesses will largely have to bear.

As construction operations are delayed, several participants mentioned that payment delays are likely to follow. The participants believed that this can result in cascading cash flow issues and some contractors may struggle to pay their workforce, subcontractors, and suppliers in a timely manner.

2.4.1.7. Safety Concerns Regarding Virus Spread in Workplaces

There was much concern regarding the spread of the virus in construction workplaces. The participants were of the opinion that construction work is inherently collaborative and requires that different trades work alongside each other. In many cases, this requires workers to share workspaces and facilities including portable bathrooms. Therefore, some of the participants believed that the risk of the virus spread is significantly high and that robust safety measures were to be adopted to protect workers. However, given the collaborative nature of the work, several participants mentioned that safety guidelines such as social distancing were not very feasible in construction workplaces. In fact, concerns were expressed that the safety measures recommended.

for adoption in construction workplaces may have been developed without any consultation with construction professionals that are more familiar with construction operations.

Some of the participants mentioned that the risk of transmission is particularly high given that infected individuals may not particularly experience any symptoms in the early stages of the infection and can be an active carrier of the virus. There was also mention that the risk is exacerbated by the fact that tests were not widely available and even when workers had access to tests, there is usually a delay in receiving the test results. One of the supervisors mentioned that the risk of spread is undoubtedly higher in industries that are identified as essential but experience shortages in PPE and effective measures to prevent the virus spread.

Others discussed that several subcontractors work on different sites. Therefore, one of the participants mentioned that these subcontractors can spread the virus from one workplace to the other. In fact, according to one of the project managers, one of the subcontractor employees that newly transitioned into a workplace tested positive for the virus. In response, the project had to be temporarily shut down and the other workers that worked in the proximity of the positively tested worker had to quarantine for 14 days. This resulted in significant paperwork and related challenges. Similar challenges were expected as a result of the transient nature of the workforce including independent contractors. Suppliers and delivery personnel that visit different sites were also expected to pose a higher risk of virus spread.

A few participants shared that Hispanic and Latino workers may particularly be at a heightened risk of infection given their greater involvement in essential work within and outside the construction industry. Others mentioned that the lower wages, immigration status and associated challenges, social connections with other essential workers, and their role as independent contractors in the industry expose these workers to higher risks.

2.4.1.8. Expected Increase in Disputes, Litigation, and Claims

Most of the participants expected that there will be a significant increase in the number of disputes, litigations, and claims on their projects and across the industry. They believed that the delays, temporary suspension of work, material shortages, and the additional costs that resulted from the pandemic will likely be the underlying cause for the disputes, litigations, and claims. The majority of the conflicts were expected between contractors and owners for nonperformance and delays. However, disputes were also expected in contractor-subcontractor, contractor-supplier, owner-future tenant, and contractor-insurance entity relationships.

Given the circumstances, the participants mentioned that there will be an increase in the use of the force majeure contractual clause where contractors and subcontractors claim that the delays experienced were caused by circumstances that were unforeseeable and beyond their control. If contractors and subcontractors are able to successfully offer the relevant evidence, they may be able to secure a time-extension and relief from delay-related penalties. In circumstances where a force majeure or another relevant contractual clause is absent in the contractual agreements, the contractors may seek relief in other ways. Disputes and conflicts become particularly likely when there are disagreements between the parties about the cause of the delay or the interpretation of the force majeure related contractual language. The participants also mentioned that likelihood of disputes and litigation can increase if the owner has a future tenant that has committed to occupying the constructed facility.

Some participants also mentioned that contractors and subcontractors may seek relief for the increase in cost. The likelihood of success in these circumstances is dependent on the pricing mechanism adopted per the contractual agreement. Contractors and subcontractors will also likely examine the contract to see if there are provisions to claim additional compensation using price escalation clauses. In some situations, there could also be disagreements with insurance agencies on whether the insurance policies offer coverage for a broad array of expected construction risks including nonperformance.

Other areas for conflict that the participants shared included the inability of suppliers to deliver construction material in a timely manner, suppliers seeking to cancel delivery commitments, and suppliers seeking additional compensation for losses sustained from supply disruptions.

There were also many discussions about disputes related to payments. Because of the market uncertainty, cost overruns, and cash flow challenges, it was expected that owners, contractors, and subcontractors will experience financial hardships. Therefore, the parties involved may struggle with making timely payments and honoring the commitments if cash reserves are unavailable to them. In the context of contractors and subcontractors, one of the participants mentioned that the biggest challenge is going to be cash flow issues. More specifically, the participant shared that contractors and subcontractors will need to pay suppliers after the material is delivered; however, they will receive their payment only once the material is incorporated in the facility under construction. Therefore, contractors and subcontractors were particularly expected to experience cash flow related challenges and claims.

Regardless of the conflicts and disputes experienced in the current pandemic, several participants mentioned that the pandemic has prompted industry stakeholders to take a closer look at the contractual documents and examine clauses that offer relief in uncertain circumstances. Additional information on some of the risk management effort planned in the industry is presented in *Managing Other Project Risks* section.

2.4.1.9. Workforce Related Challenges

The participants shared considerable information about workforce-related challenges. Most participants shared that a large number of furloughs and layoffs are being initiated as the workloads in the construction industry are projected to decrease substantially. In fact, one of the project engineers mentioned that the projected workload reduction will range between 50 and 60% compared to the previous years. In addition, several participants mentioned that contractors and subcontractors are experiencing significant challenges with cash flow and that these furloughs and layoffs are necessary as these businesses will not be able to make the payroll. Moreover, several participants mentioned that there is much uncertainty in the future and the demand for craft workers remains unclear given the early stages of the pandemic. Apart from craft workers, project engineers, estimators, administrative employees, and others were also likely to be impacted by furloughs and layoffs.

A significant challenge reported by some of the participants were the long-term effects of the pandemic on the construction workforce. For example, several project managers and supervisors alluded to the economic downturn that was previously experienced during the great recession when a large number of construction workers abandoned the construction industry to join other industries. These participants mentioned that these workers never returned to the construction industry following the recovery and that this has resulted in a large deficit in the number of skilled workers in the industry. The participants were worried that the current pandemic will further aggravate the situation if the laid-off workers choose to transition to other industries and not return.

Another problem that was discussed was the mental health challenges that workers experience in these uncertain times. For example, a few participants mentioned that a significant portion of the workforce are worried about their future prospects in the industry and the possibility that they may be laid off or furloughed. One participant mentioned that these workers have their own financial obligation, a family to care for, and rent and housing payments to make – which are all significant stressors for the workers. Some others, as discussed earlier, mentioned that workers are anxious that they may be exposed to the virus in the workplace and that many of the safety measures are not realistic to adopt or are not sufficiently enforced in construction workplaces. In addition, as discussed earlier, a supervisor mentioned that workers are often unable to report to work due to childcare unavailability, closure of schools, and caretaking responsibilities for sick family members; and these stressors impact their mental health.

One of the project managers mentioned that the social distancing requirement is also resulting in limited interactions among crewmembers; which may also contribute to mental health challenges. The project manager added that he had come across the term physical distancing which must replace the use of the term social distancing. The participant believed that such a change would better communicate the intent of the social distancing safety measure and argued that complementary efforts must be adopted to build comradeship between workers during this difficult time.

2.4.1.10. Increased in Demand from Local Suppliers and Manufacturers

Given that there were significant delays with material delivery particularly from overseas and across the country, many workplaces began to proactively adopt measures to find alternative material sources to reduce the risk of project delays. Preference was given to alternate local suppliers and manufacturers where the likelihood of delivery on short notice was higher. In many cases, contractors, in consultation with the architects and the designers were able to identify alternate material and equipment that local suppliers and manufacturers were able to quickly ship.

Therefore, these local suppliers experienced a significant spike in demand. More specifically, according to one of the suppliers, their sales substantially increased when compared to previous years. There was also additional demand from local suppliers for supplies such as disinfecting wipes, cleaning supplies, sanitizers and sanitizer stations, and acrylic glass (e.g., Plexiglas) that were necessary as safety measures during the pandemic for offices, retail spaces, and educational institutes.

In addition, because of the stay-at-home orders, a supplier mentioned that a larger proportion of the public began new home improvement and renovation projects. Therefore, there was an increase in demand for material for these small-scale projects. However, the supplier also mentioned that they were running low on stocks since they had not anticipated or planned for a surge in the demand. Moreover, these local suppliers were also unable to receive shipments of the raw material that they needed from outside sources to meet the local demand.

2.4.1.11. Transition to Work from Home for Non-site Personnel

In response to the pandemic and to enhance safety, a significant number of non-site professionals were able to transition to working from home. However, several participants mentioned that they experienced a significant number of challenges. For example, businesses did not have the necessary digital infrastructure to make the transition easy in many cases. Therefore, there were significant challenges with gaining access to necessary software packages and other resources which resulted in much inefficiency. In many cases, the businesses needed to make additional investments into technology to enhance their ability to efficiently work from home. For example, several businesses invested in Virtual Private Networks (VPN) to gain access to resources and software packages such as computer-aided design (CAD) remotely. Few organizations mentioned that they already had cloud solutions to access licensed software packages and business databases – which made the transition relatively easy.

In several other cases, the participants mentioned that there were additional challenges with making the transition because much of the workforce was not familiar with the newly adopted digital solutions. For example, certain individuals were not familiar with using Virtual Private Networks (VPN) to connect remotely to the business network. Others experienced challenges with adopting new communication platforms such as Zoom, Microsoft Teams, and Slack. Some employees also found it challenging to connect their business computers to their home network for a variety of reasons. Few participants also mentioned internet outages and poor internet quality as major challenges associated with remote working.

Apart from technology-related challenges, a few participants mentioned that there were more distractions at home that interfered with their ability to work effectively. In addition, many of the employees also had additional duties at home such as taking care of their children given that schools were online and childcare was not operational.

Because of the many challenges that employees experienced with technology and working from home, a few organizations decided to ask their employees to return to the office after providing safety measures such as acrylic (e.g., Plexiglas) panels between desks, sanitation stations, and sufficient spacing between workspaces.

2.4.2. New Opportunities as a Result of the COVID-19 Pandemic

2.4.2.1. Ability to Secure Loans at Low-Interest Rates

The participants shared that one of the largest opportunities comes from the low-interest rates that are available to owners, contractors, and potential home buyers. For example, one of the project managers indicated that they just secured a new project involving the construction of a hotel as the owner was able to secure a loan with a much lower interest rate than usual. The project manager also mentioned that such low-interest rates are rare and that this offers a good opportunity for strong businesses to grow and be prepared to take advantage of the markets when the recovery begins. There were also participants that discussed the availability of the small business loan program, commonly known as the PPP loans or the Paycheck Protection Program, that small contractors were leveraging to ensure that their employers were paid and that their workforce successfully weathered the ongoing pandemic.

The participants also mentioned that the demand for new residential construction is likely to increase because potential buyers can lock-in a low-interest rate for the life of the mortgage that can go up to 30 years. One of the participants mentioned that a few families are expected to spend more on residential expansion projects by leveraging the low-interest rates as they will spend more time in their homes; which will benefit small contractors. Also, few participants mentioned that potential home buyers are moving from rented properties in cities to the suburbs where they can purchase larger and more spacious homes using the low-interest rates; which will also increase sales in the residential sector.

2.4.2.2. Demand Increase for Transportation, Residential, Fast-Track Medical, and Other Projects

A large number of participants shared that the demand for a variety of construction projects has increased. For example, one of the project managers stated that Departments of Transportation (DOTs) are approving new projects and accelerating ongoing ones to take advantage of the lower traffic volumes following the shelter-in-place orders. The project manager added that this is a rare opportunity to work on infrastructure and highway projects, particularly in urban areas, where high traffic is typically a major concern and can result in much inconvenience and delays to drivers. In fact, one of the contractors from Texas reported that the limited volume of traffic has offered more lane closure opportunities and has allowed for the acceleration of projects. Another project engineer reported that the pandemic has enhanced the safety and productivity of workers as the traffic flow has reduced. Another manager mentioned that the pandemic has offered an opportunity to safely work on infrastructure projects that have been neglected for decades.

In terms of residential projects, apart from the additional demand following the reduction in the mortgage and interest rates, demand for new construction was expected to increase as the inventory of homes in the market were expected to reduce. This was because fewer owners of existing homes were expected to list their homes for sale and allow public access to their properties during a pandemic. The shortage of inventory was expected to increase the sale of new homes.

Apart from transportation and residential projects, given the medical emergency that was being experienced due to the pandemic, the participants believed that more fast-track medical and patient care facilities will be built and renovated. Additional construction projects were also expected to build new research centers and medical labs to counter future medical emergencies.

In the commercial sector, many participants believed that there will be an increase in the construction of warehouses and storage units to support the substantial increase in online shopping. The participants mentioned that many of the retail spaces are also likely to be renovated as new warehouses as the demand for retail space reduces. The demand was further expected to increase as a growing number of businesses were expected to transition into the online shopping space.

Other projects that were expected to increase as a result of the pandemic included renovation work in universities and schools as students were away from campus, office renovations in preparation for employees to return and work safely during a pandemic, utility work as the number of internet subscribers increased and traffic flow reduced, and renovation of public buildings such as museums and public offices with the decline in the number of visitors.

2.4.2.3. Recruitment of Skilled Workers

As discussed above, a large number of furloughs and layoffs were expected not only from the construction industry, but also from other industries including retail, manufacturing, and airlines. While this was an adverse outcome for many organizations and workers, a few participants believed that their organizations benefitted from the situation. More specifically, these participants stated that while the industry in the past suffered from a shortage of skilled workers, suddenly there was a surplus of skilled workers looking for positions in the market. A project manager mentioned that their organization was able to recruit a number of skilled and experienced electricians that were typically difficult to come across in the industry. The project manager mentioned that well-established and financially-strong contractors will particularly benefit from their ability to hire a strong workforce.

2.4.2.4. Conducting Internal Reviews and Improving Existing Systems

With a reduction in the workload experienced in the construction industry and fewer new opportunities, many construction businesses resolved to perform comprehensive evaluations of their processes and systems to identify areas for improvement. As per several participants, their construction businesses began to examine their strategic vision, partnerships, their execution plans, their bidding approach, risk assessment approach, material planning protocol, software resources, and others to identify inefficiencies and strategic efforts that can be adopted to enhance success. According to one participant, these businesses focused on coming out stronger at the end of the pandemic and ready to thrive in a post-pandemic market with improved processes and systems.

Several organizations focused on performing maintenance operations for their construction equipment and tools. Two project managers mentioned that their organizations are examining the prospect of switching a larger number of positions to work-from-home positions. These managers argued that such a change can allow them to transition to a smaller office while reducing overhead costs and improving flexibility. Several businesses resolved to improve their technological infrastructure to better facilitate collaborations between suppliers, subcontractors, and other partners. One of the participants shared that their organization was in the last stages of proposing a new organizational structure to enhance communication channels and accountability.

2.4.3. Efforts to Manage the Challenges of the COVID-19 Pandemic

2.4.3.1. New Safety Measures Adopted in the Construction Industry

The participants reported a number of safety measures that were being adopted along with their implementation challenges. Among others, the use of cloth face coverings was enforced widely in construction workplaces. However, in many cases, there were significant shortages in the availability in face coverings in the market and workplaces. Moreover, workers often forgot to bring their face coverings to work when they returned the next day, which further aggravated the shortage of face masks and coverings in many cases.

Even when face coverings were available, several supervisors reported that it was challenging to enforce the requirements in workplaces. For example, several workers often removed the face coverings due to discomfort and fogging of safety glasses. Workers also often complained of their discomfort with the masks, especially when performing strenuous tasks that were associated with a higher breathing rate and perspiration. Workers also expressed discomfort when working in humid conditions with their face coverings. In many other cases, workers often covered their mouths but did not cover their noses; which limits the effectiveness of cloth face coverings. Another supervisor mentioned that even when workers placed the mask correctly over their nose and the mouth, it often would not stay in place and would fall below the nose as they worked. Another significant challenge was that workers often reused face coverings without rewashing them. However, this was unrealistic to monitor as per one of the supervisors.

Workers and employees were also given instructions to follow social distancing guidelines. In addition, to promoting social distancing efforts, several other approaches were adopted to support social distancing among site personnel. These included staggering work crews such that different work crews reported to work at different times to limit the number of workers in the workplace at the same time, posting signage to remind workers of the requirements of social distancing, preventing food trucks from coming into the site that typically encouraged crowding, limiting the number of workers in the breakroom, setting-up open public break and lunch spaces, closing the site trailer, use of social distancing floor markers placed 6ft. apart, encouraging nonessential workers to work from home, asking supervisors to work from their trucks or vehicles, reducing and postponing work in confined spaces, and others. While these efforts were all useful, some participants mentioned that it was unrealistic to maintain the 6ft. requirement between each of the workers at all times due to the collaborative nature of construction operations; where workers are required to work alongside each other. Moreover, like monitoring the usage of face covering, it was unrealistic for site personnel to monitor that workers always followed social distancing guidelines as work progressed.

One of the supervisors mentioned that when workers used face coverings, many believed that the 6ft. social distancing requirement no longer applied; as the face covering offered sufficient protection. The supervisor mentioned that this belief is untrue and the recommended practice is to adopt multiple safety measures to limit the likelihood of virus spread. In a number of instances, the supervisor mentioned that safety professionals must intervene were when such behaviors are observed.

Another widely adopted safety measure was offering workers and site personnel training on the safety risks of COVID 19 and the safety measures that are to be adopted. The biggest challenge of delivering these training sessions was that the traditional classroom-type training approaches were no longer safe given the social distancing guidelines. Therefore, new training approaches that comply with the social distancing requirements were necessary. Some of the employers tried to adopt online training sessions. However, technology constraints were a significant issue because workers often did not have access to compatible computers and phones. Computer literacy and access to good internet was also a challenge in many cases. In several other cases, the contractors and the subcontractors did not have the infrastructure necessary to deliver training programs online given the unexpected demand for online training. Therefore, in some cases, training was offered over conference phone calls. However, trainers struggled with this format of training since the conversations were largely one-sided with little to no participation from the training participants. In many cases, according to a participant, it was not clear if the workers were actually paying attention or benefiting from the training. Moreover, the inability to see the facial expressions of the training participants was a challenge for trainers as they were unable to see the facial expressions as is the case in a classroom-type training setting. To overcome all of these challenges, some of the employers offered the training in open spaces in the workplace while also complying with the social distancing requirements.

Other safety measures that were adopted without much challenge were administering temperature checks prior to entry into the workplace, the placement of sanitizers and hand wash stations at the entrance and various locations in the worksite, disinfecting tools and surfaces, discouraging sharing of tools and equipment including PPE, encouraging workers with any COVID-19 like symptoms to remain at home, adopting air purification and filtration systems, and others. One concern that was reported by a supervisor regarding the temperature checks was the concern regarding the accuracy of these checks. More specifically, the supervisor was concerned that the temperature checks may be impacted by ambient temperature and environmental conditions if testing was performed in a non-controlled location (e.g., open space at the entrance to the workplace).

2.4.3.2. Managing Other Project Risks

Given the rapid change in governmental policies during the pandemic, several participants reported that their businesses maintained a task force or team of qualified employees or consultants who were tasked with examining proposed governmental policies and industry patterns to identify best practices for risk management. In many cases, such a task force or team was also delegated the responsibility of identifying and adopting safety measures that were recommended for the safe operation of construction workplaces. The taskforce continuously updated operational plans and offered guidance to the site leadership on managing work in construction workplaces. In one of the projects, while they did not have the resources to support a task force, one of the project managers examined the lessons learned database and past claims to identify possible solutions that were proposed in the past that may apply in the current crisis.

Much of the input that participants shared was related to managing delays on their projects; which appeared to be the largest risk apart from the safety concerns being experienced. Some participants mentioned that delays on their projects were inevitable and only the impacts of the delay can be minimized. Others mentioned that they were reviewing their original schedules to make modifications that may be helpful in reducing delays. For example, some participants mentioned that they were considering the adoption of night and weekend shifts. One of the project managers mentioned that the introduction of additional shifts would also be helpful given that one of their subcontractors were not willing to share the workplace with other trades because of the safety risks during a pandemic. Several other participants mentioned the work of several advocacy groups, trade unions, and associations such as the Associated General Contractors (AGC) of America, North America’s Building Trades Unions (NABTU), and the American Subcontractors Association (ASA) that were urging governmental agencies to render construction activities as being essential for recovery and offering exemption from shelter-in-place orders. According to these participants, if these efforts are successful, significant delays and associated hardships will be alleviated.

Another area that was highlighted was efforts to reduce the impacts of material delivery delays and related challenges. One of the participants mentioned that some businesses that were proactively monitoring the evolving pandemic were able to place material delivery requests prior to when deliveries became more challenging and shortages of supplies were experienced in the market. Some other subcontractors were able to resolve these issues by finding alternate vendors and local suppliers that were able to deliver material on time. Several other contractors were examining the project schedule to identify material that was needed throughout the project cycle and actively contacted vendors to ensure that they will be able to make deliveries as planned. Nonetheless, several workplaces were unable to find alternate approaches to have the material delivered as per initial plans; particularly when customized products and fabricated elements were necessary.

As projects were experiencing delays and price escalations, several participants mentioned that they began reviewing the contracts to assess expected impacts and provisions that they can use in their defense. Several participants mentioned that they were keeping detailed records of the causes of the delays and price increases with the hope of requesting additional time and compensation. Such records were also expected to be useful to manage the risk of liquidated damages and delay-related penalties. Several of the participants also mentioned that such records will be useful for their defense if disputes or ligations occur on their projects. Apart from these efforts, few project managers mentioned that they were working on notices that were planned to be sent to project owners alerting them of expected delays and cost escalations.

One of the other major risks that was expected was cash flow issues as a result of price escalations and delayed payments. Several participants mentioned that businesses were taking advantage of various governmental programs and reliefs to alleviate some of the challenges. These included new loans and economic relief plans that were becoming available for small businesses such as the Paycheck Protection Program (PPP). One of the supervisors mentioned that an employer planned to use these programs to pay their workforce and ensure that they maintain their trained employees and skilled workers despite the pandemic. The supervisor mentioned that this was important for the long-term success of the business as the construction industry has struggled with labor shortage issues. One of the participants mentioned that their organization maintained a generous contingency and emergency account which will be used to address the experienced cash flow challenges.

2.5. Study Limitations and Suggested Future Efforts

While the study makes important contributions, there are a few limitations that may be addressed in future efforts. First, although the study captures important findings related to the effects of the COVID-19 pandemic on the construction industry, there may be additional effects that may have not been captured in the current study due to a number of reasons. For example, the exploratory nature of the study was designed to only capture the effects of the pandemic as experienced by the participants involved in the study. While the participants represented 17 states across four different sectors with varying roles, there are a number of states and stakeholders that were not represented in the reported effort due to the time constraints associated with capturing the early effects of the pandemic and limitations on the resources available to the research team. Nonetheless, it needs to be noted that the participating professionals were socially connected with other professionals and stakeholders across the United States and shared a significant amount of pertinent and useful information.

Second, the scope of the article was only limited to the early effects of the pandemic as experienced between the declaration of the national emergency in the United States on March 13, 2020, and May 30, 2020, when the data collection efforts were concluded. Therefore, the effects of the pandemic and the related management efforts that may have occurred after the targeted timeline may vary. For example, given the evolving nature of the pandemic, it is unclear what the future will look like as the industry continues to grapple with the pandemic.

Third, while the current effort offers an overview of the effect of the pandemic on the construction industry as reported by industry stakeholders, it does not offer quantitative findings such as the average delay experienced, the average cost overruns expected, or the financial impacts on organizations. Future efforts may build upon the current findings to quantify the impacts of the pandemic on the industry. Future effects may also focus on investigating the effects of the pandemic on the global construction industry and developing universal state-of-the-art solutions to tackle the continued crisis. Efforts may also focus on vetting interventions and best practices to prepare for future unexpected pandemics and emergencies.

2.6. Conclusion

The COVID-19 pandemic has resulted in substantial disruptions and hardships across nations and industries. Like the other industries such as airline, retail, and restaurants, the construction industry has also been impacted in a number of ways. Through interviews with Subject Matter Experts (SME), the current article focused on cataloging the early impacts on the pandemic as reported by construction stakeholders. The study findings identified that the construction industry experienced a number of adverse effects. These included material delivery delays, shortage of material, permitting delays, lower productivity rates, cash flow related challenges, project suspension, price escalations, and potential conflicts and disputes.

Despite the number of challenges, there were a number of new opportunities that were experienced in the construction industry as a result of the pandemic. These included opportunities that resulted from lower interest rates; demand increase in the medical, transportation, and residential sectors; and the ability to recruit skilled workers.

The research effort also unveiled specific efforts that were adopted to manage the challenge of the COVID-19 pandemic in construction workplaces. These included safety measures such as requiring workers to wear face coverings, implementing social distancing guidelines, adopting COVID-19 related safety training, and encouraging work-from-home initiatives. Other risk management measures to combat the effects of the pandemic included establishing a task force that is tasked with offering COVID-19 related guidelines, proactive steps to reduce the risk of delays, advocacy efforts seeking to establish construction operations as being essential and leveraging governmental relief programs to preserve businesses and the workforce.

The presented research offers an understanding of the impacts of the COVID-19 pandemic on the construction industry. The findings of the effort will be useful to governmental agencies as they seek to elevate the adverse effects experienced in the construction industry. Industry representatives may use the findings to identify risk management efforts that may be appropriate for their own organizations. Researchers may use the findings to identify problem areas and propose relevant interventions to support the efforts of the industry.

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Chapter 3: Severe Injuries among Construction Workers

3.1. Abstract

Construction workers continue to sustain unacceptable numbers of workplace injuries. These workplace injuries have economic impacts besides human suffering. However, the impacts of these injuries carry more effect if the sustained injury is classified as severe or serious. On January 1, 2015, the Occupational Safety and Health Administration (OSHA) began requiring all occupations working under its authority to report severe workplace injuries. This study obtained construction-related reports and leveraged frequency and categorical data analyses techniques in assessing the cases. Between the program's start and February 28, 2021, more than 11,000 severe construction injuries were reported to the new database, ranking the construction industry second behind the manufacturing industry. Furthermore, an analysis of the injuries' attributes revealed the following key findings: (1) the most common event types are falls to lower level followed by struck-by object or equipment; (2) the top two construction sectors to sustain severe injuries are commercial and institutional building construction contractors and electrical contractors and other wiring installation contractors; (3) the most frequently associated sources with such injuries are ladders and structural elements (e.g., roofs and windows); (4) the most commonly injured body parts are upper extremities, lower extremities, and trunk; (5) the top two sustained injury natures are traumatic injuries to bones, nerves, and spinal cord, followed by open wounds. The results also unveiled overrepresented relations between the attributes' categories which can be used in performing risk assessments. The findings can inform future mitigation efforts that aim to reduce the rate of severe injuries among construction workers.

3.2. Introduction

The construction industry plays a vital role in the U.S. economy. According to the U.S. Bureau of Labor Statistics (BLS), the construction industry employed nearly 7,494,000 workers in 2019 (BLS 2021a). Additionally, the U.S. Bureau of Economic Analysis (BEA) estimated that the construction industry accounted for nearly 4.2% of the U.S. gross domestic product in 2019 (BEA 2021). During the early months of the COVID-19 pandemic, construction businesses were mostly considered “essential” while shelter-in-place orders were being enforced in many states (Alsharef et al. 2021). It is also projected that there will be a substantial demand for new infrastructure projects and rehabilitation of existing ones, given that the American Society of Civil Engineers (2021) recently assigned a C grade to the current infrastructures.

While the construction industry plays an essential role in economic development, the industry also struggles with several challenges. One of its main challenges is poor safety performance. Unfortunately, the construction industry continuously reports high injury rates. In 2019, the industry reported nearly 79,660 nonfatal injuries (CPWR 2020). These workplace injuries have significant economic impacts besides the incalculable human suffering they cause. Fundamentally, the impacts of these injuries carry more emotional effects if the sustained injury is classified as severe or serious. Specifically, serious or severe injuries can cause permanent or temporary disabilities to the injured person. Other impacts may include extended days away from work, productivity reductions upon returning to work, or restricted activities upon returning to work. This can cause a substantial impact on construction organizations that have been struggling to recruit and maintain skilled construction craftworkers (Welfare et al. 2021).

OSHA has been monitoring severe workplace injuries across all industries that fall under its authority. Since January 1, 2015, employers have been required by law to report severe workplace injuries within 24 hours of the incidents to OSHA. OSHA has also been collecting these injury reports in an online database that is updated periodically. The severe injury reports database is freely available online to employers, safety researchers, and the general public (OSHA 2015). In the first-year assessment report of OSHA's severe injury reporting program, it was argued that one of the reasons for launching the program is increased safety: that when an employer reported severe workplace injuries and workplace inspections are initiated by OSHA, the employers are expected to strive for a safer workplace to prevent future incidents (Michaels 2016).

Understanding the patterns in which construction workplace injuries occur provides the basis for developing effective accident prevention policies that can reduce injury rates (Hinze et al. 2005; Huang and Hinze 2003). Many of the past analyses have focused on analyzing construction fatalities (Ling et al. 2009; U.S. Bureau of Labor Statistics 2020), injuries while performing risky tasks such as crane operations (Beavers et al. 2006), specific events such as falls (Huang and Hinze 2003; Kang et al. 2017) and struck-by incidents (Brown et al. 2021; Hinze et al. 2005), or injuries for specialty trades such as electrical contractors (Abudayyeh Osama et al. 2003; Al-Bayati et al. 2021; Albert and Hallowell 2013). However, no past research efforts have comprehensively investigated severe construction injuries. This study bridges this gap in the literature by assessing reported construction-related severe injuries in OSHA's new severe injury database. From this new database, the study obtained more than 11,000 reports about injuries that occurred between January 2015 and February 2021. Access to a national database of severe construction injuries for analysis is valuable to organizations that are attempting to reduce the frequency of severe or serious injuries. Such efforts can also provide valuable insights into how construction stakeholders must implement innovative safety interventions to mitigate severe workplace incidents and improve safety performance.

3.3. Background

3.3.1. Contributing Factors to Construction Workplace Injuries

It has been established that the construction industry plays an essential role in economic development. The industry is, unfortunately, substantially dangerous. Construction sites are dynamic spaces in which numerous trades work simultaneously, frequently sharing limited space while utilizing heavy materials, sharp tools, and heavy equipment. Working in such an environment makes performing construction tasks significantly challenging and puts workers in risky, uncomfortable, or awkward positions. Additionally, construction workers are constantly working under contractual deadline obligations to deliver projects on time and within schedule, which frequently requires adding overtime and weekend hours. These unfavorable situations allow for numerous hazards that remain largely unrecognized by construction workers and unmanaged by safety professionals, project managers, and construction workers (Albert et al. 2014, 2020; Jeelani et al. 2017). Such failures to manage and control these hazards substantially increase the likelihood of sustaining workplace injuries.

A large and growing body of literature has investigated the factors that contribute to construction workplace injuries. According to Abdelhamid and Everett (2000), construction accidents can be attributed to failures to identify unsafe site conditions, working in unsafe conditions after identifying the unsafe conditions, or acting unsafely. Suraji et al. (2001) and Mitropoulos et al. (2005) introduced a systems thinking approach in modeling the causes of construction accidents. The central premise of systems thinking modeling is that different factors, including the design, planning, and execution of the construction, collectively increase or decrease the likelihood of construction workplace injury (Mitropoulos et al. 2005; Suraji et al. 2001; Zhang et al. 2020). Recently, several studies have suggested that injuries occurred due to interacting with fundamental attributes in the work environment, including machinery, hammers, and wind (Hallowell et al. 2020; Tixier et al. 2016). For example, Tixier et al. (2016) utilized natural language processing techniques to extract 102 attributes from more than 2,000 injury reports. These attributes are useful in establishing injuries' precursors; they can be potentially utilized as the warning signs that lead to injuries (Alexander et al. 2017a; b; Tixier et al. 2016). Alexander et al. (2017a; b) identified 16 precursors typically associated with construction fatalities; these include events such as fatigue, significant overtime, and productivity pressures. In sum, a systems thinking approach is critical to managing the impact of all factors contributing to construction workplace injuries.

3.3.2. Past Assessments of Construction Workplace Injuries

Construction worksites generate rich safety-related data. One important source of safety data is historical records of injury reports. Several stakeholders collect and maintain past injury report records, including construction businesses, regulatory agencies, insurance organizations, and medical providers. In the U.S., employers are required by law to report workplace fatalities to OSHA (BLS 2020). Additionally, injured workers file workers' compensation claims through their employers via insurance. Past historical records of injury reports are typically maintained in private or public databases. Injury reports provide critical information about how the injury or fatality occurred. They typically include clear narratives describing the circumstances that led to sustaining the workplace injuries along with other attributes such as the workers' trades. There has been a large and growing body of literature that investigated past construction accident reports. These efforts have been broadly devoted to investigating injury reports associated with: (1) most frequent events, (2) specific race, (3) particular trades, (4) specific construction tasks, and (5) specific parts of the body.

OSHA has been monitoring the most frequent events resulting in workplace fatalities and launched the Fatal Four (falls, struck-by, caught in/between, and electrocution) training outreach program to reduce these four events at construction workplaces (Albert et al. 2020). Injuries and fatalities resulting from fall events in particular continue to be a major concern in the construction industry. Huang and Hinze (2003) examined 7,543 OSHA accident reports between January 1990 and October 2001 and found falls to account for nearly 34% of the total injuries. Likewise, recent statistics by the BLS (2020) indicated that 401 construction workers lost their lives due to fall events at construction sites, accounting for nearly 38% of total fatalities in construction. Another event that has been closely studied is struck-by. Hinze et al. (2005) obtained and analyzed struck-by-related injury reports from OSHA's Integrated Management Information System (IMIS) database. It was found that struck-by incidents represent about 24% of fatalities and serious injury cases. Given that Hispanic construction workers comprise a significant chunk of the U.S. construction workforce, Dong and Platner (2004) investigated Hispanic worker fatalities between 1992 and 2000. It was found that Hispanic workers were involved in nearly 24% of the fatalities although they constituted only around 16% of the total workforce, putting this community of workers at a relatively higher risk of sustaining workplace injuries compared with other races (Dong and Platner 2004).

Safety researchers have also focused on specific trades and tasks. Given the considerable amount of risk associated with working with electricity, a large number of previous research studies have investigated electrical contractors' workplace injuries. For example, Abudayyeh et al. (2003) and recently Al-Bayati et al. (2021) both found sprains and strains to be the most prominent sustained injuries among electrical contractors. Additionally, it was observed that electrocution is a major cause of death for electrical workers (Albert and Hallowell 2013; Janicak 2008). Another trade that received attention is roofing, given the risks associated with its tasks. Not surprisingly, most roofers sustained injuries by slipping and tripping while working at heights (Fredericks et al. 2005a). As for analyzing injuries associated with a specific construction task, Fredericks et al. (2005b) examined 166 fatality cases, obtained from the IMIS database, involving steel erection work, and fall events represented the most frequent event among the collected fatalities. As for studies related to a particular body part, Hinze and Giang (2008) examined a random sample of about 600 injury reports involving eyes. It was reported that in more than 80% of the cases, the injured workers sustained the injuries while not wearing safety goggles or protection. In summary, maintaining, collecting, and analyzing historical records of past injury reports are useful in assessing the reasons and circumstances for these injuries. This serves as the first step in reducing their high rates.

3.3.3. Severe/Serious Injuries and Fatalities in the Construction Industry

The BLS (2021b) broadly classifies occupational injuries and illnesses as either fatal or nonfatal incidents. More specifically, Heinrich et al. (1980) classified injuries into three categories (fatal, serious, and minor) and depicted their prevalence into the famous Heinrich's safety pyramid (Heinrich et al. 1980; Marshall et al. 2018). Given their drastic consequences, several research interventions and initiatives have been devoted to reducing the rate of serious injuries and fatalities. Nevertheless, the annual number of construction-related fatalities continues to be significantly high. According to the recently published statistics by the BLS (2020), 1,061 construction workers lost their lives at construction sites, accounting for nearly one-fifth of the total fatalities. Additionally, Carter and Smith (2006) reported that construction workers in the United Kingdom are nearly two times more likely to sustain serious injuries than all other occupations. To better understand the factors associated with severe and fatal construction cases, Oguz Erkal et al. (2021)

recently utilized Delphi methodology to identify factors that predict serious injuries and fatalities. The predictors were categorized into business factors, project factors, and crew demographics. The study reported the top predictors at the project level as: (1) presence of a project manager and (2) validated project leading indicators. At the business level, the top-ranked predictors were (1) intervention protocol and (2) investment in safety research and development. Lastly, the highest weighted scores for the crew category were assigned to (1) the ratio of field management to worker and (2) a newly formed crew (Oguz Erkal et al. 2021).

There is no disagreement on the definition of a fatality workplace case; however, there is no consensus on what represents a serious or severe workplace injury. Hallowell and Gambatese (2009) classified the severity of injuries into 11 subjective levels that include, among others: major first aid, medical case, lost work time, permanent disablement, and fatality. For each severity level, a severity score number (e.g., medical case, 128; fatality, 26,214) is assigned; these can be used to quantify construction activities' risks (Hallowell and Gambatese 2009). Furthermore, Martin and Black (2015) combined serious injuries and fatalities (SIFs) into one definition and collectively defined SIF as "any injury that resulted in a fatality, life-threatening injury or illness, or life-altering injury/permanent disability." In 2015, OSHA (2015) launched the severe injury reporting program and defined a severe work-related injury as a sustained injury resulting in "an amputation, in-patient hospitalization, or loss of an eye." The reported occupational injuries are stored in an openly accessed database that remained largely unexamined.

3.3.4. OSHA's New Severe Injury Reporting Program

OSHA launched a new severe injury reporting program in response to the substantial number of severe workplace injuries across all industries (Michaels 2016). OSHA updated its regulation part 1904 that pertains to recording and reporting occupational injuries and illness.

Under the new standard number 1904.39, beginning on January 1, 2015, employers were required to report any workplace incident that results in hospitalization, amputation, or loss of an eye to OSHA within 24 hours (Occupational Safety and Health Administration 2015). OSHA (2015) defined hospitalization as formal admission to a hospital or clinic and receiving treatment. Amputation cases are recorded when the body part is wholly or partially amputated, either with bone loss or without bone loss. Failure to report severe workplace injuries to OSHA results in a citation for non-reporting and a financial penalty (Michaels 2016). In the impact evaluation report, one year after the implementation of the new program, it was reported that one of the new program's goals was to identify at-risk workers and apply more enforcement and compliance on their places of work. Also, the program forecasts that when employers engage with OSHA by reporting severe injuries, the employers will be more likely to reduce and potentially eliminate workers' exposures to the hazards that result in severe injuries (Michaels 2016). OSHA has been compiling severe injury reports from states with federal OSHA jurisdictions (i.e., states with non-approved OSHA state plans) in an online database that is updated periodically and can be accessed at www.osha.gov/severeinjury. Unfortunately, it was noted in the evaluation report that a total of 10,388 occupational incidents were filed by the end of 2015 (Michaels 2016). This is an alarming trajectory.

OSHA's severe injury reports database incorporates several metadata about each incident, including the report identification number, the event's data, the employer's name, and the city and the state where the incident occurred. The database also includes the narratives that describe how the injuries were sustained. Additionally, OSHA officers assign the following attributes to each report: (1) the industry classification, (2) the event or exposure, (3) the source of injury or illness, (4) part of body affected, and (5) the nature of injury or illness. The industries are classified according to the North American Industry Classification System (NAICS). NAICS is the manual used by federal agencies to officially classify different industries in the U.S., Canada, and Mexico (U.S. Census Bureau 2017). The construction industry is assigned to NAICS 23 and broadly classified into the following subsectors (U.S. Census Bureau 2017):

- NAICS 236: Construction of Buildings: categorizes general contractors that are building new projects, altering, maintaining, and repairing existing buildings. The subsector is further broken down into sub-subsectors based on the type of building, such as residential and industrial;
- NAICS 237: Heavy and Civil Engineering Construction: classifies involved contractors in highway, bridge, and other infrastructure projects;
- NAICS 238: Specialty Trade Contractors: classifies different subcontracting activities.

The remaining attributes, namely, the event or exposure, the source of injury or illness, part of body affected, and nature of injury or illness, are classified according to the Occupational Injury and Illness Classification (OIIC) manual. The OIIC manual is published by the BLS (2012) and classifies and codes workplace fatalities, injuries, and illnesses in the Survey of Occupational Injuries and Illnesses (SOII) and the Census of Fatal Occupational Injuries (CFOI), besides severe occupational injury reports. The OIIC manual defines event or exposure as “the manner in which the injury or illness was produced or inflicted by the source of injury or illness” (e.g., falls, slips, trips, and contact with objects and equipment) in which the source of injury or illness (e.g., ladders and fasteners, connectors, ropes, ties) is coded according to the “objects, substances, equipment, and other factors that were responsible for the injury or illness incurred by the worker or that precipitated the event or exposure.” As for the nature of injury or illness, it is classified in a way that “identifies the principal physical characteristic(s) of the work-related injury or illness for the part of body affected" (U.S. Bureau of Labor Statistics 2012). These injury attributes are essential in understanding the pattern in which severe injuries are sustained at workplaces.

3.4. Point of Departure and Research Objectives

Reviewing the literature revealed that serious or severe construction injuries continue to create challenges for construction organizations and regulatory agencies. Past studies particularly focused on assessing construction injuries related to Fatal Four events such as falls (Huang and Hinze 2003), contractor type or dangerous tasks (Al-Bayati et al. 2021; Beavers et al. 2009; Hinze and Gambatese 2003), injuries sustained by a specific race (Dong and Platner 2004), or specific injured body parts (Hinze and Giang 2008). There is, however, a dearth of research that solely focused on various injuries' severities and especially severe or serious injury types. It is vital to assess such injury types; Martin and Black (2015) concluded that it is important to group and investigate the reasons for such injury types separately from other incident types (e.g., minor injuries) to understand and prevent them from happening in the workplace. Before OSHA responded to the high prevalence of severe workplace injuries by mandating that these incidents be reported separately, it was challenging to compile and isolate severe cases from other injury types. Consequently, the pattern of severe construction-related injuries has been a persistent gap in the body of knowledge.

The overarching goal of this paper is to assess reported construction-related cases in OSHA's new severe injury database. Specifically, this study's objectives are to:

1. Compare the proportion of construction-related injuries to other industry sectors.
2. Investigate the monthly trend of construction-related severe injuries.
3. Assess the injuries' attributes and evaluate overrepresented categories.
4. Examine the relationships between the injuries' attributes.

The following two sections comprehensively describe the research methodology and present the findings.

3.5. Research Methods

3.5.1. Phase I: Data Extraction and Research Question Formulation

The data captured as part of the *severe injury reporting program* was first accessed from the program's webpage (i.e., www.osha.gov/severeinjury) in the fall of 2021. At the time of access, the webpage included all severe injuries reported between January 1, 2015 and February 18, 2021. This included over 65,000 injury reports from various industries. For each of the injury reports, apart from the employer and workplace information, the database also includes a North American Industry Classification System (NAICS) code that offered clarity on the industry where the incident was experienced. Using the NAICS code, incidents from the construction industry were filtered and extracted (i.e., NAICS Sector 23) for the purpose of the current investigation. This resulted in 11,340 incident reports that fit the scope of the current investigation.

The database included useful attributes that were of interest to the current study. Apart from the date of the incidents and the identity of the employers, the database included the *event type* (e.g., falls to lower level, struck-by object or equipment), the *injury source* (ladders, hand tools, etc.), the *injured body part* (head, upper exterminates, lower extremities, etc.), and the *injury nature* (open wounds, traumatic injuries to bones, nerves, or the spinal cord, etc.) – as defined in the Occupational Injury and Illness Classification (OIIC) manual for each incident (BLS 2012). The NAICS code (U.S. Census Bureau 2017), discussed earlier, also offers information on the specific *construction sectors* (e.g., roofing contractors, drywall and insulation contractors) where the incidents were experienced. The complete list of attributes and their categories are presented in Table 3-1. Codes (e.g., E1, E2, S1, etc.) that correspond to each of the attribute categories are also included for easy reference in subsequent sections.

After examining the extracted data that is relevant to the construction industry, the research questions that must be targeted were formulated to gain a better understanding of injury patterns. The first set of questions focused on examining if certain attribute categories are more overrepresented than others in the database. For example, there was interest in examining if workers are more vulnerable to experiencing severe injuries as a result of certain *event types* than others. Such information can offer insights into high-risk problem areas that must be prioritized as part of injury reduction efforts. The complete first set of targeted research questions is as follows:

- Are construction workers especially vulnerable to experiencing severe injuries as a result of certain *event types*?
- Are construction workers especially vulnerable to experiencing severe injuries as a result of certain *injury sources*?
- Are construction workers especially vulnerable to experiencing severe injuries that *injure* certain *body parts*?
- Are construction workers especially vulnerable to experiencing severe *injuries* that are of a certain *nature*?
- Are construction workers involved in certain *construction sectors* especially vulnerable to experiencing severe injuries?

Table 3-1: Attributes, Attribute Categories, and Chi-Square Goodness-Of-Fit Test Results

Attribute	**Attribute Categories**	**#**	**ε_i**	**Chi-Square Test Statistic**	**p-value**
Event Type (Total #:11,340)	E1 - Falls to lower level (e.g., fall from aerial lift, scaffolding, etc.)	3934	103.7	18075.66	<0.001
	E2 - Struck by object or equipment (e.g., struck by mobile equipment, crane boom, excavator bucket, etc.)	2618	59.1		
	E3 - Caught in or compressed by equipment or objects (e.g., foot caught between wood pallets, hand caught in equipment)	1378	17.1		
	E4 - Exposure to electricity (e.g., contact with powerlines, electrified equipment, etc.)	539	-11.3		
	E5 - Exposure to temperature extremes (e.g., hot or cold working conditions, contact with hot welding torch, etc.)	479	-13.3		
	E6 - Vehicular incident (e.g., struck by vehicle in work zone or roadway)	423	-15.2		
	E7 - Falls on same level (e.g., fall while walking, fall on slippery surface, trip and fall over object on floor, etc.)	407	-15.8		
	E8 - Struck against object or equipment (e.g., striking against a running saw, running into an equipment, etc.)	256	-20.9		
	E9 - Nonroadway incidents involving motorized land vehicles (e.g., truck rollover, construction roller slides down slope, etc.)	251	-21.0		
	E10 - Fires (equipment or vehicle catches fire, gasoline ignition)	125	-25.3		
	E11 - Struck, caught, or crushed in collapsing structure, equipment or material (e.g., building collapse, excavation/trench cave-ins, crane collapse, etc.)	102	-26.1		
	E12 - Other low frequency events	599	-9.3		
	E13 - Nonclassifiable / Insufficient information	229	-21.8		
Injury Source (Total #:11,340)	S1 - Ladders	1323	33.7	5101.16	<0.001
	S2 - Structural elements (e.g., joists, trusses, skylight, roof, walls, HVAC systems, forms, door, fences, etc.)	1251	30.6		
	S3 - Building materials (e.g., lumber, pipes, bricks, ducts, etc.)	804	11.4		
	S4 - Structures other than buildings (e.g., scaffolds, staging, rail lines, bridges, utility poles, etc.)	780	10.3		
	S5 - Floors, walkways, and ground surfaces (e.g., temporary plywood covers, working platforms, stairs, walkways, roads, etc.)	672	5.7		
	S6 - Machine, tool, and electric parts (e.g., electrical wiring, motors, powerlines, electrical transformer elements, switchgear, appliances, accessories, etc.)	610	3.0		
	S7 - Motorized highway vehicles (e.g., automobiles, buses, trucks, etc.)	608	2.9		
	S8 - Construction, logging, and mining machinery (e.g., excavators, earthwork rollers, skid-steer loaders, back hoes, dozers etc.)	602	2.7		
	S9 - Material and personnel handling machinery (e.g., conveyors, elevators, cranes, etc.)	521	-0.8		
	S10 - Powered handtools (e.g., powered nail guns, screw guns, hand saws, hand drills, grinders, powered chain saws, etc.)	506	-1.5		
	S11 - Environmental and elemental conditions (e.g., weather and air quality)	404	-5.9		
	S12 - Metal, woodworking, and special material machinery (e.g., stationary drills, metal sheet cutting equipment, table saw, etc.)	335	-8.8		
	S13 - Powered off-road and industrial vehicles (e.g., forklifts, pallet jacks, etc.)	291	-10.7		
	S14 - Fasteners, connectors, ropes, ties (e.g., nails, clamps, bolts, screws, brackets, etc.)	230	-13.3		
	S15 - Containers (e.g., drums, buckets, etc.)	214	-14.0		
	S16 - Vehicle and mobile equipment parts (e.g., wheels tire, engine parts, etc.)	156	-16.5		
	S17 - Scrap, waste, debris (e.g., metal fragments, concrete rubble from demolition, falling debris, etc.)	109	-18.5		
	S18 - Nonpowered handtools (e.g., utility knives, unpowered saws, etc.)	106	-18.7		
	S19 - Confined spaces	103	-18.8		
	S20 - Other low frequency sources	1202	28.5		
	S21 - Nonclassifiable / Insufficient information	513	-1.2		
Injured Body Part (Total #:11,340)	P1 - Upper extremities (e.g., shoulder, arm, elbow, hand, finger, etc.)	3289	49.7	5210.97	<0.001
	P2 - Lower extremities (e.g., leg, thigh, knees, foot, etc.)	2333	24.3		
	P3 - Trunk (e.g., back, hip, chest, ribs, lungs, back, spinal cord, etc.)	1619	5.4		
	P4 - Multiple body parts (e.g., upper extremities and head)	1589	4.6		
	P5 - Head (e.g., skull, brain, face, ears, nose, etc.)	1000	-11.1		
	P6 - Body systems (e.g., gastrointestinal system, respiratory system, etc.)	612	-21.4		
	P7 - Neck - including throat	77	-35.6		
	P8 - Nonclassifiable / Insufficient information	821	-15.8		

Table 3-1 (continued)

Injury Nature (Total #:11,340)	N1 - Traumatic injuries to bones, nerves, spinal cord (e.g., fractures, paralysis from spinal injury, pinched nerves, etc.)	4196	98.6	16997.14	<0.001
	N2 - Open wounds (e.g., cuts, lacerations, etc.)	2763	53.9		
	N3 - Other traumatic injuries and disorders (e.g., injuries to internal organs and blood vessels of the trunk, electrocutions, asphyxiations, drownings, allergic reactions, inflammation, etc.)	1638	18.9		
	N4 - Burn and corrosions (e.g., thermal burns, chemical burns, etc.)	708	-10.1		
	N5 - Multiple traumatic injuries (e.g., fractures and burns)	473	-17.4		
	N6 - Intracranial injuries (skull fracture, concussion, contusion, etc.)	438	-18.5		
	N7 - Effects of environmental conditions (e.g., dehydration, heat exhaustion, frost bites, etc.)	364	-20.8		
	N8 - Traumatic injuries to muscles, tendons, ligaments, joints (e.g., sprain, strain, torn cartilage, dislocation, etc.)	165	-27.0		
	N9 - Surface wounds and bruises (e.g., abrasions, scratches, blisters, etc.)	112	-28.6		
	N10 - Other low frequency injury natures	37	-31.0		
	N11 - Nonclassifiable / Insufficient information	446	-18.2		
Construction Sector (Total #:11,340)	CS1 - Commercial and institutional building construction (e.g., commercial general contractors and construction management firms, etc.)	1217	30.9	3076.55	<0.001
	CS2 - Electrical contractors and other wiring installation contractors	1135	27.3		
	CS3 - Highway, street, and bridge construction	941	18.7		
	CS4 - Roofing contractors	930	18.3		
	CS5 - Plumbing, heating, and air-conditioning contractors	821	13.5		
	CS6 - All other specialty trade contractors (e.g., fence installation, billboard erection, etc.)	530	0.6		
	CS7 - Structural steel and precast concrete contractors	513	-0.1		
	CS8 - Residential building construction (e.g., residential general contractors and construction management firms, etc.)	495	-0.9		
	CS9 - Poured concrete foundation and structure contractors	478	-1.6		
	CS10 - Site preparation contractors	472	-1.9		
	CS11 - Water and sewer line and related structures construction	451	-2.8		
	CS12 - Industrial building construction	444	-3.1		
	CS13 - Power and communication line and related structures construction	348	-7.4		
	CS14 - Drywall and insulation contractors	334	-8.0		
	CS15 - Oil and gas pipeline and related structures construction	333	-8.0		
	CS16 - Other heavy and civil engineering construction (e.g., retention wall installation, tunneling contractors, railroad contractors, dam, and hydroelectric station contractors, etc.)	317	-8.7		
	CS17 - Masonry contractors	316	-8.8		
	CS18 - Framing contractors	310	-9.0		
	CS19 - Painting and wall covering contractors	229	-12.6		
	CS20 - Other building equipment contractors (e.g., elevator installation contractors, escalator installation contractors)	192	-14.2		
	CS21 - Finish carpentry contractors	110	-17.9		
	CS22 - Other low frequency sectors	424	-4.0		

The next set of questions focused on gaining a more nuanced understanding of severe workplace injuries. More specifically, the questions targeted the examination of relationships between the attributes. For example, one of the targeted questions focused on examining if there is a relationship between the severe injury event types and the construction sectors the workers are employed in. In other words, the research question focused on examining if workers in certain construction sectors were more vulnerable to experiencing severe injuries as a result of certain event types than others. The complete second set of research questions that were targeted is as follows:

- Does the *construction sector* of employment correlate with the severe injury *event type*, *injury source*, *injured body part*, and *injury nature*?
- Does the *injury source* correlate with the severe injury *event type*, *injured body part*, and *injury nature*?
- Does the severe injury *event type* correlate with the *injured body part* and the *injury nature?*
- Does the *injured body part* correlate with the severe *injury nature*?

3.5.2. Phase II: Data Analysis Strategy

Prior to the investigation of the targeted research questions, some exploratory analyses of the data were first performed. These analyses focused on comparing the relative distribution of severe injuries across industries – with a particular interest in the construction industry. The analyses also focused on examining the distribution of injuries over time since the introduction of the severe injury reporting program in 2015.

Next, the targeted research questions were pursued. To investigate the first set of research questions and examine if certain attribute categories that correspond are overrepresented when compared to others (e.g., are construction workers more vulnerable to experiencing severe injuries as a result of certain event types than others?), the *chi-square goodness of fit* test was adopted. Accordingly, the *chi-square test statistic* as presented in Equation 1 was computed. As can be seen, the chi-square test statistic captures the magnitude of disparity between the number of injuries observed in each of the attribute categories and the number of expected injuries if none of the attribute categories are overrepresented. When the disparity between the observed number of injuries compared to the expected number of injuries is greater, the computed chi-square test statistic will be larger. If the p-value associated with the chi-square value is less than 0.05, the inference that certain attribute categories are overrepresented compared to others can be accepted.

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \qquad (1)$$

where, χ^2 is the *chi-square test statistic*; *k* is the total number of attribute categories that are relevant to a specific research question, O_i is the observed count or frequency of injuries that corresponds to a particular attribute category i; E_i is the expected count or frequency of injuries for the attribute category *i* if none of the attribute categories are overrepresented [i.e., number of injuries are equally distributed across the attribute categories – i.e., $(E_i = N/K)$]; and N is the total number of incidents (i.e., N = 11,340 for the current study).

While the *p*-value associated with the chi-square test statistic offers insights on whether particular attribute categories are overrepresented, it does not pinpoint specific attribute categories that are overrepresented. To identify these overrepresented attribute categories, the standardized residuals as presented in Equation 2 were computed for each of the attribute categories. When the computed standardized residual is positive for a particular attribute category, it suggests that the specific attribute category is linked with a larger proportion of injuries than expected; and is overrepresented. Accordingly, it may be concluded that additional efforts may need to be steered towards prioritizing the reduction of injuries that are linked with attribute categories that are overrepresented on the basis of higher standardized residuals.

$$\varepsilon_i = \frac{O_i - E_i}{\sqrt{E_i}} \quad (2)$$

Where, ε_i is the standardized residual from that corresponds to the *chi-square goodness of fit* test; O_i is the observed count or frequency of injuries that corresponds to a particular attribute category i; E_i is the expected count or frequency of injuries for the attribute category *i* if none of the attribute categories are overrepresented [i.e., number of injuries are equally distributed across the attribute categories – i.e., $(E_i = N/K)$]; and *N* is the total number of incidents (i.e., *N* = 11,340 for the current study).

Next, to examine if there is a relationship between the attributes (e.g., are construction workers in certain *construction sectors* more likely to experience injuries related to certain *event types*?) per the second set of targeted research questions, the *chi-squared test for independence* was adopted. Accordingly, *the chi-square test statistic* that encompasses the two attributes of interest was computed using Equation 3. Like in the previous case, a larger *chi-square* test statistic from the *chi-square test of independence* corresponds to a larger correlation between the two attributes of interest. If the *p*-value associated with the *chi-square* test statistic is less than 0.005, the inference that the two attributes of interest are correlated can be accepted.

$$\chi^2 = \sum_{i=1}^{c} \sum_{j=1}^{r} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \quad (4)$$

where, χ^2 is the *chi-square test for independence*; *c* is the total number of attribute categories that is part of the first variable of interest; *r* is the total number of attribute categories that is part of the second variable of interest; O_{ij} is the observed count or frequency of injuries that corresponds to a particular attribute category combination ij; E_{ij} is the expected count or frequency of injuries that corresponds to a particular attribute category combination ij in the hypothetical case that none of the combinations of the attribute categories is more prominent than another [i.e., number of injuries are distributed on the basis of the marginal frequency across the attribute categories of interest – i.e., ($E_{ij} = N_{i \times} N_j/N$)]; N_i is the marginal frequency or count of injuries that corresponds to a specific attribute category associated with the first variable of interest; N_j is the marginal frequency or count of injuries that corresponds to a specific attribute category associated with the second variable of interest; and N is the total number of incidents (i.e., N = 11,340 for the current study).

Similar to the computation of the standardized residuals for the first set of research questions, standardized residuals were also calculated for the second set of research questions to identify attribute category combinations that are overrepresented or more likely relative to the expected count. The standardized residuals were computed using Equation 5 which accounts for the marginal frequency or count of injuries that corresponds to each of the attribute categories across the two variables of interest. As in the previous case, a positive standardized residual suggests that a particular attribute category combination is relatively more likely than expected. According to Agresti (2018), when the standardized residual computed using Equation 5 is greater than 3, it suggests that the particular attribute category combination significantly contributes to a larger chi-square value – thereby offering more robust evidence that a relationship exists.

$$\varepsilon_{ij} = \frac{O_{ij} - E_{ij}}{\sqrt{E_{ij} \times (1 - N_i/N) \times (1 - N_j/N)}} \quad (7)$$

where ε_{ij} is the standardized residual from the chi-square test of independence; O_{ij} is the observed count or frequency of injuries that corresponds to a particular attribute category combination ij; E_{ij} is the expected count or frequency of injuries that corresponds to a particular attribute category combination ij in the hypothetical case that none of the combinations of the attribute categories is more prominent than another [i.e., number of injuries are distributed on the basis of the marginal frequency across the attribute categories of interest – i.e., ($E_{ij} = N_i \times N_j / N$)]; N_i is the marginal frequency or count of injuries that corresponds to a specific attribute category associated with the first variable of interest; N_j is the marginal frequency or count of injuries that corresponds to a specific attribute category associated with the second variable of interest; and N is the total number of incidents (i.e., N = 11,340 for the current study).

3.6. Study Findings

3.6.1. Exploratory Data Analysis Findings

The distributions of severe injuries across industries are presented in Figure 3-1. As can be seen, construction workplaces reported 11,340 severe injuries which translates to over 18% of all severe injuries since 2015. The only industry that accounted for a higher number of injuries is manufacturing, which accounted for over 20,000 severe injuries. Some of this disparity may be attributed to the larger workforce employed in the manufacturing industry compared to the construction industry within the United States. For example, according to the U.S. Bureau of Labor Statistics, the manufacturing industry accounts for roughly 10% of the workforce while the construction industry accounts for approximately 7% of the workforce. (BLS 2021a).

However, it must be noted that construction workplaces have consistently accounted for more fatal incidents than the manufacturing industry. For example, between 2015 and 2020, construction workplaces accounted for roughly 19% of fatalities while the manufacturing industry accounted for less than 7% of the fatalities (BLS 2021b).

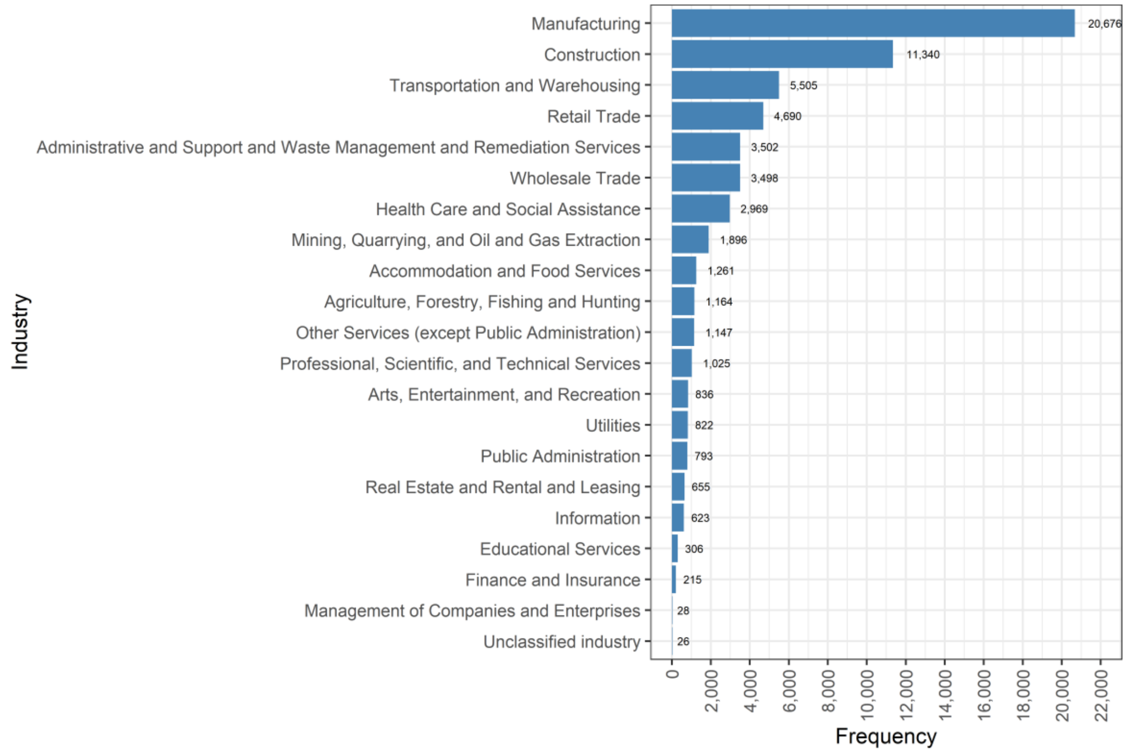

Figure 3-1: The Distribution of Occupational Severe Injuries across Different Industries

Figure 3-2 presents the distribution of the reported severe injuries as it pertains to the construction industry over time since the inception of the *severe injury reporting program*. As can be seen, the data demonstrate a cyclic or seasonal pattern where the number of reported injuries rises and falls alternatively over time. To examine details of the pattern more closely, the data for each of the years were plotted independently as can be seen in Figure 3-3. As shown, while there has been significant variability over the months, an inverted u-shaped pattern was evident across each year with the highest number of injuries generally reported over the summer months – when the volume of construction operations generally tends to be higher compared to the rest of the year.

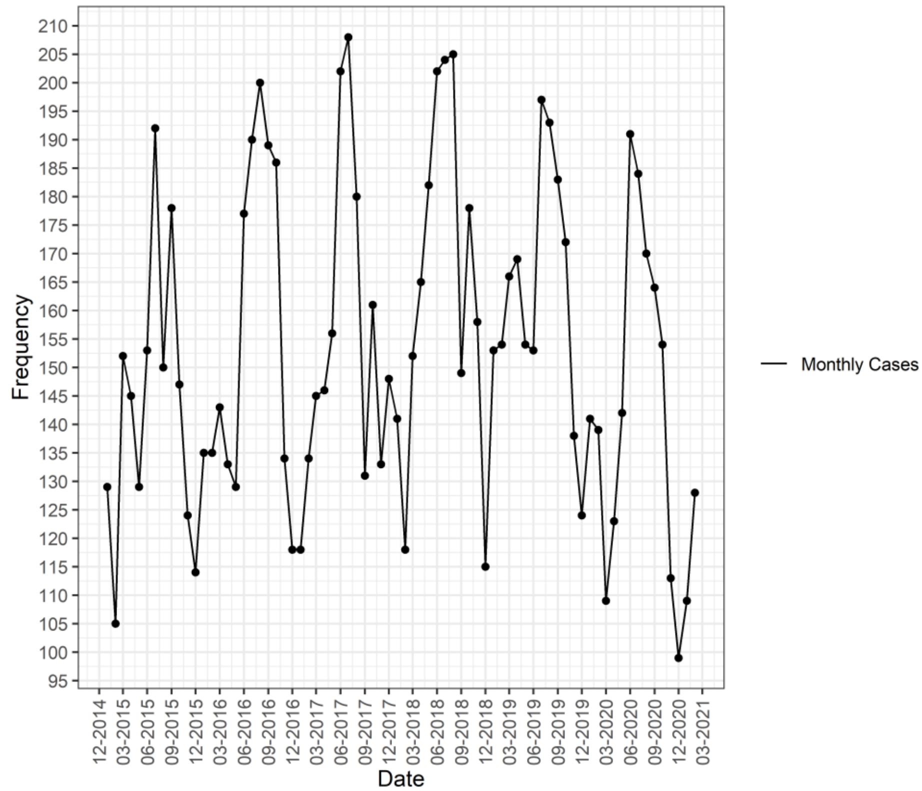

Figure 3-2: Longitudinal Time Series of Severe Construction Injury Cases

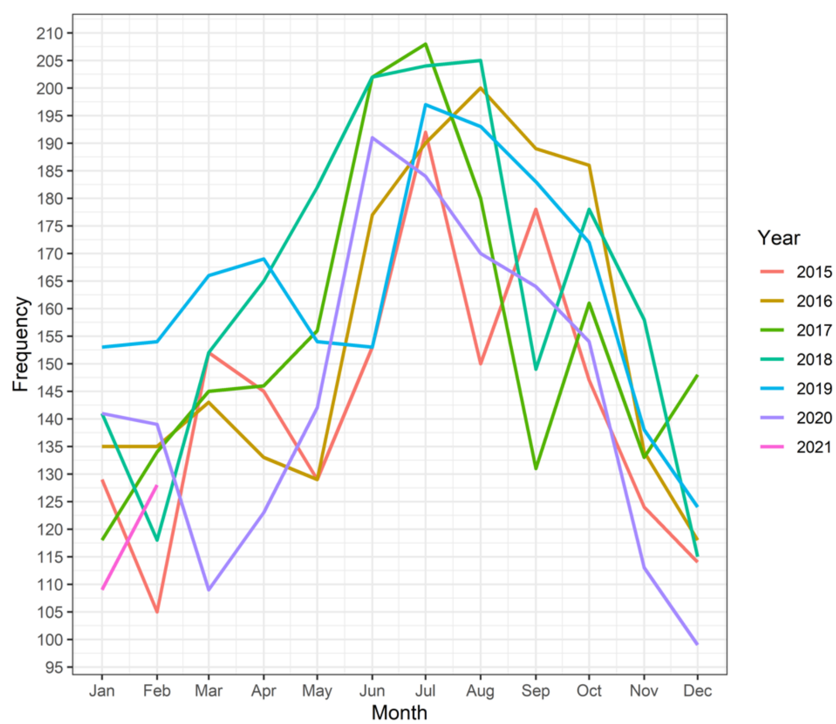

Figure 3-3: Yearly Time Series of Severe Construction Injury Cases

3.6.2. Findings of Attribute Categories that are Overrepresented

After the exploratory analysis, the first set of research questions that examined if certain attribute categories were overrepresented was pursued per the research plan. The results of the analysis are presented in Table 3-1. The *chi-square test statistic* for the *event type* was associated with a *p*-value that is less than 0.001. This suggests that construction workers are more vulnerable to experiencing severe injuries as a result of certain *event types* than others. An examination of the standardized residuals suggests that *falls to lower levels* (E1) (ε_i = *+103.7*) is the most common event type that construction workers disproportionately experience. These events included falls from aerial lifts, scaffolding, staging, leading edges, openings in the floor slab, and others. This was followed by *struck-by object or equipment* (E2) (ε_i = *+59.1*) incidents that often involved contact with heavy equipment or falling objects. *Caught in or compressed by equipment or object* (E3) (ε_i = *+17.1*) incidents were also overrepresented where a body part (e.g., upper or lower extremities) was often caught between elements of running equipment or stockpile of material such as lumber or steel sections.

Like *event type*, the *chi-square test statistic* and the associated *p*-values for each of the attributes including *injury source*, *injured body parts*, *injury nature*, and *construction sector* suggested that certain attribute categories were overrepresented. For example, when considering *injury source*, *ladders* (S1) (ε_i = *+33.7*); *structural elements* (S2) (ε_i = *+30.6*) such as joists, trusses, and skylights; *building materials* (S3) (ε_i = *+11.4*) such as lumber and pipes; and *structures other than buildings* (S4) (ε_i = *+10.3*) were overrepresented among others. On the other hand, when considering the *injured body part*, most injuries affected *upper extremities* (P1) (ε_i = *+49.7*) that include the hand and shoulders, *lower extremit*ies (P2) (ε_i = *+24.3*) that include legs and knees, the *trunk* (P3) (ε_i = *+5.4*), and multiple *body parts* (P4) (ε_i = *+4.6)*.

When examining injury nature, a disproportionate number of injuries were found to result in *traumatic injuries to bones, nerves, and the spinal cord* (N1) (ε_i = *+98.6*) which includes fractures, pinched nerves, and others. This was followed by *open wounds* (N2) (ε_i = *+53.9*) largely associated with the use of hand tools and *other traumatic injuries and disorders* (N3) (ε_i = *+18.9*) that were mostly linked with electrocution.

Finally, the results suggest that much of the incidents were reported among *construction sectors* that include *commercial and institutional building construction* (CS1) (ε_i = *+30.9*); *electrical contractors and other wiring installation contractors* (CS2) (ε_i = *+27.3*); *highway, street, and bridge construction* (CS3) (ε_i = *+18.7*); *roofing contractors* (CS4) (ε_i = *+18.3*); and *plumbing, heating, and air conditioning contractors* (CS5) (ε_i = *+13.5*).

3.6.3. Findings from the Relationships between Attributes

Having addressed the first set of research questions, the second set of research questions was pursued. The findings from the analysis are presented in Table 3-2 through Table 3-5. As can be seen, the *chi-square test* statistic and the *p*-values associated with each of the examined relationships suggest that a statistically significant relationship exists between the attributes examined. The results from the examination of the residuals are presented in detail below. Given the nature of the content, readers may selectively examine the sections that are of particular interest or relevance to them in the following sections.

Moreover, to maintain brevity, only the top three attribute categories that are overrepresented per the findings in the previous section (i.e., see Table 3-1) are discussed below. Readers that are interested in the other attribute categories may interpret Table 3-2 through Table 3-5 in a similar fashion as has been done below. In the same manner, only the attribute category combinations associated with the thee highest standardized residuals that are greater than “3” per

Agresti (2018) criterion discussed earlier are presented below. Low frequency attribute categories (e.g., *other low frequency events* (E12), *other low frequency sources* (S20), etc.) and those that were not classifiable or did not include sufficient information (i.e., *nonclassifiable / insufficient information* (E13, S21, etc.) as captured in Table 3-1 have been excluded in the below discussions.

3.6.3.1. Relationship Between Construction Sector and Event Type

The standardized residuals in Table 3-2 demonstrate that *roofing contractors* (CS4) that spend considerable amounts of time at heights (e.g., working on the roof, working with ladders, etc.) are particularly vulnerable to experiencing *fall to lower level* (E1) incidents (ε_{ij} = +26.7). Examples of operations that the *roofing contractors* (CS4) were involved in during the incidents include placement of shingles, installation of skylights, and routine maintenance operations such as replacement and repairing of damaged roof elements. Apart from roofing contractors, *drywall and insulation contractors* (CS14) also sustain a disproportionate number of *fall to lower level* (E1) incidents (ε_{ij} = +10.6). These incidents largely occurred while hanging wallboards or placing insulation in areas such as the ceiling and other elevated locations. In the same manner, *framing contractors* (CS18) that are engaged in the erection of the building frame are also vulnerable to experiencing *fall to lower level* (E1) incidents (ε_{ij} = +9.7).

In contrast, the *construction sectors* particularly susceptible to experiencing *struck by object or equipment* (E2) incidents include *poured concrete foundation and structure contractors* (CS9) that often work alongside concrete mixer trucks, cranes, and structural forms (ε_{ij} = +6.6); *site preparation contractors* (CS10) that frequently work beside excavators, dozers, and rollers (ε_{ij} = +5.8); and entities involved in *water and sewer line and related structures* (CS11) that work adjacent to both heavy equipment and large sections of pipes (e.g., concrete and cast iron pipes) (ε_{ij} = +5.0).

Finally, when considering *caught in or compressed by equipment or objects* (E3) incidents, *construction sectors* that are particularly susceptible included entities involved in *other heavy and civil engineering construction* (CS16) *(ε_{ij} = +5.0)*, *oil and gas pipeline and related structures construction* (CS15) *(ε_{ij} = +4.5)*, and *industrial building construction* (CS12 *(ε_{ij} = +3.7)*. Many of these incidents resulted in injuries to the hand while performing maintenance or troubleshooting operations involving machinery, large equipment, or industrial plants. Some of the incidents were also experienced when handling structural elements or materials such as structural steel, formwork, pipes, and storage containers.

3.6.3.2. Relationship Between Construction Sector and Injury Source

The standardized residuals in Table 3-2 demonstrate that electrical contractors and other wiring installation contractors (CS2) (ε_{ij} = +11.5); plumbing, heating, and air-conditioning contractors (CS5) (ε_{ij} = +11.3), and roofing contractors (CS4) (ε_{ij} = +9.4) are particularly likely to experience injuries that are linked with ladder (S1) use. This is the case since electrical contractors and other wiring installation contractors (CS2) frequently use ladders (S1) to perform overhead work involving the placement of electrical and communication systems (e.g., wiring for lighting and audio systems), plumbing, heating, and air-conditioning contractors (CS5) use ladders (S1) to access mechanical systems that are housed in the ceiling (e.g., piping fixtures and HVAC systems ducts), and roofing contractors (CS4) adopt ladders (S1) to gain access to the roof as part of roofing operations.

In the same manner, roofing contractors (CS4) were also particularly susceptible to be involved in injuries involving structural elements (S2) (ε_{ij} = +39.9) as they installed skylights, worked on the roof, and repaired damaged and deteriorated joists that offered support to the roofing system. Other contractors that were susceptible to injuries involving structural elements (S2) included framing contractors (CS18) (ε_{ij} = +7.7) and structural steel and precast concrete contractors (CS7) (ε_{ij} = +4.8) – many of which involved fall to lower level (E1) incidents while working at heights while on structural elements (S2) including joists, trusses, and the roof.

When examining injuries involving *building materials* (S3), *structural steel and precast concrete contractors* (CS7) were susceptible to experiencing injuries while manipulating and installing steel sections and rebar *(ε_{ij} = +7.5)*. On the other hand, entities involved in *oil and gas pipeline and related structures construction* (CS15) *(ε_{ij} = +6.8)* and *water and sewer line and related structures construction* (CS11) *(ε_{ij} = +5.8)* were particularly likely to experience incidents while working with or adjacent to pipe sections.

3.6.3.3. Relationship between Construction Sector and Injured Body Part

When examining the relationship between *construction sector* and the *injured body part* as presented in Table 3-2, the findings suggest that entities involved in *other heavy and civil engineering construction* (CS16) are especially vulnerable to experiencing injuries to their *upper extremities* (P1) *(ε_{ij} = +4.3)*. Many of these injuries were associated with the use of specialized equipment for a variety of operations including drilling, boring, welding, pumping, torqueing, cutting, cleaning, grinding, demolition, and others. *Finish carpentry contractors* (CS21) also sustained a disproportionate number of injuries to the *upper extremities* (P1) *(ε_{ij} = +3.8)*; many of which were linked with the use of mechanical saws.

Table 3-2: Relationships between Construction Sector and Four other Attributes

Attribute	Attribute Categories	Construction Sectors																						Chi-Square Test Statistic	*p*-value
		CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16	CS17	CS18	CS19	CS20	CS21	CS22		
Event Type (Total #:11,340)	E1	-2.6	-0.6	-15.1	+26.7	+2.5	-5.2	+1.9	+4.3	-6.7	-7.6	-9.8	-2.0	-5.3	+10.6	-9.8	-7.8	+5.8	+9.7	+8.5	-0.9	-0.2	+3.3	4209.4	<0.001
	E2	+3.7	-7.5	+2.1	-12.2	-3.7	+1.5	+1.2	+1.3	+6.6	+5.8	+5.0	+0.3	-0.6	-4.2	+4.5	+4.8	-0.7	+0.3	-2.4	+0.8	-0.5	+0.4		
	E3	+1.4	-2.9	+2.9	-8.3	+0.8	+3.3	+2.2	-3.3	+0.7	+0.4	+3.6	+3.7	+0.6	-3.2	+4.5	+5.0	-0.1	-5.1	-3.8	+1.7	-1.3	-1.6		
	E4	-6.4	+34.3	-4.6	-5.2	-2.0	-2.5	-4.8	-3.1	-3.2	-3.0	-1.7	-2.8	+16.2	-3.4	-1.8	-3.0	-3.0	-3.2	-2.2	-2.1	-1.9	-2.6		
	E5	-0.2	-1.5	+4.1	+2.3	+1.9	-0.3	-1.0	-2.7	+2.7	+1.7	+2.4	+0.5	+0.1	-2.2	-0.6	-1.5	-2.1	-2.9	-1.2	-0.8	-1.3	-2.2		
	E6	-0.4	-2.9	+19.4	-6.1	-3.8	+1.0	-2.9	-2.1	+0.8	+2.8	+2.1	-1.7	-0.6	-3.1	+2.2	+0.1	-1.1	-2.0	-1.6	-1.6	-1.6	-2.0		
	E7	+2.2	-0.6	+0.4	-1.7	-0.5	+2.1	-1.3	-0.7	+2.0	-0.5	+0.5	+2.1	-0.1	+0.9	+0.9	-1.3	-1.3	-1.6	-1.9	0.0	+1.1	-1.4		
	E8	+1.3	-2.7	-3.0	-2.5	+4.3	-2.4	+0.1	+6.4	-0.9	-2.1	-2.6	0.0	-1.8	+2.4	-2.1	-1.2	-0.8	-1.6	+0.4	+1.3	+9.4	+4.1		
	E9	+1.7	-1.1	+3.5	-2.9	-2.0	+2.2	-1.0	-2.2	-0.5	+3.4	-1.0	+0.7	+2.0	-2.0	+2.1	0.0	-1.2	-1.1	-0.5	+0.9	+0.4	-1.1		
	E10	-1.0	-2.3	+1.8	-2.0	+2.4	+0.9	+1.0	-2.0	-0.1	+2.6	+0.9	0.0	-1.0	-1.4	+4.4	-0.8	-1.4	-1.9	-1.0	-0.1	-0.2	+1.1		
	E11	-1.3	-2.1	+1.3	-3.0	-0.1	+1.1	-0.8	-1.2	+2.3	+2.4	+11.2	-0.5	-0.7	-1.2	-1.8	+0.7	-0.5	-0.5	-0.7	-0.6	-1.0	-2.0		
	E12	+0.1	-2.4	+4.9	-3.8	+1.4	+1.8	-0.8	+0.2	-0.5	-0.8	+0.3	-0.5	-2.0	-0.9	+3.8	+4.9	-2.2	-1.9	+0.3	-0.7	+0.1	-0.8		
	E13	+0.3	-2.9	+1.9	-4.3	+0.9	+1.4	+1.2	-1.0	-0.9	+2.8	+1.0	+0.7	-1.2	-1.9	+0.1	+2.3	+0.3	-0.9	-2.2	+2.1	+1.2	+1.6		
Injury Source (Total #:11,340)	S1	-2.9	+11.5	-10.6	+9.4	+11.3	-4.3	-3.8	+1.3	-5.8	-5.9	-6.2	-1.9	-4.2	+4.2	-6.4	-4.4	-3.2	+3.0	+8.4	+1.5	+0.9	+3.2	7595.7	<0.001
	S2	-0.9	-7.9	-7.6	+39.3	-2.4	-4.5	+4.8	+2.3	-0.7	-6.0	-6.1	-1.4	-6.2	-1.2	-5.8	-4.4	-4.3	+7.7	-1.5	-3.3	0.0	-0.3		
	S3	+2.1	-5.3	-1.0	-6.4	-0.6	-1.5	+7.5	-2.3	+0.7	+0.1	+5.8	+4.4	-2.5	-1.4	+6.8	+4.3	-0.1	-2.0	-3.7	-0.5	-1.0	+0.2		
	S4	+1.4	-4.8	-1.8	-6.1	-6.2	+0.8	-2.9	+3.3	-3.1	-2.7	-4.0	+0.1	+3.7	+11.6	-4.4	-2.9	+24.0	-0.1	+6.9	-0.9	+0.2	+1.7		
	S5	+1.8	-1.4	-0.5	-5.5	-1.3	+2.4	+0.7	+2.5	+0.5	+0.6	-1.6	+2.0	-1.3	+3.1	+0.3	-0.4	-0.2	+3.6	-2.1	-0.4	+0.6	-0.7		
	S6	-5.7	+32.9	-5.8	-6.4	-3.2	-1.5	-4.9	-3.8	-2.4	-3.2	-0.5	-1.9	+16.2	-3.2	+0.3	-1.3	-3.5	-3.5	-3.3	-0.1	-2.1	-2.4		
	S7	-2.6	-1.5	+20.6	-6.4	-4.8	+2.3	-2.9	-3.4	+5.5	+1.4	-0.5	-3.0	+4.9	-3.9	+3.5	+0.5	-3.0	-3.2	-1.3	-2.4	-1.7	-2.8		
	S8	-0.8	-5.2	+15.8	-6.9	-5.3	-1.0	-4.3	-2.5	+0.8	+12.2	+9.0	-0.1	-0.6	-3.9	+4.3	+1.8	+0.6	-4.2	-3.3	-3.3	-2.5	-2.8		
	S9	+2.6	+1.9	-0.9	-4.2	-3.1	+4.8	+5.7	-1.5	-0.7	-0.8	-2.2	+1.1	-0.8	-1.4	-2.2	-0.7	-1.5	-2.0	+0.8	+7.4	-2.3	+0.1		
	S10	+3.9	-4.3	+1.5	-4.6	-0.1	-0.8	-1.9	+3.1	+5.1	+0.9	+1.4	-0.9	-2.8	-2.7	-2.9	0.0	+1.9	+4.0	-1.4	-0.9	+1.9	+1.0		
	S11	+0.6	-1.1	+3.0	+0.5	-0.4	+0.3	-0.8	-2.6	+3.3	+2.1	+2.1	0.0	+0.8	-1.8	-0.3	-0.7	-0.7	-2.5	-0.1	-1.1	-1.0	-2.4		
	S12	+0.5	-2.9	-4.4	-1.7	+5.7	-0.7	+2.1	+5.0	-2.2	-1.7	-2.9	+1.1	-3.3	-0.3	-2.6	-0.5	-0.1	-1.1	+0.1	+1.9	+11.2	+3.6		
	S13	+4.4	-2.2	-1.8	-2.6	-1.2	+2.1	-0.3	-0.2	-0.4	+0.6	-2.0	+0.5	+1.4	-1.6	+1.2	+0.7	+1.8	+1.1	-2.1	+1.0	+0.7	+0.4		
	S14	-1.4	-2.7	-2.9	+0.3	+0.3	+0.7	+1.8	+2.6	-0.2	+0.1	-0.1	-0.7	+1.5	-1.9	+2.5	+2.3	-2.6	+4.4	-0.3	+1.1	+1.9	-1.6		
	S15	+1.8	-0.6	-1.4	-2.2	-0.4	0.0	+0.1	-0.1	+0.3	-0.7	+1.6	+0.2	-1.0	+1.9	+3.2	0.0	-0.8	-1.6	-0.6	-0.9	-0.1	+1.8		
	S16	-1.2	-1.5	+3.2	-2.6	-2.6	+1.4	+0.4	+0.5	+1.8	+5.0	+1.2	0.0	+0.6	-1.2	+3.1	+1.8	-1.6	-2.1	-1.8	-1.7	-0.4	-1.6		
	S17	+0.4	-1.9	+3.5	-2.1	-1.8	+0.9	-1.4	+2.5	+0.2	+0.2	+0.8	+0.9	-1.3	-1.3	+1.0	+0.6	0.0	-1.8	-1.5	-0.6	-1.0	+3.0		
	S18	-0.1	-0.2	+0.1	-2.0	-1.0	-1.4	-0.4	+0.7	+4.1	-1.2	-1.6	-0.6	+1.6	+1.1	+1.7	+3.0	-0.6	-1.1	-0.1	+0.2	-1.0	+0.5		
	S19	-1.6	-2.4	+0.5	-3.0	-0.9	-0.4	-2.2	-1.2	+0.8	+3.8	+17.7	-1.5	+1.1	-1.8	-1.2	+0.1	-1.7	-1.7	-1.5	+0.2	-1.0	+0.1		
	S20	-0.6	-3.9	+0.6	-6.5	+8.6	+2.3	-1.5	-2.6	-0.7	+2.1	+1.4	+0.9	-1.2	+1.4	+3.0	+4.9	-3.8	-3.0	+1.0	+1.1	-1.1	-0.2		
	S21	+0.6	-2.0	-1.2	-3.6	+0.7	+2.1	+3.2	-1.0	+0.5	+1.5	+1.1	+0.7	-1.5	-1.9	+2.4	+0.7	-2.0	+0.3	+0.2	+2.6	-0.5	-0.3		
Injured Body Part (Total #:11,340)	P1	+1.3	0.0	-0.4	-9.4	+2.9	+2.0	+0.2	-0.4	+2.0	-1.2	0.0	+2.4	-0.7	-2.1	+1.3	+4.3	-0.6	-2.9	-1.2	+2.8	+3.8	+0.4	550.8	<0.001
	P2	+1.6	-6.2	+4.9	-1.1	-2.9	-0.4	+0.5	0.0	+1.0	+2.1	+0.4	-0.8	-1.8	+2.0	+3.8	+2.6	-0.6	-0.7	-1.3	-0.6	-2.3	+0.6		
	P3	+0.5	-2.2	-1.8	+3.5	-0.7	-0.3	+0.7	+2.3	-1.8	-0.5	+1.2	-1.3	+1.0	+0.2	-0.4	-2.3	+2.1	+1.9	+0.4	-2.4	-0.5	+0.1		
	P4	-2.8	+3.7	-1.5	+8.0	+0.3	-0.9	+0.3	-0.8	-0.4	-1.8	-2.9	-0.9	-0.3	+0.4	-3.5	-3.5	-0.5	+1.9	+2.7	+1.3	-0.9	-0.8		
	P5	+0.3	+1.2	-1.1	-2.3	+0.5	+0.2	-0.4	+1.8	-1.7	+0.1	+0.2	+1.2	-1.9	+0.9	+0.5	-0.6	+0.4	+1.8	-1.2	-0.2	+0.4	+0.3		
	P6	-1.5	+2.3	-2.4	+6.4	-0.3	-1.1	0.0	-1.7	-1.2	-0.2	+0.1	-1.3	+0.8	+0.2	-2.8	-1.5	+0.5	+1.2	+1.1	-0.8	-1.1	+1.2		
	P7	-0.8	+4.8	+1.1	-1.4	0.0	-0.1	-2.1	-2.4	+1.1	+2.2	+1.0	+0.2	+5.4	-1.7	-0.5	-1.5	-1.3	-2.7	+0.5	-1.1	-1.2	-2.6		
	P8	+0.3	-0.3	+0.3	+0.3	-0.7	-0.3	-0.8	+1.5	-0.1	+0.5	+1.7	-0.6	-0.9	+0.5	-0.9	-0.8	-0.1	+0.6	-0.5	-1.2	+1.5	+0.1		
Injury Nature (Total #:11,340)	N1	+0.4	-5.0	-1.8	+7.6	-2.0	-1.0	+0.6	+0.2	-0.5	+0.4	-2.1	-0.5	-1.6	+4.6	+0.4	-1.3	+0.6	+1.9	+2.4	-1.8	-2.5	+1.2	1238.4	<0.001
	N2	+2.9	-7.0	+1.9	-10.6	+2.5	+1.9	-0.3	+2.2	+2.6	-1.5	+1.9	+2.6	-2.8	-3.0	+2.1	+5.4	-0.8	-0.9	-2.5	+3.8	+4.3	+2.8		
	N3	+0.6	+0.8	+0.6	-1.1	-0.1	+0.2	+0.9	-1.1	-1.6	+1.3	+0.5	+1.2	+2.6	-1.3	+0.6	-1.3	+0.7	-0.1	-0.6	-1.4	-0.8	-2.3		
	N4	-5.6	+22.4	-0.1	-2.8	+2.1	-0.6	-3.7	-4.4	-2.3	-1.3	0.0	-1.7	+8.4	-3.4	0.0	-1.8	-3.7	-4.4	-2.6	-1.5	-2.3	-1.7		
	N5	-1.5	+0.3	0.0	+2.8	-1.7	-0.5	+1.3	+2.4	-0.2	+0.1	-0.4	-1.8	-1.5	-0.8	-1.4	-1.2	+0.8	+0.9	+1.5	+2.5	-0.8	-0.2		
	N6	-0.3	+1.0	-1.7	+0.2	+0.6	+0.8	+0.3	+1.6	-2.3	-0.5	-0.9	+0.2	-2.1	+2.0	-1.4	-1.3	+0.5	+2.4	-1.0	+0.6	+1.4	+0.4		
	N7	+0.8	-0.8	+3.1	+0.8	-1.1	-0.8	-0.4	-2.3	+3.4	+2.4	+1.8	+0.5	+1.2	-1.5	-0.2	-1.3	-1.3	-2.3	-0.5	-0.9	-0.8	-2.7		
	N8	-1.2	-0.1	+0.1	+0.4	0.0	-0.6	+0.6	+0.3	+0.4	-0.3	+0.2	-1.4	-1.4	+1.0	-0.9	+1.1	+1.1	-0.2	+0.4	-1.1	+5.1	-0.5		
	N9	+1.2	-1.6	-0.4	-1.1	-0.8	-0.1	0.0	+0.1	+3.0	-0.8	+1.7	-1.7	-1.3	+0.4	-0.2	-0.1	+2.2	+1.1	+3.2	-0.7	-0.1	-2.1		
	N10	-0.5	+0.7	+1.7	0.0	+1.5	+0.2	+0.3	-0.5	+0.4	-1.3	-1.2	-0.4	-1.1	+0.9	-1.1	+1.0	+1.0	-1.0	-0.9	-0.8	-0.6	-0.3		
	N11	-0.1	-1.4	-1.9	+6.4	-1.0	-0.4	+0.7	+0.1	-1.2	+0.8	-0.9	-1.4	-0.8	+0.8	-2.9	-1.3	+1.3	+1.4	+2.1	-0.6	-1.6	+0.6		

Table 3-3: Relationships between Injury Source and Three other Attributes

Attribute	Attribute Categories	Injury Source																					Chi-Square Test Statistic	*p*-value
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21		
Event Type (Total #:11,340)	E1	+51.3	+33.5	-20.5	+28.9	+3.4	-18.2	-5.2	-14.2	-3.4	-16.8	-14.9	-13.4	-8.9	-11.2	-6.7	-3.1	-7.6	-7.5	+0.1	-20.2	-1.1	40008.9	<0.001
	E2	-20.6	-10.2	+31.4	-10.2	-13.7	-1.5	-4.9	-0.8	-4.0	+36.9	-7.5	-9.0	-2.8	+12.6	+7.3	+5.4	+14.8	+14.7	-5.6	+3.3	-4.8		
	E3	-14.1	-9.4	+9.2	-7.0	-8.8	-3.1	-3.2	+12.5	+18.9	-6.9	-7.6	+24.3	+0.7	+8.4	+6.1	+6.4	-3.3	-3.2	-3.8	+4.6	-4.6		
	E4	-8.2	-8.0	-4.9	-5.2	-5.8	+75.1	-4.1	-4.5	-2.7	-3.6	-3.4	-3.6	-3.3	-1.9	-3.0	-2.8	-2.3	+0.4	-2.3	-4.9	+0.1		
	E5	-8.1	-7.9	-5.8	-6.1	-5.6	-5.3	-5.3	-4.9	-4.9	-3.9	+87.9	-3.9	-3.6	-2.9	-2.4	-2.6	-1.7	-2.2	-2.1	+6.9	-3.7		
	E6	-7.6	-7.4	-5.8	-5.7	-5.3	-5.0	+41.2	+22.9	-2.5	-4.5	-4.0	-3.7	+17.6	-3.0	-2.9	-2.5	-2.1	-2.0	-2.0	-5.8	-4.1		
	E7	-7.5	-3.5	-4.9	-4.0	+70.3	-4.9	-4.7	-4.9	-4.3	-4.4	-3.9	-3.6	-3.3	-3.0	-2.1	-1.6	-2.0	-2.0	+0.2	-5.8	-4.2		
	E8	-5.5	-2.3	-1.0	-3.4	-4.1	-2.5	-3.6	-2.4	-1.7	+0.8	-3.1	+47.6	-2.6	+2.6	-0.9	-1.9	+1.0	+1.1	-1.5	-0.2	-2.0		
	E9	-5.8	-5.6	-4.4	-4.4	-4.0	-3.8	+6.7	+17.3	+7.8	-3.5	-3.1	-2.8	+36.6	-2.3	-2.2	-1.9	-1.6	-1.6	-1.5	-4.5	-3.2		
	E10	-4.1	-4.0	-2.8	-3.1	-2.8	-2.7	-1.9	-1.1	-2.5	-1.6	-1.7	-2.0	-1.3	-1.6	-0.9	-1.3	-0.2	-1.1	-1.1	+23.9	+4.9		
	E11	-3.7	+3.4	-2.8	+1.2	-1.7	-2.4	-2.0	-2.4	-0.8	-2.2	-1.9	-1.8	-1.6	-1.5	-0.7	-1.2	0.0	-1.0	+59.8	-2.2	-2.2		
	E12	-7.4	-6.6	-4.5	-5.0	-2.6	-4.5	+3.0	-2.2	-2.7	-4.6	-4.6	-4.4	-2.5	-2.1	+4.2	-0.1	-1.2	+0.2	-0.2	+32.5	+8.1		
	E13	-5.6	-3.9	+0.7	-3.6	-3.3	-2.5	-1.3	+1.1	-0.2	-2.0	-2.9	-1.1	-1.6	+0.6	-1.1	-1.2	+3.3	-1.5	-1.5	-2.2	+35.5		
Injured Body Part (Total #:11,340)	P1	-13.5	-11.0	+6.8	-9.7	-8.1	+2.6	-4.9	+2.5	+5.3	+19.6	-11.3	+27.2	-2.0	+5.3	+2.7	+3.0	+0.1	+8.4	-5.9	+4.8	-1.0	9160.9	<0.001
	P2	+3.2	-3.9	+7.9	+0.3	+4.5	-8.1	+2.2	+9.0	-2.4	-3.6	-8.7	-8.9	+6.9	+1.8	0.0	+3.8	-0.1	-3.8	+1.9	-0.9	-3.1		
	P3	+7.5	+7.8	-5.1	+7.3	+7.3	-7.5	+2.0	+0.4	+1.2	-6.5	-8.2	-7.3	-0.1	-3.4	-0.9	-0.3	-2.6	-2.3	+4.0	-5.0	+0.7		
	P4	+7.8	+13.1	-5.8	+3.9	-0.9	+5.9	+3.9	-4.5	-2.3	-7.6	-8.0	-7.3	-1.0	-5.2	-1.6	-3.5	-1.5	-3.6	+0.4	-0.6	-1.0		
	P5	+2.9	-1.2	+1.0	+0.8	+5.2	-1.1	+0.2	-4.3	-0.9	-1.1	-6.4	-5.2	-1.6	+6.3	+1.0	-1.9	+7.3	+2.6	+0.7	-2.5	+2.8		
	P6	+2.7	+5.7	-5.1	+6.1	-1.5	+2.4	+2.4	-3.8	+0.9	-6.1	-5.1	-4.8	-0.9	-4.3	+0.1	-1.0	-1.4	-1.8	+1.7	-0.1	+5.2		
	P7	-8.7	-8.7	-6.5	-6.4	-6.4	+11.3	-5.7	-5.7	-4.0	-4.1	+77.4	-4.2	-3.9	-3.1	-3.5	-3.0	-2.5	-2.0	-2.0	+3.8	-1.3		
	P8	-1.1	+0.9	-0.2	+0.3	+0.2	-2.1	-1.6	+1.5	-1.9	+3.6	-1.1	-0.2	+0.7	-1.3	+1.3	-1.0	+3.8	-0.9	+1.6	+0.3	-0.8		
Injury Nature (Total #:11,340)	N1	+18.9	+13.2	-0.6	+10.6	+10.4	-13.6	+4.1	+0.9	+1.0	-16.1	-15.6	-12.4	+3.4	-8.3	-1.7	+1.4	-3.3	-4.1	+3.3	-11.0	-3.1	16966.9	<0.001
	N2	-18.8	-13.9	+7.7	-11.4	-9.5	-4.9	-5.6	+3.3	+2.7	+34.0	-8.9	+27.4	-2.5	+16.9	+3.2	+2.8	+5.0	+7.3	-4.6	+4.4	-1.3		
	N3	-1.1	-0.1	+1.7	+0.4	0.0	+2.8	+1.6	+2.1	+1.6	-6.0	-7.4	-4.6	+2.5	-1.0	-0.4	-0.4	+2.0	-0.6	+1.2	+2.6	+1.0		
	N4	-9.7	-9.2	-6.1	-6.7	-4.9	+47.6	-4.6	-4.3	-4.7	-4.4	-4.4	-4.6	-4.0	-2.9	-0.1	-3.2	-1.9	-0.2	-2.6	+21.8	+1.7		
	N5	+4.9	+6.7	-1.9	+2.1	0.0	-4.3	+4.1	-1.1	+0.3	-3.7	-3.8	-3.3	+0.3	-2.5	+1.1	-1.0	-0.7	-1.2	+1.3	-4.0	+0.4		
	N6	+6.2	+2.8	-1.1	+2.3	+5.8	-4.2	+2.5	-2.7	-1.2	-4.4	-4.1	-3.7	-0.4	-2.0	-0.8	-1.3	-0.1	-0.6	+1.6	-2.8	+1.9		
	N7	-7.0	-6.8	-5.4	-5.3	-4.9	-4.6	-4.6	-4.6	-4.3	-4.2	+100.6	-3.4	-3.1	-2.8	-2.7	-2.3	-1.9	-1.9	-1.9	-6.5	-4.2		
	N8	+0.2	-0.1	-0.5	-0.4	+1.7	-2.0	-0.3	+1.5	+0.2	-1.7	-2.5	-1.8	+0.4	-1.3	+1.7	+0.5	-1.3	+1.2	-0.4	+2.9	+0.2		
	N9	+0.6	+1.4	+2.6	-0.3	-0.7	-1.7	+1.7	+2.1	-2.3	-1.8	-1.5	-1.3	-0.5	-0.2	-0.8	-0.4	+0.9	0.0	+3.0	-2.7	+2.7		
	N10	-1.7	-1.6	-1.7	-1.7	-0.8	-0.7	-1.5	-0.7	-0.6	-1.3	+1.5	-1.1	-1.0	-0.9	-0.8	-0.7	-0.6	+1.1	+1.2	+5.9	+7.4		
	N11	+4.1	+5.8	-3.5	+7.9	-0.5	-4.7	+2.4	-2.1	+0.3	-4.4	-4.1	-3.5	+0.8	-3.1	-0.1	-0.5	-1.1	-2.1	+0.5	-3.8	+4.4		

Table 3-4: Relationships between Event Type and Two other Attributes

Attribute	**Attribute Categories**	**Event Type**													**Chi-Square Test Statistic**	***p*-value**
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13		
Injured Body Part (Total #:11,340)	P1	-31.7	+8.7	+51.3	-2.2	-11.3	-11.2	-4.3	+18.9	-6.0	-3.8	-5.4	-7.7	+7.3	11024.69	<0.001
	P2	-2.6	+13.5	-14.5	-11.1	-10.3	+16.5	+6.0	-4.6	+6.1	-2.4	+1.7	+1.4	+0.5		
	P3	+19.9	-6.7	-12.5	-9.0	-8.5	-1.5	+7.5	-5.3	+2.2	-2.8	+4.7	+3.4	-3.4		
	P4	+22.3	-12.3	-15.2	+8.1	-2.4	+2.0	-5.4	-6.4	+0.7	+10.5	+1.1	-3.4	-4.8		
	P5	+4.5	+9.2	-11.0	-3.4	-6.1	-4.4	+4.3	-1.9	+0.9	-0.6	-1.1	0.0	-1.0		
	P6	+14.0	-10.2	-8.8	+6.5	-3.0	+2.9	-5.0	-4.5	-1.5	+3.1	+2.5	+1.4	+0.9		
	P7	-18.4	-13.9	-9.3	+23.2	+69.7	-5.0	-4.9	-3.9	-3.5	-2.3	-2.4	+11.1	-2.5		
	P8	-0.4	+4.9	-2.9	-2.0	-1.3	-1.7	-0.5	-0.6	+2.6	-0.9	-0.8	+0.5	-0.5		
Injury Nature (Total #:11,340)	N1	+34.5	-5.4	-18.9	-18.2	-17.1	+6.7	+8.8	-11.1	+5.4	-8.4	+3.8	-6.7	-5.2	20501.79	<0.001
	N2	-38.8	+24.4	+44.7	-12.8	-12.7	-7.7	-6.3	+23.8	-4.6	-6.4	-4.8	-6.5	+8.6		
	N3	-0.8	+0.2	-4.9	+8.7	-9.1	+2.4	+0.3	-5.0	+2.7	-4.1	+1.5	+8.5	+0.6		
	N4	-19.6	-15.1	-10.1	+63.9	+15.8	-5.4	-2.8	-4.2	-3.9	+41.3	-2.6	+6.2	-3.7		
	N5	+11.8	-3.4	-6.0	-5.0	-4.7	+4.3	-1.5	-2.4	+0.2	-1.0	+0.9	-0.4	-2.5		
	N6	+11.6	-2.2	-7.5	-4.8	-4.5	-1.9	+3.0	-2.3	+0.1	-2.3	-0.5	+1.1	-0.3		
	N7	-14.1	-10.6	-7.2	-4.3	+92.3	-3.8	-3.7	-2.9	-2.9	-2.0	-1.8	-4.6	-2.8		
	N8	+0.5	-3.0	-3.1	-2.9	-2.7	-0.1	+1.7	-0.4	+0.7	-1.4	+0.4	+13.4	-0.2		
	N9	-0.2	+5.0	-2.5	-2.4	-2.2	+1.9	-1.0	+0.9	-1.6	-1.1	+2.0	-1.2	-0.9		
	N10	-4.1	-2.9	-2.3	-1.4	+0.4	-1.2	-0.3	-0.9	-0.9	-0.6	-0.6	+16.2	+8.5		
	N11	+15.9	-6.8	-6.4	-4.6	-4.5	+3.2	-3.6	-3.3	-0.3	-2.3	+2.0	-1.0	+1.0		

A disproportionate number of injuries to the lower extremities (P2) are sustained by *highway, street, and bridge construction workers* (CS3) (ε_{ij} = *+4.9)* – many of which involved vehicular traffic or heavy equipment. *Oil and gas pipeline and related structures construction* (CS15) workers also experienced a disproportionate number of injuries to the *lower extremities* (P2) (ε_{ij} = *+3.8)* as a result of a variety of sources including large pipes, heavy equipment, and others.

Finally, roofing contractors (CS4) are especially vulnerable to injuring the *trunk* (P3) (ε_{ij} = *+3.5)*. Many of these injuries impact the ribs, spine, and other body parts and are linked to falls from heights when working particularly on the roof and with ladders.

Table 3-5: Relationship between Injured Body Part and Injury Nature

Attribute	**Attribute Categories**	**Injured Body Part**								**Chi-Square Test Statistic**	***p*-value**
		P1	P2	P3	P4	P5	P6	P7	P8		
Injury Nature (Total #:11,340)	N1	-26.0	+36.1	+14.1	+7.7	-11.7	-10.9	-19.5	+2.0	24121.93	<0.001
	N2	+64.2	-14.4	-21.1	-22.6	-3.7	-14.5	-14.4	-0.2		
	N3	-13.4	-5.7	+24.1	+0.3	-5.3	-10.2	+17.1	+1.3		
	N4	-1.1	-9.5	-8.8	+18.7	-2.1	+11.8	-6.4	-1.3		
	N5	-9.7	-7.0	-3.8	+33.7	-3.6	-2.8	-5.3	-1.8		
	N6	-13.6	-10.9	-8.7	-8.6	+68.6	-6.0	-5.1	-1.8		
	N7	-12.3	-9.9	-7.9	-7.8	-6.0	-5.2	+80.7	-1.6		
	N8	-0.1	+3.5	+6.6	-3.9	-3.7	-2.7	-3.1	+1.8		
	N9	-4.3	+0.7	+3.8	-0.2	+0.4	+2.9	-2.5	+1.4		
	N10	-3.5	-1.1	+4.6	-2.5	-1.9	-1.7	+10.2	-0.5		
	N11	-13.8	-11.0	-8.8	-8.7	-6.7	+77.1	-5.1	-1.8		

3.6.3.4. Relationship between Construction Sector and Injury Nature

Findings in Table 3-2 suggest that roofing contractors (CS4) (ε_{ij} = +7.6) and drywall and insulation contractors (CS14) (ε_{ij} = +4.6) are particularly likely to experience traumatic injuries to bones, nerves, and spinal cord (N1) when compared to what is statistically expected had a relation not existed between the attributes. Many of these injuries, as discussed earlier, resulted from falls to lower level (E1) events. In contrast, entities involved in other heavy and civil engineering construction (CS16) (ε_{ij} = +5.4), finish carpentry contractors (CS21) (ε_{ij} = +4.3), and other building equipment contractors (CS20) (ε_{ij} = +3.8) are particularly susceptible to experiencing open wounds (N2). These open wounds largely resulted from the use of specialized equipment such as drills and pumps among entities involved in other heavy and civil engineering construction (CS16), mechanical saws among finish carpentry contractors (CS21), and conveyors, cranes, hoppers, elevator systems, and other stationary equipment among other building equipment contractors (CS20).

3.6.3.5. Relationship between Injury Source and Event Type

As shown in Table 3-3, the relative risk of *falls to lower level* (E1) is particularly high when work involves working with *ladders* (S1) *(ε_{ij} = +51.3)* and working on *structural elements* (S2) *(ε_{ij} = +33.5)* such as roofs, joists, and other elements that present a leading edge. The risk for *falls to lower levels* (E1) is also high for work involving *structures other than buildings* (S4) *(ε_{ij} = +28.9)* such as scaffolding, staging, falsework, and highway bridges.

In contrast, significant risks for *struck by object or equipment* (E2) incidents exists when work involves working with *powered handtools* (S10) *(ε_{ij} = +36.9)*. These include tasks where *powered handtools* (S10) such as saws and drills are used. *Struck by object or equipment* (E2) incidents also commonly involve *building material* (S3) *(ε_{ij} = +31.4)*. Many of these incidents involve falling material such as rebar, steel sections, lumber, and pipes that can strike workers. A substantial amount of risk for *struck by object or equipment* (E2) incidents also involve *scrap, waste, and debris* (S17) *(ε_{ij} = +14.8)*. Sources of *scrap, waste, and debris* (S17) include concrete projectiles generated from chipping operations, airborne metal shavings resulting from machining operations (e.g., milling, drilling, etc.), and falling scrap material during clearing and cleaning operations.

Finally, *caught in or compressed by equipment or objects* (E3) incident often involved *metal, woodworking, and special material machinery* (S12) *(ε_{ij} = +24.3)*such as stationary mechanical saws, and other specialized machinery (e.g., sheet metal rollers, pipe groover, threader machine etc.). These types of incidents are also common in work involving *material and personnel handling machinery* (S9) *(ε_{ij} = +18.9)* such as conveyors, aerial lifts, and cranes in the context of rigging operations. In the same manner, a disproportionate number of *caught in or compressed by equipment or objects* (E3) incidents are linked with *construction, logging, and mining machinery* (S8) *(ε_{ij} = +12.5)* such as excavators, earthwork rollers and others. An example incident of this nature is an earthwork roller that rolled over the foot of a worker.

3.6.3.6. Relationship between Injury Source and Injured Body Part

Injuries to the *upper extremities* (P1) were particularly common for work involving *metal, woodworking, and special material machinery* (S12) *(ε_{ij} = +27.2)* such as mechanical drills, metal sheet cutting equipment, and table saws (see Table 3-3). In the same manner, injuries to the *upper extremities* (P1) were also common for tasks involving *powered handtools* (S10) *(ε_{ij} = +19.6) and nonpowered handtools* (S18) *(ε_{ij} = +8.4)*. Examples of *powered handtools* that were commonly involved in these incidents included powered nail guns and hand saws. On the other hand, examples of nonpowered handtools involved in the incidents included utility knives, unpowered saws, and others.

When considering *lower extremities* (P2), a disproportionate number of the injuries involved *construction, logging, and mining machinery* (S8) *(ε_{ij} = +9.0)* and *powered off-road and industrial vehicles* (S13) *(ε_{ij} = +6.9)*. Several of these incidents involved injuries to the leg and feet after contact was made with a piece of equipment such as excavators, skid-steers, forklifts and others. A disproportionate number of injuries to the *lower extremities* (P2) also involved *building materials* (S3) *(ε_{ij} = +7.9).* In many of these incidents, the foot of the worker was caught or crushed between elements such as steel sections, rebar, lumber pallets, and others. Cases also involved falling material such as glass and steel sections on the feet.

Injuries to the *trunk* (P3) were most associated with *structural elements* (S2) *(ε_{ij} = +7.8)* such as joists, trusses, and skylight. Many of these injuries were associated with falls when workers worked on these *structural elements* (S2). Many injuries to the *trunk* (P3) also followed fall incidents when workers worked on *ladders* (S1) *(ε_{ij} = +7.5)* and *structures other than buildings* (S4) *(ε_{ij} = +7.3)* such as scaffolding, staging, falsework, and others.

3.6.3.7. Relationship between Injury Source and Injury Nature

Traumatic injuries to the bones, nerves, spinal cord (N1) were disproportionately associated with ladders (S1) (ε_{ij} = +18.9), structural elements (S2) (ε_{ij} = +13.2) such as joists, roof, trusses, and structures other than buildings (S4) (ε_{ij} = +10.6) that included scaffolding, staging, and other temporary structures as shown in Table 3-3. Many of these incidents followed falls from these sources that resulted in fractures to the hands and legs.

Open wounds (N2), on the other hand, were most associated with power handtools (S10) (ε_{ij} = +34.0) and metal, woodworking, and special material machinery (S12) (ε_{ij} = +27.4.0). Many of these incidents involved laceration and cuts when workers used machinery and tools such as table saws, mechanical drills, and others. Likewise, a disproportionate number of open wounds (N2) were also linked with fasteners, connectors, ropes, and ties (S14) (ε_{ij} = +16.9). These incidents often involved contact with nails when using nail guns and contact with unprotected screws that protruded from lumber and other structural elements.

3.6.3.8. Relationship between Event Type and Injured Body Part

Much of the injuries to the *upper extremities* (P1) resulted from *caught in or compressed by equipment or object* (E3) ($\varepsilon_{ij} = +53.1$) incidents as captured in Table 3-4. These incidents often involved injuries to the hands and fingers while workers operated hand tools and machinery. Many of these incidents also involved crushing of the hand or fingers when workers handled *structural elements* (S2) or and *building material* (S3). Other influential events that pose a high risk of injuries to the *upper extremities* (P1) include *struck against object or equipment* (E8) ($\varepsilon_{ij} = +18.9$) incidents and *struck by object or equipment* (S2) ($\varepsilon_{ij} = +8.7$) incidents. Many of these incidents involved cases where workers made physical contact with moving and sharp elements in equipment and machinery and vice versa. A significant number of the *struck by object or equipment* (S2) incidents also involved falling objects (e.g., pipes, fasteners, and structural members) that made contact with workers.

When examining injuries to the *lower extremities* (P2), *vehicular incidents* (E6) ($\varepsilon_{ij} = +16.5$) where vehicle operators made contact with workers posed a disproportionate amount of risk. These incidents occurred not only in the context of highway work zones; but also in the context of traditional construction workplaces. Many of these incidents involved dump trucks, delivery trucks, and other mobile equipment. A significant proportion of injuries to the *lower extremities* (P2) also resulted from *stuck by object or equipment* (S2) ($\varepsilon_{ij} = +13.5$) incidents that either involved falling objects or contact with equipment components such as the bucket of an excavator or the boom of a crane. *Nonroadway incidents involving motorized land vehicles* (E9) where the operator is injured following incidents such as equipment rollovers (e.g., truck) and equipment sliding down uneven terrains were also common causes of injuries to the *lower extremities* (P2) ($\varepsilon_{ij} = +6.1$).

Finally, the risk of injuries to the *trunk* (P3) was substantially high following *falls to lower level* (E1) *(ε_{ij} = +19.8)* incidents and *falls on same level* (E7) *(ε_{ij} = +7.5)* incidents. Injuries to the *trunk* (P3) are also particularly likely following *struck, caught, or crushed in collapsing structure, equipment or material* (E11) *(ε_{ij} = +4.7)* incidents. Many of these incidents involved excavation and trench collapses or cave-ins. Others also involved collapsing structures following strong winds and structural collapse after bracing members were removed during construction operation.

3.6.3.9. Relationship between Event Type and Injury Nature

Traumatic injuries to the bones, nerves, and spinal cord (N1) usually followed falls to lower level (E1) (ε_{ij} = +34.5) incidents and falls on same level (E8) (ε_{ij} = +8.8) incidents as shown in Table 3-4. A significant number of these injuries also followed vehicular incidents (E6) (ε_{ij} = +6.7) predominantly affecting highway, street, and bridge construction workers (CS3). Much of the injuries resulted in fractures that impacted the hands, legs, and ribs.

On the other hand, open wounds (N2) such as cuts and lacerations were common as a result of caught in or compressed by equipment or object (E3) (ε_{ij} = +44.7) incidents. These incidents were largely related to the operation of equipment such as stationary drills and table saws that presented sharp elements. Many of these incidents also involved parts of the body (e.g., upper extremities (P1) being pinched when handling material such as pipes and structural steel. Other events that led to open wounds (N2) involved struck by object or equipment (E2) (ε_{ij} = +24.4) incidents and struck against object or equipment incidents (E8) (ε_{ij} = +23.8) – many of which followed physical contact with sharp elements that were part of handtools and machinery.

Finally, a disproportionate number of the other traumatic injuries and disorders (N3) resulted from the exposure to electricity (E4) (ε_{ij} = +8.7). The majority of these incidents resulted from the contact of sources such as electrical wiring, powerlines, electrical transformer elements, and other sources of electricity. None of the other events made a significant contribution to the chi-square test statistic when considering other traumatic injuries and disorders (N3).

3.6.3.10. Relationship between Injury Nature and Injured Body Part

Traumatic injuries to bones, nerves, and spinal cord (N1) disproportionately impacted lower extremities (P2) (ε_{ij} = +36.1) as shown in Table 3-5. The trunk (P3) was also particularly susceptible to experiencing traumatic injuries to bones, nerves, and spinal cord (N1) (ε_{ij} = +14.1); many of which involved fracture to the ribs and spinal injury. Many of these injuries also affected multiple body parts (P4) (ε_{ij} = +7.7) and the most common combinations of body parts injured were the hands and the legs.

Open wounds (N2) only largely impacted upper extremities (P1) (ε_{ij} = +64.2). As has been discussed earlier, many of these incidents resulted from the contact of tools and machinery that presented sharp components. In contrast, other traumatic injuries and disorders (N3) disproportionately impacted the truck (P3) (ε_{ij} = +24,1) which largely involved injuries to internal organs in the back and hip regions. Other traumatic injuries and disorders (N3) also impacted the neck – including throat (P7) (ε_{ij} = +17.1) regions and many of these incidents involved falls or being struck by building materials and equipment parts.

3.7. Discussion and Conclusion

The presented effort represents the first investigation of incident reports captured via the *severe injury reporting program* that is relevant to the construction industry. The findings offer valuable insights that can be strategically leveraged to enhance workplace safety as discussed below:

First, the investigation found that workers in the construction industry sustain more severe injuries than workers in other industries, with the exception of the manufacturing industry.

Therefore, regulatory bodies and industry leaders must prioritize strategic initiatives directed at severe injuries in the context of the construction industry apart from focusing on the manufacturing industry. Moreover, the evidence demonstrated that the number of reported severe injuries follow a cyclic or seasonal pattern – with more injuries reported over the summer months. Armed with this knowledge, regulatory bodies and industry leaders may also want to allocate additional resources over the summer months to manage work-related safety risks in the construction industry. For example, OSHA and other affiliated agencies may invest additional resources towards safety campaigns and training programs to strengthen the focus on workplace safety in the summer months. Likewise, OSHA may increase their compliance assistance and inspection efforts over the summer months to ensure that safe and healthy workplaces are offered to construction workers. In the same manner, construction businesses may also offer training and adopt complementary interventions to tackle the expected surge in high-risk severe injuries over summer.

Second, the study findings unveiled event types that are overrepresented among the severe injury reports from the construction industry. These events include *falls to lower level*, *struck by object or equipment*, and *caught in or compressed by equipment or objects* incidents. Accordingly, as a starting point, the construction industry may strategically prioritize their efforts towards tackling these overrepresented severe injury *event types*. In the same manner, the study suggests that *injury sources* that include (1) *ladders;* (2) *structural elements;* (3) *building materials;* and (4) *structures other than buildings* must be prioritized as part of injury prevention efforts. Likewise, the industry may streamline their efforts to tackle high-priority incidents linked with *injured body parts* (e.g., *upper extremities* and *lower extremities) and injury nature* (e.g., *traumatic injuries to bones, nerves*) – given their prevalence. Severe injury prevention initiatives may also need to be prioritized in particularly high-risk *construction sectors* as identified in the current article.

Third, the findings also offer a data-driven approach to reducing severe injury incidents. For example, to tackle *falls to lower level* incidents – which is one of the *event type* that needs to be prioritized – the related *injury sources* may be identified from Table 3-3. An examination of Table 3-3 reveals that the *injury source* that presents the highest relative risk for *falls to lower level* are *ladders*. Accordingly, efforts may be devoted to enhancing safety for work that involves *ladders*. For example, training on the safe use of ladders may be promoted and offered in construction workplaces. Likewise, industry leaders may encourage the use of aerial lifts and scissor lifts that offer protective in-built guardrails that have been shown to be safer than *ladders* for work at height. Safer designs that eliminate the need to work at heights where *ladders* may possibly be needed may also be pursued per the *prevention through design (PtD)* concept. Similar strategic initiatives may be adopted to reduce the risk posed by other sources that are disproportionately linked with *falls to lower level* incidents – which include *structural elements*, *structures other than buildings*, and *floors, walkways, and ground surfaces* as captured in Table 3-3. To maximize the benefits of these strategic initiatives that target *falls to lower level*, construction sectors that disproportionately experience these events – such as *roofing contractors, drywall and insulation contractors, framing contractors, painting and wall covering contractors, and masonry contractors* – may be particularly targeted per Table 3-2 findings. If *construction sectors* that are particularly injured while working with ladders must be targeted, then *electrical contractors and other wiring installation contractors* ($\varepsilon ij = +11.5$); *plumbing, heating, and air-conditioning contractors* ($\varepsilon ij = +11.3$), *roofing contractors* ($\varepsilon ij = +9.4$); *painting and wall covering* *contractors*, and *drywall and insulation contractors* must be particularly targeted per findings in Table 3-2.

Fourth, the findings also offer insights on the benefits of prioritizing the prevention of specific *event types*. For example, an emphasis on the prevention of *falls to lower level* events, as discussed above, may lead to fewer injures to *multiple body parts*, the *trunk*, *body systems*, and the *head* as shown in Table 3-4. Moreover, these efforts are expected to translate to fewer *traumatic injuries to bones, nerves, and spinal cord*, *multiple traumatic injuries*, and *intracranial injuries* as also shown in Table 3-4. On the other hand, an emphasis on the prevention of *caught in or compressed by equipment or objects* incidents is expected to significantly reduce injuries to the *upper extremities* that result in *open wounds* as captured in Table 3-4.

Using the above discussed approach, high-risk areas may be prioritized and addressed. The success of these initiatives may be evaluated on a continual basis by examining future incidents reported via the severe injury reporting program. If successful reduction in the high-risk areas is achieved, subsequent efforts may focus on targeting other areas that continue to pose significant risks to construction workers. Such a systematic approach to addressing severe injuries among construction workers may translate to fewer workplace injuries and better working conditions. Ultimately, these efforts that target the safety of construction workers may yield a more productive and effective workforce – that is empowered to address the infrastructure needs of our communities and the broader society.

Finally, by targeting severe injuries, the current study complements existing research that has heavily focused on the analysis of fatal incidents. The findings demonstrate that there are similar patterns when comparing attributes associated with both fatal and severe injuries. For example, while previous research has identified *falls to lower levels* as being the leading cause of construction-related fatal incidents, the current investigation found that *falls to lower levels* is also the leading cause of severe injuries. In the same manner, *struck by object or equipment* and *caught in or compressed by equipment or objects* incidents are overrepresented in both fatal and severe injuries. Accordingly, currently adopted efforts such as the OSHA-led *fall prevention campaign* and the *construction focus-four program* will also be beneficial to tackling severe injuries – apart from fatal incidents that have been the traditional focus.

However, the current investigation has also offered new and complementary insights that are not particularly highlighted in the investigation of fatal incidents. For example, the current findings suggest that injuries to the upper extremities such as hands must be prioritized to prevent severe injuries; while research efforts on fatal incidents largely have not focused on examining injured body parts. Likewise, while most of the fatal falls are linked with *structural elements* that include roofs, the current investigation found that ladders are the most influential *injury source* among severe injuries. Finally, the current study offers a comprehensive analysis of all severe injuries as opposed to much of previous research that has narrowly focused on areas such as *falls to lower levels* or *struck by object or equipment* incidents. Accordingly, users of the research can leverage the findings to tackle any severe injury type regardless of *event type*, *injury source*, *injured body parts* or other attributes.

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Chapter 4: Work-Related Safety Incidents among Driver License Examiners

Alsharef, A., Albert, A., Uddin, S. J., Kittur, N. B., Chavan, S., and Jaselskis, E. (2021). "Work-Related Safety Incidents among Driver License Examiners." *Safety Science*, Elsevier, 140, 105304.

4.1. Abstract

Driver license examiners serve as the first line of defense against unsafe drivers and driving practices. Nonetheless, these examiners themselves are exposed to high levels of safety risk as they test new drivers – with limited driving proficiency and experience. A deeper understanding of these incidents can inform the development of effective injury prevention policies and interventions. Towards achieving this goal, the current study focused on performing exploratory content analyses of safety incident reports maintained by the North Carolina Division of Motor Vehicles (NCDMV) that involved driver license examiners. Apart from demonstrating that numerous incidents are experienced during driving tests, the five key findings include the following: (1) The most common *event types* that driver license examiners experience are *collision with fixed object*, *overexertion and physical bodily reaction*, and *collision with another vehicle*; (2) The most common *contributing factors* are *failure to maintain control of vehicle* and incidents experienced while examiners *are exiting the vehicle*; (3) Most incidents that result in injury involve injuries to *multiple body parts,* followed by injuries to the *back*, *leg*, and *neck*; (4) The most common *injury types* are *strain*, *sprain*, and *bruising and contusion*; (5) The *injury outcomes* are *medical case, permanent disability*, *report only*, and *temporary disability*. The results also reveal particular relationships that are overrepresented in the incident reports. For example, *collision with fixed object* is associated particularly with *failure to maintain control of vehicle*. The findings can inform future efforts that seek to reduce injury rates among driver license examiners.

4.2. Introduction

Every year, driver license examiners administer millions of driving tests across nations (Bureau of Infrastructure, Transport, and Regional Economics 2017, Driver and Vehicle Licensing Agency 2020, Federal Highway Administration 2011). The primary purpose of these tests is to ensure that new drivers – who are issued licenses – are able to safely operate motor vehicles to minimize the risk of traffic crashes and property damage (e.g., Haire et al. 2011; NCDMV 2020, Zakhareuski 2020). Therefore, driver license examiners play a crucial role in reducing traffic incidents and crash rates; and serve as the first line of defense against unsafe drivers and driving practices (McDavid and Echaore-McDavid 2009; Rosenbloom et al. 2007).

Despite their significant role in preventing crashes and enhancing traffic safety, driver license examiners are themselves exposed to high levels of safety risk as they test new drivers who typically have limited driving experience and proficiency (e.g., North Carolina Office of State Human Resources 2013; Smith 2018). In fact, evidence suggests that a large number of driver license examiners are injured on a regular basis as they administer driving tests (Martz 2011). Some estimates indicate that at least one examiner is injured every three days during driving tests (Driver and Vehicle Licensing Agency2017). Evidence also suggests that driver license examiners experience a disproportionate number of near-misses and unsafe situations every year (Driver and Vehicle Licensing Agency 2017; North Carolina Department of Transportation 2019).

Apart from the physical pain and distress, such injuries result in substantial costs in terms of medical expenses and worker compensation claims – that exceed hundreds of thousands of dollars (Economic Policy Institute 2013; National Safety Council 2018; North Carolina Department of Transportation 2019). These incidents also result in productivity loss that interferes with the efficient administration of driving tests and the operations of licensing offices. When driver license examiners are injured, their ability to enhance traffic safety proactively, protect the public, and serve the community is impeded. Therefore, research that focuses on reducing work-related injuries among this community of workers is imperative to ensure the safety of driver license examiners, new drivers, and the public.

As a first step towards tackling this problem, understand the safety challenges and risks that driver license examiners face is critical. Such efforts can facilitate the adoption of appropriate policies and interventions that promote safety during the administration of driving tests. Unfortunately, previous research has not focused on addressing the safety challenges experienced by driver license examiners.

Although anecdotal accounts of the risks that driver license examiners face are available (e.g., testing inexperienced driver) (Martz 2011; North Carolina Department of Transportation 2019; White 2016), large amounts of textual data in the form of incident reports, maintained by driving licensing agencies, remain largely unexamined. The currently reported effort focused on performing exploratory content analyses of incident reports maintained by the NCDMV – as part of a strategic initiative to enhance safety among driver license examiners. The investigation focused on identifying attributes such as *event type*, *contributing factor*, *injured body part*, and others that were associated with the reported incidents. The investigation also focused on assessing if a relationship exists between the identified attributes (e.g., *event type* vs. *contributing factor*). These findings will serve as the foundation for future efforts that seek to identify and test prospective interventions to address the identified safety issues.

4.3. Background

4.3.1. Reducing Traffic-Related Safety Incidents

Globally, more than a million lives are lost every year as a result of traffic safety incidents (World Health Organization 2018). In the United States, traffic crashes account for more than 30,000 deaths and over four million traumatic injuries every year (Association for Safe International Road Travel 2019; National Safety Council 2019). In fact, traffic safety incidents have been identified as one of the leading causes of mortality across nations (World Health Organization 2018). Apart from the pain and suffering, these incidents also result in adverse economic and societal outcomes. For example, estimates suggest that the economic and societal burden of traffic incidents in the United States exceed $870 billion every year (Blincoe et al. 2015).

Given the scale and significance of traffic-related incidents, much research has been devoted to understanding factors that contribute to traffic incidents. For example, a large body of research has examined the role of personal factors such as the age and experience of drivers on crash likelihood (e.g., Chang and Yeh 2007; Oltedal and Rundmo 2006). Similarly, others have examined behavioral factors such as speeding and drunken driving (e.g., Møller and Haustein 2014; Ristic et al. 2013; Stanton and Salmon 2009), environmental factors such as weather, rain and snow (e.g., Qiu and Nixon 2008; Yan et al. 2014; Yu and Abdel-Aty 2014), and highway characteristics such as the layout and the condition of roads on the risk of traffic incidents (e.g., Hummer et al. 2016; Wang et al. 2013; Weng and Meng 2012).

As our understanding of factors that cause injuries and crashes has increased, strategic initiatives to enhance safety have been adopted. Examples of such initiatives include establishing and enforcing speed limits (Archer et al. 2008), requiring the use of seatbelts (Kidd and Singer 2019), replacing road intersections with roundabouts (Daniels et al. 2008), placement of guardrails alongside roads (Soltani et al. 2013), and illuminating roadways using artificial lighting after sunset (Monsere et al. 2008).

Apart from the above-discussed initiatives, an effective and upstream measure used to reduce traffic incidents is the administration of driving tests by driver license examiners. This measure focuses on assessing the driving skill of prospective drivers prior to the issuance of driver licenses (e.g., Haire et al. 2011; North Carolina Division of Motor Vehicles 2020, Zakhareuski 2020). Such driving tests are almost universally adopted across nations including the United States, Australia, Canada, United Kingdom, and others – although the specific test requirements may vary across states, provinces, territories, and jurisdictions. For example, in the United States, more than 200 million active licenses have been issued following driving tests (Federal Highway Administration 2019). Likewise, in Canada and Australia, there are more than 26 million and 16 million active drivers that have been issued licenses after following the established procedures that include a driving test (Department of Infrastructure and Regional Development 2017; Statista 2019). In the United Kingdom, more than 15 million driving tests were conducted in the last decade following which over 7 million licenses were issued (United Kingdom Department of Transportation 2020). Unfortunately, the driver license examiners that administer these tests, as already discussed, are themselves vulnerable to being injured while testing inexperienced drivers (North Carolina Office of State Human Resources 2013; Smith 2018).While the failure rates among the tested drivers are often not shared publicly by the governing agencies, evidence from over 20 countries suggest that more than 30% of the prospective drivers fail to sufficiently demonstrate driving competency (e.g., fail to operate vehicle safely during the driving test) (Haire et al. 2011; Hong Kong Transport Department 2017). In some cases, such as the United Kingdom, failure rates in driving tests can often exceed 40% (Driver and Vehicle Standards Agency 2020).

Not surprisingly, a large number of driver license examiners are injured on-the-job while administering driving tests (Driver and Vehicle Licensing Agency 2017; Martz 2011).

Given their essential role in promoting traffic and public wellbeing, research that focuses on enhancing the safety and efficiency of driver license examiners is necessary. Such efforts will enable driver license examiners to offer superior services; while also enhancing traffic safety.

4.3.2. Significance of Work-Related Injury Prevention

More than 4000 work-related fatal incidents and more than three million non-fatal incidents are reported in the United States every year (U.S. Bureau of Labor Statistics 2019). These injuries and incidents result in undesirable outcomes that impact workers, their employers, and the broader society. For example, injured workers may experience disabilities, may not be able to return to work, and may be unable to provide for their loved ones (Occupational Safety and Health Administration 2012). On the other hand, employers may need to bear additional costs associated with medical expenses, worker compensation claims, litigations, and property damages (Liberty Mutual 2020; National Safety Council 2019). In the same manner, the broader community that depends on the injured workers for services – may experience service interruptions and delays (National Safety Council 2019). For example, when a driver license examiner is injured, scheduled driving tests may need to be canceled or delayed. Such delays in the issuance of licenses can impede customers from achieving their own goals of contributing to their families and the wider society; and lead to customer dissatisfaction. Not surprisingly, estimates suggest that workplace injuries in the United States result in a collective loss that exceeds $170 billion and 100 million workdays every year (National Safety Council 2019; Occupational Safety and Health Administration 2012).

To prevent these work-related incidents, strategic initiatives have been undertaken to understand injury causes and identify appropriate injury prevention methods. For example, in the healthcare setting, early investigations unveiled that workers tasked with lifting and transferring patients experienced a disproportionate number of lower-back injuries (Edlich et al. 2005). This finding prompted the development and adoption of mechanically-powered patient-lifting equipment which yielded a 35% reduction in lower-back injuries among healthcare workers in the United States (Bell et al. 2008). In the same manner, interventions have been adopted for a variety of applications including reducing falls in construction workplaces (Zuluaga and Albert 2018), addressing tractor-related incidents among agriculture workers (Franceschetti et al. 2019), and prevention of explosions in the oil and gas industry (Nolan 2014).

Unlike some of these previously discussed efforts, an emerging body of literature has taken a systems thinking approach in unveiling the network of complex and interconnected risk factors that lead to work-related incidents (Hulme et al. 2019; Newnam et al. 2021; Salmon et al 2020). These efforts have advocated for a holistic understanding of risk factors that arise at various levels (i.e., network of upstream and downstream factors) and is associated with decisions and actions of all actors and decision-makers within a system (e.g., governmental regulators, managers, supervisors, frontline staff). For example, in the context of freight transportation crashes, apart from driver-related risk factors, Newnam and Goode (2015) unveiled a system of factors including road design, vehicle safety features, employer policies, and governmental regulations that are all linked with safety incidents. Accordingly, Newnam and Goode (2015) advocated for the adoption of interventions that target each of the risk factors across the interconnected levels. For example, upstream policies established by governmental agencies or employers such as banning the use of cellphones, discouraging driving during high-risk periods (e.g., midnight to 5:59 am), and the development of fatigue management programs are all possible solutions to complement driver-initiated controls such as speed management and drug use abstinence efforts (Newnam and Goode 2015). Similar systems thinking approaches have been used in various domains including healthcare (e.g., Newnam et al. 2021), construction (e.g., Wong et al. 2016), aviation (Daramola 2014), mining (e.g., Donovan et al. 2017), and others to tackle the interconnected network of safety risk factors.

Like in all the above discussed efforts, an understanding of the safety challenges and risk factors associated with the administration of driving tests can facilitate the development and implementation of new interventions to protect driver license examiners. Unfortunately, as already discussed, the safety of this community of workers has not been targeted in previous studies. Efforts in this area will be beneficial not only for driver license examiners, but will also result in lower costs to transportation agencies and superior service to the broader community.

4.4. Research Methods and Formulation of Research Questions

4.4.1. Stage I: Identification and Extraction of Key Incident Attributes

To gain an understanding of the safety incidents that driver license examiners experience, incident reports maintained by the NCDMV was obtained and examined. The database includes incidents that were reported by driver license examiners and other NCDMV affiliates as part of incident investigations – for the purpose of recording, reporting, and initiating worker compensation claims. The database includes incidents experienced by examiners while administering driving tests for commercial and non-commercial driving licenses.

In total, between 2000 and May 2018, when the currently reported investigation was initiated, 400 driving test related incidents were recorded. These reports includes incidents that occurred from the time a driver license examiner exited the licensing office to administer a driving test until the examiner reentered the licensing office at the conclusion of the test. Accordingly, the database does not include incidents that occurred when a licensing examiner was inside the physical licensing office; such incidents may include tripping over a power cord or experiencing a puncture from a sharp object (such as a stapler) while within the premises of the physical office. However, the incident reports include incidents that occurred after the examiner exited the office and moved toward the driver's vehicle to initiate the test and prior to reentry into the office – such as trips and falls in the parking lot.

In the first stage of the qualitative content analyses effort, four members of the research team collaboratively examined each of the incident reports to determine and extract key incident attributes (Elo and Kyngäs 2008; Saldaña 2015). Given that it was unclear as to what would constitute key attributes at this initial stage of the effort, relevant attributes were iteratively identified as the injury reports were reviewed – one at a time.

At the end of the first stage of the review, the key attributes of interest that were determined to be the focus of the study were identified. The first of these identified attributes of interest is the *driving test stage*, which is captured in three categories: before test initiation, during the driving test, and after test completion, and designated respectively as *before*, *during*, and *after*. The *before* category includes incidents that occurred between the time the driver license examiner exited the licensing office and when the examiner entered the driver's vehicle to begin the test. Examples of such reported incidents include tripping over parking curbs, injuries sustained during pre-inspection of the vehicle, and incidents that occurred while entering the vehicle. The *during* category captures incidents that occurred after the driver license examiner entered the vehicle to administer the test until the driving test was completed and the examiner was ready to exit the vehicle. Finally, the *after* category captures incidents that occurred while the driver license examiner was exiting the vehicle until the examiner re-entered the licensing office at the conclusion of the driving test.

Apart from (1) driving test stage other attributes of interest included the (2) event type – such as collision with fixed object, collision with another vehicle, and fall to lower level; (3) contributing factor – such as failure to maintain control of vehicle, speeding, and abrupt acceleration; (4) injured body part – such as back, leg, and neck; (5) injury type – such as strain, bruising or contusion, inflammation, and fracture; and (6) injury outcome – such as permanent disability, temporary disability, and medical case (i.e., incidents where the examiner was able to return to work immediately after receiving medical attention). Table 4-1 presents the complete list of attributes and the corresponding attribute categories in the left two columns. As can be seen, the incident reports largely only captured downstream factors that were captured as being linked directly with the incident for recording and reporting purposes. Moreover, as can be seen, the incident reports also largely did not capture psychological and non-physical factors such as stress, mental alertness, concentration, perceived workload, and other that have been identified in the broader literature to be linked with traffic incidents (e.g., Cantin et al. 2009; Kontogiannis 2006).

After the attributes were identified using an iterative approach, five members of the research team reviewed each of the incident reports – once-again one at a time – and collaboratively identified and extracted the attributes present in each of the incident reports. For illustrative purposes, Figure 4-1 presents an excerpt from an example incident report along with the associated attributes and the attribute categories that the research team extracted.

Table 4-1: Attributes, Attribute Categories, and Chi-Square Goodness-Of-Fit Test Results

Attribute	Attribute Categories	#	ε_i	Chi-Square Test Statistic	*p*-value
Driving Test Stage (Total #: 396)	During	250	+10.27	158.77	<0.001
	Before	79	-4.61		
	After	67	-5.65		
Event Type (Total #: 396)	Collision with fixed object	125	+10.73	266.67	<0.001
	Overexertion and physical bodily reaction	89	+5.61		
	Collision with another vehicle	76	+3.77		
	Fall on the same level	50	+0.07		
	Fall to lower level	25	-3.48		
	Struck by or against	15	-4.90		
	Exposure to harmful substances, surfaces, or environments	7	-6.04		
	Others / Unknown / Unreported	9	-5.76		
Contributing Factor (Total #: 396)	Failure to maintain control of vehicle	81	+11.96	290.27	<0.001
	Exiting the vehicle	48	+5.12		
	Uneven surface / Object on ground / Loss of balance	47	+4.91		
	Fault of other driver	38	+3.05		
	Abrupt acceleration	32	+1.80		
	Entering the vehicle	25	+0.35		
	Abrupt braking	23	-0.06		
	Backing vehicle from parking space	22	-0.27		
	Failure to yield right of way	17	-1.30		
	Speeding	10	-2.75		
	Manual handling / Lifting	10	-2.75		
	Abrupt postural change / Poor posture	9	-2.96		
	Unsafe lane change / Oversteering / Overcorrecting	8	-3.17		
	Weather conditions	7	-3.38		
	Failure to stop at stop sign or red light	7	-3.38		
	Animal / Insect	5	-3.79		
	Others / Unknown / Unreported	7	-3.38		
Injured Body Part (Total #: 396)	Multiple body parts	109	+12.17	342.33	<0.001
	Back	96	+10.00		
	Leg	40	+0.67		
	Neck	37	+0.17		
	Arm and shoulder	34	-0.33		
	Knee	24	-2.00		
	Hand	21	-2.50		
	Head	10	-4.33		
	Abdomen and hip	6	-5.00		
	Chest	6	-5.00		
	None	13	-3.83		
Injury Type (Total #: 396)	Strain	208	+28.67	1023.44	<0.001
	Sprain	64	+4.67		
	Bruising or contusion	49	+2.17		
	Multiple types	30	-1.00		
	Discomfort and pain	13	-3.83		
	Laceration	7	-4.83		
	Inflammation	5	-5.17		
	Fracture	5	-5.17		
	Burn	1	-5.83		
	Heatstroke	1	-5.83		
	None	13	-3.83		
Injury Outcome (Total #: 396)	Medical case	278	+17.99	435.78	<0.001
	Permanent disability	54	-4.52		
	Report only	39	-6.03		
	Temporary disability	25	-7.44		

Note: # represents count or frequency; ε_i represents standardized residual

Of the initial 400 incident reports, four were excluded from subsequent analyses because they did not sufficiently capture the targeted key attributes or provide a clear description of the incident. Accordingly, the remaining 396 incident reports served as the database for this study.

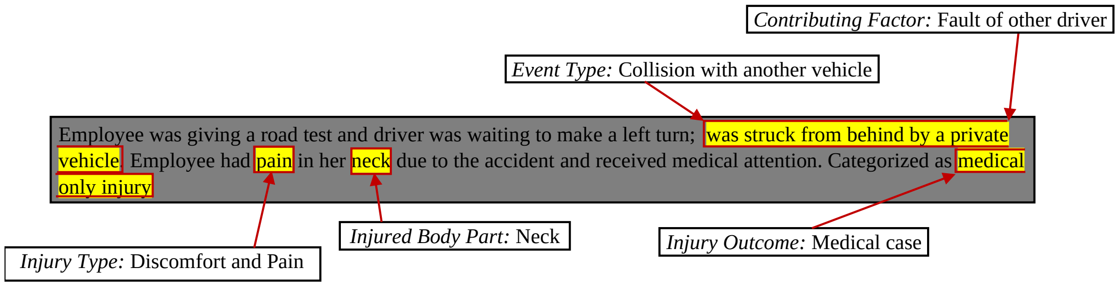

Figure 4-1: Example of Incident Report Excerpt and Attribute Extraction Attribute Extraction

4.4.2. Stage II: Formulation of Targeted Research Questions

After extracting the attributes from each of the 396 incident reports , the research team formulated research questions to gain a better understanding of the safety-related challenges faced by driver license examiners. The first set of research questions focused on examining if particular attribute categories are overrepresented or particularly prominent in the database. For example, based on the attribute categories presented in Table 4-1, one of the questions targeted whether driver license examiners are more likely to experience incidents at particular stages of the driving test (i.e., before, during, or after). Such information can offer important insights and reveal problem areas that must be prioritized to reduce injury rates among driver license examiners. The complete first set of targeted research questions is as follows:

- Are driver license examiners especially vulnerable to injury / incident at particular *driving test stages*?
- Are driver license examiners especially vulnerable to experiencing particular *event types?*

- Are driver license examiners especially vulnerable to injury / illness as a result of particular *contributing factors*?
- Are driver license examiners especially vulnerable to injuring particular *body parts*?
- Are driver license examiners especially vulnerable to experiencing particular *injury types*?
- Are driver license examiners especially vulnerable to experiencing particular *injury outcomes*?

After the first set of questions were identified, the second set of formulated questions focused on obtaining a more nuanced understanding of the safety incidents. These questions targeted the examination of relationships between the attributes. For example, one of the research questions was designed to examine whether or not there exists a relationship between the *driving test stage* and the resulting *event type*. More specifically, this question sought to examine if particular *event types* are more likely than expected at different times of the driving tests. The complete second set of targeted research questions is as follows:

- Does the driving test stage correlate with the (1) event type, (2) contributing factor, (3) injured body part, (4) injury type, and (5) injury outcome?
- Does the contributing factor correlate with the (1) event type, (2) injured body part, (3) injury type, and (4) injury outcome?
- Does the event type correlate with the (1) injured body part, (2) injury type, and (3) injury outcome?
- Does the injured body part correlate with the (1) injury outcome?
- Does injury type correlate with the (1) injury outcome?

4.5. Data Analysis and Results

4.5.1. Examining Attribute Categories that are More Prominent

As discussed above, the first set of research questions focused on whether particular attribute categories were more prominent or more likely to be associated with work-related incidents. To investigate this set of questions, the *chi-square goodness-of-fit test* was adopted (Agresti 2018). This was accomplished by first computing the *chi-square test statistic*, presented in Equation 1, and comparing it to the *chi-square distribution* – to assess if there are significant disparities between the number of safety incidents observed (O_i) and the number of incidents expected (E_i). While the observed count refers to the number of incidents where a particular attribute category is relevant in the dataset, the expected count refers to the number of incidents expected in the hypothetical case where none of the attribute categories are more prominent than another. Accordingly, the expected count can be calculated simply by distributing the total number of incidents (i.e., 396 in the current study) equally across the relevant attribute categories as shown in Equation 2. For example, for the *driving test stage* attribute, the expected count can be calculated by distributing the total number of incidents (i.e., 396) across the three attribute categories (i.e., *during*, *before*, and *after* – 396/3). Likewise, for the *event type* attribute, the incidents are equally distributed across the eight attribute categories (i.e., 396/8). Table 4-1 shows the total number of attribute categories that is relevant to each of the attributes.

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \qquad (1)$$

where, χ^2 is the *chi-square test statistic*; O_i is the observed count or frequency that represents the number of incidents that corresponds to a particular attribute category *i*; E_i is the expected count or frequency for the attribute category *i* in the hypothetical case that none of the attribute categories is more prominent than another attribute category; and k is the total number of attribute categories that are relevant to the research question of interest.

$$E_i = \frac{N}{k} \quad (2)$$

where, E_i is the expected count or frequency for a particular attribute category i in the hypothetical case that none of the attribute categories is more prominent than another attribute category; N is the total number of incidents (i.e., 396) in the database; and k is the total number of attribute categories that are relevant to the research question of interest.

The results of the tests are also presented in Table 4-1. As shown, for the *driving test stage* attribute, of the 396 total work-related incidents, 250 occurred *during* the driving test, 79 occurred *before* the driving test, and 67 occurred *after* the driving test. The computation of the *chi-square test statistic* using these observed counts and the expected count of 132 (396 total incidents distributed equally across the three attribute categories – i.e., 396/3) yielded a *chi-square value* of 158.77. A comparison of the test statistic with the *chi-square- distribution* yielded a *p*-value that was less than 0.05 – which suggests that the three different times are not represented equally or that incidents are more likely to occur at certain times.

In the same manner, the findings suggest that particular *event types* [F(7) = 266.67], *contributing factors* [F(16) = 290.97], and *injured body parts* are more likely than others. [F(10) = 342.33]. Likewise, driver license examiners are more likely to experience certain *injury types* [F(10) = 266.67] and *injury outcomes* [F(3) = 437.78] than others. Therefore, in summary, the results for the first set of research questions indicate that driver license examiners are more likely to (1) experience injury in certain *driving test stages*, (2) experience certain *event types* , (3) be impacted by certain *contributing factors* , (4) encounter incidents that result in certain *injured body* *parts* , (5) experience certain *injury types*, and (6) experience certain *injury outcomes* compared to other respective attribute categories.

Apart from examining the count data that correspond to each of the attribute categories, to more specifically identify the attribute categories that are more likely to be associated with incidents, the standardized residuals as presented in Equation 3 was computed for each of the attributes. In the equation, the numerator represents the residual – which is the difference between the observed and expected count for each of the attribute categories. The denominator is the square root of the expected count – which is an estimate of the standard deviation of the residuals that standardizes the residual for easier interpretation. A positive standardized residual indicates that an attribute category is more prominent or more likely to occur relative to the other attribute categories (Kateri 2014). In contrast, a negative residual indicates that the corresponding attribute category is relatively less represented in the data. A standardized residual of zero indicates that the observed count and the expected count are equal – suggesting that the corresponding attribute category is neither overrepresented nor underrepresented in the dataset.

$$\varepsilon_i = \frac{O_i - E_i}{\sqrt{E_i}} \tag{3}$$

where, ε_i is the standardized residual from the *chi-square goodness-of-fit* test; O_i is the observed count or frequency that represent the number of incidents that correspond to the attribute category *i*; and E_i is the expected count or frequency for the attribute category *i* in the hypothetical case that none of the attribute categories were more prominent than another.

Table 4-1 also presents the standardized residuals. The positive standardized residuals suggest that incidents are more likely to be experienced by driver license examiners *during* the driving test compared to *before* and *after* the driving test. The *event types* that driver license examiners are more likely to experience include (1) *collision with fixed object*, (2) *overexertion* *and bodily reaction*, (3) *collision with another vehicle*, and (4) *fall on the same level*. The *contributing factors* that are more likely to be associated with incidents include (1) *failure to maintain control of vehicle*, (2) *exiting the vehicle*, (3) *uneven surface / object on the ground / loss of balance*, (4) *fault of other driver*, (5) *abrupt acceleration*, and (6) *entering the vehicle.*

Most incidents result in injuries to *multiple body parts* among driver license examiners. In addition, driver license examiners are particularly likely to experience injury to their (1) *back*, (2) *leg*, and (3) *neck*. When considering injury type, driver license examiners most commonly experience (1) *strain*, (2) *sprain*, and (3) *bruising or contusion*. Finally, for the *injury outcome* attribute category, *medical case*, which involves the transportation of the driver license examiner to a healthcare facility following an incident and before the examiner is able to return to work the next day, is more likely than the other *injury outcome* categories.

4.5.2. Examining Relationships between Attributes

Having addressed the first set of questions, the second set of research questions were pursued. As mentioned earlier, the second set of research questions focused on examining if there are relationships between the different attributes or if the attributes are independent (e.g., *driving test stage* and *injury type*). To examine these questions, the *chi-square test of independence* was adopted.

For the *chi-square test of independence*, the *chi-square test statistic* is computed using a slight variation of Equation 1 – as presented in Equation 4 – to account for the two attributes that are relevant to each of the research questions. Given that the data for the *chi-square test of independence* are generally presented in the form of a contingency table where the rows correspond to one of the attributes and the columns correspond to the other attribute of interest (Kateri 2014), the expected value is calculated using the marginal frequencies of the rows and columns as presented in Equation 5. The obtained *chi-square test statistic* is compared against the *chi-square distribution* using the robust generalized *Fisher's exact test* to obtain the *p*-value to account for any contingency table cells with an expected count of less than 5 (Mehta and Patel 2011).

$$\chi^2 = \sum_{i=1}^{c} \sum_{j=1}^{r} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \tag{4}$$

where, χ^2 is the chi-square test statistic; O_{ij} is the observed count or frequency representing the number of incidents that correspond to a particular attribute category combination *ij*; E_{ij} is the expected count or frequency for a particular attribute category combination *ij* in the hypothetical case that none of the combinations of the attribute categories is more prominent than another; *c* represents the total number of attribute categories that is represented as columns in the contingency table; and *r* represents the total number of attribute categories that is represented as rows in the contingency table.

$$E_{ij} = \frac{N_i \times N_j}{N} \tag{5}$$

where, E_{ij} is the expected count or frequency for a particular attribute category combination *ij* in the hypothetical case that none of the combinations of the attribute categories is more prominent than another; N_i is the marginal frequency or count for each of the columns in the contingency table; N_j is the marginal frequency or count for each of the rows in the contingency table; and N is the total number of incidents in the database (i.e., 396).

While the *chi-square test of independence* is sufficient to show whether a relationship exists between two attributes of interest, it does not provide a measure of the strength of the relationship. Therefore, *Cramer's V*, which is widely used alongside the chi-square test of independence, was computed using Equation 6 (Cramer and Howitt 2004). *Cramer's V* ranges between 0 where there is no association between the variables and 1 where a complete association is present. Using the obtained *Cramer's V*, the magnitude of the relationship is interpreted using the criteria suggested by Cohen (1992) – A *Cramer's V* between 0.1 and 0.3 (~ i.e., explains between 1% and 9% of total variance) is considered small, between 0.3 and 0.5 (~ i.e., explains between 9% and 25% of total variance) is considered moderate, and over 0.5 (~ i.e., explains over 25% of total variance) is considered large.

$$V = \frac{\chi^2/N}{\min(c-1, r-1)} \qquad (6)$$

where, χ^2 is the chi-square test statistic computed using Equation 4; N is the total number of incidents in the database (i.e., 396); *c* is the total number of attribute categories that are represented as columns in the contingency table; and *r* is the total number of attribute categories that are represented as rows in the contingency table.

The results of the analysis examining the relationship between the *driving test stage* and the other relevant attributes are presented in Table 4-2. As shown, there was a statistically significant relationship (i.e., $p < 0.05$) between the *driving test stage* and the *event type*. In other words, certain event types are more likely to occur at different stages of the driving test. Moreover, the associated *Cramer's V* (i.e., 0.656) suggests that the magnitude of this relationship is large.

Table 4-2: Relationship between Driving Test Stage and the other Five Attributes

Attribute	Attribute Categories	Driving Test Stage: During #	During ε_{ij}	Before #	Before ε_{ij}	After #	After ε_{ij}	Chi-Square Test Statistic	*p*-value	Cramer's V
Event Type (Total #: 396)	Collision with fixed object	125	+10.3	0	-6.8	0	-6.0	340.99	<0.001	0.656
	Overexertion and physical bodily reaction	37	-4.8	30	+3.6	22	+2.3			
	Collision with another vehicle	76	+7.4	0	-4.9	0	-4.3			
	Fall on the same level	2	-9.3	33	+8.6	15	+2.7			
	Fall to lower level	0	-6.8	3	-1.1	22	+9.9			
	Struck by or against	2	-4.1	9	+3.9	4	+1.1			
	Exposure to harmful substances, surfaces, or environments	1	-2.7	3	+1.5	3	+1.9			
	Others / Unknown / Unreported	7	+0.9	2	+0.2	0	-1.4			
Contributing Factor (Total #: 396)	Failure to maintain control of vehicle	81	+7.7	0	-5.0	0	-4.6	609.683	<0.001	0.877
	Exiting the vehicle	0	-9.7	0	-3.7	48	+16.4			
	Uneven surface / Object on ground / Loss of balance	2	-8.9	33	+9.2	12	+1.7			
	Fault of other driver	36	+4.2	2	-2.4	0	-2.9			
	Abrupt acceleration	32	+4.5	0	-2.9	0	-2.7			
	Entering the vehicle	0	-6.8	25	+10.3	0	-2.3			
	Abrupt braking	23	+3.8	0	-2.5	0	-2.2			
	Backing vehicle from parking space	22	+3.7	0	-2.4	0	-2.2			
	Failure to yield right of way	17	+3.2	0	-2.1	0	-1.9			
	Speeding	10	+2.4	0	-1.6	0	-1.4			
	Manual handling / Lifting	1	-3.5	9	+5.6	0	-1.4			
	Abrupt postural change / Poor posture	4	-1.2	4	+1.9	1	-0.5			
	Unsafe lane change / Oversteering / Overcorrecting	8	+2.2	0	-1.4	0	-1.3			
	Weather conditions	1	-2.7	3	+1.5	3	+1.8			
	Failure to stop at stop sign or red light	7	+2.0	0	-1.3	0	-1.2			
	Animal / Insect	0	-2.9	2	+1.1	3	+2.6			
	Others / Unknown / Unreported	6	+1.2	1	-0.4	0	-1.2			
Injured Body Part (Total #: 396)	Multiple body parts	80	+2.6	15	-2.0	14	-1.3	139.637	<0.001	0.42
	Back	71	+2.5	15	-1.3	10	-1.9			
	Leg	4	-7.3	22	+5.8	14	+3.3			
	Neck	37	+4.9	0	-3.2	0	-2.9			
	Arm and shoulder	19	-0.9	10	+1.4	5	-0.3			
	Knee	4	-4.9	6	+0.6	14	+5.7			
	Hand	8	-2.4	7	+1.5	6	+1.5			
	Head	7	+0.5	2	0.0	1	-0.6			
	Abdomen and hip	1	-2.4	3	+1.8	2	+1.1			
	Chest	6	+1.9	0	-1.2	0	-1.1			
	None	13	+2.8	0	-1.8	0	-1.6			

Table 4-2 (continued)

Injury Type (Total #: 396)	Strain	155	+4.9	33	-2.3	20	-4.0	78.97	<0.001	0.316
	Sprain	22	-5.2	19	+2.1	23	+4.5			
	Bruise or contusions	22	-2.8	18	+3.1	9	+0.3			
	Multiple types	21	+0.8	2	-1.9	7	+1.0			
	Discomfort and pain	10	+1.0	2	-0.4	1	-0.9			
	Laceration	2	-1.9	3	+1.5	2	+0.9			
	Inflammation	0	-2.9	2	+1.1	3	+2.6			
	Fracture	4	+0.8	0	-1.1	1	+0.2			
	Burn	0	-1.3	1	+2.0	0	-0.4			
	Heatstroke	1	+0.8	0	-0.5	0	-0.4			
	None	13	+2.8	0	-1.8	0	-1.6			
Injury Outcome (Total #: 396)	Medical case	179	+0.8	57	+0.2	42	-1.3	7.919	0.244	0.141
	Permanent disability	30	-1.2	12	+0.4	12	+1.2			
	Report only	21	-1.3	10	+0.9	8	+0.7			
	Temporary disability	20	+1.8	1	-2.1	4	-0.1			

Note: # represents Count or Frequency; ε_{ij} represents Standardized Residual

It is important to note that a larger standardized residual will not always correspond with a higher observed count. This is because the computation of the standardized residual includes the expected count apart from the observed count. More specifically, the computation of the standardized residual captures the difference between the observed count and the expected count – thereby indicating the relative likelihood compared to what would be expected if a relationship did not exist between the examined attribute categories (i.e., relative likelihood compared to what was expected). Therefore, a larger standardized residual simply indicates that the observed count is further away from the expected count (i.e., more likely than expected); thereby contributing to a larger *chi-square test* statistic.

Table 4-2 presents the computed standardized residuals. When the standardized residual associated with a particular attribute category combination is positive, that attribute category combination is relatively more likely to occur than expected (Kateri 2014). Moreover, since standardized residuals are analogous to *z*-scores, a standardized residual that is greater than '2' or '3' suggests that the relationship is associated with a significance level or *p-value* less than 0.05 or 0.002 respectively (Agresti 2018). For the sake of brevity, the paragraphs below discuss only selected standardized residuals that are larger than 3 because they (1) offer substantial evidence that the particular attribute combination is more likely to occur than expected and (2) contribute heavily to a significant chi-square test statistic. Also, the discussion ignores cases where a significant relationship is not evident between two attribute of interest (e.g., *driving test stage* and *injury outcome*) based on the *chi-square test of independence* discussed earlier.

With regard to the relationship between *driving test stage* and *event type*, *collision with fixed object* (ε_{ij} = 10.3) (e.g., utility poles, roadway signage, etc.) and *collision with another vehicle* (ε_{ij} = 7.4) are more likely than expected to occur *during* driving tests. However, *before* the driving test, driver license examiners are more likely to experience *fall on the same level* (ε_{ij} = 8.6) (e.g., trips over curbs or falls during vehicle entry), s*truck by or against incidents* (ε_{ij} = 3.9) (e.g., striking hand on vehicle door during entry), and *overexertion and physical bodily reaction* (ε_{ij} = 3.6) (e.g., strain while entering vehicle). After the driving test, driver license examiners may experience *fall to lower level* (ε_{ij} = 9.9) incidents, particularly when exiting the vehicle.

With regard to contributing factor, failure to maintain control of vehicle (ε_{ij} = 7.7), abrupt acceleration (ε_{ij} = 4.5), fault of other driver (ε_{ij} = 4.2), abrupt braking (ε_{ij} = 3.8), backing vehicle from parking space (ε_{ij} = 3.7) (e.g., backing into another car), and failure to yield right of way (ε_{ij} = 3.2) are particularly common during driving tests. Before the driving test, a disproportionate number of incidents is associated with entering the vehicle (ε_{ij} = 10.3) (e.g., strain during entry), uneven surface / object on ground / loss of balance (ε_{ij} = 9.2), and manual handling / lifting (ε_{ij} = 5.6) (e.g., moving traffic cones). Finally, after driving tests, incidents are particularly more likely to occur than expected when driver license examiners are exiting the vehicle (ε_{ij} = 16.4) (e.g., fall from the vehicle).

With regard to *injured body part*, *during* the driving test, driver license examiners are susceptible to injuries to the *neck* (ε_{ij} = 4.9) (e.g., from the jerking action caused by abrupt acceleration) more than expected. *Before* the driving test, injuries to *leg* (ε_{ij} = 5.8) (e.g., from falls in the parking lot) are overrepresented; whereas injuries to *knee* (ε_{ij} = 5.7) and *leg* (ε_{ij} = 3.3) are more common than expected *after* driving tests (e.g., from a fall from the vehicle).

With regard to *injury type*, *strain* (ε_{ij} = 4.9) (e.g., back strain after a collision) is likely to occur *during* the driving test; *bruising or contusion* is more likely than expected to occur *before* the driving test (ε_{ij} = 3.1) (i.e., injury after a trip or fall); and *sprain* (ε_{ij} = 4.5) is significantly more likely than expected after the driving test (e.g., ankle sprain on exiting the vehicle).

The remaining research questions that were part of the second set of research questions were also examined using the same approach discussed above. Table 4-3 presents the analysis results that examine the relationship between *contributing factor* and the other attributes. As can be seen, a statistically significant relationship is evident between *contributing factor* and (1) *event type*, (2) *injured body part*, and (3) *injury type* (i.e., $p < 0.05$). The relationship between *contributing factors* and *event type* is strong (i.e., Cramer's $V = 0.707$). On the other hand, the relationships between the *contributing factor and injured body part* and *injury type* are small (i.e., Cramer's $V = 0.295$) and moderate (i.e., Cramer's $V = 0.366$), respectively.

The standardized residuals in Table 4-3 indicate that collision with fixed object (e.g., curb, guardrail, etc.) is strongly linked with failure to maintain control of vehicle ($\varepsilon_{ij} = 11.9$), abrupt acceleration ($\varepsilon_{ij} = 7.1$), backing vehicle from parking space ($\varepsilon_{ij} = 4.3$), and speeding ($\varepsilon_{ij} = 4.0$). Overexertion and physical bodily reaction incidents are commonly linked with exiting the vehicle ($\varepsilon_{ij} = 3.4$), entering the vehicle ($\varepsilon_{ij} = 5.1$), abrupt braking ($\varepsilon_{ij} = 8.7$) (e.g., strain as a result of jerking), manual handling / lifting ($\varepsilon_{ij} = 3.6$), and abrupt postural change / poor posture ($\varepsilon_{ij} = 4.8$). Collision with another vehicle was largely linked with fault of other driver ($\varepsilon_{ij} = 12.4$), failure to yield right of way ($\varepsilon_{ij} = 8.6$), unsafe lane changing / oversteering / overcorrecting ($\varepsilon_{ij} = 3.1$), and failure to stop at stop sign or red light ($\varepsilon_{ij} = 3.5$). Falls on the same level is associated particularly with uneven surface / object on ground / loss of balance ($\varepsilon_{ij} = 16.4$) and weather conditions ($\varepsilon_{ij} = 3.6$); whereas fall to lower level is much more likely when exiting the vehicle ($\varepsilon_{ij} = 12$). Struck by or against incidents are associated with entering the vehicle ($\varepsilon_{ij} = 4.4$) (e.g., striking hand on vehicle during entry) and weather conditions ($\varepsilon_{ij} = 3.5$) (e.g., windy conditions cause vehicle door to slam on hand). Finally, exposure to harmful substances, surfaces, or environments was particularly associated with animal / insect.

Table 4-3: Relationship between Contributory Factor and Four other Attributes

Attribute	Attribute Categories	Contributing Factor: Failure to maintain control of vehicle		Exiting the vehicle		Uneven surface / Object on ground / Loss of balance		Fault of other driver		Abrupt accelerati-on		Entering the vehicle		Abrupt braking		Backing vehicle from parking space		Failure to yield right of way		Speeding		Manual handling / Lifting		Abrupt postural change / Poor posture		Unsafe lane change / Overste-ering / Overcor-recting		Weather conditio-ns		Failure to stop at stop sign or red light		Animal / Insect		Others / Unkno-wn / Unrepor-ted		Chi-Square Test Statistic	*p* -value	Cra-mer's V
		#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}			
Event Type (Total #: 396)	Collision with fixed object	70	+11.9	0	-5.0	0	-5.0	0	-4.4	28	+7.1	0	-3.5	0	-3.4	16	+4.3	0	-2.9	9	+4.0	0	-2.2	1	-1.3	0	-1.9	0	-1.8	0	-1.8	0	-1.5	1	-1.0	1386.3	<0.001	0.7
	Overexertion and physical bodily reaction	2	-4.8	20	+3.4	5	-2.1	0	-3.5	2	-2.3	16	+5.1	22	+8.7	0	-2.6	0	-2.3	1	-1.0	7	+3.6	8	+4.8	3	+1.0	0	-1.4	2	+0.4	0	-1.2	1	-0.5			
	Collision with another vehicle	6	-3.0	0	-3.6	0	-3.6	36	+12.4	1	-2.4	0	-2.5	1	-1.9	5	+0.4	17	+8.6	0	-1.6	0	-1.6	0	-1.5	5	+3.1	0	-1.3	5	+3.5	0	-1.1	0	-1.3			
	Fall on the same level	1	-3.5	3	-1.4	41	+16.4	0	-2.5	0	-2.2	1	-1.3	0	-1.9	0	-1.8	0	-1.6	0	-1.2	0	-1.2	0	-1.2	0	-1.1	4	+3.6	0	-1.0	0	-0.9	0	-1.0			
	Fall to lower level	0	-2.6	22	+12.0	1	-1.3	0	-1.7	0	-1.5	2	+0.4	0	-1.3	0	-1.3	0	-1.1	0	-0.8	0	-0.8	0	-0.8	0	-0.7	0	-0.7	0	-0.7	0	-0.6	0	-0.7			
	Struck by or against	0	-2.0	2	+0.1	0	-1.4	2	+0.5	0	-1.2	5	+4.4	0	-1.0	0	-1.0	0	-0.8	0	-0.6	2	+2.7	0	-0.6	0	-0.6	2	+3.5	0	-0.5	0	-0.4	2	+3.5			
	Exposure to harmful substances, surfaces, or environments	0	-1.4	1	+0.2	0	-1.0	0	-0.9	0	-0.8	0	-0.7	0	-0.7	0	-0.6	0	-0.6	0	-0.4	0	-0.4	0	-0.4	0	-0.4	1	+2.5	0	-0.4	5	+16.8	0	-0.4			
	Others / Unknown / Unreported	2	+0.1	0	-1.1	0	-1.1	0	-1.0	1	+0.3	1	+0.6	0	-0.8	1	+0.7	0	-0.6	0	-0.5	1	+1.7	0	-0.5	0	-0.4	0	-0.4	0	-0.4	0	-0.3	3	+7.3			
Injured Body Part (Total #: 396)	Multiple body parts	23	+0.2	7	-2.1	13	0.0	19	+3.3	9	+0.1	1	-2.7	8	+0.8	8	+1.0	4	-0.4	4	+0.9	2	-0.5	1	-1.1	2	-0.2	6	+3.5	1	-0.8	0	-1.4	1	-0.8	344.2	<0.001	0.3
	Back	27	+2.1	9	-0.9	3	-3.0	9	-0.1	10	+1.0	6	0.0	5	-0.3	8	+1.4	4	-0.1	1	-1.1	2	-0.3	5	+2.2	2	+0.1	0	-1.5	3	+1.2	1	-0.2	1	-0.6			
	Leg	1	-3.0	11	+3.1	19	+7.3	1	-1.6	0	-2.0	4	+1.0	0	-1.7	0	-1.6	1	-0.6	1	0.0	1	0.0	0	-1.0	0	-1.0	0	-0.9	0	-0.9	1	+0.7	0	-0.9			
	Neck	11	+1.5	0	-2.4	0	-2.3	4	+0.3	6	+1.9	0	-1.7	7	+3.6	1	-0.8	2	+0.4	2	+1.2	0	-1.0	0	-1.0	2	+1.5	0	-0.9	1	+0.5	0	-0.7	1	+0.5			
	Arm and shoulder	5	-0.9	4	-0.1	4	0.0	1	-1.4	3	+0.2	4	+1.4	3	+0.8	2	+0.1	1	-0.4	1	+0.2	2	+1.3	0	-0.9	1	+0.4	0	-0.8	1	+0.5	1	+0.9	1	+0.5			
	Knee	3	-1.0	12	+5.9	5	+1.4	1	-0.9	0	-1.5	3	+1.3	0	-1.3	0	-1.2	0	-1.1	0	-0.8	0	-0.8	0	-0.8	0	-0.7	0	-0.7	0	-0.7	0	-0.6	0	-0.7			
	Hand	2	-1.3	4	+1.0	2	-0.3	0	-1.5	0	-1.4	4	+2.5	0	-1.2	0	-1.1	0	-1.0	0	-0.8	2	+2.1	2	+2.3	0	-0.7	1	+1.1	0	-0.6	1	+1.5	3	+4.5			
	Head	1	-0.8	0	-1.2	0	-1.2	1	0.0	1	+0.2	2	+1.8	0	-0.8	0	-0.8	3	+4.1	0	-0.5	0	-0.5	0	-0.5	0	-0.5	0	-0.4	1	+2.0	1	+2.5	0	-0.4			
	Abdomen and hip	1	-0.2	1	+0.3	1	+0.4	0	-0.8	0	-0.7	1	+1.1	0	-0.6	0	-0.6	0	-0.5	0	-0.4	1	+2.2	1	+2.4	0	-0.4	0	-0.3	0	-0.3	0	-0.3	0	-0.3			
	Chest	3	+1.8	0	-0.9	0	-0.9	0	-0.8	0	-0.7	0	-0.6	0	-0.6	0	-0.6	2	+3.5	1	+2.2	0	-0.4	0	-0.4	0	-0.4	0	-0.3	0	-0.3	0	-0.3	0	-0.3			
	None	4	+0.9	0	-1.4	0	-1.3	2	+0.7	3	+2.0	0	-1.0	0	-0.9	3	+2.8	0	-0.8	0	-0.6	0	-0.6	0	-0.6	1	+1.5	0	-0.5	0	-0.5	0	-0.4	0	-0.5			
Injury Type (Total #: 396)	Strain	52	+2.4	16	-2.8	9	-4.9	21	+0.4	22	+1.9	15	+0.8	15	+1.3	13	+0.6	8	-0.5	7	+1.1	6	+0.5	7	+1.5	6	+1.3	1	-2.0	6	+1.8	0	-2.4	4	+0.2	529.6	<0.001	0.4
	Sprain	7	-2.1	17	+3.9	20	+5.2	4	-1.0	2	-1.6	5	+0.5	3	-0.4	1	-1.5	0	-1.9	0	-1.4	0	-1.4	2	+0.5	1	-0.3	1	-0.1	0	-1.2	0	-1.0	1	-0.1			
	Bruise or contusions	10	0.0	5	-0.4	14	+3.9	3	-0.9	1	-1.7	3	-0.1	0	-1.9	2	-0.5	4	+1.4	2	+0.7	1	-0.2	0	-1.1	0	-1.1	3	+2.5	0	-1.0	0	-0.8	1	+0.2			
	Multiple types	5	-0.5	6	+1.4	3	-0.3	5	+1.4	2	-0.3	0	-1.5	3	+1.0	3	+1.1	2	+0.7	1	+0.3	0	-0.9	0	-0.9	0	-0.8	0	-0.8	0	-0.8	0	-0.6	0	-0.8			
	Discomfort and pain	1	-1.2	0	-1.4	0	-1.3	3	+1.7	2	+1.0	1	+0.2	2	+1.5	0	-0.9	1	+0.6	0	-0.6	1	+1.2	0	-0.6	0	-0.5	0	-0.5	1	+1.6	1	+2.1	0	-0.5			
	Laceration	0	-1.4	2	+1.3	1	+0.2	0	-0.9	0	-0.8	1	+0.9	0	-0.7	0	-0.6	0	-0.6	0	-0.4	2	+4.4	0	-0.4	0	-0.4	0	-0.4	0	-0.4	0	-0.3	1	+2.5			
	Inflammation	0	-1.1	1	+0.5	0	-0.8	0	-0.7	0	-0.7	0	-0.6	0	-0.6	0	-0.5	0	-0.5	0	-0.4	0	-0.4	0	-0.3	0	-0.3	0	-0.3	0	-0.3	4	+15.9	0	-0.3			
	Fracture	2	+1.1	0	-0.8	0	-0.8	0	-0.7	0	-0.7	0	-0.6	0	-0.6	0	-0.5	2	+4.0	0	-0.4	0	-0.4	0	-0.3	0	-0.3	1	+3.1	0	-0.3	0	-0.3	0	-0.3			
	Burn	0	-0.5	1	+2.7	0	-0.4	0	-0.3	0	-0.3	0	-0.3	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.1	0	-0.1	0	-0.1	0	-0.1	0	-0.1			
	Heatstroke	0	-0.5	0	-0.4	0	-0.4	0	-0.3	0	-0.3	0	-0.3	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.1	1	+7.5	0	-0.1	0	-0.1	0	-0.1			
	No Injury	4	+0.9	0	-1.4	0	-1.3	2	+0.7	3	+2.0	0	-1.0	0	-0.9	3	+2.8	0	-0.8	0	-0.6	0	-0.6	0	-0.6	1	+1.5	0	-0.5	0	-0.5	0	-0.4	0	-0.5			
Injury Outcome (Total #: 396)	Medical case	54	-0.8	28	-1.9	34	+0.3	26	-0.3	29	+2.6	19	+0.7	19	+1.3	13	-1.2	12	0.0	8	+0.7	7	0.0	5	-1.0	5	-0.5	4	-0.8	6	+0.9	5	+1.5	4	-0.8	50.1	0.389	0.2
	Permanent disability	13	+0.7	11	+2.0	4	-1.1	5	-0.1	1	-1.8	3	-0.2	2	-0.7	2	-0.6	3	+0.5	1	-0.3	2	+0.6	3	+1.7	0	-1.1	1	+0.1	1	+0.1	0	-0.9	2	+1.2			
	Report only	7	-0.4	5	+0.1	8	+1.8	1	-1.6	2	-0.7	2	-0.3	1	-0.9	5	+2.1	1	-0.6	1	0.0	1	0.0	1	+0.1	2	+1.5	2	+1.7	0	-0.9	0	-0.7	0	-0.9			
	Temporary disability	7	+1.0	4	+0.6	1	-1.3	6	+2.5	0	-1.5	1	-0.5	1	-0.4	2	+0.6	1	-0.1	0	-0.8	0	-0.8	0	-0.8	1	+0.7	0	-0.7	0	-0.7	0	-0.6	1	+0.9			

Note: # represents Count or Frequency; ε_{ij} represents Standardized Residual

With regard to *injured body part*, injuries that involve *multiple body parts* were associated with the *fault of other drivers* (ε_{ij} = 3.3) and *weather conditions* (ε_{ij} = 3.5) (e.g., slipping on ice or snow); injury to the *leg* is associated with *exiting the vehicle* (ε_{ij} = 3.1) and *uneven surface / object on ground / loss of balance* (ε_{ij} = 7.3); *neck* injuries were largely associated with *abrupt braking* (ε_{ij} = 3.6); *knee* injuries occur particularly when exiting the vehicle (ε_{ij} = 5.9); and *abdomen and, hip* (ε_{ij} = 4.1), and *chest* injuries (ε_{ij} = 3.5) are largely associated with *failure to yield right of way*.

With regard to injury type, sprain is disproportionately linked with exiting the vehicle (ε_{ij} = 3.9) and uneven surface / object on ground / loss of balance (ε_{ij} = 5.2) (e.g. leg sprain); bruising and contusion is linked with uneven surface / object on the ground / loss of balance (ε_{ij} = 3.9); laceration is associated with manual lifting / handling (ε_{ij} = 4.4); inflammation is associated with animals / insect (ε_{ij} = 15.9); fracture is associated with failure to yield right of way (ε_{ij} = 4) and weather conditions (ε_{ij} = 3.1); and heatstroke is associated with weather conditions (ε_{ij} = 7.5).

Table 4-4 presents the results of the relationship between *event type* and the remaining attributes. A statistically significant relationship is evident between *event type* and *injured body part* (i.e., $p < 0.05$). The strength of the relationship is small (i.e., Cramer's $V = 0.276$). Similarly, a statistically significant relationship is evident between *event type* and *injury type* (i.e., $p < 0.05$), and the strength is *moderate* (i.e., Cramer's $V = 0.422$).

As per the standardized residuals, with regard to *injured body part*, (1) *leg* injuries are more likely when *fall to the same level incidents* occur (ε_{ij} = 6.0); (2) *knee* injuries are more likely when *fall to lower level* incidents were occur (ε_{ij} = 3.9), (3) hand injuries are more likely when *struck by or against incidents* occur (ε_{ij} = 4.9), and (4) *abdomen and hip* injuries are commonly experienced as a result of *overexertion and physical bodily reaction* (ε_{ij} = 3.6).

With regard to injury type, strain is particularly likely as a result of collision with fixed object (ε_{ij} = 3.8) and overexertion and physical bodily reaction (ε_{ij} = 3.4). Sprain is common with fall on the same level (ε_{ij} = 5.3) and bruising and contusion is linked with both fall on the same level (ε_{ij} = 4.0) and struck by or against incidents (ε_{ij} = 3.3). Laceration is linked particularly with struck by or against incidents (ε_{ij} = 7.5). Inflammation (ε_{ij} = 13.4), fracture (ε_{ij} =7.5), and heatstroke (ε_{ij} = 7.5) are largely associated with exposure to harmful substances, surfaces, or environments.

Table 4-5 presents the relationship between *injured body part* and *injury outcome* and Table 4-6 presents the relationship between *injury type* and *injury outcome*. Both relationships are statistically significant (i.e., $p < 0.05$). The strength of the relationship is weak between *injured body part* and *injury outcome* (Cramer's V = 0.295) and is moderate between *injury type* and *injury outcome* (Cramer's V = 0.323).

As per the standardized residuals presented in Table 4-5, *report only* incidents are linked particularly to cases where no body part (*none*) sustained injury (ε_{ij} = 9.2). Table 4-6 indicates that *report only* incidents correlate with no injuries (*none*) (ε_{ij} = 9.2) (e.g., a vehicle crash that results in no injuries) and in several instances involve *bruising and contusion* (ε_{ij} = 3.2).

Table 4-4: Relationship between Event Type and Three other Attributes

Attribute	Attribute Categories	Event Type																Chi-Square Test Statistic	*p* -value	Cramer's V
		Collision with fixed object		Overexertion and physical bodily reaction		Collision with another vehicle		Fall on the same level		Fall to lower level		Struck by or against		Exposure to harmful substances, surfaces, or environments		Others/ Unknown/ Unreported				
		#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}			
	Multiple body parts	36	+0.4	18	-1.8	27	+1.7	16	+0.8	5	-0.9	4	-0.1	1	-0.8	2	-0.4			
	Back	42	+3.0	25	+1.0	18	-0.1	4	-2.9	3	-1.5	1	-1.6	1	-0.6	2	-0.1			
	Leg	2	-3.8	11	+0.8	1	-2.8	17	+6.0	6	+2.4	2	+0.4	1	+0.4	0	-1.0			
	Neck	18	+2.3	8	-0.1	9	+0.8	0	-2.4	0	-1.7	0	-1.3	0	-0.9	2	+1.3			
	Arm and shoulder	8	-1.1	10	+1.0	6	-0.2	4	-0.2	3	+0.6	1	-0.3	2	+1.9	0	-0.9			
Injured Body Part (Total #: 396)	Knee	3	-2.1	8	+1.3	1	-1.9	6	+1.9	6	+3.9	0	-1.0	0	-0.7	0	-0.8	210.776	<0.001	0.276
	Hand	3	-1.8	4	-0.4	0	-2.3	3	+0.2	2	+0.6	5	+4.9	1	+1.1	3	+3.8			
	Head	2	-0.8	0	-1.7	5	+2.5	0	-1.2	0	-0.8	2	+2.7	1	+2.0	0	-0.5			
	Abdomen and hip	1	-0.8	5	+3.6	0	-1.2	0	-0.9	0	-0.6	0	-0.5	0	-0.3	0	-0.4			
	Chest	3	+1.0	0	-1.3	3	+1.9	0	-0.9	0	-0.6	0	-0.5	0	-0.3	0	-0.4			
	None	7	+1.8	0	-2.0	6	+2.5	0	-1.4	0	-1.0	0	-0.7	0	-0.5	0	-0.6			
	Strain	83	+3.8	61	+3.4	42	+0.5	8	-5.5	6	-3.0	3	-2.6	0	-2.8	5	+0.2			
	Sprain	8	-3.6	19	+1.5	5	-2.5	21	+5.3	9	+2.8	0	-1.7	0	-1.2	2	+0.5			
	Bruise or contusions	13	-0.8	0	-4.0	8	-0.5	15	+4.0	6	+1.8	6	+3.3	0	-1.0	1	-0.1			
	Multiple types	9	-0.2	5	-0.8	8	+1.1	4	+0.1	3	+0.9	1	-0.1	0	-0.8	0	-0.9			
	Discomfort and Pain	3	-0.7	3	+0.1	5	+1.8	0	-1.4	0	-1.0	1	+0.7	1	+1.6	0	-0.6			
Injury Type (Total #: 396)	Laceration	0	-1.8	0	-1.4	0	-1.3	1	+0.1	1	+0.9	4	+7.5	0	-0.4	1	+2.2	492.675	<0.001	0.422
	Inflammation	0	-1.5	1	-0.1	0	-1.1	0	-0.9	0	-0.6	0	-0.4	4	+13.4	0	-0.3			
	Fracture	2	+0.4	0	-1.2	2	+1.2	1	+0.5	0	-0.6	0	-0.4	0	-0.3	0	-0.3			
	Burn	0	-0.7	0	-0.5	0	-0.5	0	-0.4	0	-0.3	0	-0.2	1	+7.5	0	-0.2			
	Heatstroke	0	-0.7	0	-0.5	0	-0.5	0	-0.4	0	-0.3	0	-0.2	1	+7.5	0	-0.2			
	None	7	+1.8	0	-2.0	6	+2.5	0	-1.4	0	-1.0	0	-0.7	0	-0.5	0	-0.6			
	Medical case	91	+0.8	64	+0.4	50	-0.9	33	-0.7	15	-1.2	12	+0.8	6	+0.9	7	+0.5			
Injury Outcome (Total #: 396)	Permanent disability	15	-0.6	13	+0.3	11	+0.2	6	-0.4	6	+1.6	1	-0.8	1	+0.1	1	-0.2	14.692	0.838	0.111
	Report only	11	-0.5	8	-0.3	7	-0.2	9	+2.1	2	-0.3	2	+0.5	0	-0.9	0	-1.0			
	Temporary disability	8	0.0	4	-0.8	8	+1.7	2	-0.7	2	+0.4	0	-1.0	0	-0.7	1	+0.6			

Note: # represents Count or Frequency; ε_{ij} represents Standardized Residual

Table 4-5: Relationship between Injured Body Part and Injury Outcome

Attribute	Attribute Categories	Injured Body Part																						Chi-Square Test Statistic	*p*-value	Cramer's V
		Multiple body parts		Back		Leg		Neck		Arm and shoulder		Knee		Hand		Head		Abdomen and hip		Chest		None				
		#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}			
Injury Outcome (Total #: 396)	Medical case	71	-1.4	71	+0.9	29	+0.3	28	+0.8	26	+0.8	17	+0.1	17	+1.1	8	+0.7	4	-0.2	5	+0.7	2	-4.4	103.152	<0.001	0.295
	Permanent disability	16	+0.4	12	-0.4	6	+0.3	7	+1.0	2	-1.4	5	+1.1	3	+0.1	1	-0.3	1	+0.2	1	+0.2	0	-1.5			
	Report only	14	+1.2	4	-2.1	3	-0.5	1	-1.5	2	-0.8	1	-1.0	1	-0.8	1	0.0	1	+0.6	0	-0.8	11	+9.2			
	Temporary disability	8	+0.5	9	+1.4	2	-0.4	1	-0.9	4	+1.4	1	-0.4	0	-1.2	0	-0.8	0	-0.6	0	-0.6	0	-1.0			

Note: # represents Count or Frequency; ε_{ij} represents Standardized Residual

Table 4-6: Relationship between Injury Type and Injury Outcome

Attribute	Attribute Categories	Injury Type																						Chi-Square Test Statistic	*p*-value	Cramer's V
		Strain		Sprain		Bruising and contusion		Multiple types		Discomfort and pain		Laceration		Inflammation		Fracture		Burn		Heatstroke		None				
		#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}	#	ε_{ij}			
Injury Outcome (Total #: 396)	Medical case	154	+1.8	50	+1.5	30	-1.5	17	-1.7	11	+1.2	5	+0.1	5	+1.5	3	-0.5	0	-1.5	1	+0.7	2	-4.4	124.295	<0.001	0.323
	Permanent disability	31	+0.8	10	+0.5	4	-1.2	6	+1.1	1	-0.6	0	-1.1	0	-0.9	1	+0.4	1	+2.5	0	-0.4	0	-1.5			
	Report only	8	-4.2	2	-2.0	11	+3.2	4	+0.7	1	-0.3	2	+1.7	0	-0.7	0	-0.7	0	-0.3	0	-0.3	11	+9.2			
	Temporary disability	15	+0.8	2	-1.1	4	+0.6	3	+0.9	0	-1.0	0	-0.7	0	-0.6	1	+1.3	0	-0.3	0	-0.3	0	-1.0			

Note: # represents Count or Frequency; ε_{ij} represents Standardized Residual

4.6. Discussions, Study Contributions, and Recommendations

This research effort represents the first formal investigation of incident reports that involve driver license examiners. The findings offer important insights into incidents that driver license examiners experience and reveal that particular attributes (e.g., *event type*, *contributing factor*, *injured body part*, etc.) and attribute categories are associated with specific work-related incidents. These findings can be leveraged strategically to enhance the safety of driver license examiners and new drivers during driving tests.

As a starting point, efforts should be devoted to tackling high-priority problem areas that are indicated by the attribute categories that are overrepresented in the incidents experienced by driver license examiners. Specifically, based on the findings reported in Table 4-1, priority should be given to preventing incidents that occur *during* driving tests, which account for more than 63% of all reported incidents. Efforts also should be prioritized to address overrepresented *event types* that comprise over 85% of the incidents and include *collision with fixed object*, *overexertion and physical bodily reaction*, *collision with another vehicle*, and *fall on the same level*. Similar efforts can be undertaken to tackle the overrepresented attribute categories in the context of *contributing factor*, *injured body part*, *injury type*, and *injury outcom*e that represent more than 68%, 71%, 81%, and 70% of the incidents, respectively.

While there is a dearth of previous research that examines particular incidents that driver license examiners experience, these findings reveal several commonalities between incidents that occur during driving tests and those that generally occur across the licensed population. For example, as is the case in the current study, *event types* such as *collision with fixed objects* and *collision with another vehicle* are also overrepresented among the general driving population (National Highway Traffic Safety Administration 2018). However, *speeding* as a *contributing* *factor was* relatively underrepresented (i.e., negative residual) in the current investigation of driving tests as opposed to in the general population where *speeding* is overrepresented (National Highway Traffic Safety Administration 2018). This disparity may potentially be attributable to the fact that prospective drivers may not be sufficiently confident or skilled to drive faster (Feng et al. 2016), or the driver may be extra cautious given the presence of a driver license examiner who monitors the speed as part of the driving test (e.g., California Department of Motor Vehicles 2016). The data also includes attributes such as *fall on the same level*, *manual handling / lifting*, etc. that are largely not captured as part of the general driving-related incidents; which are nonetheless relevant to the professional role of driver license examiners as is the case among freight transportation workers (Goode et al. 2014).

Apart from revealing the high-priority problem areas, the findings of the current study also offer insights on adopting a systems thinking approach to more holistically address some of these high-priority problem areas. For example, for the high-priority *event type*, *collision with fixed object*, one of the relevant *contributing factors* was found to be *backing vehicle from parking space*. Armed with this knowledge, driver license agencies, driver license examiners, new drivers, vehicle manufactures, and research scientists (i.e., actors represented in the system) can all play a complementary role in preventing such incidents. For example, from a heightened awareness of such collisions, driver license examiners could scan the environment to complement and reinforce the scanning efforts of drivers as they back out of the parking space. This way, the driver license examiners may be able to offer timely warnings to stop the vehicle if a collision becomes imminent. To ensure that this suggestion (and other similar ones) becomes standard practice for driver license examiners, driver license agencies and Division of Motor Vehicles (DMVs) may offer relevant training to their examiners. Driver license agencies and DMVs may also focus on educating new drivers about these common causes of incidents along with guidelines to prevent such incidents as part of driver training programs. New drivers who are informed of the likelihood of a *collision with fixed object* while exiting the parking space may be more cautious about preventing such incidents if they are aware of how common such incidents are. In addition, when possible, new drivers could be encouraged to use vehicles with collision avoidance technologies, such as backing cameras, park-assist systems, and blind-spot warnings for their driving test, after sufficient practice (Noy et al. 2018). Vehicle manufacturers can also play a vital role in preventing incidents by incorporating these features in their vehicles at a reasonable cost and governmental agencies may offer incentives for such incident-prevention efforts. Research scholars may invest their efforts in research that focuses on improving the efficiency and reliability of such safety technologies and in designing parking spaces that minimize the risk of safety incidents when *backing vehicle from parking space*. Such a systems thinking approach where the role and strengths of the network of actors and decision-makers are integrated to minimize safety incidents can yield substantial benefits.

Apart from the benefits of reducing unnecessary safety incidents, protecting the community of driver license examiners, and safeguarding new drivers, such efforts can translate into additional benefits such as a reduction in property damage, development and design of safer vehicles and parking spaces, fostering the development of safer and competent drivers, enhancing the efficiency of license issuance, promoting traffic safety, and others. As can be seen, such a systems thinking approach offers benefits that go beyond workplace safety and have spillover and beneficial effects on traffic safety, property preservation, and a myriad number of other factors.

However, despite the significant benefits offered by systems thinking, it needs to be noted that the incident reports examined in the current effort largely only captured downstream factors that were directly found to be linked with the experienced incidents for reporting and worker compensation purposes. For example, more upstream factors such as the role of actors that include vehicle manufactures, designers, and governmental agencies were not captured as part of the incidents reports. This is a significant limitation of the data used in the current effort. Similar weaknesses with the underlying data and the focus of previous investigations have been reported in the context of occupational safety, healthcare, and other research areas (e.g., Hulme et al. 2019; Goode et al. 2014; Newnam and Goode 2015). Accordingly, a more holistic approach to incident investigations that leverages the benefits of systems thinking is recommended in the future to ensure a more comprehensive understanding of driving test-related incidents (Hulme et al. 2019, Newnam and Goode 2015). In the same manner, it will be useful to develop approaches that transportation agencies can use to capture psychological and non-physical factors that were not examined in the current study (e.g., stress, mental alertness, concentration, perceived workload) as part of accident investigation efforts to promote a more comprehensive understanding of incidents that are experienced during driving tests.

Within the context of the data, another example of a high-priority *event type* from the investigation is *overexertion and physical bodily reaction*. Given that a vast majority of these incidents can be attributed to instances when driver license examiners are *exiting the vehicle*, *entering the vehicle*, *manual handling / lifting*, and engaging in *abrupt postural change / poor posture*, relevant ergonomics training would be useful. Such efforts to reduce *overexertion and physical bodily reaction* can cascade into additional benefits. For example, if the number of *overexertion and physical bodily reaction* instances can be reduced successfully using interventions such as ergonomic training and other such efforts, a statistically significant reduction in the number of *strain* injuries and injuries to the *abdomen and hip* is likely to follow, as per the results shown in Table 4-4. In addition, as already discussed above, a systems thinking approach can also be applied in this context to more comprehensively address *overexertion and physical bodily reaction* incidents among driver license examiners.

In short, possible interventions can be identified to tackle each of the high-priority attribute categories. Once these interventions are adopted and a successful reduction in the incidents associated with the high-priority attribute categories is observed, future efforts may focus on targeting the remaining attribute categories. Such an approach can potentially reduce injury rates and empower driver license examiners to better serve their communities and maintain their own safety and the safety of others. These efforts also can reduce worker compensation claims and enable these DMV workers to return safely to their families at the end of each work-day. Given the global prevalence of driving tests, such strategic initiatives can protect a large number of driver license examiners that globally serve their communities while enabling them to efficiently serve the public.

4.7. Conclusion and proposed Future Work

Driver license examiners ensure that driver licenses are issued only to individuals who are able to operate motor vehicles safely. Accordingly, driver license examiners serve as the first line of defense against unsafe drivers and driving practices. Despite their important role in enhancing traffic safety and serving the public, they are nonetheless exposed to high levels of safety risk. Unfortunately, research that focuses on protecting this community of workers is currently lacking. To address this dearth of research and to gain a better understanding of the safety challenges that driver license examiners face, this study empirically examined NCDMV incident reports that involve driver license examiners. The investigation incorporated content analysis of the incident reports to extract fundamental attributes and attribute categories that are associated with each of the examined incidents. The findings reveal potential high-priority problem areas that driver license agencies and driver license examiners may target to reduce the likelihood of work-related injuries. For example, some of the high-priority incidents that need to be addressed include *collision with fixed object*, *overexertion and physical bodily reaction*, *collision with another vehicle*, and *fall on the same level*. This study also examined relationships among the attribute categories to achieve a more nuanced understanding of the safety-related challenges experienced by driver license examiners and to identify prospective safety solutions.

Future efforts should focus on identifying interventions that span across levels and decision-makers using a holistic systems thinking approach and testing the efficacy of the interventions in reducing incidents experienced by driver license examiners. Given the global prevalence of driver license tests, future efforts may also replicate the research effort with databases maintained by other DMVs and transportation agencies within and beyond the United States. Such efforts will be useful in assessing the generalizability of the current findings and can potentially generate complementary insights. It is recommended that these follow-up efforts, when relevant, adopt a confirmatory approach as opposed to the exploratory nature of the present investigation; along with predefined hypotheses and appropriate corrections for multiple statistical tests (Bender and Lange 2001; Streiner and Norman 2011). Such follow-up efforts will be useful in assessing the robustness of the findings and protecting the global driver license examiner workforce.

4.8. References

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Chapter 5: Assessing the Impact of Regulatory Changes on Capital Projects in the United States

Alsharef, A., Jaselskis, E., Mostafavi, A., Zhu, J., Stoa, R., Banerjee, S., Rasoulkhani, K., Li, Q., and Chowdhury, S. (2019). "Assessing the Impact of Regulatory Changes on Capital Projects in the United States." *CIB World Building Congress*, Hong Kong, 310–320.

5.1. Abstract

Regulations, regulatory changes, and uncertainty can have profound effects on capital facilities during all phases of a project's life cycle. Both new and existing capital projects are vulnerable to newly imposed, existing or revised regulations. Regulatory compliance can cause a significant amount of disruption to capital facilities and thus its impact should be evaluated. This paper assesses the impact of regulations and regulatory changes on various companies/organizations in the United States and identifies some strategies for addressing them. The research methodology involved conducting a survey to better understand how companies address regulations by assessing the impact of regulations. Results from 27 surveys indicate that it has been more difficult to anticipate and adapt to regulations changes over the last 15 years. Federal Environmental regulations were found to be the most impactful regulations type followed by workplace safety. Additionally, the survey responders cited increased design and construction cost as the most frequent resulting effect of regulations closely followed by uncertainty-induced delays in projects development process at critical decision points. More than half of the surveyed organizations were able to mitigate the impact of regulations by identifying the regulatory change early. Findings from this study can help organizations to better understand the effect of regulations on building and operating projects and better plan for regulation compliance.

5.2. Introduction and Background

Regulations govern the design, construction, and operation of capital projects. They are known for being dynamic and frequently subject to revisions and hence imposing risks and opportunities for both contractors and owners primarily related to environmental, workplace safety, and labor regulations. A significant challenge is that different regulations apply to individual project categories at different locations—recently, there has been an increase in building regulations (Benhart and Shaurette 2011; Imrie and Street 2009). This makes tracking and complying more complex and increases the cost and time for compliance (Zhang and El-Gohary 2013). It also makes the planning and design phases more challenging, and hence organizations need to be prepared to anticipate and adapt to the impact of regulations on their capital projects.

Projects are subjected to the compliance from different levels of regulations including International, Federal, State, and Local. For example, Occupational Safety and Health Administration (OSHA) administers the safety programs at the Federal level in the U.S. that assures protection from work-related injuries and health issues under the Occupational Safety and Health Act (Donnelly 1982). There are also 22 States with OSHA approved plans (Occupational Safety and Health Administration 2018a). OSHA has been proposing and imposing new regulations following a seven-stages rulemaking process (Occupational Safety and Health Administration 2018b).

Regulations have a significant impact on performance and cost. For instance, the amount of emissions and pollutants from construction sites would limit the working hours of construction equipment, especially heavy-duty diesel (Ahn et al. 2013; Lewis and Rasdorf 2017). Jaselskis et al. (2017) found that the timing of issuing environmental permits plays a crucial factor in predicting the let date of transportation projects. Greenstone et al. (2012) studied the economic impact of environmental regulations on the competitiveness of the U.S. Manufacturing industry. They found that environmental regulations, regulated by the Environmental Protection Agency (EPA) are becoming more stringent. They estimated a decrease of nearly 2.6% on manufacturing plant productivity and approximately $21 billion annual economic cost as a result of EPA's air quality regulations. According to Ryan (2012), onerous environmental regulations increased the cost of constructing a new brownfield facility by about $5 million because of the testing requirements of the EPA's Clean Air Act.

Noncompliance with regulations would subject the project to severe consequences. For instance, in the United Kingdom, a significant number of penalties were imposed on organizations for breaching the Health and Safety at Work Act (Arewa et al. 2018). Misinterpreting the rule could be a source for rule breaching. Baxendale and Jones (2000) found that designers were slow to adopt new rules when implemented. Additionally, the construction industry is known for its slow pace of innovation, adoption, and integration of new technology (Macomber 2003; Nam and Tatum 1992).

Clearly, regulations have an impact on the execution and operation of capital facilities and their impact remains to be assessed. This paper presents findings from an organizational survey that is part of a larger study funded by the Construction Industry Institute (CII) to better understand and evaluate the impact of regulations throughout the project lifecycle. The larger study also investigates approaches companies can use to be more proactive in addressing regulatory change and uncertainty. Assessing the impact of regulations is the first step of developing the framework to deal with regulations and better plan for regulation compliance.

5.3. Methodology

A survey was developed to collect data to better understand the impacts of regulations and regulatory changes in the United States and methods to be more proactive in addressing regulations, regulatory change and uncertainty. Questions were developed from a comprehensive literature review; interviews with regulators and company subject matter experts (SME), and research team input. Two versions of surveys were created—one that could be filled out by multiple SMEs in a company (organizational survey) or one that could be completed by one person (individual survey). For both survey types, the data were collected using Qualtrics (2018). The survey contains eight sections and took about 30 minutes to complete. The sections of the survey are as follows:

- Company/organization information,
- Regulation and their Impact,
- Relationship with Regulators,
- Horizon Scanning and Monitoring,
- Risk and Opportunity Assessment,
- Business Structures and Practices, and
- Crossing Challenges and Opportunities.

This paper presents the responses for the first two sections of the survey. The survey was sent to 55 organizations from April 2018 to October 2018. The research team received 26 valid organizational surveys and one valid individual survey (~47% response rate). The results are presented in the following section.

The first section of the survey captured general information about the organizations in order to more fully understand the characteristics of the respondents. The collected information pertains to the company/organization type, types of projects, and the number of respondents to each survey and their affiliated department within the organization. The organization's size was measured by the number of employees, and these numbers were obtained from public data.

The second section of the survey assesses the regulations changes and their impacts on the surveyed organizations. The questions in this section examine the most impactful categories of regulations that affect the organizations and the level of regulations (e.g., International or Federal) that impact them. Next, the survey measures the percentage of projects that faced uncertainty due to regulatory change as a percent of the organization's total number of projects over the last fifteen years. It also quantifies the percentages of overall capital investment that faced uncertainty due to regulatory changes (percent based on the capital investment). Five-point scales were assigned to the percentages ranging from 0-19.19% to 80-100%, and the percentages were treated on an ordinal scale and ranked from one to five (Allen and Seaman 2007; Boone and Boone 2012) The weighted mean (Fink 2015) was then calculated as shown in Eq.(1):

$$Average\ Rating = \frac{\sum w_j x_i}{\sum x_i} \qquad (1)$$

Where x_i is the number of respondents that selected each category and w_j is the associated weight to the category ranging from one to five.

The survey asked the respondents to select up to three most impactful regulatory changes that have impacted their organizations over the last fifteen years. Subsequently, the responders were asked to choose up to three or add the resulting effects from the selected impactful regulations. The survey measures the level of difficulty (easier, the same, or more difficult) to anticipate and adapt to regulation changes. If difficult is selected, two more questions appear. The first one asks the responder to identify the reasons for the difficulty in anticipating the regulation change. The second question specifies the net impact of anticipating and adapting to regulations changes on the organization’s operation and capital projects. Finally, the section concludes by asking the responders to select the top root causes that was proven in the past to reduce the impact of regulations and regulatory changes. The following section reviews the descriptive and basic statistical findings for the first two sections of the survey.

5.4. Findings

5.4.1. Company Information

The first section provides a general information about the survey organizations. The majority of the surveyed organizations (60%) were Engineering Procurement Construction (EPC) firms while owner/operators represented 30% of the respondents (see Figure 5-1). While there are organizations with less than 500 employees represented, the highest frequency of selection is found with larger companies, particularly those with greater than 10,000 employees as can be seen in Figure 5-2. The top two business structures for the surveyed organizations are privately held followed by publicly traded as shown in Figure 5-3.

Most of the surveyed respondents (85%) represent Utilities, followed up by Power (70%), Downstream and Chemicals (70%), and Upstream, Midstream, and Mining (63%). Figure 5-4 lists the percent frequencies for the types of projects the survey respondents work on. Various departments within each organization participated in the completion of the survey. Figure 5-5 serves to further break down organizational participation by department. A representative from Project Management or Planning department participated in filling out Nearly 70% of the surveys.

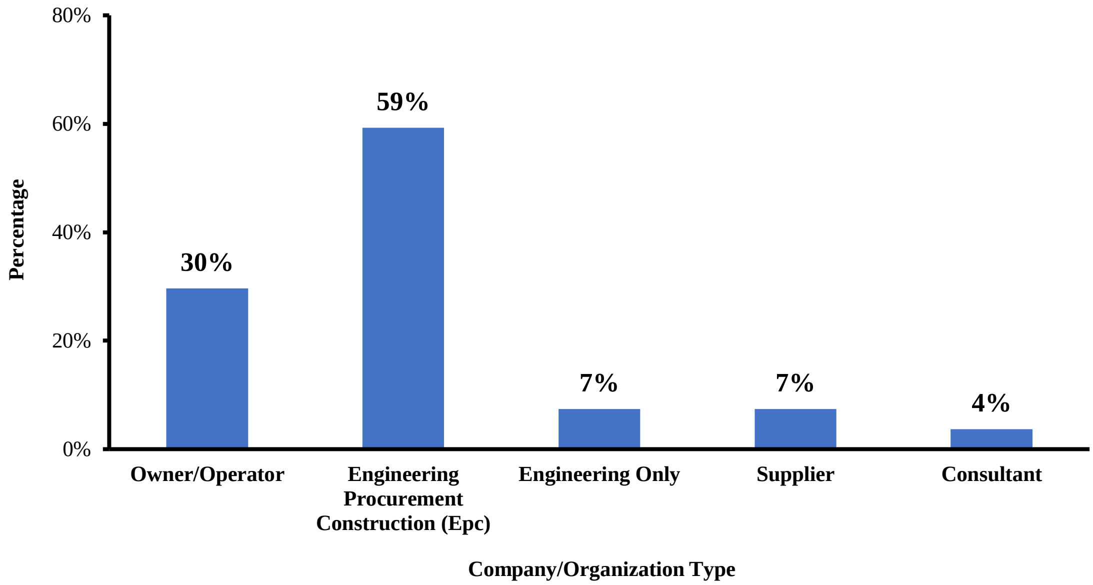

Figure 5-1: The Types of Surveyed Companies/Organizations

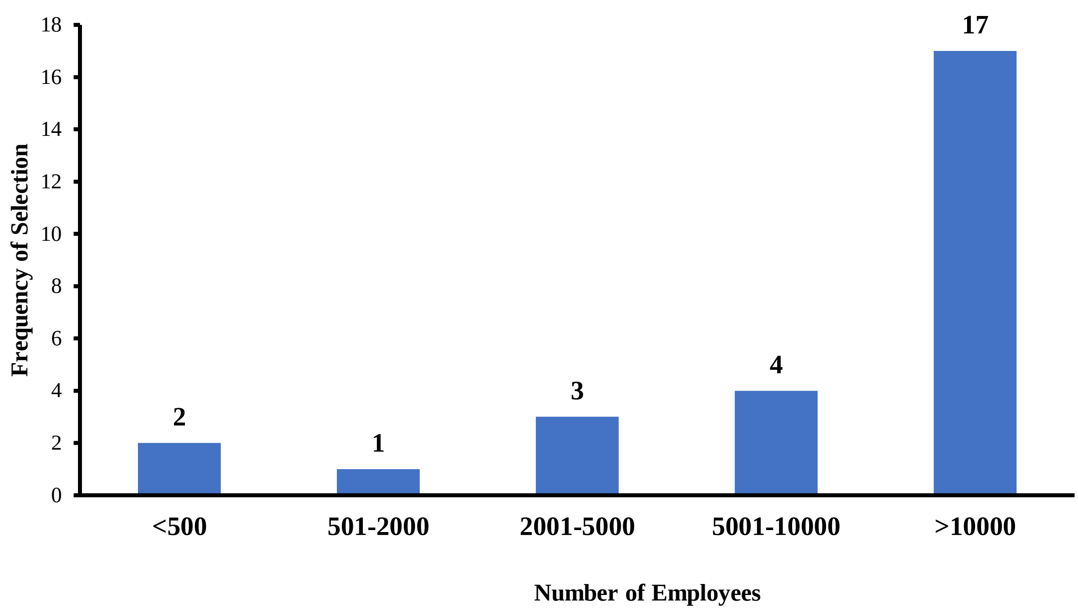

Figure 5-2: The Surveyed Companies/Organizations Size

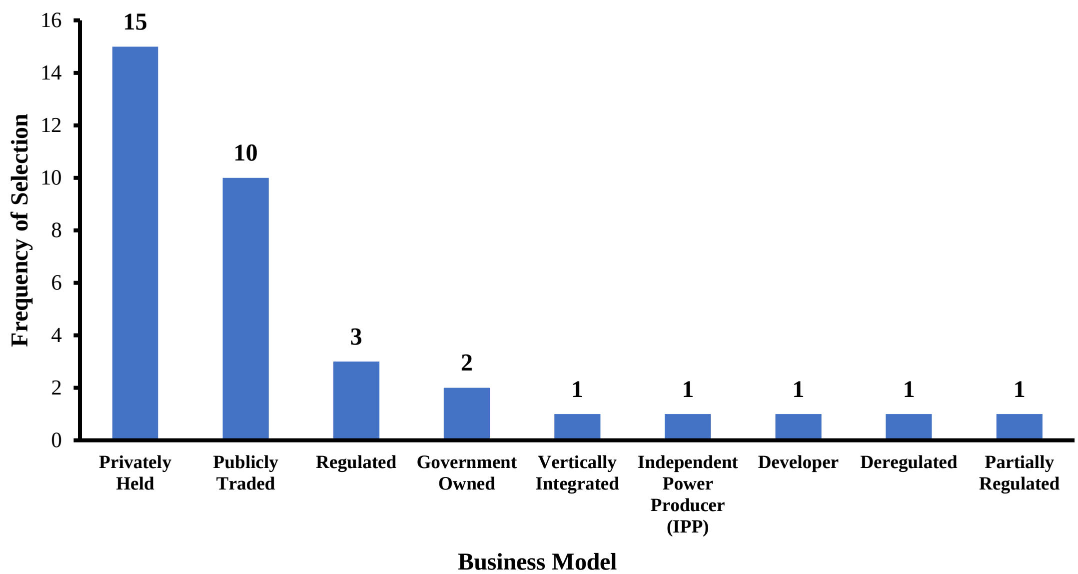

Figure 5-3: The distribution of Businesses Model for the Surveyed Companies/Organizations

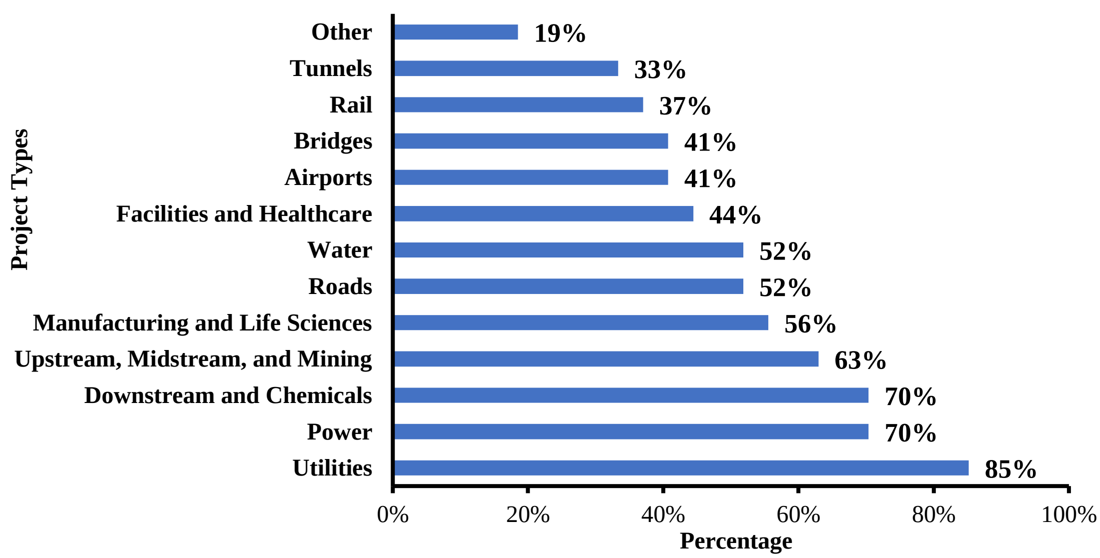

Figure 5-4: The Types of Projects that Survey Responders Represent

5.4.2. The Impact of Regulations

The second section on the survey identifies key regulations and their impact on each of the respondent companies or organizations. Data compilation in this section is represented as a percentage of selection. Figure 5-6 reveals that environmental protection regulations are responsible for the most severe impact on the surveyed regulations in which it was selected by 26 out of 27 respondents. Workplace safety was ranked as the second most impactful category and it was selected by 78% of the responders.

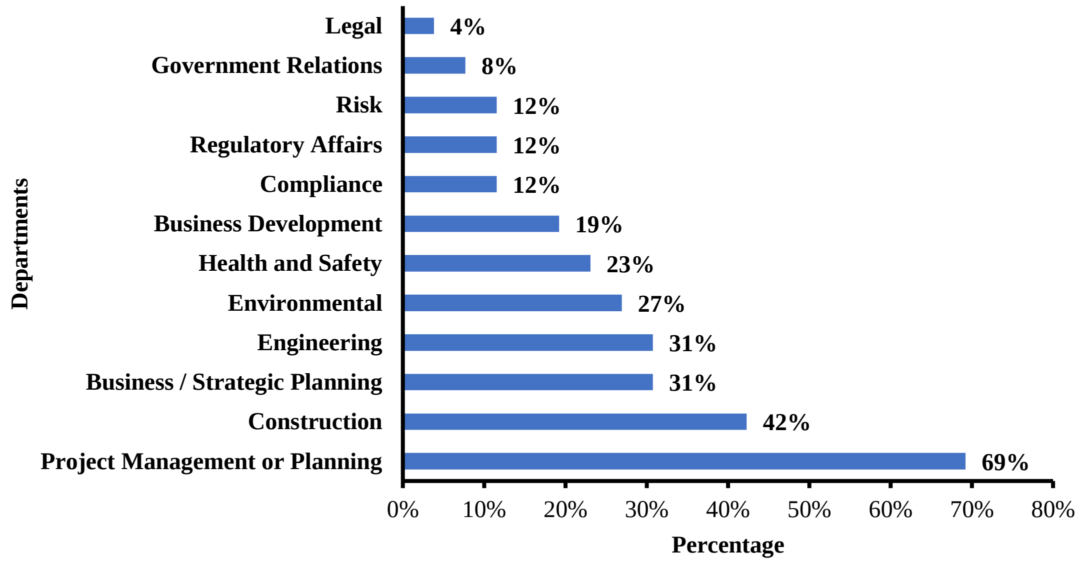

Figure 5-5: Departments within Company/Organization Participated in the Completion of the Survey

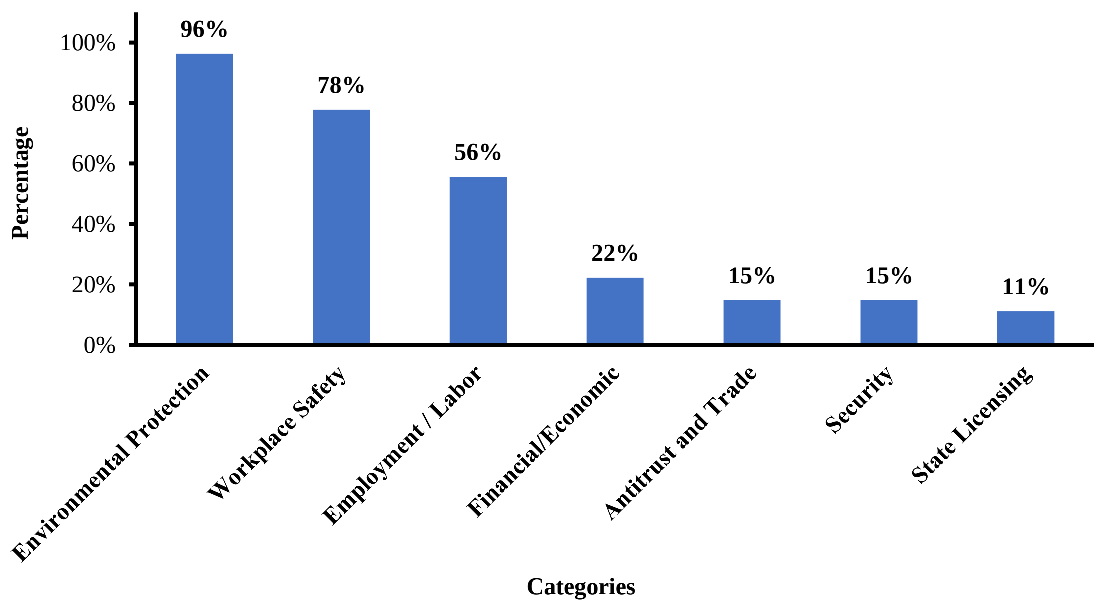

Figure 5-6: Regulations Categories

Figure 5-7 presents the results of the question: what percentage of your company's/organization's projects faced uncertainty due to regulatory changes? The average rating for the responses was 2.37, roughly between 20 and 39.99% of project portfolios faced uncertainty due to regulation change. Participants were also asked what percentage of their company's overall total capital investment has faced uncertainty due to regulatory changes (over the past 15 years) based on the total capital investment. Figure 5-8 shows that 15 companies/organizations stated that 0 -19.99% of their investment faced uncertainty because of the regulatory changes and the average rating was 1.96 which is roughly 20-39%.

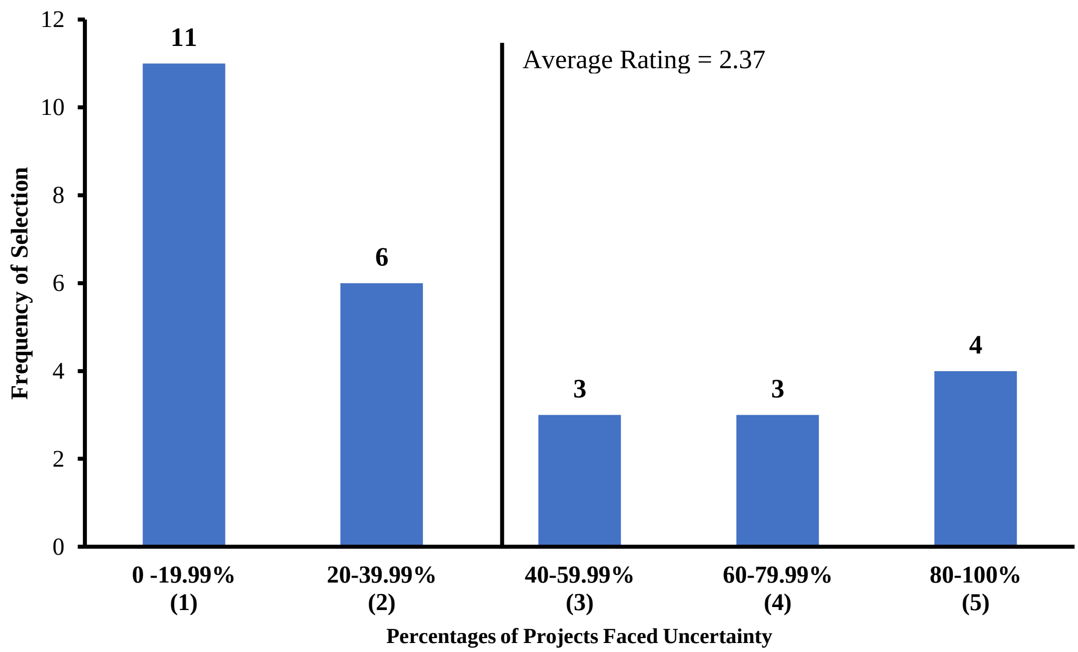

Figure 5-7: The Distribution of the Survey Respondents for the Percentages of Projects that Faced Uncertainty

Figure 5-9 displays what regulations were considered by those surveyed to be the most impactful over the last 15 years. Clean Power Plan (CPP) and Coal Combustion Residuals (CCR), both regulated by EPA, were the highest two impactful regulations. The most frequently cited resulting effects of regulations changes were increased design and construction cost. The remaining cited reasons and their frequencies are displayed in Figure 5-10.

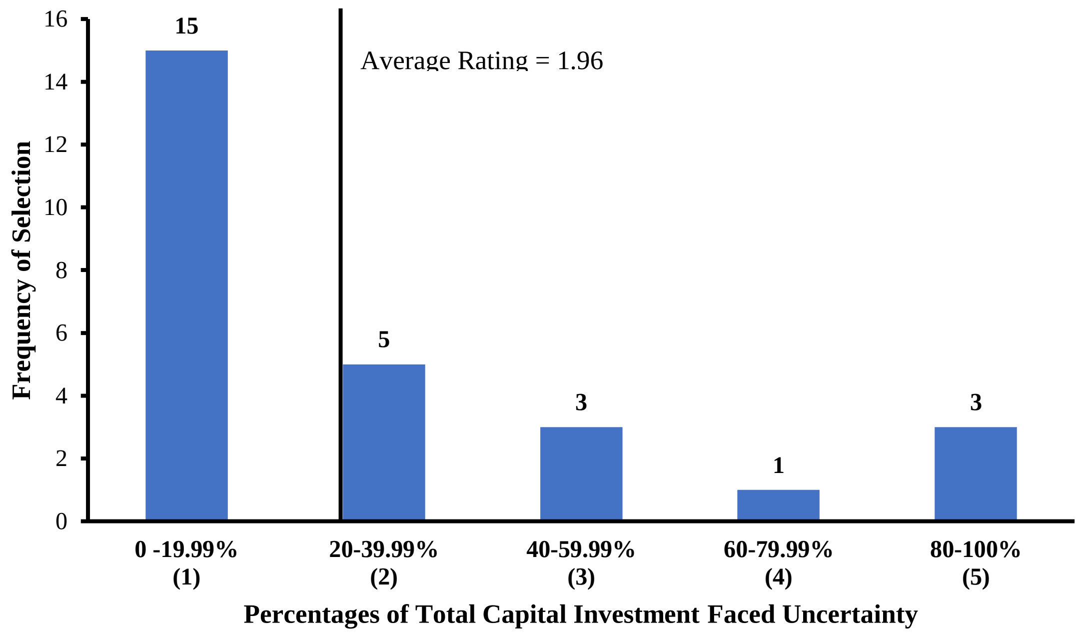

Figure 5-8: The distribution of Capital Investment that Faced Uncertainty due to Regulations Changes

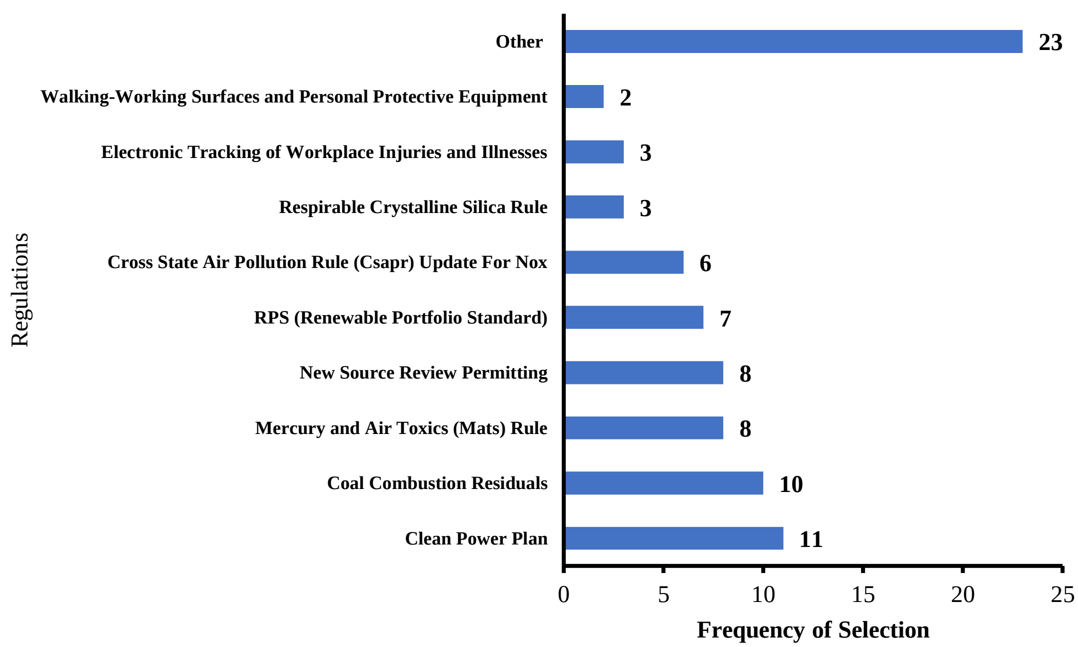

Figure 5-9: The Most Impactful Regulatory Changes over the Last 15 Years

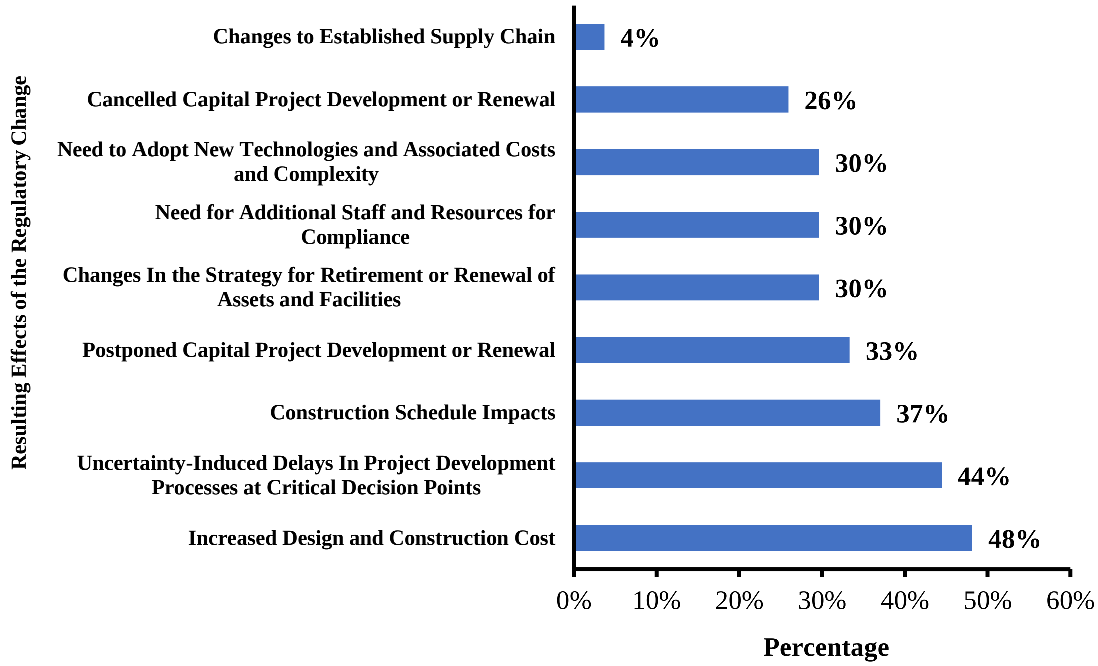

Figure 5-10: The Resulting Effects of the Regulatory Change(s)

The 27 surveyed organizations were asked if it has generally become easier, the same, or more difficult to anticipate and adapt to the regulatory changes over the last 15 years. The majority, nearly 75%, agreed that it is more difficult (see Figure 5-11). For the organizations that selected more difficult, reasons cited varied, but by large, the more frequently stated reasons were regulatory outcomes being less predictable and regulations moving at a more rapid pace than ever before as can be seen in Figure 5-12. In regard to the net impact to the surveyed organizations' operations and capital projects, Figure 5-13 shows that project planning process was impacted most heavily with increased, uncertainty. Both increased compliance staff and construction costs came second and were selected by nine respondents.

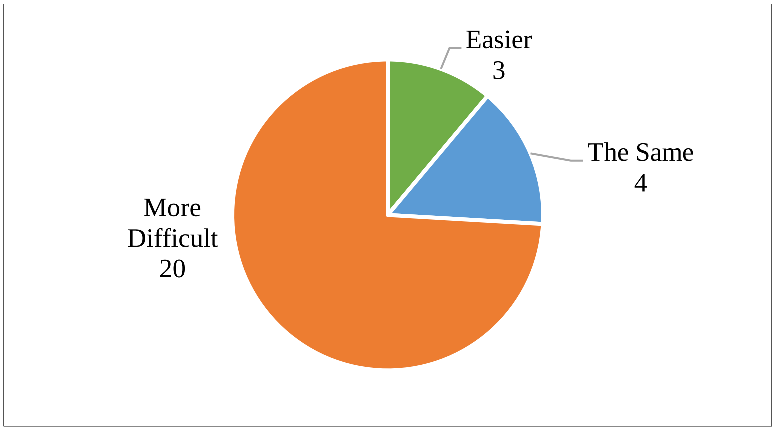

Figure 5-11: The Level of Difficulty to Anticipate and Adapt to Regulations Changes over the Last 15 Years

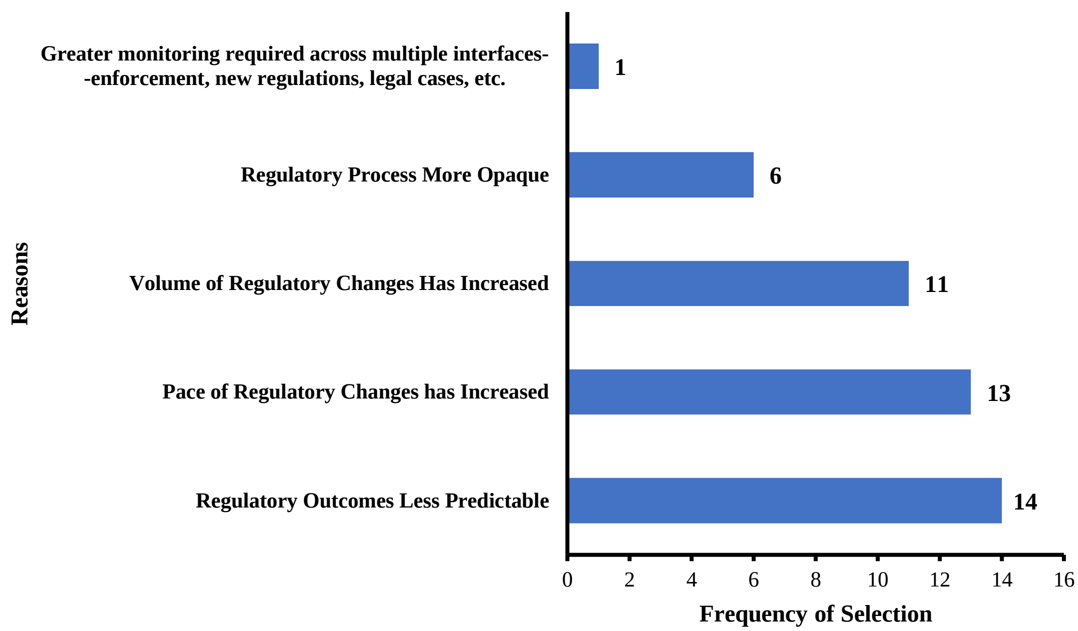

Figure 5-12: The Reasons for Facing Difficulties to Anticipate and Adapt to Regulatory Changes

Figure 5-14 shows the frequency of the causes of regulatory change(s) that have had less impact on the surveyed companies or cognizations. More than half of the surveyed organizations indicated that identifying the regulatory change early contributed to reducing the impact of the regulatory changes followed by the compliance costs and process was minimally invasive (12 selections, 46%), and sufficient information existed to minimize uncertainty.

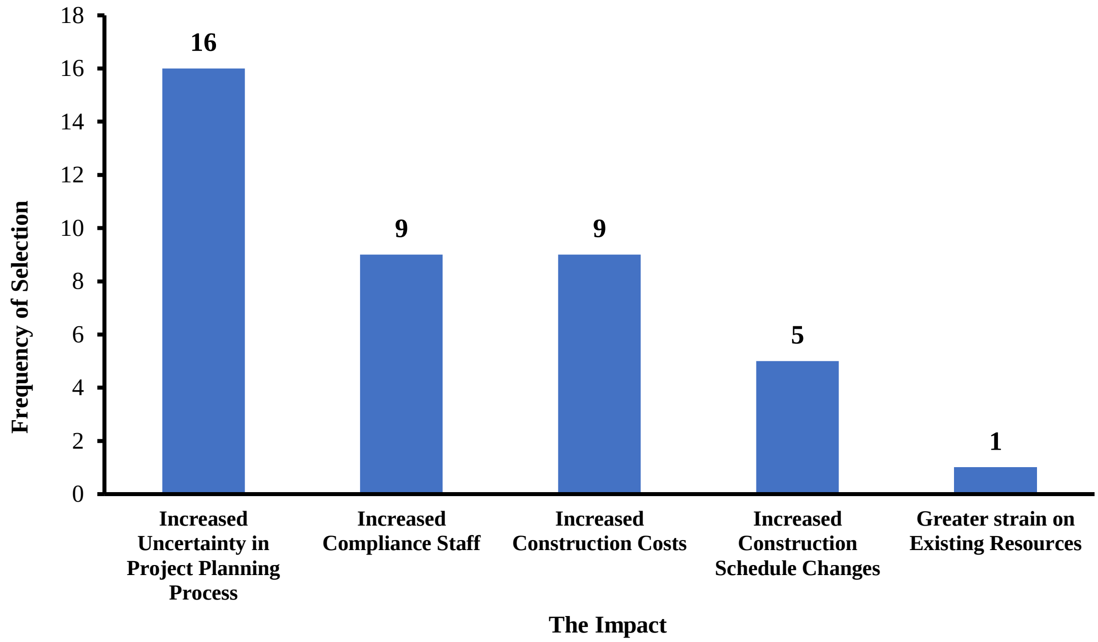

Figure 5-13: The Net Impact of Regulations to Operations and Capital Projects

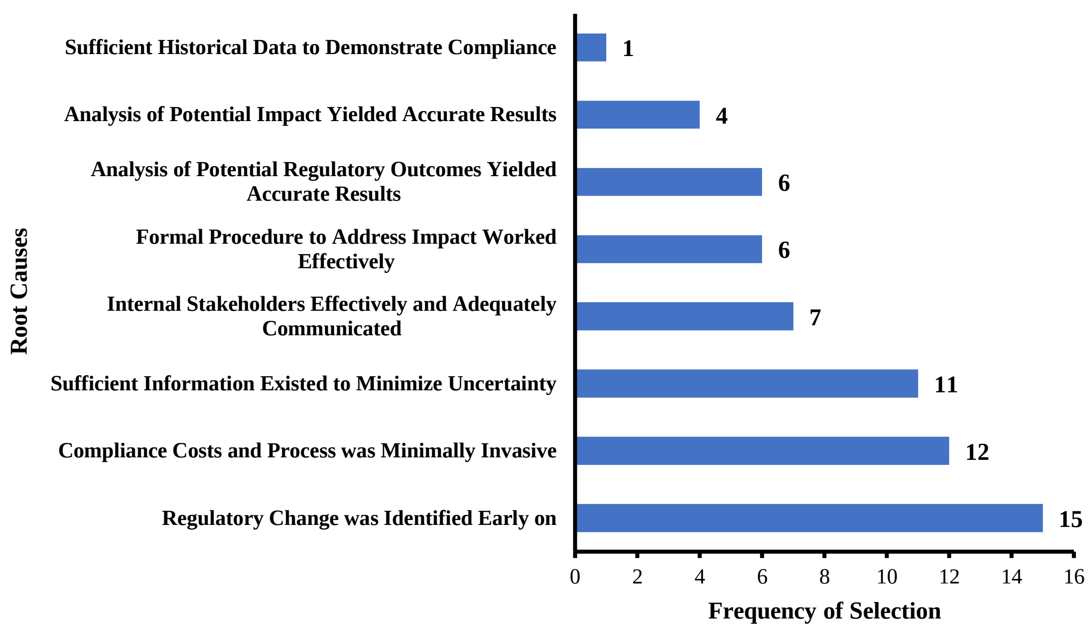

Figure 5-14: The Root Causes of Mitigating the Impact of Regulations

5.5. Discussion and Conclusion

Regulations play a significant role in delivering and operating capital projects. New regulations continue to be introduced, and current regulations are being revised in the construction industry. Such regulations exist at different levels (e.g., Federal and State), and impose risks and uncertainty throughout the project's lifecycle. This study attempts to better understand the impact of regulations and regulatory changes on capital projects in the Unites States. To achieve this objective, a survey was developed and distributed among different organizations and companies.

Results from the survey prove that the tracking and anticipating regulations have become more difficult over the last fifteen years. This means that the challenge of compliance with construction regulations are becoming more complex resulting in increased uncertainty. Another source of challenges is the increasing number of regulations that organizations need to comply with which resulted in increased compliance staff. Results also indicated that compliance drives the costs of design and construction and causes delays in planning. These can lead to a missed opportunity and impact the profitability of capital projects. Depending on the regulation, this can also increase the indirect cost of complying such as conducting regular tests and following with up with regulators (Ryan 2012).

The Survey results also reveal that Federal environmental regulations changes impose the highest risk and the Clean Power Plan was ranked as the most impactful regulation. At the time this paper was written, the EPA proposed a repeal to the CPP regulation (EPA 2017) causing a significant amount of disruption. Therefore, organizations should be more proactive in identifying and responding to regulatory changes. One of the strategies that the majority of surveyed organizations follow to mitigate the impact of regulations is the early identifications of regulations changes.

One of the limitations of the survey is the prevalence of large organizations with more than 10,000 employees. Therefore, the results might be more relevant to such organizations. The following study will analyze the remaining sections of the survey and evaluate the current practices of the surveyed organization as it pertains to dealing with regulations. Future studies should assess the impact of the cited most impactful regulations to understand the causes of disruptions and the compliance requirements better. Future studies should also develop a framework to mitigate the impact of regulations and compliance costs.

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Chapter 6: Assessing Utilities-Related Claims on Transportation Projects

6.1. Abstract

Relocation of existing utilities such as power and telecom and new construction such as water and sewer are aspects of transportation infrastructure projects that have caused significant challenges to departments of transportation (DOTs) leading to higher project costs and schedule delays. Primary risks associated with utilities include relocation delays, conflicts with new construction, utilities shown in different plan locations, unforeseen utilities, tie-in delays to existing utilities, and special requirements for utilities. To addresses these unique challenges posed by utilities on transportation projects, this study considered both qualitative and quantitative research methodologies to assess the impact of utility claims on transportation projects for a specific DOT. Utility-related claim records were obtained from an extensive database of construction claims maintained by the North Carolina Department of Transportation (NCDOT). Research findings revealed utility-related claims most often occurred on urban projects. Additionally, water-related utilities are the most frequently conflicted type of utility. As for delays, it was determined that a utility-related claim is likely to delay project completion time by nearly 70 days on average. Cost-wise, a utility claim was assessed to increase the project's cost by 2.4% of the bid amount, on average. The study also assessed the scenarios in which the utility conflict occurred. It was found that the highest proportion of the conflict was due to delays in relocating the utilities by the utility owner. Lastly, the study obtained related lessons learned from the CLEAR (Communicate Lessons, Exchange Advice, Record) program database. Most of these lessons highlight the importance of early communications and coordination with utility owners and their contractors. Findings from this study are expected to benefit transportation agencies that struggle with managing utilities on their construction projects.

6.2. Introduction

The United States has one of the largest networks of highways, bridges, and airways in the world. The U.S. Department of Transportation (2017) administers a highway and road network of over 3.9 million miles. Additionally, the Federal Highway Administration (2021) oversees more than 610,000 highway bridges. These infrastructures play a vital role in various economic activities. Substantial investments are put into building and maintaining transportation facilities. According to the United States Census Bureau (2019), the annual value of public highway and street spending was estimated in June 2019 to be more than 100 million U.S. Dollars. Delivering and managing such large infrastructure construction projects is characterized by complexities and uncertainties (Gransberg et al. 2013; Luo et al. 2017; O'Connor et al. 1993). Therefore, critical transportation projects often suffer from substantial cost and time overruns (El Asmar et al. 2020; Flyvbjerg et al. 2004; O'Connor et al. 1993).

One commonly reported cause for delays and cost overruns on transportation projects is utility infrastructures (Goodrum et al. 2008; Quiroga et al. 2019; Sturgill 2018). Utilities, including water, power, and gas, share the right-of-way with construction projects and must be relocated to avoid interrupting construction operations (Goodrum et al. 2008; Quiroga et al. 2019). However, these utilities continue to conflict on transportation projects and cause substantial disruptions to roadway projects (Caldas et al. 2008; El-Rayes et al. 2017). If these utilities are not efficiently relocated or not shown on the construction drawings, construction operations typically suspend until the issue is resolved (El-Rayes et al. 2017; Goodrum et al. 2008; Sturgill 2018). Consequently, the contractor recovers from the utility's impact on the project cost and time by submitting a construction claim to the transportation agency (Mehany and Grigg 2015; Pinto

Nunez et al. 2018). Nevertheless, no study to date has assessed the impacts of claims related to utilities on transportation projects' time and cost performances.

This study investigated the impact of utility-related claims on transportation projects. Utility-related claims were obtained from a large construction claims database maintained by the North Carolina Department of Transportation (NCODT). The overarching goal of this study is to comprehensively assess the time and cost impacts of utilities on NCDOT's projects performance. Additionally, the study investigated the scenarios in which these claims occur. Apart from assessing the impact of utilities on transportation projects, this study collected the lessons related to utilities from the newly developed NCDOT's knowledge repository program known as Communicate Lessons, Exchange Advice, Record (CLEAR) (Banerjee et al. 2020; Fullerton et al. 2021). The study's findings are expected to benefit transportation agencies across the nation and transportation contractors that are grappling with utilities during planning, designing, executing, and maintaining the transportation facility. The study's findings can be leveraged to mitigate utility issues and potentially reduce the frequency and severity of utility-related claims on public transportation projects, thereby leading to more efficiently managed capital projects.

6.3. Background Information

6.3.1. Reasons for Utility Conflicts with Transportation Projects

Transportation projects share the right-of-way with utilities-related infrastructure. Therefore, transportation agencies must coordinate with several different utility organizations, both private and public, to accommodate different types of utilities, such as electricity, water, telecommunications, and gas. The space sharing of public roads and bridges with utilities often complicates the efficient delivery of transportation projects and increases the risk of utility conflicts (Caldas et al. 2008; Goodrum et al. 2008; Mehany and Grigg 2015; Quiroga et al. 2011, 2019). Sturgill (2018) indicated that limited information is readily available to the project stakeholder during early project development, and utility coordination efforts are key to minimizing the risk of utility conflicts. According to Quiroga et al. (2011), transportation agencies typically lack adequate and updated information about their facilities. In fact, Meis et al. (2020) found that several transportation agencies do not collect updated geographically referenced data about utilities that are sharing the space with their infrastructures. Some reasons cited include costs, data management issues, and uncooperative utility organizations not sharing accurate and updated data. Another reason cited for utility relocation delays and conflicts is the short notice for utility owners to start relocating their utilities (El-Rayes et al. 2017). In several cases, the reason for such short duration is the late acquisition of the right-of-way (El-Rayes et al. 2017). Lastly, current utility-investigation technologies are still not mature and cannot accurately map, detect, and identify the subsurface utilities (Al-Bayati and Panzer 2019; Quiroga et al. 2019).

6.3.2. Impacts of Utility Conflicts on Transportation Projects

Utilities interrupt the performance of transportations projects and pose significant risks to these public projects (Sturgill 2018). In fact, delays in utility relocations by utility contractors are one of the main contributors to project delays and cost overruns on transportation projects in the U.S. (Caldas et al. 2008; O'Connor et al. 1993). The construction contractors typically recover from utility-related damages by submitting construction claims. According to Levin (2016), a construction claim is defined in federal contracts as "a *written demand or written assertion by one of the contracting parties seeking, as a matter of right, the payment of money in a sum certain, the adjustment or interpretation of contract terms, or other relief arising under or relating to the contract*." One common form of non-monetary relief typically includes granting extra days to deliver the project (Kululanga et al. 2001; Song et al. 2015). Apart from the time and cost impacts, utility conflicts with transportation projects can damage subsurface infrastructure. This damaged infrastructure can cause safety issues for construction workers and the public. Additionally, damaging the subsurface utilities can cause environmental contamination. According to Quiroga et al. (2019), striking abandoned gas pipelines can potentially lead to catastrophic safety and environmental incidents. Lastly, construction conflicts with utilities might cause service disconnects with utility consumers (Goodrum et al. 2008).

6.3.3. Management Strategies to Handle Utilities on Transportation Projects

Transportation agencies have investigated best management practices for dealing with utilities during different project phases. For example, the Illinois Department of Transportation (IDOT) surveyed 37 state departments of transportation and IDOT districts about top effective best management practices (El-Rayes et al. 2017). The IDOT study found that coordination, cooperation, communication (or "CCC") and subsurface utility engineering (SUE) are among the most utilized practices to manage utilities in the context of transportation projects (El-Rayes et al. 2017). Similarly, the Kentucky Transportation Cabinet assessed risks associated with utilities and investigated best practices to minimize those risks. Mitigation strategies include early utilities involvement in the design phase (30% or earlier) and effective utilities investigations that utilize SUE (Sturgill 2018). Chou et al. (2009) and Caldas et al. proposed expanding the scope of work on funded projects by the Texas Department of Transportation (TxDOT) to include relocating utilities. However, utility owners raised some concerns about the quality of relocating the utilities and potential damage to the physical utilities (Caldas et al. 2008). Quiroga et al. (2011) also reported the top ten strategies to manage utility issues during the project development phase. The top three strategies include: (1) developing a utility relocations curriculum for all stakeholders, (2) collecting quality data during preliminary design, and (3) incorporating drainage design to the project's preliminary design.

6.4. Point of Departure and Research Objectives

A review of the literature revealed that utilities cause substantial amounts of disruption to transportation infrastructure projects. Consequently, transportation agencies continue to suffer from utility-related claims resulting in time and cost overruns. However, no study has comprehensively assessed the impact of these utility-related claims. Specifically, the objectives of the current study are:

1. Assess the proportion of utility-related claims among all submitted claims.
2. Assess the impact of utilities-related claims on construction costs.
3. Identify and assess the factors that contribute to submitting a utility-related claim.
4. Assess the time and cost impacts of utility-related claims.
5. Obtain and report relevant lessons learned and mitigation strategies from the Communicate Lessons, Exchange Advice, Record (CLEAR) program database that would potentially reduce the frequency and impact of utility-related claims on transportation projects.

The following section provides an overview of the study's methodology, including how the utility-related utility claims were obtained and how the data analysis was approached.

6.5. Research Methodology

To achieve the research objectives, the methodologies utilized in this study followed qualitative and quantitative approaches in studying the claims associated with utilities. These construction claims were obtained from the Highway Construction and Materials System (HiCAMS) which is managed by the NCDOT (2014). First, the utility-related claims were obtained from a large database of 9,206 construction claims. These construction claims occurred on 2,627 projects. Second, a total of 1,144 valid claims related to utilities were extracted from the construction claims database. These claims occurred on 707 design-bid-build NCDOT projects that were let between 1994 to 2018.

Figure 6-1 displays the distribution of the affected projects by utility-related claims across the NCDOT's (2020) 14 divisions. According to Figure 6-1, the leading number of affected projects with utility-related claims occurred in Division 10, where the city of Charlotte, the most populated city in the state of North Carolina, is located. In this study, the bid amount was assumed to determine the project size. The bid amount of these 707 transportation projects were classified into the following categories (in USD): less than $1 million, $1 to $5 million, $5 to $20 million, and above $50 million—the latter known as megaprojects from the NCDOT's perspective (Alsharef 2015). Figure 6-2 shows the frequency of projects impacted by utility claims, clustered by the project size. Evidently, the most influenced projects by utility claims, according to Figure 6-2, are smaller-sized projects.

Figure 6-3 summarizes the research methodology followed in this study. The subsections below provide an overview of the steps followed in executing this study.

6.5.1. Stage 1: Classify Utility-related Claims

In order to classify the related utility claims, the utility-related claims were extracted by utilizing search-word capabilities in the "claim description" field. The claim description provides a narrative of the reason(s) for submitting the claim. The keywords searched include "util*," "lane," "sewer," "gas," "power," and utility providers' names in the state of North Carolina. These aforementioned keywords are examples of the keywords used in searching. Such a conservative approach in classifying the utility-related claims resulted in 2,879 claims potentially associated with utilities. In order to verify that utilities were involved in these 2,879 claims, two members of the research team independently examined the claims' narratives to confirm that each claim was indeed associated with utilities. Consequently, a total of 1,144 claims were identified and confirmed to be associated with utilities, and 1,735 claims were eliminated.

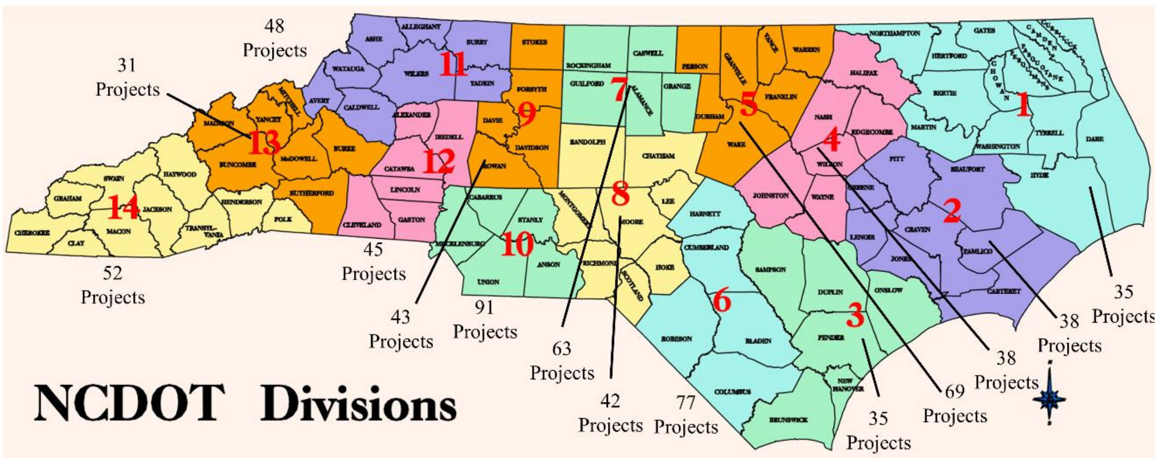

Figure 6-1: The Distribution of Associated Projects with Utility-Related Claims across NCDOT Divisions (Division Map Obtained from NCDOT (2020))

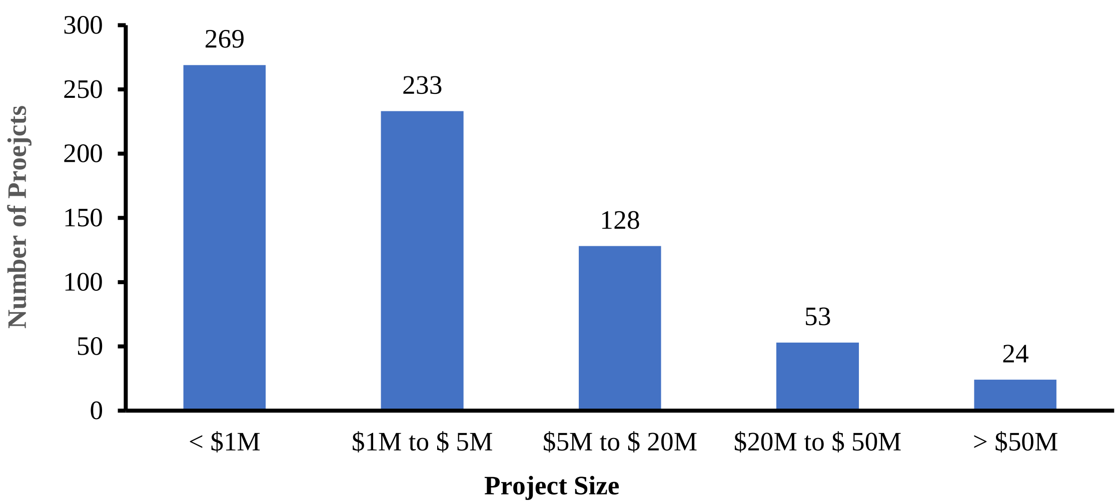

Figure 6-2: Number of Affected Project by Utilities Claims Clustered by Project Size

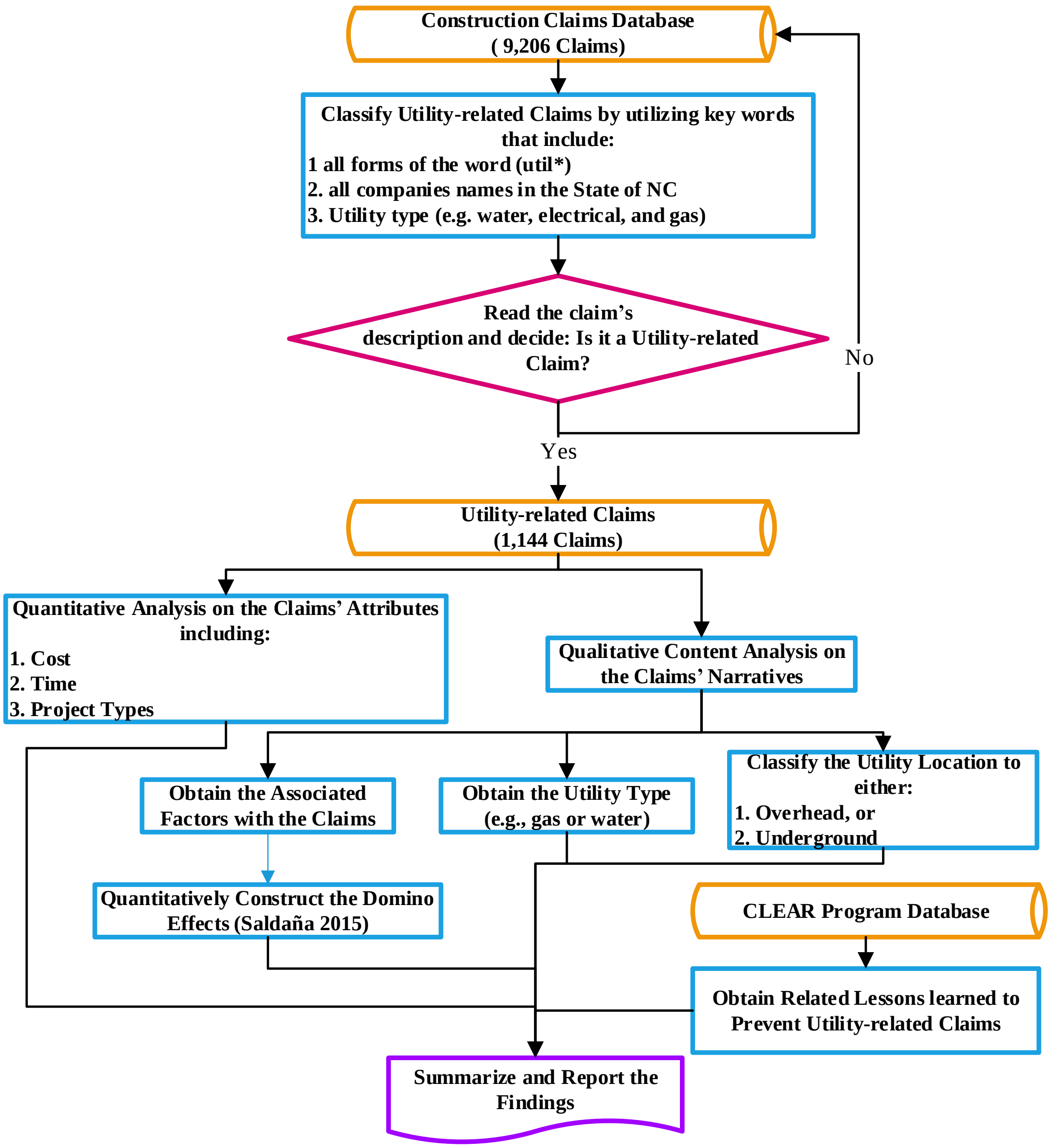

Figure 6-3: Adopted Research Process

6.5.2. Stage 2: Identification of the Factors Associated with the Claims

After identifying the claims associated with utilities, the research team qualitatively analyzed each claim's description or narratives. The claims descriptions provide a rich source of unstructured data and explain the events that led to the submission of the claim as well the utility type (e.g., electricity, water, gas, or telecommunications). The research team conducted a comprehensive content analysis of the claims narratives to structure and summarize the claims narratives. Content analysis is a common qualitative research approach that categorizes unstructured text into structured categories (Elo and Kyngäs 2008; Saldaña 2015). Following this approach, the research team obtained the following from the claims data: (1) utility type, (2) utility location (i.e., underground or above-ground), and (3) the scenario in which the utility claim occurred. In coding the scenarios, the research team followed the domino effect coding approach suggested by Saldaña (2015). The premise of the domino effect approach, as the name suggests, is creating a flow of events that would lead to the utility claim. Figure 6-4 describes this method using an example from the utility claims database.

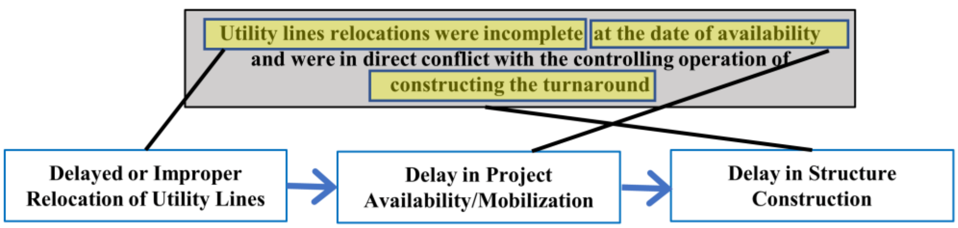

Figure 6-4: Example of the Domino Effect Coding Approach

6.5.3. Stage 3: Quantitative Analysis

After qualitatively obtaining the utility-related claims and analyzing the claims narratives, the quantitative assessment was performed. The following questions guided the quantitative analysis:

1. What is the time impact due to utility-related claims?
2. What is the cost impact due to utility-related claims?
3. What is the frequency of the number of utility-related claims per project?
4. What are the most common types of utilities involved with utility-related claims?
5. What are the most common project types that suffer from utility-related claims?

6. For projects that experienced utility-related claims, what proportion are delivered on time?

7. For projects with utility-related claims, what proportion are delivered within or below the bid amount?

6.5.4. Stage 4: Extracting Lessons Learned

After assessing the utility-related claims qualitatively and quantitatively, the research team obtained the lessons related to utility issues from the Communicate Lessons, Exchange Advice, Record (CLEAR) program database. The CLEAR database serves as a robust repository for gathering and sharing knowledge gained and best practices by NCDOT personnel (Banerjee et al. 2020; Fullerton et al. 2021). One of the objectives of establishing CLEAR database is to reduce repeat mistakes during the planning, executing, and maintaining of NCDOT projects (Banerjee et al. 2020). The obtained lessons from the CLEAR database can be utilized to mitigate the frequency and severity in terms of time and cost of utility-related claims on transportation infrastructure projects.

6.6. Research Findings

6.6.1. The Impact of Utility Claims on Project Cost and Schedule

Among the obtained 1,144 utility claims, 715 claims were granted time extensions and 125 claims were granted extra compensations. The impact for the remaining 304 claims was undetermined because the data was missing in the database. The incomplete records belong to projects that were let in the 1990s and 2000s.

In regard to 715 claims that resulted in time extensions, the mean, median, standard error, and standard deviation were calculated on the number of days granted as a result of claims approved by the NCDOT. Table 6-1 reports the findings from the summary statistics. According to Table 6-1, a utility-related claim would add about 70 days on average to the original contract time. In one claim, the contractor requested a time extension due to delays associated with relocating utilities; the contractor mobilized to the job site and was not able to begin executing the project because the relocation work had not been completed in a timely matter. Design issues also seem to cause project disruption. In one project, the contractor attempted to install the proposed sewer and water lines. However, workers encountered an unknown underground utility that halted construction and resulted in the submission of a time extension claim.

Since projects vary in size, the costs of claims related to utilities were normalized based on the bid amounts, as shown in Equation (1).

$$Utility\ Claim\ Cost\ (\%) = \frac{Claim\ Amount\ Granted\ (\$)}{Bid\ Amount\ (\$)} \qquad (1)$$

The claims database contains 125 records of the amount granted that was due to claims related to utilities. Table 6-2 reports the descriptive statistics (i.e., mean, standard error, median, and standard deviation) of these records and indicates that the associated cost of a utility-related claim would increase the project's bid amount by 2.4% on average. Nevertheless, the standard deviation is around 10%, which indicates a broad spread of data with several outliers. In one claim, the contractor requested compensation due to additional work; the contractor had constructed a detour and installed additional traffic control and safety items, including sandbags. In another claim, the contractor was delayed due to a utility conflict and requested a time extension. The contractor also asked for additional compensation for idle equipment and laborers during the utility relocation period.

6.6.2. Overall Impact of Utility Claims on Different Transportation Projects

The 1,144 utility claims occurred on 707 projects, which means several projects incurred more than one utility claim. To assess the number of utility claims on the 707 projects, Figure 6-5 reports the frequency of utility claims on these affected projects by the utility claims. Moreover, Figure 6-5 shows that 492 projects had one utility claim and one project had 19 utilities-related claims. The one project with 13 utilities-related claims and the one project with 19 utilities-related claims are both megaprojects (projects with bid amounts greater than $50 million).

The utility-related claims database included the project type for 667 projects out of the total 707 projects. A total of 1,083 claims occurred on these 667 projects. To examine the project where most of the utility claims occurred, Figure 6-6 reports the frequency of the utility-related claims on different project types. One remarkable finding from Figure 6-6 is that urban projects suffer the most from these types of claims.

The cost variance and schedule variance were calculated for the 667 projects. The cost variance, in this study, is defined as the difference between the actual project cost and the bid amount. It was found that nearly 95% (631 projects) of the projects suffered from cost overruns. As for the schedule variance, it is defined, in the study, as the difference between the revised completion date and contract completion date. Nearly 96% of the projects suffered from schedule overruns. These findings suggest that projects with utility-related claims are more likely to be delayed and delivered above the bid amount.

6.6.3. Utility Type and Location Analysis

The utility type (i.e., power, gas, water, or electrical) was coded via content analysis as explained in the research methodology section. Figure 6-7 (A) shows the frequency and percentage frequency for each utility type. In the majority of cases, the utility type was not specified in the claims' descriptions. For example, one claim stated that the project completion date was extended by 228 days due to an availability date delay as a result of a utility conflict. The availability date was postponed in this claim because of utility conflicts, but the utility type was not reported in the claim's description.

Besides coding the utility type, the utility location (overhead or underground) was coded by utilizing content analysis. Figure 6-7 (B) reports the percentage frequency of utility type by location. Excluding the unknown utility type, water-related subsurface utilities are the most frequent type of utility involved in claims. In many instances, water-line utilities are not shown on the construction drawings and are encountered during project execution. For example, a contractor was performing earthwork when the contractor encountered a water line. While the conflict was being investigated, the contractor was delayed from completing the remaining work and submitted a time extension claim. According to Figure 6-7 (B), most of the involved utility types with claims are located underground.

After classifying the utility type for each claim, the mean, median, standard error, and standard deviation were calculated for the number of granted days for each utility type as shown in Table 6-3. The reported results in Table 6-3 indicate no significant difference between various utility types. Moreover, the large reported standard deviation values suggest a substantial variation in the granted number of days for different utility types.

The summary statistics (mean, median, standard error, and standard deviation) were computed on percent cost increase for each utility type and reported in Table 6-4. One notable finding is that the percent cost of power-related utility claims is somewhat higher than other utility types, excluding the unknown ones. However, this finding is based on a relatively small sample size, as shown in Table 6-4. Similar to the granted number of days, the percent cost increase data substantially vary as indicated in the reporting standard deviation values in Table 6-4.

6.6.4. Most Frequent Domino Scenarios Leading to Utilities Claims

In order to understand the events and factors that led to utilities-related claims, the narratives of utility-related claims were qualitatively analyzed using the content analysis approach (Saldaña 2015). After coding the claims' narratives, the events and factors leading to utility-related claims were sequentially depicted in domino scenarios (Saldaña 2015). In total, 372 unique scenarios were generated after analyzing the descriptions of the 1,144 claims.

Furthermore, the research team classified the claims into four categories: (1) expected, (2) no physical conflict, (3) unforeseen, and (4) unspecified. The "expected" claims group includes delays due to utility relocation or improper relocation. The "no physical conflict" category includes delays that were not due to physical issues but were caused by, for example, waiting for a new design or permit issues. The "unforeseen" category includes cases where the existence of the utility infrastructure was not known or included in the project's scope or drawings. Lastly, "unspecified" includes claims records with limited or no information about the events that led to the claim. Figure 6-8 presents the proportions of the utility claims categories. Excluding the "unspecified" scenarios, the highest percentage of the scenarios were "expected." In most cases, the utility lines were not relocated on time, preventing the construction project contractor from mobilizing to the construction site or starting some construction activities such as earthwork. Table 6-5 presents the most frequently reported scenarios that led to utilities-related claims.

According to Figure 6-8, "no physical conflict" scenarios represented nearly 19% of the scenarios. In these cases, the physical utilities were not supposed to be relocated by the owner of the utilities. In one claim, the contractor requested that the Mechanically Stabilized Earth (MSE) retaining walls be redesigned to avoid conflicts with unknown utilities. The time required to redesign the walls delayed the controlling operation. Consequently, the contractor was granted 79 days. In a case involving permit delays, the contractor was granted 30 days due to delays in issuing a permit by the North Carolina Department of Environmental Quality for a proposed 12-inch waterline to be tied to the city's water-supply network.

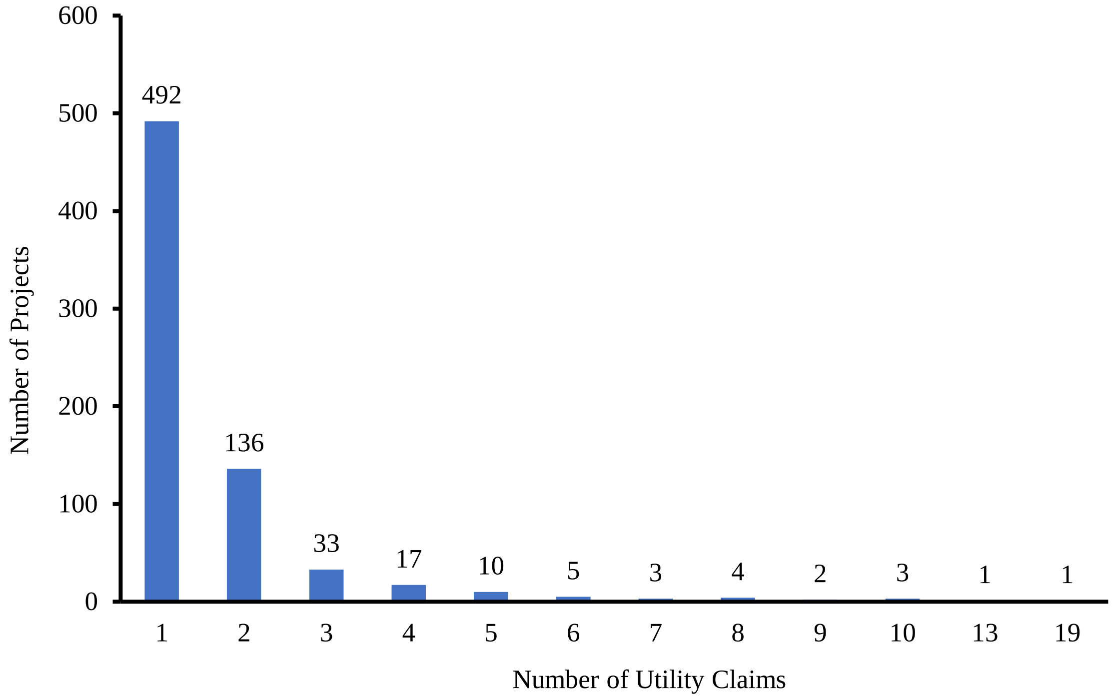

Figure 6-5: The Distribution of the Number of Utility Claims per Project

Lastly, nearly 16% of the scenarios were classified "unforeseen," as shown in Figure 6-8. These scenarios were mainly attributed to design errors or changes. For example, the contractors would encounter abandoned utilities during construction that were shown on the project's plans. In on "unforeseen" claim, a utility line not shown on the plans was encountered during storm drain installation. Besides encountering abandoned utilities, the contractor found live utilities in several scenarios while executing the project. For instance, a live water line was in conflict with the installation of a proposed 36-inch cross-line pipe. This conflict resulted in the installation of the 36-inch cross-line pipe in a location different from the one specified in the plan.

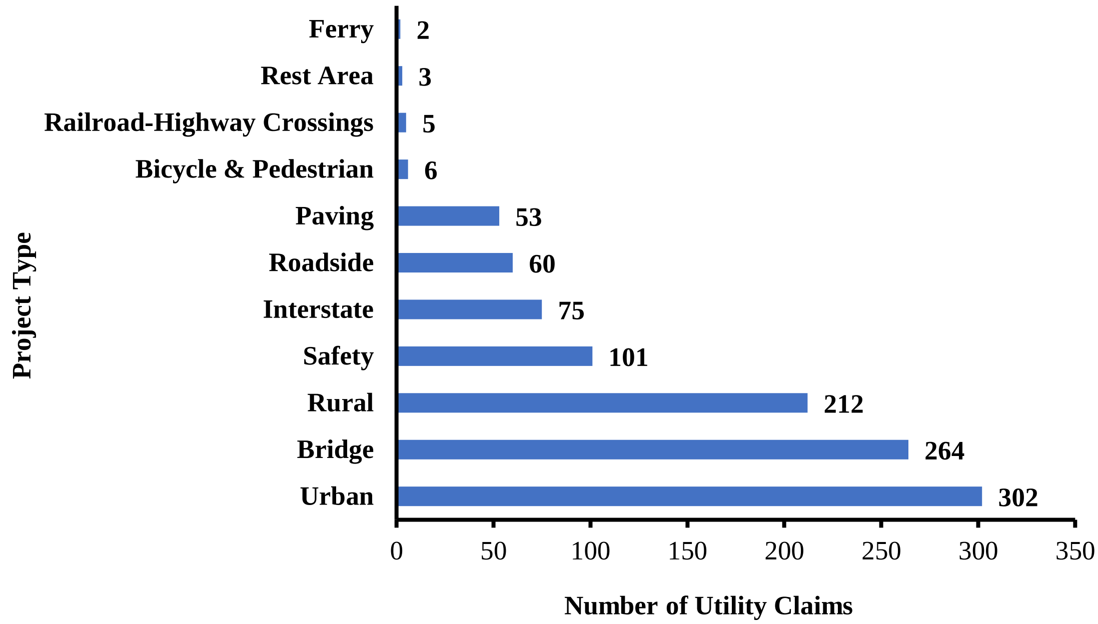

Figure 6-6: The Distribution of 1,083 Utility Claims across Different Project Types

6.6.5. Lessons Related to Utilities from CLEAR Database

Assessing the claims related to utilities reveals that utilities significantly contribute to transportation projects' time and cost overruns. The newly introduced CLEAR program database is one potential source for mitigation strategies to reduce the frequency of incurring utility claims (Fullerton et al. 2021). The lessons and best practices in the CLEAR database are reported by NCDOT personnel in the following form: (1) the submitter describes an encountered issue, (2) the submitter indicates specific details about the issue such as the location and the number of past occurrences, and (3) the submitter provides solutions to the issue. The research team extracted the lessons related specifically to utilities from the CLEAR database. Table 6-6 reports the lessons related to utilities extracted from the database. The solutions provided in Table 6-6 mainly focus on coordinating and communicating with utility owners early. One way to establish such coordination is by holding meetings with utility owners and all other stakeholders during the preconstruction stage and before the bidding process. In one solution, the submitter suggested providing early compensation to utility owners in order to achieve early or in-time utility relocations.

Table 6-1: Summary Statistics of the Days Granted to Recover from Utilities Claims

Number of Claims	715
Mean	69.75 days
Standard Error	3.46 days
Median	34.0 days
Standard Deviation	92.45 days

Table 6-2: Summary Statistics of the Percent Cost Increase due to Utilities Claims

Number of Claims	125
Mean	2.4%
Standard Error	0.92%
Median	0.26%
Standard Deviation	10.27%

Table 6-3: Summary Statistics of the Days Granted to Recover from Utilities Claims Clustered by Utility Type

Utility Type	**Number of Claims with Time Extensions**	**Mean (Days)**	**Median (Days)**	**Standard Error (Days)**	**Standard Deviation (Days)**
Water	163	63.0	26	7.9	102.0
Telecommunications	110	57.2	30	7.16	75.1
Power	112	63.1	41	7.25	76.7
Gas	35	53.1	25	12.15	71.9
Unknown	295	82.7	43	5.88	101.0

Table 6-4: Summary Statistics of the Percent Cost Increase to Recover from Utilities Claims Clustered by Utility Type

Utility Type	**Number of Claims with Cost Increase**	**Mean (%)**	**Median (%)**	**Standard Error (%)**	**Standard Deviation (%)**
Water	41	0.71	0.1	0.22	1.38
Telecommunications	16	0.65	0.3	0.215	0.86
Power	8	0.98	0.14	0.59	1.67
Gas	4	0.54	0.16	0.43	0.86
Unknown	56	4.47	0.521	2.02	15.1

Table 6-5: Highest Frequency of Domino Events Leading to Utilities-Related Claims

Scenario	Frequency
Expected	
Delayed or Improper Relocation of Utility Lines → Delay in Project Availability/Mobilization	36
Delayed or Improper Relocation of Utility Lines → Delay in Project Availability/Mobilization → Delay in Structure Construction	20
Delayed or Improper Relocation of Utility Lines → Delay in Project Availability/Mobilization → Delay in Earthwork	17
Delayed or Improper Relocation of Utility Lines → Work Suspension → Delay in Earthwork	17
Unforeseen	
Design Error/Change → Work Suspension → Delay in Earthwork	14
Design Error/Change → Extra Cost/Overhead Cost	10
Design Error/Change → Work Suspension → Delay in Structure Construction	10
Design Error/Change → Work Suspension → Delay in Utility Construction	10
No Physical Conflict	
Delay in Connecting Utility Lines by the Provider → Work Suspension → Delay in Sign Installation/Activation	32
Concurrent Utility Project by Different Entity → Work Suspension → Delay in Paving/Resurfacing Operation	20
Permit Issues → Work Suspension → Delay in Utility Construction	10

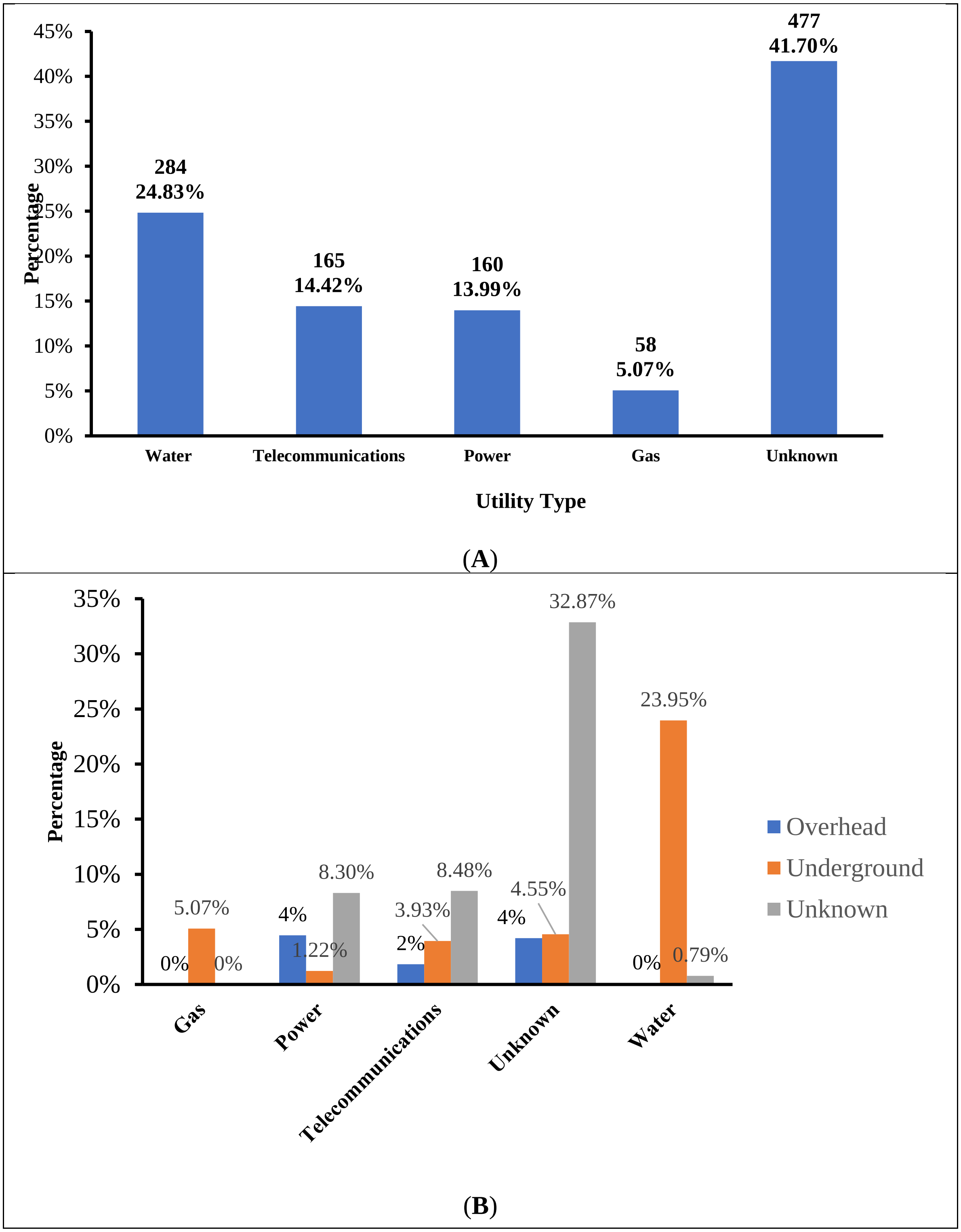

Figure 6-7: (A) Percentage Frequency of Utility Type, By Location; (B) Percentage Frequency of Utility Type by Location

6.7. Discussion

This study empirically assessed time and cost impacts on transportation infrastructure projects by via utility-related claims. Findings from this study revealed that a utility-related claim would most likely result in a time extension. Specifically, this study concluded that a utility-related claim would most likely result in the contractor being granted 70 days, on average. The utility-related claims could also result in the contractor requesting extra funds to recover from damages, such as productivity reductions that result from equipment idled during the wait for the utility owner to relocate the utilities or change orders. Additionally, around 95% of the projects studied that experienced utility-related claims were delivered above the planned cost and past the original schedule. These findings confirmed the several reported studies in the broader body of literature about the negative impacts of utilities on executing public infrastructure projects (El-Rayes et al. 2017; Goodrum et al. 2008; Mehany and Grigg 2015; Meis et al. 2020; O'Connor et al. 1993; Quiroga et al. 2019; Sturgill 2018). This study fills the knowledge gap by quantifying such impacts on the cost and schedule of transportation infrastructure projects.

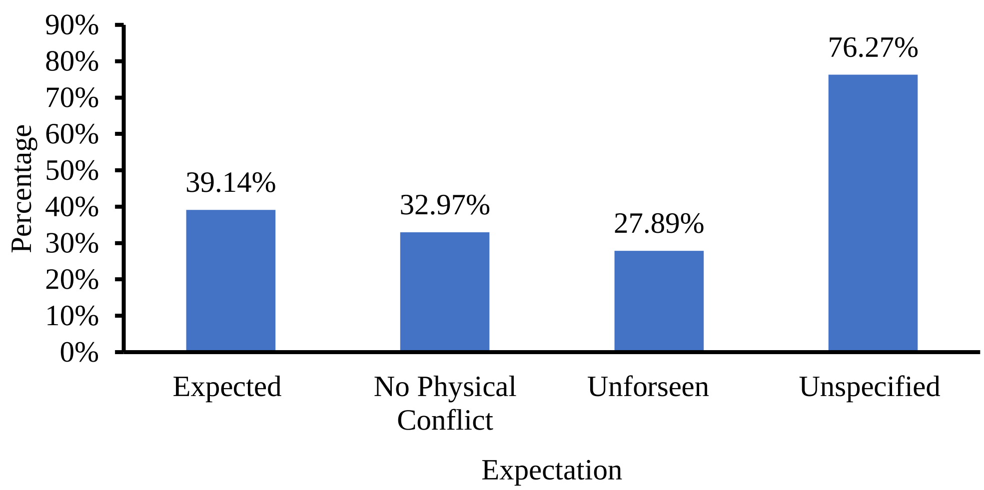

Figure 6-8: Proportions of Utilities Claims Main Categories

Table 6-6: Lessons Related to Utilities obtained from CLEAR Database

Issue Description	Issue Details	Solution to the Issue
Several utility conflicts identified on project.	Utilities not located on plans, causing delays to the contractor.	Contractor worked around utility issues by utilizing different drainage designs, traffic control phasing, and processes.
Existing 15-in. drainage pipe was not in the location as noted on the plans.	Contractor waited for a redesign which overran on pipe quantities.	Hold field meeting ahead of the project bid and let process.
Sporadic interactions between contractor and DOT; DOT and municipalities.	Utility owners are late in relocating utilities, causing schedule delays.	Need to obtain early buy-in from all stakeholders and get contractor involved.
Utilities were deep and stacked; they were “located but not picked up.”	Utility items left out of contract.	Add supplemental field surveying when there are several utilities.
Several utilities are generally involved on a widening project whose relocation can inadvertently affect nearby businesses.	Cost and schedule impacts: Added a few months to project schedule. Cost impacts nearly doubled.	Meet with utility owners and municipalities early on and try to minimize impacts due to utilities.
NCDOT Prime Contractor had crews scheduled to begin on date of availability, but utilities were not relocated.	Impacts increased project cost and delayed the schedule.	Issue was solved with SUE investigation and additional utility coordination during construction. These issues should have been resolved during preconstruction.
Coordination issues with utility companies—getting the utility owners to move utilities is a challenge.	Around 1% impact on cost and schedule.	Possible solutions include compensating the utilities to get relocation work done on time and conducting division-level meetings with utilities to improve communication and minimize surprises.

In this study, it was not surprising to discover that urban projects were affected mainly by utility-related claims. These urban projects are close to dense populations where congested utilities exist (Caldas et al. 2008; Goodrum et al. 2008; Quiroga et al. 2019). Thus, relocating these utilities could be challenging for utility contractors and will more likely result in delays as utilities are being relocated. In fact, it is likely that contractors will encounter utilities during the execution of urban projects in which the utilities were not shown or not accurately located on the projects’ plans. Encountering and not effectively managing these conflicting utilities can substantially disrupt transportation infrastructure projects (Caldas et al. 2008; Chou et al. 2009; El-Rayes et al. 2017). This study found no considerable difference in the delay durations or extra incurred costs due to encountering a specific utility type (e.g., water, gas, or power). Additionally, it was found that water-related utilities are the most frequently encountered type because they are typically located underground and are thus difficult to detect easily. In this study, it was suggested by the distribution of project sizes that utility-related claims are primarily associated with smaller projects in terms of the bid amount. One possible explanation is that the coordination and management efforts for smaller projects are commonly less comprehensive than coordination and management efforts on megaprojects.

Findings from this study established that the majority of utilities involved with claims were subsurface utilities. Several studies in the literature indicated that dealing with subsurface utilities is challenging and complex (Al-Bayati and Panzer 2019; Kraus et al. 2012; Sturgill 2018). One source for this challenge is that transportation agencies and utility owners lack complete and accurate location information of utility infrastructures. In fact, Meis et al. (2020) asserted the urgent need for establishing GIS data for as-built utility infrastructures. Additionally, Al-Bayati and Panzer (2020) proposed creating an accurate three-dimensional database for existing utility infrastructures. These conflicted subsurface utilities with transportation projects were typically not accounted for during the design, preconstruction, or construction phases (Sturgill 2018). As for overhead utilities, this study and other studies in the literature (e.g., Chou et al. 2009; El-Rayes et al. 2017; Sturgill 2018) indicated that they were mostly not relocated on time, which affected the transportation project contractors' activities, especially mobilizing heavy equipment to the construction site and earthwork activities. Several reasons were suggested for the utility contractors' delays in relocating their utilities, including the relatively short duration of time allowed by state department agencies and the complexity of acquiring the right-of-way in a timely manner, according to the ILDOT study (El-Rayes et al. 2017).

This study found no considerable difference in the delay durations or extra incurred costs due to encounters with a specific utility type (e.g., water, gas, or power). Additionally, it was found that water-related utilities are the most frequent type since they are typically located underground. In this study, it was suggested by the distribution of project sizes that utility-related claims are primarily associated with smaller projects in terms of the bid amount. One possible explanation is that the coordination and management efforts for smaller projects are typically less extensive than those of megaprojects.

One of this study's main findings is that utility-related claims follow distinct and repeated patterns. In this study, it was revealed that the scenarios leading to utility-related claims were classified as "expected," "no physical conflict," and "unforeseen." The "expected" scenarios can be potentially mitigated by effectively applying the best management strategies reported in this study and the broader literature (Al-Bayati and Panzer 2019; El-Rayes et al. 2017; Meis et al. 2020; Sturgill 2018). As for "no physical conflict" claims, some potential mitigation strategies include proactively obtaining needed permits and producing new designs. In regard to the "unforeseen" utility claims, they were reported to cause substantial disruptions to the construction project and were most likely to lead to work suspensions. Meis et al. (2020) attribute several unforeseen scenarios to inaccurate georeferenced data. The utility owners and transportation agencies are encouraged to build state and national databases to map the existing utility locations accurately. As soon as the utilities are relocated, the databases must be updated with the new information. Additionally, the lessons reported in this study emphasize the importance of early stakeholder engagement to minimize the impacts of projects interrupted by issues concerning utilities. The importance of early communication and coordination has been particularly reported by following studies (El-Rayes et al. 2017; Goodrum et al. 2008; Kraus et al. 2012; Quiroga et al. 2019; Sturgill 2018).

6.8. Conclusion

Transportation construction projects are complex. One source of complexity while building public transportation projects is managing, locating, and accommodating existing infrastructure facilities. The utilities typically interrupt the flow of building public transportation projects and cause project delays and cost overruns. Such impacts have not been assessed in the literature. Thus, this study followed qualitative and quantitative research approaches to assess the impact of utilities on public transportation projects. Utility-related claims were obtained from an extensive database of historical construction claims. It was found that utilities primarily affect the project schedule and cause time delays. Specifically, it was found that a utility-related claim would likely push the original completion date by nearly 70 days. Additionally, the study's findings revealed that the most frequently associated claims with utilities are subsurface utilities occurring on urban projects. The study also reported several lessons learned from the newly developed CLEAR program database (Fullerton et al. 2021). The lessons highlighted the importance of proactively coordinating and communicating early in the project with the utility owners and their contractors.

While this study presented several insights about the impact of utility claims on transportation projects, the study encompasses some limitations. First, there were variations in the reported information in different utility claims. For example, numerous claims lack adequate information about the factors associated with the utilities that led to claim submissions. Additionally, the utility type (e.g., gas or power) was missing for several claims. These claims were coded "unknown" in the research findings section. Second, the claims' descriptions or narratives included only the downstream factors that led to the claims. Several upstream factors can contribute to the claim, including the design time, surveying efforts, or investments in subsurface engineering efforts. Third, this study did not assess the potential damage to utilities as a result of the conflicts. These assessments can include direct effects such as damage to the physical utilities and indirect effects, including utility disconnections. Fourth, this study analyzed only utility claims that occurred on NCDOT projects. While all state transportation agencies operate under the U.S. Department of Transportation, it is possible that the findings from this study cannot be generalized to other states' transportation agencies.

Based on the reported limitations, future research efforts should investigate the impact of utility-related claims on different state transportation agencies. Such investigations would reveal the patterns in which utility-related claims occur in different states. Consequently, tailored mitigation strategies can be introduced both generally and for specific departments of transportation. As for the limited amount of information provided in the claims, contractors and state transportation departments are recommended to adequately document the reasons for the claims, the affected activities, utility type, and location. Also, there should be a field in the claim to allow the claim submitter to provide mitigation strategies to mitigate similar claims that may be submitted on the same project or future projects. Lastly, future studies should thoroughly investigate both downstream and upstream factors that cause utility-related claims. Such research efforts would guide investigating the solutions to tackling utility issues on transportation infrastructure projects.

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Chapter 7: Conclusion

7.1. Summary

Undoubtedly, there has been an exponential growth in the amount of data generated during all stages of construction projects (from project inception and planning to maintenance and demolition). However, massive amounts of data remained uncaptured and unexamined. As the engineering and construction industries are witnessing an unprecedented digital transformation, it becomes vital to leverage this data and turn it into valuable insights to solve numerous industry challenges. Accordingly, this dissertation investigated five challenges pertaining to disaster management, occupational safety, regulatory changes, and infrastructure management. This dissertation comprises five individual investigations reported in five chapters (chapter 2 to chapter 6).

The second chapter is titled “Early Impacts of the COVID-19 Pandemic on the U.S Construction Industry.” This study focused on investigating the early impacts of the COVID-19 pandemic on the U.S. construction industry since the national emergency declaration on 13 March 2020. The study objectives were accomplished by conducting semi-structured interviews with project managers, engineers, designers, and superintendents that represented different states and distinct industry sectors in the United States. Moreover, the study identified the adverse effects, new opportunities, and risk mitigation measures that are being adopted in construction workplaces. The findings of the study will be useful to governmental agencies as they seek to elevate the adverse effects experienced in the construction industry. Industry representatives may use the findings to identify risk management efforts that may be appropriate for their own organizations. Researchers may use the findings to identify problem areas and propose relevant interventions to support the efforts of the industry.

The reported study in the third chapter, "Severe Construction Injuries among Construction Workers," was inspired by the poor safety performance on constructions sites. Workplace injuries have significant economic impacts besides incalculable human suffering. However, the impacts of these injuries carry more effect if the sustained injury is classified as severe or serious. In fact, sustaining severe workplace injuries can be a life-altering event. Moreover, severe injuries cause substantial amounts of pain and can result in permanent disabilities. In order to assess, understand, and mitigate severe construction workplace injuries, over 11,000 severe construction injuries were obtained from the newly developed OSHA's new severe injury reporting program. The study comprehensively analyzed incidents' attributes and assessed overrepresented attribute categories. The study's findings are useful for construction organizations struggling with the high frequency and severity of workplace injuries. Additionally, the findings can be used in developing tailored safety interventions for severe/serious construction workplace injuries.

The fourth chapter ("Work-related Safety incidents among Driver License Examiners") investigated past incidents reports involving driving license examiners. This community of workers plays a vital role in our society as they ensure only competent drivers drive on the roads. Despite their important role in enhancing traffic safety and serving the public, they are nonetheless exposed to high levels of safety risk. To gain a better understanding of the safety challenges that driver license examiners face, the study empirically examined NCDMV incident reports that involved driver license examiners. Qualitative content analysis was performed on the incidents' narratives to identify the fundamental attributes (e.g., event type, contributing factor, and injured body part) and their categories. The study provided a deeper understanding of the safety incidents that driver license examiners experience which can inform the development of effective injury prevention policies and safety interventions.

The fifth chapter ("Assessing the Impact of Regulatory Changes on Capital Projects in the United States") was mainly driven by how the construction industry is strongly regulated and these regulations are constantly subjected to changes and reevaluations. Such regulations typically influence the design, construction, and operation of capital projects. Thus, it can be challenging for construction organizations to comply with the current abundance of regulations and anticipate future regulations. The study's overarching goal was to evaluate the impact of regulations throughout the complete construction project lifecycle (from project inception and planning to maintenance and demolition). The research methodology involved conducting an organizational survey to understand better how companies address regulations. The discoveries from the study can help organizations better understand the effect of regulations on building and operating projects and better plan for regulation compliance.

The sixth chapter ("Assessing Utilities related Claims on Transportation Projects") pertains to assessing the interruptions of utility facilities (e.g., water and gas) on transportation projects. Coordinating public transportation projects with other stakeholders is significantly challenging. This is especially true if other stakeholders must accommodate their facilities on the project's site such as utilities. Construction organizations and departments of transportation are required to consistently coordinate with utility providers regarding utility relocations during preconstruction and construction of transportation projects. However, utilities typically conflict with transportation projects and likely cause delays, cost claims, or both. This study followed qualitative and quantitative research approaches to assess the impact of utilities on public transportation projects. Findings from this study are anticipated to benefit struggling transportations agencies with managing utilities on their construction projects.

7.2. Key Research Contributions

Individual studies in this dissertation made significant key contributions to literation in the following ways:

Chapter 2: Early Impacts of the COVID-19 Pandemic on the U.S Construction Industry

This study was the first comprehensive study in the literature that investigated the impacts of the COVID-19 pandemic, the largest global health crisis in decades, on the U.S. construction industry. The study gathered and reported the following insights: (1) general and adverse impacts of Covid-19 on the construction industry including material delivery delays, shortage of material, permitting delays, lower productivity rates, cash flow-related challenges, project suspension, price escalations, and potential conflicts and disputes; (2) new opportunities as a result of the Covid-19 pandemic such as lower interest rates, demand increase in the medical, transportation, and residential sectors; and the ability to recruit skilled workers; and (3) efforts to manage the challenges of the Covid-19 pandemic which include requiring workers to wear face coverings, implementing social distancing guidelines, adopting COVID-19-related safety training, encouraging work-from-home initiatives, and establishing a task force with offering COVID-19-related guidelines, proactive steps to reduce the risk of delays. These findings are expected to guide the construction industry to navigate through the COVID-19 pandemic and future pandemics of similar natures.

Chapter 3: Severe Construction Injuries among Construction Workers

This study contributed to the construction safety literature as the first formal investigation of severe construction workplace incidents. Before OSHA responded to the high prevalence of severe workplace injuries by mandating that these incidents be reported separately since 2015, it was challenging to compile and isolate severe cases from other injury types. Consequently, the pattern of severe construction-related injuries has been a persistent gap in the body of knowledge. This study filled this gap in the construction safety literature and provided the following key research contributions:

- The construction industry is ranked second as the most dangerous workplace to sustain severe/serious injuries closely after the manufacturing industry;
- Severe construction injuries follow a seasonal pattern where a high frequency of severe incidents occurs during the summer months. Thus, national interventions should be planned proactively to mitigate such patterns before and during summer months;
- The findings suggested that several attribute categories are more prominent than others. Such results indicate that construction severe incidents follow an expected trend;
- The study revealed the "Severe Three," which represents the most prominent severe injury events: (1) falls to lower level, (2) struck-by object or equipment, and (3) caught in or compressed by equipment or objects;
- The study's results suggested that attributes are dependent, and thus there is a pattern to the occurrence of severe construction incidents. Additionally, the study presented the frequency and residual tables that construction managers and safety professionals can utilize in conducting severe risk assessment activities.

Chapter 4: Work-related Safety incidents among Driver License Examiners

Driver license examiners experience a large number of safety challenges while administering driving tests. Unfortunately, there is a dearth of research that focuses on this community of workers. To fill such gap in the occupational safety body of knowledge, this research effort represents the first formal investigation of incident reports that involve driver license examiners. The findings of this study offer an in-depth understanding of these safety challenges by unveiling the characteristics of these incidents through content and statistical analyses of incident reports. Apart from revealing that a large number of incidents are experienced during driving tests, the investigation unveiled the most common event types, contributing factors, injured body parts, injury types, and injury outcomes. The study also identified high-priority incidents that need to be addressed including collision with fixed objects, overexertion and physical bodily reaction, collision with another vehicle, and fall on the same level. The study also discovered relationships between event type and injured body part attributes. The study's findings are expected to serve as the foundation for future research efforts that seek to protect driver license examiners and the public.

Chapter 5: Assessing the Impact of Regulatory Changes on Capital Projects in the United States

Regulations, regulatory changes, and uncertainty can have profound effects on capital facilities during all phases of a project's life cycle. However, no study has comprehensively assessed such impacts on capital facilities. This study filled knowledge gap in the literature and examined how these regulations and regulatory changes are affected these critical facilities. Key findings from the study include:

- Nearly 75% of the survey responders agreed that it has become more difficult to anticipate and adapt to regulatory changes over the last fifteen years;
- The highest three reasons for facing difficulties to anticipated and adapt to regulatory changes are the following, ordered by highest frequency:
    - The regulatory outcomes are less predictable;
    - The pace of regulatory changes has increased;
    - The volume of regulatory changes has increased.

- The increased uncertainty in the project planning process is the most frequently reported net impact of regulatory changes on organizations.
- Increased design and construction costs were the highest resulting effects of regulatory changes and it was selected by nearly half of the responders. The second-highest effect was uncertainty-induced delays in project development processes at critical decision points;
- The most frequently selected root cause of disruptions was due to the uncertainty being too great to make an informed decision;
- Environmental Protection Regulations are the most impactive of regulations category followed by Workplace Safety:
    - Regulations at the Federal level are the most severe level of regulations;
    - EPA was the most frequently selected agency that gave organizations the most challenges.

Chapter 6: Assessing Utilities-Related Claims on Transportation Projects

Utilities interact with public transportation infrastructure projects and cause substantial amounts of disruptions. Consequently, transportation agencies continue to suffer from utility-related claims resulting in time and cost overruns. However, no study has comprehensively assessed the impact of these utility-related claims. This study filled this gap in the literature and made the following contributions to the body of knowledge:

- A utility-related claim would most likely result in a time extension;
- A utility-related claim is expected to delay project completion time by nearly 70 days on average;
- A utility cost claim was determined to increase the project's cost by 2.4% of the bid amount, on average;

- Water-related subsurface utilities are the most frequent utility type to conflict with transportation construction projects;
- Urban projects are more vulnerable to be interrupted by utility claims compared to other types (e.g., bridge and rural);
- Utility-related claims follow distinct and repeated patterns. This study classified scenarios leading to utility-related claims into: (1) expected, (2) no physical conflict, and (3) unforeseen;
- The obtained lessons learned to manage utilities on transportation projects highlighted the importance of proactively coordinating and communicating with utility owners early to relocate the utilities and identify the utilities' locations effectively.

Findings from this study are anticipated to benefit transportation agencies that struggle with managing utilities on their construction projects. Additionally, the study is expected to inform innovative best management practices that aim to eliminate the interruptions of utilities on transportation construction projects.

7.3. Future Research Directions

The performed scholarly work in this dissertation opens several opportunities for researchers and industry practitioners to conduct future studies in the areas of regulations, regulatory changes, and compliance; occupational safety and health; infrastructure management; construction safety; and disaster management. Future efforts are driven by the realization that the industry has not yet achieved optimal levels of efficiency, safety performance, and sustainability.

In relation to the second chapter, future studies should investigate applying new technologies as mitigations strategies to prevent the spread of COVID-19 and other airborne diseases. For example, a study should evaluate utilizing computer vision and deep learning approaches in ensuring the compliance of social distance requirements. It would also be beneficial to assess using Bluetooth technologies and computer vision to trace positive cases on construction sites. Furthermore, It would be worthwhile investigating the impact of the new COVID-19 variants on the construction both nationally and internationally. Lastly, further work will be needed to compile lessons learned and best practices to prepare the construction industry for future pandemics and disasters.

As for the third chapter, future research efforts are encouraged to periodically analyze the severe injury database as construction methods are constantly evolving and projects are becoming more complex. Additionally, safety researchers should put more emphasis on developing and designing interventions that are focused on reducing severe construction injuries. One approach would be to train workers to identify the workplace hazards that can lead to severe injuries and then eliminate, manage, or protect the workers from exposure to these hazards. Future efforts should also investigate the time-series pattern for each state individually in order to introduce campaigns that target reducing the rate of severe injuries. Given that one of the study's significant findings is that severe construction incidents follow repeated scenarios, a future study could leverage natural language processing techniques in automating classifying and coding the incidents' reports. However, since utilizing natural language processing techniques heavily relies on large amounts of data and adequate narratives describing how the incident occurred, such research efforts are expected to be fruitful once the severe injury database grows substantially.

In relation to the fourth chapter, future investigations should focus on identifying interventions that span across different levels, both upstream and downstream, using the holistic systems thinking approach. The efficacy of these interventions in reducing the experienced incidents by driver license examiners should be tested before potential implementations.

Additionally, given the global prevalence of driver license tests, future efforts may also replicate the research efforts in chapter four with other databases maintained by DMVs and transportation agencies within and beyond the United States. Such efforts will be valuable in assessing the generalizability of the current findings and can potentially generate complementary insights. It is also recommended that these follow-up efforts, when relevant, adopt a confirmatory approach as opposed to the exploratory nature of the present investigation along with predefined hypotheses. Such follow-up efforts will be valuable in assessing the robustness of the findings and protecting the global driver license examiner workforce.

In regard to the fifth chapter, future investigations should assess the impact of regulations and regulatory changes on medium and smaller-size projects. Such investigations are crucial because the reported study in chapter five primarily involved large organizations with more than 10,000 employees that construct and operate capital facilities. Thus, the reported study findings might not be extended or relevant to smaller and medium organizations. Additionally, it would be valuable to understand the causes of regulatory disruptions and how compliance can be achieved for various-sized projects. Future studies are also encouraged to leverage natural language processing to obtain and list the regulations from the contract documents. After that, it would be beneficial to automate the complying checking process of the regulations and regulatory changes.

As for the sixth chapter, further work should investigate the impact of utility-related claims on different state transportation agencies. Such investigations would reveal the patterns in which utility-related claims occur in different states. Consequently, tailored mitigation strategies can be introduced both broadly and for a specific transportation department. As for the limited amount of information provided in the claim's narrative, contractors and state transportation departments are encouraged to adequately document the reasons for the claims, the affected activities, utility type, and location. Also, a field should exist in the claim to allow the claim submitter to provide potential mitigation strategies to mitigate similar claims that might be submitted on the same project or future projects. Furthermore, future studies should systematically investigate both downstream and upstream factors that cause utility-related claims. Such research efforts would guide exploring the optimal solutions to reduce and eliminate utility-related issues on transportation infrastructure projects. Lastly, qualitatively coding construction claims is labor expensive and time demanding; therefore, it will be valuable for transportation agencies to investigate machine learning approaches in automating the coding process. Automating the process would allow the decision-makers to execute data-driven decisions that would likely reduce the frequency and severity of construction claims.

In conclusion, it is generally recommended to present the findings from analyzing data dynamically instead of statically. One advantage of utilizing a dynamic approach is automating the analysis and presentation process as new data emerge without redoing the analysis. Such dynamic tools would allow decision-makers to access recently updated analyses without recreating the figures and tables. One tool that recently received much attention from academics and practitioners across different fields is the Shiny application (Chang et al. 2021), which operates on the R programming language (R Core Team 2020). To this end, the *safety incidents prediction tool* was created for the obtained data in chapter four to pilot the dynamic data analysis concept. The *safety incidents prediction tool* can be used to rank and predict the likelihood for each attribute category. The tool can be utilized by driver license examiners while preparing for driver license tests and in adopting active safety measures that would potentially reduce the risk of workplace injuries. The *safety incidents prediction tool* can be accessed at:

https://afalshar.shinyapps.io/DMV_Tool/. Two snapshots of the outputs from the *safety incidents prediction tool* are presented in Figure 7-1.

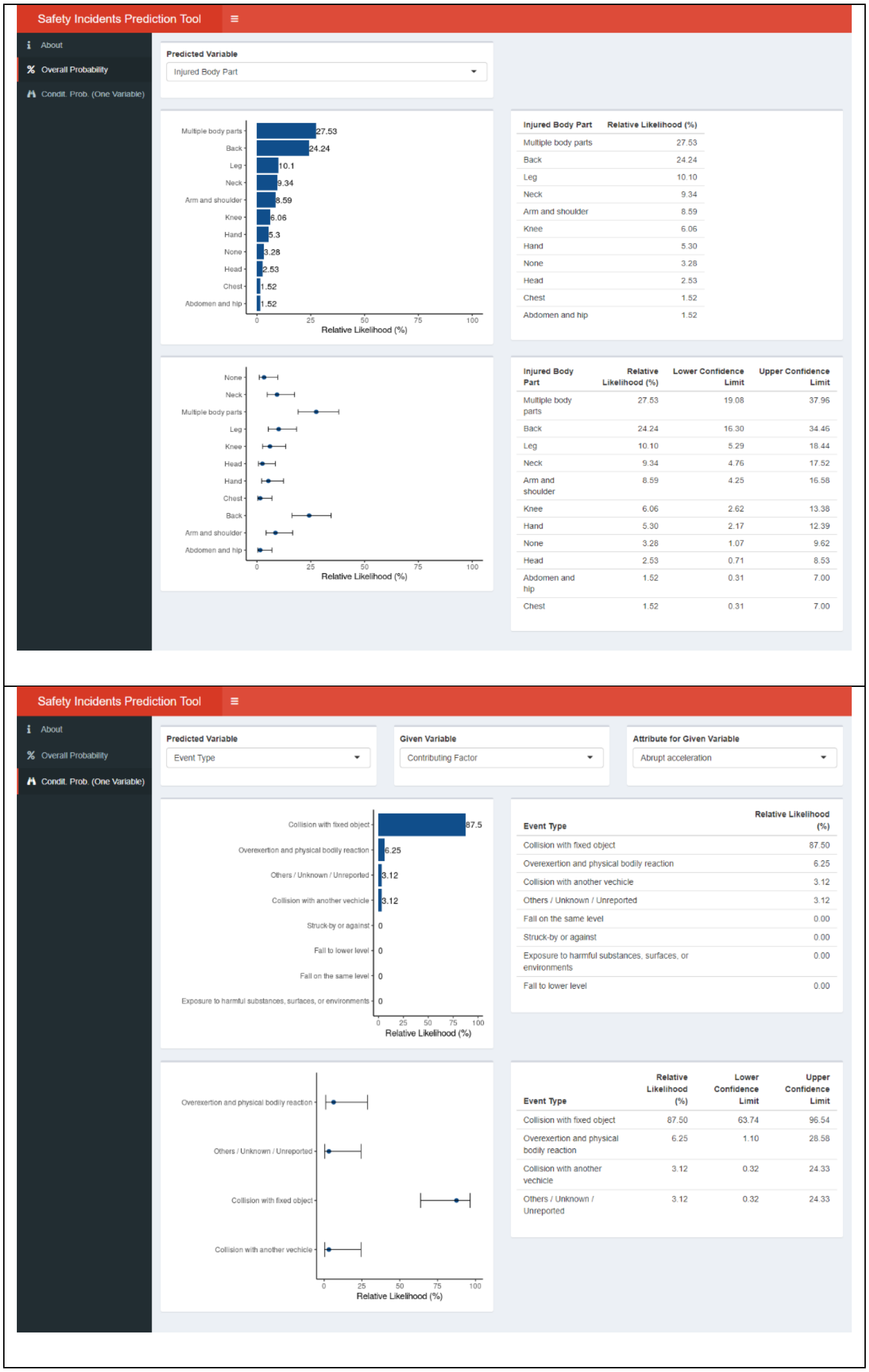

Figure 7-1: Two Snapshots of the Outputs from the *safety incidents prediction tool*

7.4. References

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