Spring 1-1-2016

# Using Precursor Analysis to Predict and Prevent Fatal and Disabling Injury in Construction

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USING PRECURSOR ANALYSIS TO PREDICT AND PREVENT FATAL AND DISABLING INJURY IN CONSTRUCTION

By

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B.S., University of Colorado Boulder, 2014

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

Of the requirements for the degree of

Master of Science

Department of Civil, Environmental, and Architectural Engineering

2016

This thesis entitled:
Using Precursor Analysis to Predict and Prevent Fatal and Disabling Injury in Construction
Written by Dillon Charles Alexander
Has been approved for the Department of Civil, Environmental, and Architectural Engineering

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Alexander, Dillon Charles (M.S., Civil Engineering)

Using Precursor Analysis to Predict and Prevent Fatal and Disabling Injury in Construction

Thesis directed by Professor Matthew Hallowell

Construction fatalities continue to plague the industry. In order to prevent fatalities, new methods of evaluating work conditions and making predictions are needed. Assorted industries and organizations, such as nuclear energy, NASA, chemical manufacturing, and commercial airlines have used precursor analysis to predict and prevent catastrophic events. Through a series of three papers, the presented thesis aims to adapt the fundamental processes of precursor analysis to the construction arena in an effort to predict and prevent future fatality and disabling injury.

First, a comprehensive catalog of 43 potential precursors was established by triangulating results from a literature review; deterministic event analysis of 21 fatalities; and brainstorming sessions with construction safety, law, regulation, and psychology experts. The 43 potential precursors were then translated into a precursor data collection protocol. The protocol involved questions and field observations to assess the presence or absence of each precursor *before* an event occurs. The protocol was applied to collect data for 19 new cases, which included (1) events where high-energy work was successfully completed without incident; (2) near misses where high-energy was released but no one was harmed; and (3) fatal or disabling injury events. Using these cases, a controlled experiment was conducted where a group of 12 experts were asked to predict each case outcome using only the leading information collected via the protocol and their judgment. Later, the same experiment was conducted with moderately experienced professionals and students for validation and to test generalizability. A permutation test of the predictions indicate that people of all levels are able to distinguish between success and failure far better than random using only leading information.

Next, the following hypothesis was tested: the probability of fatal and disabling events can be predicted by a small number of precursors that can be identified prior to an incident. Testing this hypothesis involved obtaining case data using the precursor analysis protocol, performing principal component analysis to reduce the dimensions of the dataset, building a mathematical predictive model using generalized linear modeling, and testing the predictive validity of the model with independent validation cases. The results indicated that there are 16 principal precursors that, when organized into a generalized linear model, are able to predict the outcome of new cases far better than random ($p < 0.001$). With further validation and testing, this new methodology can serve as the foundation for the first objective and valid precursor analysis program for construction.

Lastly, there was a need to determine when the created precursor analysis process should be implemented. Precursor analysis requires dedicated time and resource and therefore should only be used on those work situations that have potential to cause fatal and disabling injury. To do this, the hypothesis that the quantity and intensity of energy observable prior to an incident predicts variability in the severity of the incident was tested. The hypothesis is built upon the theory that energy is translated to an injury through uncontrolled release of the energy, transfer of the energy to the human body, and the vulnerability of the body and associated protective equipment. To test the hypothesis, a multi-phase experiment was conducted. First, over 500 injury reports were gathered from national databases and private companies for fall and struck-by injuries involving either potential or kinetic energy. For each report, the leading information describing the work operations and environment and the lagging information describing the injury were extracted, separated, and isolated. Second, the magnitude of the energy was estimated by a group of engineers who were only given leading information. Once energy magnitude was quantified, the distribution of energy magnitude was compared across injury severity levels using analysis of variance tests. Significant differences across severity levels was revealed and, as a result, hazard energy thresholds were tentatively established to guide users as to when precursor analysis should be performed for future work scenarios.

## ACKNOWLEDGEMENTS

This research project would not have been possible without the help and support of several key contributors whom played vital roles in the success of the project. First, I would like to thank the Construction Industry Institute (CII) who recognizes the need for improvement in preventing devastating fatal and disabling injury within the construction industry by providing the funding for this project. Furthermore, I would like to thank the 12 members apart of the CII research team, 321, who showed unwavering passion and dedication in advancing the construction safety profession and acted as the metaphorical heart and soul to this research.

I would also like to thanks the graduate students at the University of Colorado, graduate students University of Oregon State, and members of the Colorado Associated General Contractors who voluntarily participated in the relatively time consuming validation experiment. Each group's participation provided important feedback data regarding the effectiveness of the developed precursor process. In particular, I would like to thank Siddarth Bhandari and Dylan Hardison of the University of Colorado for their willingness to help at certain stages of the research project.

Lastly, I want to thank the professors acting as my Master's Defense committee: Professor Paul Goodrum, Professor John Gambetese, and Professor Matthew Hallowell. Aside from participating in my committee, these individuals were always genuinely kind to me and willing to provide guidance on a moment notice. In particular, I want to thank my advisor and friend, Professor Matthew Hallowell, who originally inspired me to pursue my Master's Degree as I originally had no intention of such an undertaking during my undergraduate studies. Prof. Hallowell continually

pushed me to reach my full potential and, in doing so, instilled a confidence to succeed within my future career that I had not had prior. Reflecting upon the past two years, meeting Hallowell and pursuing my Master's Degree in Civil Engineering has been a pivotal turning point in my life, and I am forever grateful to Prof. Hallowell for providing the opportunity.

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# CHAPTER 1: INTRODUCTION

## OBSERVED PROBLEM

In 2015 the United States Bureau of Labor Statistics (BLS) released the 2013 census data for work-related fatalities, injuries, and illnesses (BLS 2015). Construction recorded the highest number of fatalities of any industry, with a total of 856. Tragically, this marks the highest number of fatalities in the construction industry since 2009 and, more importantly, highlights the growing concern that the fatality rate in construction has recently plateaued (see Figure 1). Coincidentally, researchers have expressed that traditional safety strategies have recently reached saturation and are ultimately limited in their effectiveness due to their reactive and regulatory nature (Esmaeili and Hallowell, 2012; Hallowell and Gambatese, 2007). As recent BLS data suggest, there is a need for new injury prevention methods that focus purely on the fatalities that continue to plague the industry. Deviating from the traditional safety methods and using leading information to predict and prevent catastrophic fatalities is a logical next step for the industry.

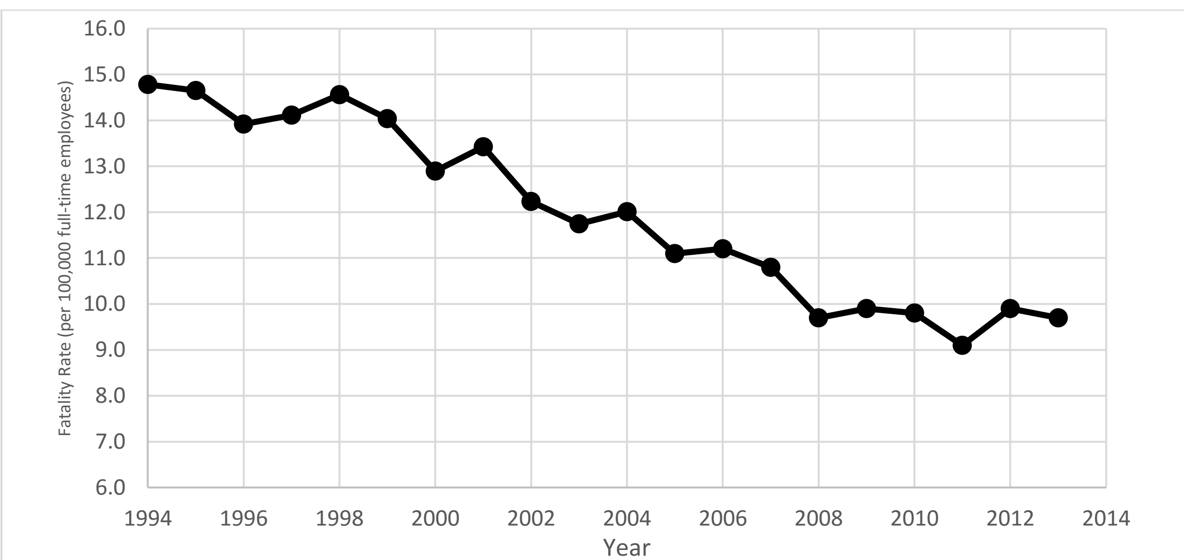


***Figure 1: Construction Fatality Rate per 100,000 equivalent full-time workers (Source: BLS 2015)***

One of the challenges of analyzing fatal and disabling injuries is that they (fortunately) occur infrequently in comparison to less severe events. The infrequent nature of fatal events make it especially difficult to identify latent factors and analyze causal trends. Researchers have expressed frustration in this regard, questioning why devastating fatal incidents continue to occur given the amount of investigation and analysis that has taken place and our current level of safety knowledge (Wu et al. 2010). Fortunately, other industries, whose existence relies on the successful management and prevention of infrequent and catastrophic events, have found a successful strategy to manage rare, high-impact events via precursor analysis.

Precursors, defined as *"the conditions, events, and sequences that precede and lead up to accidents,"* (National Academy of Engineering 2004), were first introduced following the *Three Mile Island* nuclear plant meltdown of 1979 (Minarick, 1990). Due to public outrage, *Three Mile Island* nearly eliminated the entire nuclear industry within the United States. It became clear to the Nuclear Regulatory Commission (NRC) that a subsequent incident could not occur and the Accident Sequence Precursor (ASP) program would be the NRC's solution. Other industries that must manage the risk of catastrophic events, such as the aviation industry, chemical manufacturing industry, and medical/prescription drug industry, and the National Aeronautical and Space Agency's (NASA) space program, have since followed the NRC's lead and created industry-specific precursor analysis programs (National Academy of Engineering, 2004). Although precursors from various industries may not be directly translatable to other industries, the precursor identification and analysis processes are fundamentally similar. In the presented thesis, the aim is to adapt the processes used in other industries to create the first precursor analysis process for the construction industry.

**THESIS FORMAT AND CONCEPTUAL OVERVIEW**

This thesis follows a three journal paper format in which each subsequent chapter aligns with an independent journal paper that have their own respective abstract, introduction, literature review, research methods, analysis, and conclusions. Although independent, the three journal papers constitute the findings of the two-year research project performed by the Construction Industry Institute research team 321. The ultimate goal of this project was to conduct rigorous scientific research that yielded a precursor analysis protocol for construction that enables practitioners to: (1) assess conditions in a leading fashion; (2) identify the presence of, and quantify, precursors in a structured and methodical fashion; and (3) predict and prevent the potential for fatal and disabling injury. In pursuit of this goal, the following essential questions were addressed by each respective journal paper where each paper sought to address subsequently presented limitations:

1) Are there precursors of fatal and disabling injuries in construction and, if so, can they be identified and used in a predictive fashion to prevent the occurrence of fatal and disabling injury?
2) If initial prediction is successful, is it possible to objectively utilize precursor information using statistical techniques to more reliably and efficiently predict fatal and disabling injury?
3) If precursor analysis proves to be a viable option in predicting and preventing fatal and disabling injury, when should the analysis procedure be implemented (i.e. when is there potential for a work situation to be fatal or disabling)?

The first and second journal paper are currently under review for the *Journal of Construction Engineering and Management* while the third paper is under review for the *Journal of Safety Science.*

Lastly, an Executive Summary will be provided in Chapter 5 of this thesis. This section will provide a concise recollection of all notable findings and implications of this research as well as an outline of the practical precursor analysis procedure derived from this research.

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# CHAPTER 2: PRECURSORS OF CONSTRUCTION FATALITIES: ITERATIVE EXPERIMENT TO TEST THE PREDICTIVE VALIDITY OF HUMAN JUDGMENT

## ABSTRACT

Construction fatalities continue to plague the industry. In order to prevent fatalities, new methods of evaluating work conditions and making predictions are needed. Assorted industries and organizations, such as nuclear energy, NASA, chemical manufacturing, and commercial airlines have used precursor analysis to predict and prevent catastrophic events. This paper presents the first steps toward a comprehensive precursor analysis process for the construction industry. First, a comprehensive catalog of 43 potential precursors was established by triangulating results from a literature review; deterministic event analysis of 21 fatalities; and brainstorming sessions with construction safety, law, regulation, and psychology experts. The 43 potential precursors were then translated into a precursor data collection protocol. The protocol involved questions and field observations to assess the presence or absence of each precursor *before* an event occurs. The protocol was applied to collect data for 19 new cases, which included (1) events where high-energy work was successfully completed without incident; (2) near misses where high-energy was released but no one was harmed; and (3) fatal or disabling injury events. Using these cases, a controlled experiment was conducted where a group of 12 experts were asked to predict each case outcome using only the leading information collected via the protocol and their judgment. Later, the same experiment was conducted with moderately experienced professionals and students for validation and to test generalizability. A permutation test of the predictions indicate that people of all levels are able to distinguish between success and failure far better than random using only leading information. Future research is proposed to reduce the scope of the protocol and to create objective methods of prediction using statistical tools, thereby making the precursor analysis process less resource intensive and more reliable.

## INTRODUCTION

In 2015 the United States Bureau of Labor Statistics (BLS) released the 2013 census data for work-related fatalities, injuries, and illnesses (BLS 2015). Construction recorded the highest number of fatalities of any industry, with a total of 856. Tragically, this marks the highest number of fatalities in the construction industry since 2009 and, more importantly, highlights the growing concern that the fatality rate in construction has recently plateaued.

One of the challenges of analyzing fatal and disabling injuries is that they (fortunately) occur infrequently in comparison to less severe events. The infrequent nature of fatal events makes it especially difficult to identify latent factors and analyze causal trends. Researchers have expressed frustration in this regard, questioning why devastating fatal incidents continue to occur in the construction industry given the amount of investigation and analysis that has taken place and our current level of safety knowledge (Wu et al. 2010). Fortunately, other industries that rely on the prevention of infrequent and catastrophic events have found a successful strategy to manage rare, high-impact events: precursor analysis.

Similar to the National Academy of Engineering (2004), we define a precursor as a *reasonably detectable event, condition, or action that serves as warning signs to a fatal or disabling injury.* Precursor analysis was first introduced following the Three Mile Island nuclear plant meltdown of 1979 (Minarick, 1990). Other industries such as aviation, chemical manufacturing, and pharmaceuticals, and the National Aeronautical and Space Agency's (NASA) space program have all since created specific precursor analysis programs (National Academy of Engineering, 2004). Although precursors from some industries may not be directly translatable to other industries, the precursor identification and analysis processes are fundamentally similar.

Our goal in the present study was to create an empirically validated precursor analysis method for high-impact construction events (i.e., fatalities and disabling injuries). In pursuit of this goal, we established the following objectives:

1. Identify and document causal factors of construction fatalities;
2. Translate the list of factors into a series of leading questions that can be asked in the field;
3. Apply the precursor questionnaire to collect responses for cases of successful work (no incident) and failed work (fatality, injury, or near miss);
4. Conduct a controlled experiment to measure the extent to which the data collected via the protocol and judgment can be used together in a leading and predictive fashion to distinguish between success and failure; and
5. Measure the generalizability of the method by repeating the experiment with multiple groups with varying degrees of industry experience.

This research is a step toward the long-term goal of creating a precursor analysis method that can be reasonably applied in a leading fashion to identify anomalous work situations that have extraordinary potential for a fatal event.

## BACKGROUND

The purpose of this background section is to describe the precursor analysis process implemented by industries that have developed and maintained successful programs and to describe the state of precursor analysis in construction. We relied heavily on reports published for NASA's Accident Precursor Analysis (APA) program, the aviation industry's Aviation Safety Action Program (ASAP), and the nuclear industry's accident sequence precursors (ASP) program. We also provide a targeted review of academic literature that highlights the causes of construction fatalities (see Table 1).

## Precursor analysis programs in other industries

Each industry exhibits a distinctive set of precursors that emanate from the unique tasks, environments, and risks present in the industry. For example, reflecting the complexity of the nuclear energy production and distribution system, the ASP program includes 422 individual precursors that relate to nuclear core damage (Minarick, 1990). Although NASA must also manage a complex system, their precursors are very different and focus on the malfunction of system components (NASA/Sp-2011-3423, 2011). Further, aviation precursors relate more to human error, noncompliance, high tolerance of risk, lack of hazard recognition, inadequate management procedures, and lack of competence (Wiegmann and Shappell, 2001). Despite the differences in precursors among industries, the method of creating each program was surprisingly similar. The creation process can be sequenced into four fundamental steps: (1) conducting an in-depth deterministic analysis of past incidents to identify potential precursors; (2) building a system for incident investigation with focus on suspected precursors; (3) conducting a probabilistic risk assessment (PRA) for continuously updated datasets; and (4) building an information feedback loop for continuous improvement. Although the aviation, transportation, medical, chemical manufacturing, and space exploration industries have all modified the original ASP program to their specific needs, the four fundamental steps for building a precursor analysis program remained consistent.

### *Component 1: Identify precursors from past events using deterministic event analysis*

The creation of a precursor analysis system begins by leveraging historical information from events to identify potential precursors of future events. To achieve this, both NASA and the nuclear industry incorporated deterministic event analysis of past incidents. Deterministic event analysis is the process of identifying causal factors and emerging trends by examining the circumstances of past events (ETSON 2013). To begin, root cause analysis is applied to identify precursors by analyzing the type of human error involved, whether the procedure was adequate or followed correctly, characteristics of the working environment, the qualifications of those involved, and the presence or absence of organizational barriers

(IAEA, 2004). Then, Reason's (1990) *Swiss Cheese* model is typically used to organize and layer the precursors into an investigation protocol. Once candidate precursors are identified and prioritized, industries begin to formally collect and analyze a large volume of targeted precursor data to uncover patterns and latent causes.

***Component 2: Incident investigation with specific information criteria***

Detailed data drive all successful precursor programs. When collecting data required for precursor analysis, successful industries have established comprehensive incident investigation protocols that create homogeneity and ensure standard quality of the data. For instance, the ASP program relies on analyzing reports of undesired events, which include key criteria such as the description of the complete event, the event sequence, a determination of deviations from standard protocol, root cause analysis, actual or potential consequences, and future corrective actions (ETSON, 2013; IAEA, 2004). All nuclear power plants participate in the ASP program and event reports are submitted to the regulatory body for further review in a standardized format (IAEA, 2004). Only events with severe or potentially severe consequences are considered for further analysis (Johnson and Rasmuson, 1996). NASA's APA program also includes an investigation system that uses reports for all anomalous events. These reports must follow established information criteria when submitted to the NASA database and are subsequently evaluated by the APA committee if anomalous events are deemed to have potentially severe consequences (NASA/Sp-2011-3423, 2011). Similarly, the aviation industry has developed and implemented a standardized but voluntary program for the submission of incidents (DOT FAA/AFS-230, 2002; DOT FAA/AFS-800, 2006).

It is important to note that, because catastrophic events are rare, analyzing only high impact cases would not yield a sufficient dataset for any pattern recognition or advanced diagnostic statistics. To address this barrier, operational data from potentially severe incidents (i.e., potentially high-impact "near misses" or "close calls") are typically leveraged to develop a sufficient quantity of data for analysis (McFadden and

Towell 1999). Here, our position is that successful cases are also needed in order to adequately identify conditions that distinguish success from failure.

***Component 3: Precursor data analysis and modeling***

To complement deterministic event analysis and large-volume data collection, industries have used diagnostic and predictive statistics to measure the significance of each precursor. Such data also provide further insight regarding latent patterns. In order to make probabilistic approaches a legitimate option, a large, homogeneous data set is required. As precursor programs mature and more precursor data are obtained, the use of probabilistic modeling techniques becomes a viable option (IAEA, 2004).

The primary advantage of probabilistic risk analysis is that it allows for personnel to quantitatively and objectively prioritize safety concerns. For instance, the US Nuclear Regulatory Commission (NRC) has established a threshold that a safety event can only be considered a precursor if the probability of core reactor damage is greater than one in a million (IAEA, 2004; Johnson and Rasmuson, 1996). With such a threshold, in the twenty years following the establishment of the ASP program, 422 precursors have been identified and recorded (Minarick, 1990). In contrast, British Airways used data reduction techniques and probabilistic risk analysis performed by Stephans and Talso (1997) to empirically establish the *Rule of 3*, which triggers a warning if three or more precursors are present for any given flight.

***Component 4: Precursor alert systems and continuous improvement***

After precursors have been identified, programs have been established to facilitate the collection of large volumes of reliable data, and advanced statistics have been used to make valid predictions, the precursor analysis system must alert the workforce when danger is detected. An effective alert system must include surveillance and quick notification of work teams when precursors are identified and conditions are ripe for a high-impact event. The ASAP, for example, mandates corrective actions to prevent precursor occurrence, which is enforced by the Federal Aviation Administration for all program members (DOT FAA/AFS-230, 2002). Similarly, the NRC ensures compliance with new regulations as precursors are uncovered (Johnson and Rasmuson, 1996) and surveillance systems are used to alert workers of precursors that could lead to reactor core damage (IAEA, 2004). NASA and the medical industry also heavily rely on surveillance alarm systems to alert workers of potential events (Bates et al., 1999; NASA/Sp-2011-3423, 2011). The primary advantage of surveillance systems is they can be built into work-flow processes very easily such as the Computerized Physician Order Entry (CPOE) system used for ordering prescription drugs in hospitals (National Academy of Engineering, 2004).

In addition to an alert system, the precursor analysis program must be built such that it can be continuously improved. Specifically, as more data become available and new factors are identified, data collection tools and predictive models must be updated. Continuous improvement is especially important in prediction because initial models typically have low skill but have the potential to improve greatly as models are tested and databases grow in quantity and improve in quality (Minarick, 1990; NASA/Sp-2011-3423, 2011). In order to create an analysis program that is fluid, a feedback loop must be established. An effective feedback system typically involves a reporting system that is regularly updated as new information is discovered or as characteristics of the work change (ETSON, 2013; McFadden and Towell, 1999; NASA/Sp-2011-3423, 2011). The industry must be committed to updating predictive models, which is not a time-consuming task, but requires knowledge in advanced statistics. The industry must also pay close attention to patterns in prediction error and seek to learn from the cause of errors.

## Precursor analysis in construction

Precursor analysis for construction safety is a relatively new field of inquiry. Inspired by the nuclear industry's ASP program, Wu et al. (2010) developed a conceptual precursor model to analyze historical data to predict potential accident scenarios. Building upon the work of Cambraia et al. (2010), the Wu, et al. (2010) model closely follows Heinrich's (1931) Safety Pyramid theory by describing near-miss incidents as the base of the pyramid with predictive validity for high-impact events. In their theory, preventing near misses is a pre-requisite to preventing high-impact events. Wu et al. (2010) use Reason's (1990) *Swiss Cheese* accident causation model and Gibb et al.'s, (2006) causation model as frameworks to classify potential precursors as either immediate, shaping, or originating factors depending on their proximity to the event. Wu et al. (2010) then defined a list of precursors specifically for scaffolding operations such as failing to wear fall protection and missing scaffolding boards. The precursors include immediate, and sometimes latent, conditions related to scaffolding work.

The research in precursor analysis for construction safety has yet to reach maturity as there is not a codified list of causal factors based on comprehensive deterministic event analysis, predictive models have yet to be created or validated, and no alert and continuous improvement systems have been established. Wu, et al., (2010) has presented a conceptual plan to implement precursor analysis in construction that shares similarities to the suggested approach presented in this study. However, the plan remains theoretical without confirmation or robust empirical validation.

## RESEACH METHODS

The goal of this research was to create and validate a method for predicting the potential for construction worker fatalities through a formal precursor analysis. In other words, we aimed to create a structured method for distinguishing conditions that would likely lead to success (no event) from those that indicate potential failure (near miss, injury, or fatality). Since this was the first attempt at a data-driven method for precursor analysis, our research required a sequence of steps across two main phases. As shown in Figure 2, in the first phase we aimed to create a comprehensive catalog of potential precursors by triangulating results from a variety of sources. Although there are many studies of causal factors of construction fatalities, the potential precursors are highly dispersed in the literature. Once a catalog was established, each potential precursor was converted into a question to ask project personnel. Then, the protocol was used to collect cases of successful work, near misses, and high-impact events (fatal or disabling injuries). Once cases were collected, a series of iterative experiments were conducted to measure the extent to which individuals could use the precursor protocol and their judgment to distinguish between success and failure. It is important to note that we focused on using human judgment to make assessments because we did not yet have access to the volume of data needed to make objective predictions.

This project was completed by a Construction Industry Institute research team. The team included 14 industry experts and two academic researchers. The industry professionals represented both client and contractor organizations, all of which have sophisticated safety programs. The expertise of the research team was an important asset to enhance the validity, reliability, and practicality of the work. The expert team averaged 22 years of experience in construction safety; 10 team members possessed bachelor degrees in construction safety or related field; and four individuals had received master's degrees specifically in construction or occupational safety. Furthermore, every team member had earned at least two professional certifications related to construction safety. Unless otherwise specified, this expert team executed the steps of the research process described below. In general, input from the 12 subject matter experts was used when expertise was needed from the safety domain and the academic researchers managed the research process without inserting their own judgments.

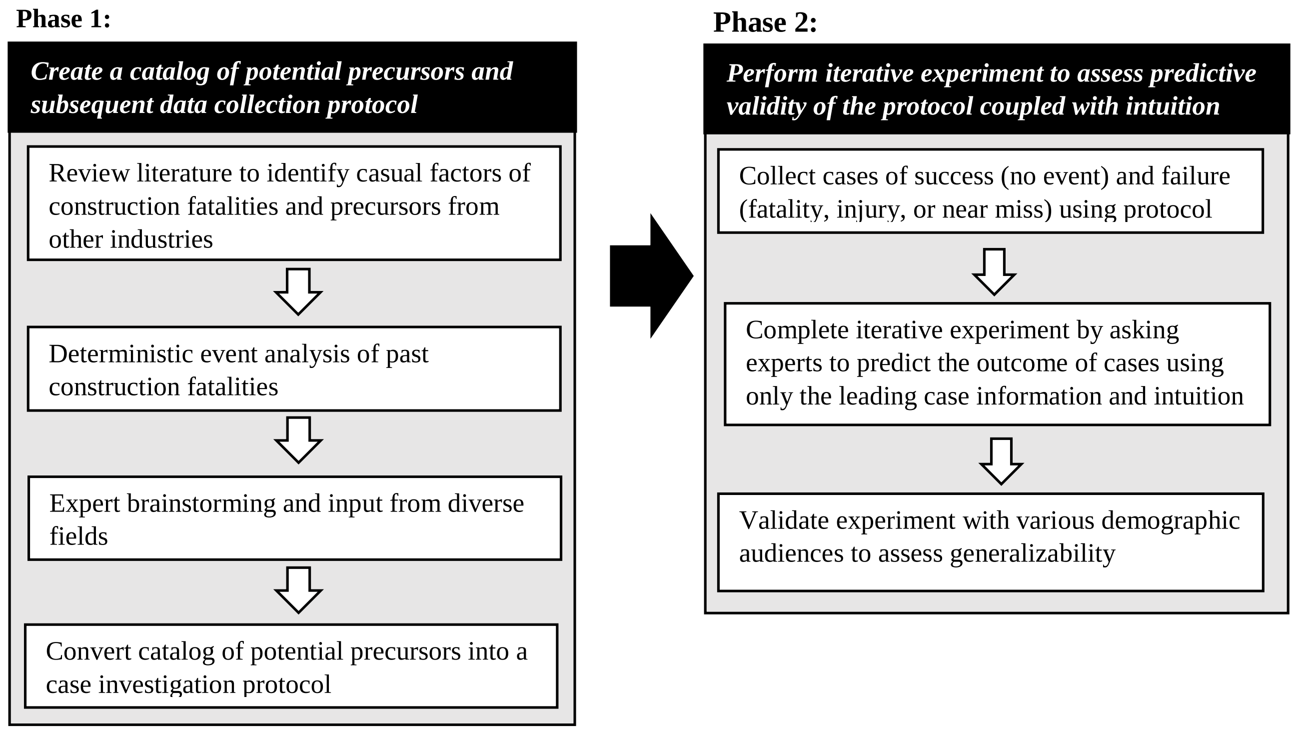


***Figure 2: Research progression and overarching methods***

**Phase 1: Create complete catalog of potential precursors and subsequent data collection protocol**

Precursor programs must begin with an in-depth deterministic analysis of historical data to establish an initial set of potential precursors that can be subsequently collected and analyzed (IAEA, 2004; NASA/Sp-2011-3423, 2011; Wiegmann et al., 2005; Wu et al., 2010). To create the most comprehensive catalog of potential precursors we followed a multi-step process that began with a detailed review of literature.

***Step 1: Leverage existing knowledge***

The goal of step 1 was to leverage existing knowledge to establish an overarching framework for precursor analysis. To accomplish this goal, we reviewed all available literature pertaining to precursor analysis, focusing primarily on the most successful precursor programs in other industries (e.g., ASP and APA programs). Each of the aforementioned industries has publically available handbooks that provide detailed information about their respective programs (DOT FAA AFS-230, 2002; IAEA, 2004; NASA/Sp-2011-

3423, 2011; Wiegmann and Shappell, 2001). In addition to the available industry handbooks, we conducted a comprehensive review of academic literature to catalog identified causes of construction fatalities. The literature related to construction fatalities was highly dispersed since factors were identified in over 30 studies. To show connection between identified precursors, references are provided in Table 1. For brevity, we do not provide a comprehensive discussion of this literature base.

### *Step 2: Deterministic event analysis*

Much like deterministic analysis techniques performed for other industries (IAEA, 2004; Wiegmann and Shappell, 2001), our method consisted of first uncovering the immediate causes of an injury or fatality (e.g., worker unaware of safe work procedure). Then, the subject matter experts elucidated reasons why the immediate conditions existed as a method to uncover possible latent causes (e.g., lack of training specific to work, inexperience, etc.).

To perform deterministic event analysis, the subject matter experts were divided into three size sub-groups of approximately equal number. Each sub-group was asked to analyze a series of National Institute of Occupational Safety and Health (NIOSH) Fatality Assessment and Control Evaluation (FACE) reports. The NIOSH FACE reports are detailed written accounts of a construction fatality. The review process began by asking each team member to individually review a FACE report and make an individual assessment of casual factors. Following individual assessments, each sub-group spent approximately two hours discussing the case via teleconference. As obsvered by ETSON (2013), this two-step process ultimately yielded the immediate causes, root causes, and causal factors of each incident.

The detailed fatality reports were analyzed with the following distribution of hazard energy sources: gravity (n=8), motion and mechanical (n=8), and electrical and pressure (n=8). We ended the deterministic event analysis after 24 reports because no new factors were identified in the seventh round of reviews (i.e., 21$^{st}$

report). At that point replication had been achieved; however, a final round of reviews was performed to ensure validity. In total, the deterministic analysis revealed 33 causal factors as listed in Table 1.

A notable limitation of this phase was that NIOSH FACE reports tend to be biased in numbers toward fatalities that occurred to Hispanic workers and young workers. Thus, the distribution of precursors identified were biased toward those related to experience, training, cultural, and language issues. Although the reports were biased toward these cases, the goal of the deterministic event analysis was to catalog as many causes as possible. Thus, the distribution was not a significant limiting factor for the ultimate validity and reliability of our results.

***Step 3: Identifying latent precursors through group brainstorming***

One of the team's concerns with identifying precursors from literature review and deterministic event analysis alone was that some precursors would remain latent because they had not been documented by a NIOSH investigator or past researchers. Thus, the team used its collective 311 years of experience to brainstorm and document other precursors that they had witnessed. The group brainstorming took place in the first day of a two-day face-to-face meeting. In this meeting, the results from the literature review and deterministic event analysis were presented first and new, previously unidentified precursors were identified and discussed.

Because the team was comprised of construction safety professionals from clients and contractors, we aimed to involve experts from other fields to broaden our scope. A one-day meeting was held between the research team and the following five external experts: attorney, risk consultant, OSHA inspector, applied psychologist, and human factors engineer. The experience of each consulted individuals ranged from 10 to 35 years in their respective profession. In total, 11 new causal factors were identified during this brainstorming session.

### *Step 4: Convert list of potential precursors into a precursor investigation protocol*

A very important characteristic of a precursor analysis process is that it is leading in nature rather than retrospective. The previous research steps were all retrospective in that they focused on accounts of past injuries or emanated from past experiences. Thus, we needed to convert the list of causal factors into a series of questions that could be asked or observations that could be made *prior* to an injury. For example, if *overtime* was listed as a factor, the factor could be converted to a simple question of *how many hours have you been working this week?* This transformation from retrospective factors to leading questions and observations yielded the precursor analysis investigation protocol. The precursor analysis protocol served two purposes: (1) to provide a uniform format to collect data for cases that would be used in the subsequent experiment, and (2) to act as a template for future data collection efforts. The protocol was deliberately crafted by the research team to be simple, direct, and invoke open-ended responses from the client, project management, and workers. To ensure that the protocol was exhaustive and internally valid, redundant questions and observations were built so that each of the 43 casual factors was specifically targeted at least twice. The key feature of this protocol was that all of the questions and observations could be made prior to an incident and, ideally, before a work period even begins.

## Phase 2: Perform iterative experiment to assess initial predictive potential of identified casual factors

The ideal method of validating precursors would be to observe construction work in real-time, measure the presence of casual factors, make a prediction, and observe whether the work resulted in serious injury. However, such a method would be both unrealistic and unethical. Therefore, in order to balance practicality and scientific precision, a structured experimental procedure was designed that would allow the outcome of past work situations to be used for assessment. The experimental procedure, outlined in Figure 3, involved an iterative process where the predictive skill of the research team was assessed. We elaborate on each of these experimental steps below.

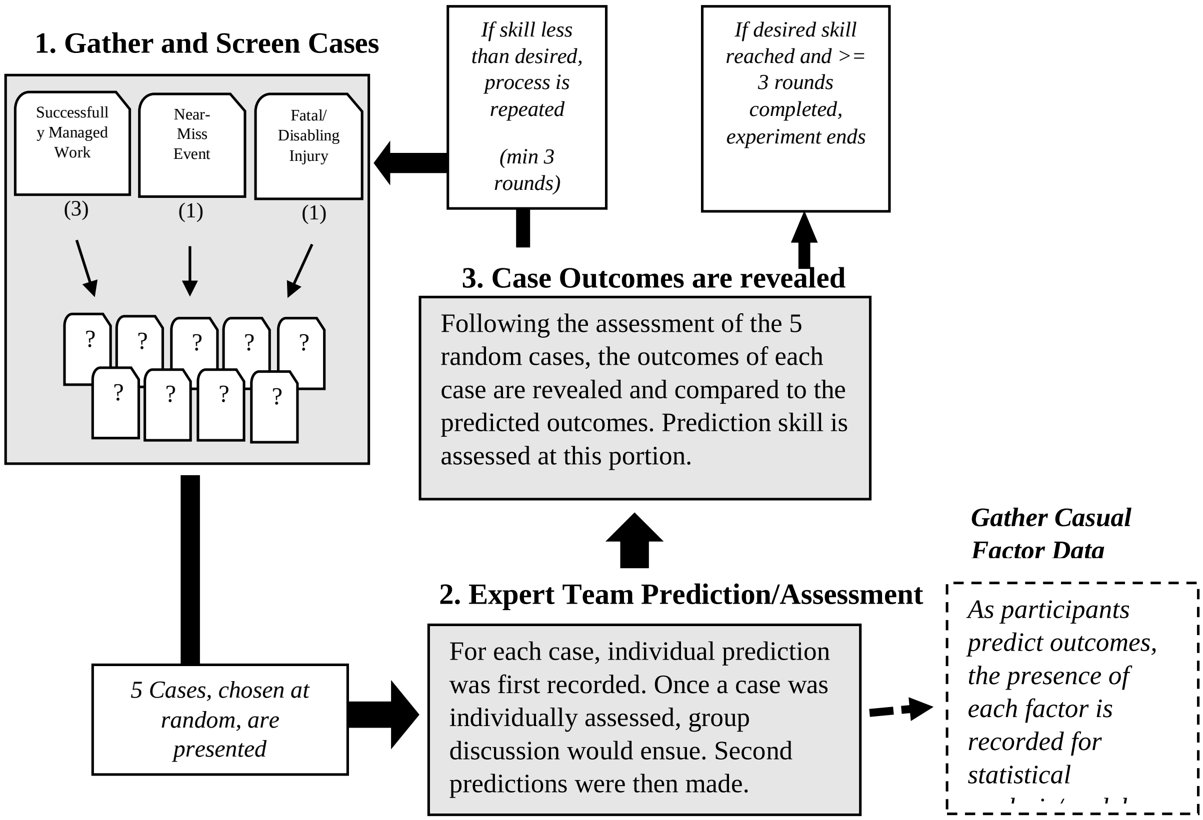


***Figure 3: Experimental procedure to test predictive validity of potential precursors***

***Step 1: Gather and Screen Work Scenario Cases***

Phase 1 of this research process yielded a protocol for collecting leading information for a particular work period. Phase 2 began by applying this protocol to collect data for actual work scenarios. Here, the term data refers to the complete answers for all questions and observations in the protocol for a particular work operation. We referred to a complete protocol as a "case." Each case was associated with one of the three following outcomes:

1) ***Fatal/Disabling Injury:*** the work scenarios resulted in an unwanted release of hazard energy that caused someone to suffer a fatal or disabling injury.
2) ***'Near-Miss' Incident:*** the work scenario resulted in an unwanted release of hazard energy that did not result in a fatal or disabling injury, but had the potential to result in a fatal or disabling injury.

3) ***Successfully Managed Case:*** the work scenario involved sufficient energy to cause a fatal or disabling injury but did not result in an unwanted release of this energy.

As indicated previously, we could not ethically observe conditions, make an assessment, and wait to observe actual outcomes without intervention. To address this ethical restriction, we collected data for cases retrospectively but applied the cases in the subsequent experiment prospectively. For example, if a near miss was encountered on a research team member's project site, the team member would apply the protocol to collect case data for that work situation. Because the event had already occurred, the responses would be in past tense. The responses were then re-written in a leading fashion as if the response was given at the beginning of the work operation. In this conversion, only the tense was changed. For example, if a worker in a post-incident investigation noted that a carpenter *was* performing electrical tasks, we would note on the protocol form for that case that a carpenter *is* or *will be* working on electrical tasks. This subtle change was essential for simulating a predictive investigation rather than a post-incident analysis during the subsequent experiment. The retrospective-to-leading conversion was a necessary limitation to our research approach that was applied for ethical reasons. The academic researchers managed this conversion process.

Since our goal was to simulate a more realistic ratio of success to failure in our distribution of cases for the experiment, we collected three success cases for every one near miss case and every fatality case (i.e., a 3:1:1 ratio). Success cases were investigated in the same fashion as near miss and fatal cases with the same protocol. In total we collected 19 cases, each with responses to approximately 80 items.

***Step 2: Expert team assesses cases and make predictions***

Once cases had been collected, an iterative experiment was performed to measure the extent to which an expert group could correctly predict the outcome of a case using only their judgment and the leading information contained within the case protocol. It is important to note that the outcomes of each case had been removed and isolated for every case and no member of the expert group was aware of the actual outcome. The research team member who collected the data for a particular case was not involved in the prediction for that case. The academic members of the research team managed the experimental process and also did not make predictions.

The experiment was conducted in a series of rounds. In each round, five cases were selected using stratified random sampling where three success cases, one near miss, and one incident case were included. A potential limitation was introduced in that participants were aware of this deliberate distribution; however, to minimize the prediction advantage, the order in which the cases were presented was randomized.

Each experiment round followed a strict procedure. First, the case was presented to the expert group in its entirety, including the responses to every question on the protocol and a summary of objective observations. Immediately following the presentation of the case, the expert team members were asked to complete an evaluation form, which asked them to identify whether each of the factors from Table 1 was present, partially present, or definitely not present (1, 0.5, or 0, respectively). These data were collected because they would be useful for future statistical analyses and for future guidance on interpreting responses to the questions in the protocol. Once an inventory of the factors had been performed, each individual was asked to make an independent prediction of the outcome of the case (success, near miss, or fatal/disabling incident) prior to discussing the case with other members of the group. After all team members made a prediction, the team was free to discuss their perspectives.

Once all five cases in a round had been assessed, the academic researchers informed the expert group of the actual outcomes of the case. The predictive skill (% correctly predicted by the group) represented the score for each round. Because we found that the leading information for fatal/disabling injuries and near-miss incidents were indistinguishable during the experimental rounds, we grouped the cases together as one outcome (failure) in our subsequent analysis. With this grouping, the expert team was essentially distinguishing success from failure using only leading information. The team goal was to obtain a predictive skill equal to or exceeding 80% for two or more consecutive rounds (i.e., 4 out of 5 cases correctly predicted for at least 2 rounds).

***Step 3: Validate with diverse groups***

The last step in this phase was to expand the experiment to include groups of individuals who were not involved in the initial creation of the precursor data collection protocol. Additionally, we wanted to assess the extent to which less experienced groups could also make correct predictions using the same methods. Thus, we aimed to conduct independent experiments with a group of university graduate students with minimal construction safety experience and a group of moderately experienced industry professionals. The validation experiment rounds followed the same general protocol as the initial experiment with the expert group. The one notable exception was that we did not ask these validation groups to identify the presence or absence of each factor, only to review the protocol and make a prediction.

The two validation groups had different demographics from the subject matter exerts on the research team. The student group included 23 people who averaged 23 years of age, 5.41 years of construction experience, and 1.06 years of safety-specific experience. They were recruited from the University of Colorado and Oregon State University graduate programs. Thirteen moderately experienced professionals were recruited from the Colorado Associated General Contractors. They averaged 45.5 years of age, 21.4 years of construction experience, and 15.5 years of safety-specific experience.

## RESULTS AND ANALYSIS

The results of phase 1 are summarized in detail in Table 1, which shows the potential precursors, their definitions, and the supporting literature. In this table, we reference both precursor analysis programs from other industries and academic literature from the construction safety domain. Since the experimental results confirmed their predictive validity as a cohort, the potential precursors are referred to simply as precursors in Table 1. After all potential precursors had been identified, they were converted into a series of questions and observations, which comprised the precursor data collection protocol listed in Table 2.

***Table 1: List of precursors, definitions, and supporting literature***

| Causal Factor | Definition | Additional Research Identifying Factor |
|---|---|---|
| **1) Client is Inactive/Removed** | Client is inactive in demands for safety and exhibits a lack of contractor oversight. | 6, 17, 18, 19, 20, 29 |
| **2) Communication Gap(s)** | Communication between parties is lacking. This includes all parties involved including management, the foreman, and the workers. | 2, 4, 11, 23, 28, 31, 35, 36 |
| **3) Congested Workspace/ Crowding** | Multiple crafts and equipment working in one area. Hard to maintain situational awareness. | 1, 11, 18, 19, 30 |
| **4) Crew/Supervisor incompatibility** | Refers to the relationship between either crew members themselves or crew members with their supervisor and whether people are comfortable with each other. This may include asking for assistance, asking about a procedure, and telling someone to stop working unsafely. | 4, 28, 30 |
| **5) Crew Members are unaware of Work procedure** | Crew members are not aware of the processes and procedure pertaining to their work. | 3, 4, 19, 23, 26, 31, 33, 35, 36 |
| **6) Crew Members are not active in safety** | Crew members either show a disregard for, under-appreciate, or lack knowledge of site safety. | 2, 3, 11, 25, 27, 30, 33, 34, 35 |
| **7) Distracted Workers** | Outside influences effecting the focus a worker has on a task. This could be on-the-job or off-the-job distractions. | 3, 4, 19, 28, 35, 36 |
| **8) Fatigue** | Work fatigue that can be from a number of causes including, but not limited to, project time constraints/productivity pressures, shift work, time of day, or day of the week. | 4, 11, 18, 27, 35, 36, 37 |
| **9) Inexperience of Worker(s) with Specific Work Task** | Lack of good experience in current role or environment (e.g., day/new hires, long-term workers doing new tasks, workers who have a wealth of bad experience). | 4, 7, 25, 30, 35, 36 |
| **10) Inexperience of Crew with Specific Work Task** | The crew has little to no experience in performing the task. | |
| **11) Lack of control barrier and/or visual warning** | No control barriers were in place to prevent crews from interacting with the hazard (Hierarchy of controls) | 28 |
| **12) Lack of required or proper resources for work** | The required information, equipment, labor, and materials for the work are not available. Substitutes for these items may be being used. | 1, 2, 8, 11, 18, 19, 25, 28, 33, 36, 37 |
| **13) Lack of Verified Safety Training specific to work at hand** | No safety training specifically addresses work being performed (e.g., how to dismantle crane boom). | 2, 3, 5, 7, 18, 21, 26, 29, 30, 32, 36 |
| **14) Language Barrier** | Workers cannot communicate effectively either with each other, supervisors, or work/safety plans regarding the work. This barrier leads to communication gaps and individuals not adhering to safety directions. | 34 |
| **15) Limited Safety Supervision** | Indicates the presence of safety managers/officials on site. (A potential indicator may be the Supervisor to Worker Ratio) | 7, 9, 10, ,11, 18, 19, 21, 26, 33 |

| | | |
|---|---|---|
| **16) Line of Fire is uncontrolled** | Workers put themselves in dangerous situations, in the line of fire. | 28 |
| **17) Improvisation** | The work activities deviated from the original work plan. | 3, 4, 10, 31 |
| **18) Management not present/poor in regards to safety** | Management is not present or active on site with safety. Management's attitude towards safety is lacking. | 7, 9, 10, 11, 13, 14, 15, 17, 18, 19, 21, 25, 28, 30, 36, 37 |
| **19) New Worker(s) to Site** | Workers in a crew have had limited time at the site. | 15, 20 |
| **20) New Worker(s) to Company** | Workers are new to a company (need a threshold). | 15, 21 |
| **21) New/Recently/Seasonally Formed Crew** | A crew has recently been formed and the members have not worked together very long, creating unfamiliarity between the crew members. This includes seasonally formed crews. | 6 |
| **22) No/Poor Plan to Address Work Changes** | No plan is in place or has been discussed regarding a procedure if the work deviates from the plan. A threshold for change has not been established in addition to any discussion regarding stop work protocol or alternative work strategies. | 3, 4, 18, 23, 27 |
| **23) No/Poor Contractor pre-qualification program** | Safety is not considered a significant criteria in contractor selection, whether it be the selection of the prime or sub-contractors. | 9, 18, 20, 21, 26, 28, 29 |
| **24) No/Poor Pre-Task Plan or Discussion Specific to work** | There was no planning/discussion of the activities specific to the work being performed that day. No formal plan is in place for the operation. | 4, 10, 18, 19, 31 |
| **25) No Intervention Protocol** | No protocol such as "Stop Work" is present. People do not have the initiative, or management does not encourage, stopping work to address hazards. | 4, 18, 23, 28 |
| **26) NO Training provided to Subcontractors** | Safety training is not provided to site subcontractors. | 9, 10, 21, 30, 34 |
| **27) Payment System Discourages Safety** | Refers to the type of contractual payment system on site. A lump sum contract may be more likely to short-cut safety to increase project profit and productivity. | 13 |
| **28) Poor Contractor Safety Performance** | The contractor has had poor safety performance on the project or on past projects. | 7, 26 |
| **29) Poor Hazard Recognition** | Poor pre-task planning creating poor hazard recognition, including the ability to recognize high energy. | 1, 3, 4, 9, 19, 21 ,26, 30, 31, 34 |
| **30) Poor Housekeeping** | The work area is cluttered with materials, tools, equipment, trash, etc. | 11, 13, 19, 30, 31, 34 |
| **31) Poor Quality or inexperienced Foreman** | Foreman has little "good" experience within their role. | 7, 22 |
| **32) Risk Normalization** | Complacency in "normal" work environments, repetition, high risk tolerance – workers don't appreciate severity of consequences. At times, this has been referred to as the 'cowboy mentality'. | 4, 19, 25, 28, 31,35 |
| **33) Safety Incentive Program(s) focused on Lagging Metrics** | The safety incentive programs on site are focused on outcomes (e.g., injury rate) instead of observable safe practices. Safety programs on safety outcomes have proven to be a detriment to safety. | 14, 19, 30, 34 |
| **34) Schedule/Productivity Pressure** | Outside pressures such as productivity pressures and schedule pressures cause a worker to perform work differently to save money, time, etc., leaving safety as an afterthought.<br><br>(May include pressure from peers to not appear unknowledgeable or "weak" and thus continue on task without stopping or asking?) | 3, 4, 13, 16, 17, 18, 20, 28, 31, 35 |

| | | |
|---|---|---|
| **35) Significant Overtime** | Overtime was greater than 50% of normal working hours. | 20, 32, 36 |
| **36) Social Distance among workers** | Seniority, age, cultural barriers, social norms, etc. (e.g., 11 year old worker telling 17 year old worker to get out of hole, the hazard warning was ignored). | 24, 27, 32 |
| **37) Unaware of Life Safety Rules Pertaining to Work** | Crew members are not aware of the Life Safety Rules, or zero tolerance rules (e.g., fall protection, LOTO, etc.) that are specific to the work they are performing. | |
| **38) Unexpected Work Hours** | Worker(s) have been asked to work a shift or for an extended period that they were not expecting. | 3 |
| **39) Working Alone** | Poor hazard recognition via poor pre-task planning (includes inability to recognize high energy because they are either distracted while performing a work task or are ignorant of their situation). | 25 |
| **40) Working/Busy Foreman** | Foreman is overloaded with too many responsibilities or is a "working" foreman. In either case, the foreman is not acting like a guardian to their crew. | |
| **41) Work is in Transition** | Workers are between primary tasks. This includes moving material/equipment into place, breaking down material/equipment, relocating to different work area, or breaking for lunch/rest. | 35 |
| **42) Work Not Discipline** | Worker either performing work themselves in another discipline or is performing respective work near another discipline | |
| **43) Working beyond competency/comfort level** | Worker is performing work they are not comfortable in performing or lack the required skill/knowledge to perform said task. | 3, 11, 18, 19, 23, 25, 34, 35, 36 |
| **44) Work Pattern Anomalies Unaddressed** | Individuals have difficulty either identifying anomaly changes in their work pattern, lack of respect for the change in work, or a lack the initiative to stop work if a change occurs. | 3, 4 ,18, 19, 23, 28, 25 |

*__1)__ Abdelhamid & Everett, 2000b; **2)** Ai Lin Teo & Yean Yng Ling, 2006; **3)** Choudhry & Fang, 2008; **4)** DOE, 2009; **5)** Esmaeili & Hallowell, 2012; **6)** Fabiano et al., 2008; **7)** Fang et al., 2004; **8)** Feyer et al., 1997; **9)** Hallowell & Gambatese, 2009a; **10)** Hallowell et al., 2013; **11)** Haslam et al., 2005; **12)** Hinze & Figone, 1988; **13)** Hinze & Harrison, 1981; **14)** Hinze & Pannullo, 1978; **15)** Hinze & Parker, 1978; **16)** Hinze & Raboud, 1988; **17)** Hinze, 1978; **18)** HSE, 2003; **19)** HSE, 2004; **20)** Huang & Hinze, 2006b; **21)** Jaselskis et al., 1996; **22)** Kines et al., 2010; **23)** Kongsvik et al., 2010; **24)** Panagiotis Mitropoulos & Namboodiri, 2011; **25)** Mullen, 2004; **26)** Ng et al., 2005; **27)** Reiman & Pietikäinen, 2012; **28)** Reiman & Pietikäinen, 2010) **29)** Samelson & Levitt, 1982; **30)** Sawacha et al., 1999; **31)** Seo, 2005; **32)** Tam et al., 2004; **33)** Tam et al., 2006; **34)** Teo et al., 2005; **35)** Wachter & Yorio, 2013; **36)** Wiegmann & Shappell, 2001; **37)** Williamson et al., 1996)

### *Table 2: Entire Case analysis question and observation protocol*

| **Questions of the Client** | |
|---|---|
| **#1** | • What is the payment system on this project? |
| **#2** | • What is the general contractor's prequalification?<br>• How has the safety performance been on this project thus far?<br>• Have you had any serious incidents?<br>• How were these incidents handled?<br>• How could the safety performance be improved? |
| **#3** | • What is your role in safety on the project?<br>• What specific activities in regards to safety do you perform for this project?<br>• What are the contract specified safety activities you will perform?<br>• How often is a representative on the project specifically dedicated to safety? |
| **#4** | • What are the strengths of the contractor and their subcontractors with respect for safety?<br>• What are their weakness? |
| **Questions of the Project Manager/Superintendent/Project Management** | |
| **#1** | • What is the client's role for safety?<br>• Please explain, in detail, the extent of their typical involvement |

| | |
|---|---|
| | • Is there anything that the client could do to better support the efficiency and safety of the work? |
| **#2** | • What verifiable skills and safety training has been provided to the subcontractors?<br>• What is the subcontractor prequalification program?<br>• What mitigation strategies do you have to limit the safety risk presented by subcontractors? |
| **#3** | • *Regarding the foreman:*<br>• Please describe the foremen who are leading crews today. How would you assess their performance (e.g. compared with the very best foremen with whom you have worked, how does each one compare?)?<br>• What are their strengths and weaknesses?<br>• How many people is each supervising?<br>• Are they authorized or expected to work themselves?<br>• *Regarding the safety managers:*<br>• Please describe the safety managers. How would you assess their performance (e.g. compared with the very best safety managers with whom you have worked, how does each compare?)?<br>• What are their strengths and weaknesses?<br>• How many people are each supervising?<br>• Do the safety managers have other responsibilities other than safety? (If yes, what are they?) |
| **#4** | • What are the actions a worker should take if they encounter an unsafe condition?<br>• Is this project policy?<br>• Does management have a formal Work Intervention Protocol if a worker sees an unsafe action taking place?<br>• Does management have a formal Work Intervention Protocol if a worker sees an unsafe action taking place?<br>• Please explain any safety incentives that the workers are provided for safety<br>• How would you describe the housekeeping of the crews on site? |
| **#5** | • What do you think of the safety performance on site so far?<br>• What other incidents have happened on site?<br>• How were these incidents handled?<br>• How could the safety performance be improved on site? |
| **#6** | • Is the project ahead, behind, or on schedule?<br>• What activities are critical path?<br>• Is there any incentive for early completion?<br>• Are any of the crews pushing to complete a particular milestone or task today?<br>• Have there been any work disruptions recently causing significant changes in schedule such as delayed shipments, rework, delay form other crews, material/labor/subcontractor shortage? (If yes, how did management manage these work disruptions?)<br>• Did you start earlier or later than usual today? |
| **#7** | • What are the normal working hours for crews on site?<br>• Have any of these crews been working long hours (over 10-hour shifts?)<br>• Will any of the workers be working significant overtime today?<br>• Have any of the workers been asked to work a shift for an extended period of time or one they were not expecting?<br>• What is the schedule outlook for the next couple weeks? |
| **#8** | • Are there any crews who speak more than one language (e.g. Spanish and English speaking workers on one crew or adjacent crews)?<br>• What are the strategies to manage crews or crew members that do not speak the same language?<br>• Are there any crews that are new to the company, new to the project site, or have had recent personnel changes?<br>• Are any of the crews seasonally formed (e.g. the members only work construction for a portion of a year)? |
| **#9** | • What distractions might be present today?<br>• Are there any unusual job changes, visitors, weather patterns?<br>• How are the workers' social and family lives?<br>• Are there any social/personal distractions?<br>• Is there any risk of fatigue from outside behavior? |
| **Questions of the Crew and Individuals** | |
| **#1** | • What tasks are you performing today?<br>• Who is going to perform each task?<br>• Where is everyone going to be working?<br>• Is there ever a time where someone will be working along (out of sight and/or earshot of others)?<br>• What other work is being conducted near your work area? |
| **#2** | • How long have you all been working for this company?<br>• How long have you been working on this project?<br>• How long have you been working in this exact discipline?<br>• Who is our leader/foreman? What are his primary duties? |
| **#3** | • What experience do you have with this exact task?<br>• What specific training have you had for this task/equipment/environment?<br>• (Heavily Emphasize) What is different about the work you are performing today? |
| **#4** | • How long has your crew been working together?<br>• In what ways has this exact crew worked together in the past?<br>• What is your crew's experience with this task? |

| | |
|---|---|
| | • What is different about the tasks being performed today? |
| **#5** | • Who responsible for filling out and reviewing your pre-job safety plan (e.g. JSA, JHA, etc.)?<br>• When is/was the pre-job safety plan reviewed with the crew?<br>• What are all of the hazards that you might face?<br>• What are all the hazards that other crews might create around you?<br>• What are the hazards you might face if work does not go as planned?<br>• How are workers kept clear of these hazards?<br>• What are the barriers or visual warnings in place?<br>• Who is responsible for maintaining these barriers/visual warnings? |
| **#6** | • What specific actions will you take to work safely on your assigned tasks today?<br>• What are the Life Safety/unbreakable/zero tolerance rules for the tasks and work you are performing today? |
| **#7** | • *If the work is being planned:*<br>• In what ways might your work change from what is planned (anything, even minor)?<br>• How will your crew manage these potential changes?<br>• Do you, or other crew members, have authority to stop work if they see an unsafe condition? (If yes, when was the last time one of your crew members stopped work due to safety?)<br>• If you encounter changes in the work plan, when will your crew stop working?<br>• *If work is already underway:*<br>• Is your work going exactly as planned?<br>• Is there anything at all deviating from your original plan?<br>• Of your remaining work, what could change?<br>• How will your crew manage these potential changes?<br>• Do you, or other crew members, have authority to stop work if they see an unsafe condition? (If yes, when was the last time work was stopped due to safety?) |
| **#8** | • What happens if you do not reach your productivity target/deadline today?<br>• How much pressure do you feel to finish this task on time (1 to 10)?<br>• Has there been any work disruptions causing you to be less productive (e.g. lack of equipment, material, labor, engineering information, etc.)? |
| **#9** | • Is there anything that could make your job easier or safer (e.g. more appropriate equipment, tools, more people, etc.)?<br>• In what ways could you be better supported to complete your tasks efficiently and safety?<br>• How often do you see someone who is solely dedicated to safety on site? (If yes, how good of job do they do in supporting your crew?) |
| **#10** | • Is there anything work-related distracting you from your work?<br>• Is there anything outside of working distracting you from your work?<br>• How many hours of sleep have you been getting this week?<br>• Have you had any sleep disruptions that might have made you tired today?<br>• What are the hours you have been working?<br>• Has anyone been working longer hours or hours they did no initially expect?<br>• Are there things outside of work preventing you from getting enough sleep?<br>• Is there anything outside of working distracting you from your work? |
| **#11** | • What do you think of the safety performance on site?<br>• What other incidents have happened on site?<br>• How were these incidents handled?<br>• How do you think the safety performance could be improved? |

The results of the experiment with the expert group rounds are reported in Table 3. For each case, a correct prediction for the group was defined as greater than 50% of the experts correctly predicted the outcome of the case. As one can see, after the third iteration of the experiment, the expert group reached a collective predictive skill greater than 80% for two consecutive rounds (i.e., at least 4 out of 5 correctly predicted cases for each round). A fourth round with four cases was included, however, to obtain sufficient data to support future statistical tests. A fifth case could not be included in this extra experiment round due to time constraints and case availability.

In total, 19 cases were included in the experiment and 16 of 19 were correctly predicted by the majority of the subject matter experts. There was modest variability in the individual assessments. Fortunately, all cases that were incorrectly predicted by the group were Type II errors (i.e., where successful cases are incorrectly predicted to be failure cases). These Type II errors are preferred over Type I errors (i.e., where failure cases are incorrectly predicted to be success) because the Type II errors are conservative.

***Table 3: Iterative Precursor Experiment Results***

**Iteration 1** — **Iteration Score: 60%** — ***Participants: 12***

| Case # | Actual Outcome | Majority Predicted Outcome | % of Group who Predicted Correctly | Correct or Incorrect? |
|---|---|---|---|---|
| 4 | Success | Success | 75% | Correct |
| 3 | Near-Miss | Fatal/Disabling | 92% | Correct |
| 2 | Success | Near-Miss | 42% | Incorrect |
| 5 | Success | Near-Miss | 25% | Incorrect |
| 1 | Fatal/Disabling | Fatal/Disabling | 100% | Correct |

**Iteration 2** — **Iteration Score: 100%** — ***Participants: 9***

| Case # | Actual Outcome | Majority Predicted Outcome | % of Group who Predicted Correctly | Correct or Incorrect? |
|---|---|---|---|---|
| 16 | Near-Miss | Near-Miss | 78% | Correct |
| 14 | Success | Success | 89% | Correct |
| 6 | Success | Success | 100% | Correct |
| 9 | Fatal/Disabling | Near-Miss | 100% | Correct |
| 11 | Near-Miss | Fatal/Disabling | 100% | Correct |

**Iteration 3** — **Iteration Score: 80%** — ***Participants: 9***

| Case # | Actual Outcome | Majority Predicted Outcome | % of Group who Predicted Correctly | Correct or Incorrect? |
|---|---|---|---|---|
| 20 | Near-Miss | Near-Miss | 55% | Correct |
| 8 | Success | Near-Miss | 33% | Incorrect |
| 15 | Near-Miss | Near-Miss | 56% | Correct |
| 13 | Fatal/Disabling | Fatal/Disabling | 89% | Correct |
| 12 | Success | Success | 89% | Correct |

**Iteration 4** — **Iteration Score: 100%** — ***Participants: 9***

| Case # | Actual Outcome | Majority Predicted Outcome | % of Group who Predicted Correctly | Correct or Incorrect? |
|---|---|---|---|---|
| 7 | Near-Miss | Near-Miss | 89% | Correct |
| 18 | Success | Success | 67% | Correct |
| 17 | Near-Miss | Near-Miss | 89% | Correct |
| 24 | Success | Success | 100% | Correct |

When interpreting the results in Table 3 it is important to note that the predictions were made using only the leading case data and the judgment of the experts. There were no objective tools available for use.

To measure the extent to which the predictions were better than random, a permutation test was performed. Since the participants were given three prediction options (success, near miss, fatal/disabling) and we considered fatal/disabling and near miss cases as one group (failure) for analysis, the participants had a 66% chance of selecting failure at random and a 33% chance of selecting success at random for each case. Thus, we used a permutation model that accounted for this random distribution and the number of cases per round. According to the permutation analysis, there is only a $1.6*10^{-5}$ probability that the expert group could only have reached the level of skill of 16/19 correct predictions from random chance alone.

For the validation experiment, the student group completed 10 cases and the moderately experienced professional group completed 6 cases. Again, the cases were randomly selected and were presented in the same ratio of success to failure as the primary experiment. The validation cases were purposefully selected so that there was no overlap in cases between the validation groups. Tables 4 and 5 show the results for the student group and the professional group, respectively. The research team performance (i.e., the expert group from the primary experiment) are provided for each case for reference.

The student group was able to return statistically significant results by successfully predicting 8 out of the 10 cases and achieving a permutation test p-value of 0.007. This performance was slightly less accurate than the expert team's performance of 9 out of 10 for the same cases. The moderately experienced group successfully predicted 5 out of 6 cases and obtained a permutation test p-value of 0.0064. This score was the same as the expert group. The results indicate that the case protocol and judgment can be used by all three groups to predict outcomes far better than random guessing. The professional groups had slightly better performance than the students but this difference was not found to be statistically significant. Students also were more variable in their individual assessments than their industry counterparts, indicating that at least modest professional experience is desired.

***Table 4: Validation with university students***

| Case # | Validation Group Performance | Research Team Performance |
|---|---|---|

| | | |
|---|---|---|
| **11** | Correct | Correct |
| **16** | Correct | Correct |
| **6** | Correct | Correct |
| **14** | Incorrect | Correct |
| **9** | Correct | Correct |
| **13** | Incorrect | Correct |
| **20** | Correct | Correct |
| **12** | Correct | Correct |
| **8** | Correct | Incorrect |
| **15** | Correct | Correct |
| **Score:** | ***(8/10)*** | ***(9/10)*** |
| **p-value** | *0.007* | $2.4 * 10^{-4}$ |

***Table 5: Validation results with external industry members***

| Case # | Inexperienced Group Performance | Research Team Performance |
|---|---|---|
| **5** | Correct | Incorrect |
| **18** | Incorrect | Correct |
| **7** | Correct | Correct |
| **17** | Correct | Correct |
| **1** | Correct | Correct |
| **24** | Correct | Correct |
| **Score:** | ***(5/6)*** | ***(5/6)*** |
| **p-value** | *0.0064* | *0.0064* |

## LIMITATIONS

When attempting to create an ecologically valid predictive method for use in a complex system, we encountered several practical and ethical challenges that defined how the experiment could be performed. Additionally, the fact that this was the first experimental study of precursor analysis for the construction industry meant that we needed to err toward being comprehensive with our approach rather than selective and efficient. The specific limitations associated with our approach are discussed below.

First, despite the success in distinguishing between success and failure, these predictions were purely based on judgment, which is subject to human bias. Further, although the group majority was reported when assessing skill, there was variability in the predictions for each case (see Table 3), indicating that individual assessments are still not completely reliable. Thus, we highly recommend objective tools based upon statistical analyses to complement human judgment.

Second, the cases were based upon a conversion from retrospective to leading information. As previously discussed, we could not ethically apply the protocol in a leading fashion to collect data. Rather, we collected the data following an incident or a successful work period and converted it to present tense. Although we lost a minor amount of fidelity through this translation, we preserved internal validity by editing tense and disallowing anyone who knew the outcome of the case from participating in the experiment.

Third, the ratio of success and failure cases was much lower in the experiment than would be encountered in reality. That is, in reality there are vastly more successful work periods than those where no injuries or near misses occur. Unfortunately, it would not be possible to use realistic ratios because of time and resource constraints. As the protocol is applied in practice greater insight may be obtained regarding whether the protocol is overly conservative because of this limitation.

Finally, as one can see from the small sample of questions from the protocol in Table 2, the full protocol for all precursors is very long and is extremely time consuming to deploy in the field. Although effective, the protocol is too resource intensive to be used regularly. To address this practical limitation, we recommend additional data collection and statistical analyses that identify the most predictive elements of the protocol. With this knowledge the protocol could be strategically shortened without compromising predictive validity.

## CONCLUSIONS

With the objective of creating foundational research for the development of precursor analysis in construction, two foundational steps were completed during the first phase of this research: 1) deterministic event analysis to create a complete catalog of potential precursors; 2) and creation of a protocol to gather precursor data. Casual factors of fatal and disabling injuries were comprehensively catalogued for the first time and cross-referenced with existing research. The result of this process was a codified list of 43 casual factors specific to fatal and disabling injuries. This inventory was the foundation for a precursor analysis for construction and will hopefully lessen the continuation of discordant research regarding casual factors and precursors within the industry.

Once the potential precursors were documented, they were converted into a series of leading questions and observations by a highly experienced expert research team. The creation of this protocol represented an important transformation from incident investigation to incident prediction. The protocol was applied to collect data for 19 actual cases, which were subsequently used in an experiment.

The purpose of the experiment was to assess the extent to which the information from a case and judgment could be used to correctly predict fatalities or near-fatal events. In other words, the experiment was designed to measure the extent to which the protocol and judgment can be used to distinguish success from failure before an event occurs. The results of the iterative experiment indicate that experts performed far better than random as a group, correctly predicting 16 of 19 cases.

To validate the primary experiment, the experimental procedure was repeated with minimally experienced university graduate students and moderately experienced industry professionals. This was a vital step because these validation groups were not involved in the creation of the protocol and represent more realistic users of the protocol. The results of the validation indicate that both students and moderately experienced professionals are also far better than random at prediction as a group, with students having slightly lower skill and higher variability in their individual assessments.

The results indicate that this sequential method of establishing an initial precursor analysis protocol for the construction industry was successful. The protocol, based on literature from outside and within the construction domain, provides a clear and structured method for collecting leading information. Simply, the protocol is a discussion that can be held with the workforce prior to or during work upon which a prediction can be made using judgment. Participant groups of all levels of experience used this protocol and their judgment to make predictions that were far better than random guessing.

Despite the apparent benefits of the current protocol, it must be reduced in length to be feasible for widespread adoption. Further, the methods of prediction should become more objective to reduce the variability in individual predictions observed in the experiment. Additional data and multivariate statistics may jointly address these limitations. Data reduction techniques could be used to reduce the number of questions in the protocol, and predictive modeling could be used to add objectivity to the prediction process. These areas of research, along with independent statistical validation, are the subject of the companion paper.

Although exploratory precursor analysis previously existed within the construction domain (Chen et al., 2012; Wu et al., 2010), these past studies were largely conceptual. The present research is the first tangible step toward a formal method of precursor analysis in the industry with validated tools. Drawing from the experience of NASA, the nuclear industry, the aviation industry, and others, this study provides an important first step for construction. Despite this progress, precursor analysis should always remain a continuously developing and data driven process, and only one component of a comprehensive worker safety program. We hope that future research can build upon the preliminary results and improve upon the experimental methods.

**ACKNOWLEDGEMENTS**

The authors would like to acknowledge the generous funding of the Construction Industry Institute, which supported this research effort and the participation of the members of Research Team 321. The opinions expressed in this article are solely those of the authors and do not necessarily reflect the opinion of the Construction Industry Institute, its members, or all Research Team members and research participants.

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# CHAPTER 3: PRECURSORS OF CONSTRUCTION FATALITIES: STATISTICAL ANALYSIS AND CONSTRUCTION OF A PREDICTIVE MODEL

## ABSTRACT

Fatalities continue to plague the construction industry. To address this ongoing concern, researchers have begun to develop and test proactive methods of construction safety such as risk analysis, leading indicators, and predictive analytics. The present study aims to build upon these current methodologies by creating and testing the first objective precursor analysis program for construction fatalities. Specifically, the following hypothesis was tested: the probability of fatal and disabling events can be predicted by a small number of precursors that can be identified prior to an incident. Testing this hypothesis involved obtaining case data using a precursor analysis protocol described in the companion to this paper, using principal component analysis to reduce the dimensions of the dataset, building a mathematical predictive model using generalized linear modeling, and testing the predictive validity of the model with independent validation cases. The results indicated that there are 16 principal precursors that, when organized into a generalized linear model, are able to predict the outcome of new cases far better than random ($p < 0.001$). With further validation and testing, this new methodology can serve as the foundation for the first objective and valid precursor analysis program for construction.

## INTRODUCTION

Despite significant investments in prevention, injury and fatality rates are unacceptable. According to the Bureau of Labor Statistics (2014), fatality rates in particular have plateaued and even increased in recent years. Some have attempted to explain this plateau with evidence that the industry has reached saturation with respect to traditional safety program elements (Esmaeili, et al., 2015a). In response, researchers and practitioners have begun to explore new safety technologies, risk-based approaches, and predictive analytics.

Compared with other industries like aerospace and nuclear, construction lacks empirically validated methods for injury and fatality prediction. This is due, in part, to the unique challenges presented by the dynamic, diverse, and transient nature of construction work. Such characteristics inhibit data collection and often preclude generalization (Chua and Goh, 2005; Gillen, et al., 2002). In an effort to overcome the challenges of data availability, researchers have resorted to opinion-based data collected via expert workshops (Hallowell and Gambatese, 2009; Rozenfeld, et al., 2010). Unfortunately, opinion-based data are often subject to a plethora of judgement biases like recency, primacy, and contrast (Gustafson, 1998; Kahneman and Tversky, 1982; Sjöberg, 2000). Recently, researchers have begun to build predictive models using empirical data and more fundamental approaches to the characterization of safety risk that enable broader generalization (Esmaeili et al. 2015a;b; Tixier 2016a;b). Others have attempted to predict safety performance using leading indicators that are characterized by management practices (Hallowell et al. 2013). Collectively, this emerging body of research has enabled more advanced methods of predictive safety, including precursor analysis.

In the companion to this paper, Alexander et al. (2016) built upon the work of the National Aeronautical and Space Administration (NASA), nuclear industry, and commercial airline industry to take the first steps toward a precursor analysis protocol for construction. Alexander et al. cataloged a comprehensive list of precursors to fatal and disabling construction injuries and validated their predictive validity through an experiment. The experiment used human judgment to distinguish between success and failure using leading information obtained through a systematically-developed protocol. The present study builds upon that work by adding statistical objectivity and empirical validation. Empirical data collected from actual work scenarios were used to build a predictive model, which was validated with an independent dataset. In the end, both subjective and objective methods of precursor analysis are valuable as numerical techniques may not be realistic in all work scenarios but do add rigor and precision when feasible.

In this paper, we build upon but deviate from past methods of proactive safety analysis. First, we take a new approach to the characterization and collection of the independent predictor variables. Specifically, the leading data were collected via a brief but targeted conversation with workers *prior* to a work period rather than observations or accounts collected *after* an incident. Second, we make the first attempt to objectively distinguish success (i.e., completion of work with no unwanted release of energy) from failure (i.e., work with an unwanted release of energy that either did or had the potential to cause significant injury or death). Because all past safety prediction models have been built using reports of injuries, they were all limited to predicting the severity or type of outcome *if one were to occur* (e.g., Esmaeili et al. 2015b; Tixier et al. 2016). This work deviates by including cases of both success and failure and creating models that forecast the probability that a fatality or disabling injury *will occur at all*.

## BACKGROUND AND THEORY

The present study builds on existing theory of construction safety risk analysis, safety leading indicators, and predictive analytics for safety. We used knowledge in these domains to elucidate our points of departure and the salient knowledge contributions. Since the companion paper presents a thorough literature review on the topic of precursor analysis, this topic is not covered in detail here. However, the salient characteristics of precursor analysis are provided below as an induction for the reader:

- The investigation is performed for one specific crew for one specific work period;

- Most precursors relate to human factors;
- Precursors are anomalous rather than routine conditions;
- Data are collected via a conversation with workers prior to work;
- Precursors are not affected by but not necessarily defined by the trade or type of work performed;
- The process is applied to work situations with the potential to severely injury or kill workers; and
- The method distinguishes success from failure using predictions made via probabilistic methods.

In the subsequent discussion, we note how these characteristics define a new approach to predictive safety that deviates from existing methods.

## Safety risk analysis

Risk is generally defined as a potential event that results in an outcome that is different from what is planned. In the context of safety, the unwanted outcome is a potential injury, illness, or fatality. Researchers have consistently modeled safety risk as the product of injury frequency and injury severity as it relates to a specific unit of analysis such as a trade, activity, or working environment (Baradan and Usmen, 2006; Hallowell and Gambatese, 2009; Jannadi and Almishari, 2003). Diverse units have been analyzed using a wide range of data sources.

### *Units of analysis*

When modeling risk, one must select a unit of analysis, defined here as the 'who' or 'what' being studied. Early safety risk studies focused on the risk of differnet injury types  for construction trades (Brauer 1994; Hinze et al. 2005; Barandan and Usmen 2006). These risks were quantifiable because high-level data were available from the Bureau of Labor Statsitics (BLS). Although analysis of safety risk for trades allowed for comparisons and prioritization, this appraoch was limited in terms of its application to a particular work scenario. Following these initial safety risk studies, the units of analysis have become increasingly granular and specific. For example, Sun et al. (2008) studied specific risks associated with crane operations;

Hallowell and Gambatese (2009) quantified risks for specific formwork construciton activities; Esmeaili and Hallowell (2012) quantified risks for highway construction tasks; and Wu et al. (2012) studied the risks of tools invovled in struck-by injuries. Very recently, Esmaeili et al. (2015) and Tixier et al. (2016) identified and validated fundamental units of analysis for construction work such as uneven work surface, work at height, ladder, and so forth. They used fundamental attributes in an effort to build a robust and generalizeable method of safety risk quantification.

Although the units of analysis vary considerably across studies, all focused on physical chacteristics of the work environment and associated activities. Existing risk analyses do not include human factors such as distraction, productivity pressure, and fatigue. Thus, a major way that precursor analysis deviates from safety risk analysis is via a focus on the characterstics and conditions of the workers that are present just before or during work.

***Data sources***

The sources of data for safety risk analysis are inherently related to the units of analysis. Risk analysts modeling general trades (e.g., Barandan and Usmen 2006) and injury types (Huang and Hinze 2003) used Bureau of Labor Stataitics and Occupational Safety and Health Administration reports. The benefit is that these data are empirical; however, they are very limited in application. Alterantively, researchers who studied specific work activities (Everett 1999; Jannandi and Almishari 2003; Hallowell and Gambatse 2009) used subjective ratings of risks based on the opinions of experts because of a lack of empirical data. Unfotunately, the practical applicability gained from these specific analyses was accompanied by the judgment-based biases that plague probability assessments. To jointly address these limitations, Desvignes (2014), Esmaeili et al. (2015a, 2015b); Prades, (2014), and Tixier et al. (2016) all modeled risk of fundamental attributes using empirical data extracted from injury reports. These studies leveraged large data sources and content analysis methods such as natural language processing to extract meaningful data form injury reports.

The principal characteristics of all safety risk analysis data sources are that they are collected retrospectively from past events; include all severity levels; and include only data related to failures (i.e, injuries, fatalities, or near miss events). Precursor analysis is different because the data are collected prior to work being performed via a conversation with workers; the protocol focuses only on high-impact events (fatalities and disbaling injuries); and both successes (no event) and failures (event) are included for data analysis.

### Safety leading indicators

Safety leading indicators are the measures of system conditions that provide a forecast of future performance (Salas and Hallowell 2016). Researchers have begun to study leading indicators in an effort to transition from lagging indicators of performance (i.e., total recordable injury rate) to measures that can be collected and acted upon prior to an injury (Hallowell et al. 2012). These studies invariably focus on measuring the extent to which supposed leading indicators predict future safety outcomes.

Leading indicators for construction safety can be traced back to the seminal work of Liska et al. (1993) who identified proactive safety management strategies such as pre-task planning, required project training and orientation, and near miss investigation. Jaselskis et al. (1996) validated these techniques by correlating their metrics with experience modification rates and recordable injury rates. In recent years, Hinze et al. (2013) and Salas and Hallowell (2016) measured the correlation between leading and lagging indicators with increased volume of data and more precise definitions. At present, validated leading indicators include, but are not limited to, the frequency of pre-task safety meetings, frequency of safety audits, and the frequency of client participation in safety orientation. All indicators are measures of management activity that are aggregated across a large project or program of projects.

Other industries have also developed safety leading indicators programs but they tend to differ in scope and definition. For example, in the nuclear industry Reiman and Pietikäinen (2010) classified leading indicators into two groups: monitoring leading indicators and driving indicators. They claim that monitoring indicators are the objective metrics that indicate safety performance, which are analogous with the term safety leading indicator traditionally used in construction. Alternatively, driving leading indicators include situational factors like the quality of supervisors and hazard identification ability of personnel (Reiman and Pietikäinen, 2010, 2012), which are analogous to precursors according to our epistemological position.

Although construction safety leading indicators and precursor analysis both aim to identify and correct deficiencies before events occur, precursor analysis deviates in several significant ways. First, precursor analysis focuses on the conditions of the workforce rather than management activity. Second, the data are collected and analyzed for specific construction situations (e.g., a work period) rather than aggregated across a project. Finally, precursor analysis aims to predict and prevent high-impact events rather than safety performance in general. These important differences distinguish the two complementary methods of proactive safety measurement.

## Predictive analytics for safety

Safety leading indicators programs and risk analyses are predictive in nature in that they involve measures of existing conditions that correlate with future performance. However, the analytical methods are limited as they do not yield probabilities of specific outcomes for a given work scenario. Researchers have recently attempted to make such probabilistic assessments using a variety of analytical methods. We used this body of literature as inspiration for our analytical methods.

### *Extant models*

One of the earliest probabilistic models for safety was created by Chua and Goh (2005). They used a Poisson distribution and Boolean logic to model accident data and predict performance. Despite demonstrating success in predicting injury outcomes at the project level, the predictor data were too general to produce specific assessments for tasks or environments (Esmaeili et al., 2015b). Other methods of safety prediction include development of a prediction matrix based on behavior observation (Chen and Yang, 2004); neural network analysis techniques to relate safety management systems to accident data (Goh and Chua, 2013); probabilistic forecasting of loss-of-control events via expert panel workshops (Rozenfeld, et al., 2010); and prediction of injury outcomes using fundamental attributes of the work environment (Esmaeili et al. 2015b; Tixier et al. 2016).

Although a variety of predictive models have been created for construction safety, they are not able to distinguish between events or non-events (i.e., success and failure). That is, existing models are able to predict the probability of various outcomes *if an event were to occur*. This very important distinction exists because previous models used observations, analysis, or reports of injuries. Without inclusion of observations, analysis, or reports of non-event situations, it is not possible to distinguish success from failure in predictive models (Hollangel 2014). This study presents a precursor analysis that delivers a new probabilistic forecasting method that departs from existing models and approaches. Most importantly, the models created here are based upon a dataset of both success and failure, allowing for a mathematical distinction between the two.

***Methods of model building***

When creating predictive models, researchers often seek large datasets with many diverse predictor variables. However, when the number of predictor variables is very large, predictive models require exponentially more input data and become unwieldy and inefficient. Thus, data reduction techniques are used to reduce an initial set of predictor variables to the most meaningful by exploring covariance. For example, Cooper and Phillips (2004); Esmaeili et al., (2015b); Fang et al. (2004) all used principal component analysis (PCA) to reduce the dimensions of their data. PCA is a valuable technique that uses an orthogonal transformation to identify a set of lineraly uncorrelated variables (i.e., principal components) that serve as a smaller set of predictors.

Once the dimensions of a safety dataset are reduced, multiple regression analysis can be used to predict multiple outcomes (Johnson, 2007; Tam and Fung, 1998) or generalized linear models (GLM) with logit transformation are used to predict a binary outcome (Esmaeili et al., 2015b; Fang, et al., 2006). Both forms of analysis regress the independent variables against the dependent variable(s) to identify the predictors with the most explanatory power. Once a predictive model has been created with the base dataset, the models are generally validated against an independent dataset. This is a critical step in all predictive analytics because it explains the extent to which the predictive models are able to correctly predict the outcome of new observations better than random. We use this combination of PCA, GLM, and independent validation in our methods.

## RESEACH METHODS

We aimed to test the hypothesis that *the probability of fatal and disabling events can be predicted by a small number of precursors that can be identified prior to an incident.* In order to test this hypothesis, a multi-step process was implemented which involved identifying key predictor variables, collecting data, reducing the number of the predictor variables, creating of a predictive model, and validating the model with an independent dataset. Each step in this multi-phase research process is described below. Also, Figure 4 illustrates the general process used to build the predictive model, including the isolation of the leading data for each case (independent variables) and the lagging outcomes for each case (dependent variable), the reduction of the dimensions of the independent variable to principal components, and construction of the predictive model.

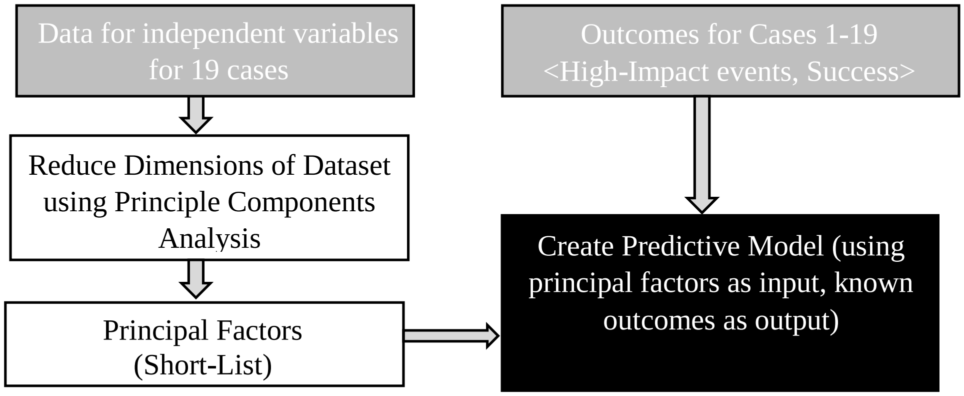



***Figure 4: Statistical modeling techniques to create a predictive model***

### Step 1: Gather structured data via interpretations of the precursor analysis protocol

The companion paper described an iterative experiment where participants of varying levels of expertise (1) reviewed leading information collected via a precursor analysis protocol for 19 cases; (2) assessed the presence or absence of each precursor in each case based upon the interview responses in the protocol; and (3) made a prediction of the outcome. As shown in Figure 5, this process yielded a dataset represented by a matrix of 19 cases by 43 precursors and an independent array of 19 actual outcomes for each case. Each case was associated with one of three actual outcomes described below:

4) ***Fatal or Disabling Injury:*** the work scenarios resulted in an unwanted release of hazard energy that caused someone to suffer a fatal or disabling injury.
5) ***Near-Miss Incident:*** the work scenario resulted in an unwanted release of hazard energy that did not result in fatal or disabling injury, but had the potential to result in a fatal or disabling injury.
6) ***Successfully Managed Case:*** the work scenario did not result in an unwanted release of hazard energy and no incident of note occurred. In other words, the work could be labeled as a safety success.

It should be noted that we considered both fatal/disabling injuries and near miss incidents as events in our analysis and model building. Only events where no unwanted release of energy was considered successful.

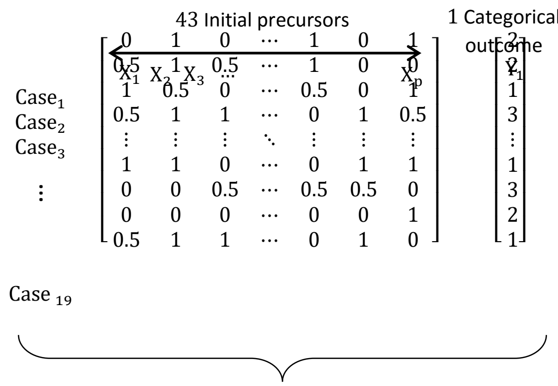



***Figure 5: Structured data set of 19 cases, 43 ternary attributes (absent=0, partially present = 0.5, or present=1), and* 1 *categorical safety outcome (success=1, near miss=2, or fatal or disabling=3)***

It should be noted that the presence of absence of each precursor was assessed using only leading information collected via the precursor analysis protocol. The protocol involves a brief discussion with the work crews prior to the execution of the work and strategic observations of leading conditions.

## Step 2: Eliminate redundancy in initial data collection instrument

Because the dataset involved questions and observations related to 43 precursors, the protocol naturally required 2-3 hours to implement in the field. The benefit of this process was that it yielded rich input data but the significant time and resource requirements needed to collect each case returned a relatively small dataset. Thus, the strategic reduction of the number of independent predictor variables was paramount.

Before using statistical procedures, the team of experts aimed to reduce redundancy and combine initial precursors logically when they were functionally similar (i.e., precursors were combined into one more inclusive, higher-level variable when possible). For example, *new workers to the site* and *new workers to the organization* were combined into one factor *new workers to the organization or site* because these factors were, in essence, capturing the same fundamental vulnerability. Also, *payment system* (e.g., lump sum or cost plus) was removed because other factors captured the natural implications of the payment system (e.g., *productivity pressure*) and the manifestation of this potential precursor with the crew was deemed to be more relevant. Using this process, 14 factors were logically combined or removed, yielding a set of 30 potential precursors. For brevity, we refer the reader to Construction Industry Institute (2016) for a complete discussion of this process, including the specific reasoning for any omission or combination of potential precursors.

### Step 3: Use principal components analysis to objectively reduce the dimensions of the dataset

Once precursors were logically combined, principal component analysis (PCA) was used to strategically reduce the number of precursors by examining collinearity (Joliffe 1986). Here, we used PCA to identify highly correlated precursors and group them together as new independent variables. One of the advantages of PCA is that it retains almost all of the original variation while dramatically reducing the dimensionality of the original dataset (Massey 1965).

Functionally, PCA uses an orthogonal transformation to objectively reduce a large set of potentially correlated variables into a smaller set of uncorrelated variables called principal components (Joliffe 1986). Assuming joint normality, the first principal component accounts for the largest amount of variance, the second principal component is uncorrelated with the first and accounts for the next greatest proportion of the variance, and so forth. Since our dataset consists of a matrix $X_{(N,M)}$ shown in Figure 2 with N rows (cases) by M columns (precursors), the covariance matrix of X, **S**, was computed and subjected to Eigen decomposition using Equation 1. Then, a principal components matrix, the same size as X, was created using Equation 2, where X is the initial precursor data matrix shown in Figure 2, S is the covariance matrix of X, E is the Eigen vector matrix of size M x M, and D is the diagonal matrix of the Eigenvalues.

$$S = E\,D\,E' \qquad \textbf{Eq. 1}$$

$$PC = X\,E \qquad \textbf{Eq. 2}$$

When selecting the number of PCs, we followed the recommendation of Jolliffe (2002), which involves examining the retained variance by the principal components. Given that the eigenvalue $\lambda_i$ is a valid measure of variance accounted for by principal component *i*, the cumulative variance retained by the first k components can be determined using Equation 3.

$$CumVar_k = \sum_{i=1}^{k} \lambda_i \bigg/ \sum_{j=1}^{n} \lambda_j \qquad \textbf{Eq. 3}$$

Once performed, PCA returned groups of precursors that demonstrated strong correlation with one another and act as single variable inputs to the subsequent GLM. This process reduced the number of predictors, the requisite data for predictive modeling, and the time burdens of practical application.

### Step 4: Build predictive model using principal components and generalized linear modeling

Using the principal components are the new set of independent variables, a predictive model was built using a regression technique known as Generalized Linear Modeling (GLM). In essence, GLM is like any other regression technique in that it quantifies the extent to which the variability in the response variable is explained by the variability in the predictor variables. However, rather than modeling the mean, GLM uses a one-to-one continuous differentiable transformation called a link function. Compared to traditional regression, GLM provides a very flexible approach to explore the relationships among a variety of variables. Because the data in matrix X are binary, the logit link function was used.

For a response variable Y logit allows one to model a smooth and invertible link that transforms the conditional expectation of Y to a set of predictors. Equation 4 was used to obtain predictors and coefficients where, G(.) is the logit link function, E(Y) is the expected value of the response variable, A is the set of predictor variables, β is the set of factors associated with each predictor, and ε is the error. The model parameters were estimated using an iterated weighted least squares method that maximizes the likelihood function. Here, the set of predictors were the principal components and the response variable was the probability of high-impact injury.

$$G(\mathrm{E}(Y)) = \eta = f\,(X) + \varepsilon = A\beta_T + \varepsilon \qquad \textbf{Eq. 4}$$

This process is elegant as it yields one single equation to predict the probability of high-impact event based on responses to the precursor analysis investigation protocol. In order to be valid, however, the predictive validity of the GLM must be confirmed by measuring the extent to which it can correctly predict the outcome of new, independent cases that were not used to create the initial model.

### Step 5: Validate predictive model using results from independent case studies

GLM validation was performed with 10 independent validation cases. As shown in Figure 6, the process involved collecting cases, assessing the presence of each precursor for each case, entering these data into the GLM, obtaining a prediction, and then comparing the prediction to the actual outcome. Since the GLM yields a probability that the case was failure (serious near miss, disabling injury, or fatality), we considered the model to have successfully predicted the outcome when the model yielded a probability greater than 50% for the correct outcome. Then, we used a permutation test to measure the probability (p-value) that results as good as or better than those obtained from the GLM could have been obtained randomly.

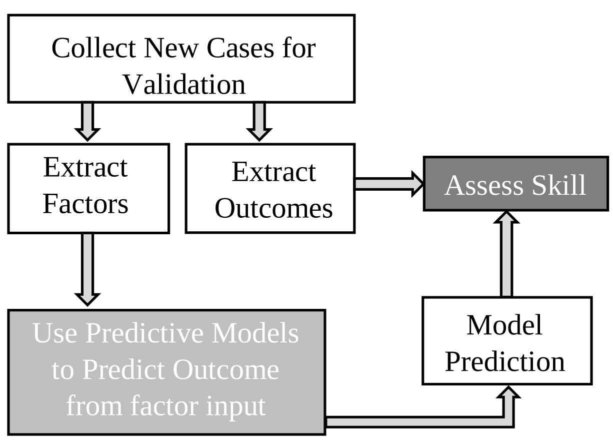



***Figure 6: Statistical validation procedure***

When assessing the validation cases, the same expert group and the same process involved in the iterative experiment in the companion paper was used to obtain values for the input variables. That is, a group of construction safety experts reviewed the responses to the precursor questionnaire and assessed whether each precursor was present (1), was partially present (0.5) or was not present (0) for each case based on the actual responses of the workers. Table 6 provides the following for each principal precursor: definition, questions in the protocol, and observations in the protocol. Because the responses received from workers are highly variable and sometimes difficult to interpret, the expert team developed a series of rules to use as guidance. Table 7 provides the set of rules and guidance obtained from the expert team for the principal precursors because the validity of the method is tied strongly in the ability to correctly interpret the responses to the questions in the precursor protocol. Even with these rules, there was some variability in the individual assessments of the experts. In the case that consensus was not achieved, the median assessments were used as input data in the GLM. The rules are provided in this paper to show the method used to convert verbal responses to numerical data and to assist practitioners with interpretation.

***Table 6: Resulting principal components and associated factors***

| **Principal Component 1: Poor Work Planning** | | | |
|---|---|---|---|
| **Precursor** | **Definition** | **Protocol Questions** | **Protocol Observations** |
| **Crew members are unaware of standard work procedure** | Crew members are not aware of the processes and procedures necessary to complete their work safely. | What tasks are you performing today?<br><br>Who is going to perform each task and where will everyone be working? | The plan described differs from the formal plan.<br><br>Workers are not following standard operating (safe work) procedures. |
| **No/poor plan to address work changes** | There is inadequate knowledge of a safe work plan for potential changes. | What is different (anything) about the work you are performing today?<br><br>In what way might your work change from what is planned (anything, even minor change) and how will your crew manage these potential changes? | None |
| **No/Poor Pre-Task Plan or Discussion Specific to Work** | The pre-task safety discussion is inadequate for this work period and/or no formal plan is in place for the operation. | (Refer to questioning for Precursor ‘Crew Members are Unaware of Standard Operating Procedure’) | There is no evidence of a genuine and detailed planning meeting prior to performing work. |

| Principal Component 2: Productivity Safety Stressors | | | |
|---|---|---|---|
| **Significant Overtime** | Workers are working more than 50% of normal working hours. | What are the hours that you have been working? How many hours do you normally work? | None |
| **Fatigue** | Workers are experiencing mental and/or physical lassitude (tiredness). | Is there anything that might make you fatigued today like long hours, stress, weather conditions, commuting, etc.? | None |
| **Schedule/Productivity Pressure** | Workers feel abnormally strong pressure to complete work quickly. | What happens if you do not reach your productivity target/deadline today?<br><br>How much pressure do you feel to finish this task on time, using a scale of 1 to 10, where 10 is high?<br><br>Have there been any recent work disruptions causing you to be less productive (equipment, material, labor, engineering information, etc.)?<br><br>Is there anything that could make your job easier or safer (equipment, tools, more people, etc.). | None |
| **Prior Safety Performance is Poor** | The project team has had poor safety performance on the project or poor performance with this work on past projects. | What do you think of the safety performance on this project so far?<br><br>How do you think the safety performance could be improved? | Serious injuries or near-miss incident has occurred with this crew in the last 2 months. |
| **Crew Members are not Active in Safety** | Crew members either show a disregard for or lack knowledge of site safety. | None | There is a lack of consistency between what you hear from the workers and what you see on site.<br><br>One or more crew members exhibits a poor attitude towards safety. |
| **Principal Component 3: Vulnerability to High Energy** | | | |
| **Lack of Control Barrier and/or Visual Warning** | No control barriers are in place to prevent crews from interacting with hazards. | What are the barriers or visual warnings in place for high-energy hazards? | Visual warnings or physical barriers are clearly missing for high energy hazards. |
| **Line of Fire is Uncontrolled** | Workers can put themselves in dangerous situations. | What are all of the hazards that you might face and how will everyone be kept clear of these hazards?<br><br>What are all of the hazards that other crews might create around you?<br><br>What specific actions will you take to work safely today? | There is an area where visual or physical barriers are inadequate for high - energy work. |
| **Improvisation** | Workers may deviate from protocol if an unexpected change occurs. | None | Crew members can be observed deviating from their original safety/work plan OR it is clear that the |

| | | | |
|---|---|---|---|
| | | | workers do not have a plan to address potential work changes. |
| **Principal Component 4: Surrounding Safety Influences** | | | |
| **Limited Safety Supervision** | The safety supervisor is not physically present during work, is overworked, or is completely absent. | How often do you interact with someone who is solely dedicated to safety on this project? | Safety professionals are not observed or their physical presence minimal. |
| **Poor Quality or Inexperienced Foreman** | Foreman has little good experience within their role. | How would you grade your foreman in regards to safety?<br><br>Is there anything your foreman could be doing better? | The foreman working or is responsible for managing too many people. |
| **Distracted Workers** | Personal, social, or work-related factors that reduce or divert attention from the task. | Is there anything that is distracting you from focusing on your work? | Obvious distractions are present on site. A worker is clearly irritable or volatile. Unusual behavior is observed. |
| **Working Alone** | A worker may be working out of sight or earshot. | Where will everyone be working today? | Crew members can be seen working alone or preparing to work alone. |
| **Congested Workspace/Crowding** | Multiple crafts and equipment operating in one small area. | None | Are there congested areas, especially where more than one crew is working? |

*Table 7: Guidance for perceiving precursors from interview responses*

| Precursor | The precursor is considered present if: | Notes for an investigator |
|---|---|---|
| Crew Members are Unaware of Standard Operating Procedure | • Crew members do not completely and concisely recite the formal work procedure for their work.<br>• Crew members demonstrate excessive hesitation in their responses.<br>• Crew members do not know where everyone will be working and who will be performing each task.<br>• The described work procedure differs from what is observed.<br>• Workers are not adhering to standard safe work procedures. | • A moderate level of familiarity with the work may be required for the interviewer to assess responses.<br>• Be wary of general or high-level answers that may indicate a lack of knowledge regarding the work procedure, or lack of care for the associated risk and risk management process.<br>• Speaking with a non-lead or more junior crew member individually can be helpful in assessing whether the entire team understands the work scope and the execution plan.<br>• Familiarity with the work activity and control requirements is important for assessing this precursor. |
| No/Poor Plan to Address Work Changes | • Crew members cannot easily identify potential changes that may occur within their work environment.<br>• Crew members do not exhibit knowledge of an appropriate management strategy for addressing potential changes. | • This factor is often associated with crews that exhibit willingness to continue forward in the face of emergent hazards or conditions without stopping.<br>• Such crews may provide general, non-substantive, or inconsistent answers about the approach to addressing emergent conditions. |
| No/Poor Pre-Task Plan or Discussion Specific to Work | • Crew members do not fully recite a clear work plan for the work they are about to perform.<br>• Crew members provide inconsistent responses.<br>• Crew members do not demonstrate awareness of their own or their co-workers' job assignments. | • If crew members do not know the details of the formal safe work procedure, they are more likely to improvise. |
| Significant Overtime | • Workers have been consistently working 12-hour shifts or more.<br>• Normal work shift has been extended by 3 or more hours. | • Workers will typically demonstrate/communicate different tolerances for extended working hours. Be aware of crew members that to be involuntarily or begrudgingly working overtime. |
| Fatigue | • Crew members appear to visibly be fatigued.<br>• Crew members state that they are fatigued.<br>• Total hours slept by individual crew members is less than 9 hours over previous 48-hour period. | • The interviewer should pay close attention to the working conditions of the crew members such as lighting, noise, and other environmental conditions that contribute to fatigue.<br>• Conditions that drive fatigue include, but are not limited to: long hours, stressful time constraints, stressful working conditions, long commute to the job-site, or having an under-resourced crew. |

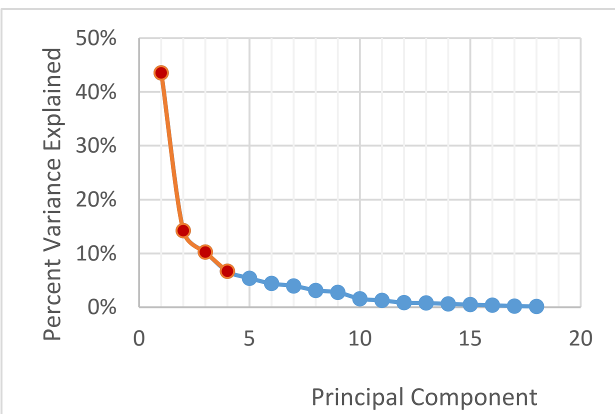
| | | |
|---|---|---|
| Schedule/Productivity Pressure | • Excessive outside pressure from management/leadership to meet a deadline/milestone is apparent.<br>• Work disruptions have caused the crew to fall behind.<br>• Productivity impacts due to inadequate resources (e.g. tools, machinery, personnel, information, permits, etc.) are apparent.<br>• Crew members are aware of a hard deadline that is approaching. | • Pressure can originate from multiple sources such as supervisors, foremen, the client, or the crew members themselves. This factor should be considered present if the level of production pressure may cause the crew to compromise safety. |
| Prior Safety Performance is Poor | • Crew members can list serious near-miss or actual safety incidents.<br>• The interviewer is aware of serious near-miss or actual safety incidents prior to conducting this precursor investigation. | • Consideration should be given to the nature and frequency of previous incidents.<br>• All severity levels should be considered, including near misses.<br>• The interviewer should be aware of bias and underreporting. |
| Crew Members are not Active in Safety | • Crew members exhibit a lack of respect or ownership for the high-energy hazards or safety controls pertaining to their work.<br>• Crew members provide general answers, especially regarding the high-energy hazards and respective controls.<br>• Crew members cite hazards listed on the Pre-Task Plan and/or Job Safety Analysis, but cannot not physically identify the hazards or provide detailed description. | • The interviewer should be wary of crews that simply sign off on a Pre-Task Safety Plan without discussing the hazards in detail.<br>• Crew members do not name high energy hazards or risks but speak in general terms only. |
| Lack of Control Barrier and/or Visual Warning | • Crew members respond by saying there is no physical barrier in place for one or more high energy hazards (e.g. barricades/tapes, fire blankets or spark barriers).<br>• The interviewer can observe that there are inadequate or missing physical barriers for one or more high energy hazards. | • Familiarity with the work activity and control requirements is important for assessing this precursor. |
| Line of Fire is Uncontrolled | • Crew members can access areas that are dangerous without proper training or certification. | • Also consider whether energy pathways are controlled for reasonably possible release scenarios. For example, if a suspended load may roll or otherwise move laterally after falling, the controlled area should be large enough to contain that path. |
| Improvisation | • Crew members have not formally planned and discussed their work procedure and associated | • Significant discrepancies between the work plan and the crew responses are signs of improvisation. |

| | | |
|---|---|---|
| | hazards. Often crew members are improvising if they cannot quickly and concisely identify the hazards associated with their work. | • Deviations that are stated confidently and without hesitation are strong indicators of improvisation. |
| Limited Safety Supervision | • Dedicated safety representatives visit the work location infrequently or not at all during high energy work.<br>• Safety supervision is absent or not readily apparent at the work site in general.<br>• Safety resources are overloaded. | • Crews may not offer direct verbal clues about how regularly safety representatives are present at their work location<br>• Crews may equate safety presence on the job with morning toolbox talks or similar meetings. Ask specifically about how often safety representatives are present at the work face during ongoing jobs, particularly when high energy is involved. |
| Poor Quality or Inexperienced Foreman | • Crew members suggest that their foreman is lacking in knowledge and/or competency to manage the work.<br>• Foreman does not exhibit a dedicated and consistent consideration of safety in the work.<br>• Foreman has not previously performed or overseen this type of work.<br>• Foreman's prior supervisory experience is limited or non-existent.<br>• Foreman does not recognize or exhibit knowledge of the high risk hazards. | • Open and honest responses may be difficult to obtain from the crew due to perceived social barriers or concerns about voicing negative Information. The Interviewer should pay close attention to the crew's non-verbal communication and probe further if the response is neutral or curt.<br>• An exhibited lack of respect or courtesy toward the supervisor can be an indicator that the crew perceives lagging experience or knowledge. |
| Distracted Workers | • Any work or home life disruptions appear to be occupying the attention of crew members<br>• Crew members are not attentive during interview, appear disengaged, or do not respond appropriately to basic questions about the work.<br>• Crew members exhibit unexpected or inappropriate emotional responses during interview. | • The interviewer's relationship with the crew can be a limiting factor in gathering information to assess distraction, especially with personal matters. Be aware of short or dismissive responses to questions in this area.<br>• Be mindful of body language and other non-verbal communication. |
| Working Alone | • A worker is, or may be, working out of sight or earshot. | • Work plans may not initially entail crew members working alone or in isolation, but changes in the work plan may create such cases. Interviewers may ask follow-up questions to determine whether reasonably anticipated changes during the job could lead to any crew member working alone. |
| Congested Workspace/Crowding | • Multiple crews' work areas overlap.<br>• Tight work space or multiple workers in a tight area. | • Consider that crowding can occur in all dimensions (e.g. crews working independently on different elevations). |

## RESULTS AND ANLAYSIS

### Principal components analysis

The PCA yielded four principal component variables consisting of a total of 16 precursors. The following four principal components explained 75% of the variability in the original dataset: poor work planning, productivity stressors, vulnerability and poor barriers, and surrounding safety influences. Since we were using PCA to cluster precursors into groups, we were interested in the pattern matrix (Figure 7), which represents the loadings of the factors on each variable. According to Kline (2002) and Bryant and Yarnold (1995), in a simple structure, each factor should have a few loadings being close to zero and loadings of 0.3 or higher can be considered at least salient (Kline 2002). As shown in the pattern matrix in Figure 8, the principal components are simple in nature. In addition, the model makes sense from a theoretical standpoint. For example, the precursors on factor 1 (crew members unaware of the work procedure, no plan to address work changes, poor pre-task planning) all measure work planning.




| PC | Eigenvalue | % Variance | Cumulative % |
|---|---|---|---|
| 1 | 1.505 | 44% | 44% |
| 2 | 0.49 | 14% | 58% |
| 3 | 0.353 | 10% | 68% |
| 4 | 0.229 | 7% | 75% |
| 5 | 0.185 | 5% | 80% |
| 6 | 0.151 | 4% | 84% |
| 7 | 0.136 | 4% | 88% |
| ... | …. | …. | ….. |
| … | …. | …. | …. |

***Figure 7: Total Variance Explained by the principal components***

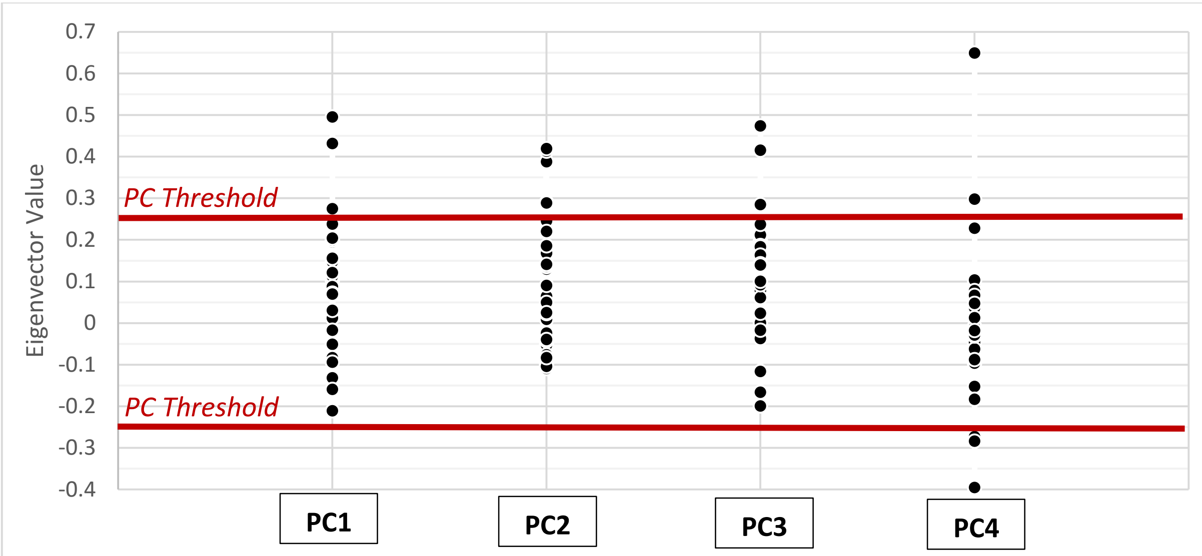



**Figure 8: Pattern matrix for principal components**

## Generalized linear model

The GLM is shown in Equation 5 in which $X_n$ represents the sum of the numerical values for each precursor within the principal component. For example, for the first principal component, if crew members unaware of the work procedure was present (score of 1), no plan to address work changes was not present (score of 0), and poor pre-task planning was partially present (score of 0.5), the numerical value of $X_1$ would be 1.5, which would be entered into the model. This model yields a probability of high-impact event with a value between 0 and 1. We considered the model to have correctly predicted the outcome when it returned a value less than 0.5 for non-event cases (success) and a value greater than 0.5 for high-impact cases (failure).

$$\textbf{Probability of event} = \frac{e^{(-1+0..20*X_1+0.56*X_2+0.46*X_3+0.24*X_4)}}{e^{(-1+0.20*X_1+0.56*X_2+0.46*X_3+0.24*X_4)}+1} \qquad \textbf{Eq. 5}$$

$$X_1 = \sum Poor\ Work\ Planning \qquad X_3 = \sum Vulnerability\ to\ High\ Energy$$

$$X_2 = \sum Producitivity\ Safety\ Stressors \qquad X_4 = \sum Surrounding\ Safety\ Influences$$

## Predictive skill of the generalized linear model

The predictive skill was tested with 10 validation cases that were not used to build the model in Equation 5. The GLM performed exceptionally well, correctly predicting all 10 validation cases. Despite the relatively small sample size, it appears that the 16 causal factors, derived from the original list of 43 causal factors, can be effectively used in the prediction of high-impact events. The permutation confirmed that the GLM performed significantly better than random (p-value << 0.001).

In order to provide the reader with a comparison of GLM predictions and the predictions made by experts in the iterative experiment, Table 8 is provided. The GLM outperformed the expert judgments and predicted every case correctly. Although our sample size was small (29 total cases), the results are very promising. These findings confirm the primary hypothesis that the probability of potentially fatal and disabling injury events can be predicted by a small number of precursors and/or combinations of precursors that can be identified prior to an incident.

One will note that Table 8 also includes predictions made via a simplified method, based on the GLM, which was created to enhance usability in field operations. This simplified method is discussed in the subsequent section.

***Table 8: Comparison of predictive skill for experts, complex regression model, and assessment rubric***

| Case # | Actual Outcome | Experiment (Intuition) Skill | Regression Model Probability | Regression Model Skill | Precursor Assessment Rubric Score | Precursor Assessment Rubric Skill |
|---|---|---|---|---|---|---|
| **Cases used for experimentation and initial model building** | | | | | | |
| 4 | Success | Correct | 32.3 % | Correct | 1 | Correct |
| 3 | Near-Miss | Correct | 89.8 % | Correct | 14 | Correct |
| 2 | Success | Incorrect | 49.6 % | Correct | 4 | Incorrect |
| 5 | Success | Incorrect | 49.6 % | Correct | 4 | Incorrect |
| 1 | Fatal/Disabling | Correct | 87.6 % | Correct | 13 | Correct |
| 16 | Near-Miss | Correct | 87.1 % | Correct | 12 | Correct |
| 14 | Success | Correct | 49.6 % | Correct | 3.8 | Correct |
| 6 | Success | Correct | 26.9 % | Correct | 0 | Correct |
| 9 | Fatal/Disabling | Correct | 64.8 % | Correct | 7 | Correct |
| 11 | Near-Miss | Correct | 94.2 % | Correct | 15 | Correct |

| | | | | | | |
|---|---|---|---|---|---|---|
| 20 | Near-Miss | Correct | 50.4 % | Correct | 4 | Correct |
| 8 | Success | Incorrect | 40.9 % | Correct | 3 | Correct |
| 15 | Near-Miss | Correct | 81.7 % | Correct | 9 | Correct |
| 13 | Fatal/Disabling | Correct | 50.4 % | Correct | 5 | Correct |
| 12 | Success | Correct | 29.3 % | Correct | 1 | Correct |
| 7 | Near-Miss | Correct | 94.0 % | Correct | 15 | Correct |
| 18 | Success | Correct | 38.7 % | Correct | 2 | Correct |
| 17 | Near-Miss | Correct | 85.9 % | Correct | 11 | Correct |
| 24 | Success | Correct | 36.9 % | Correct | 2 | Correct |
| **Cases used for statistical validation** | | | | | | |
| 22 | Near-Miss | NA | 73.3% | Correct | 7.5 | Correct |
| 10 | Near-Miss | NA | 54.3% | Correct | 5 | Correct |
| 19 | Near-Miss | NA | 62.4% | Correct | 6 | Correct |
| 27 | Success | NA | 36.3% | Correct | 2 | Correct |
| 21 | Near-Miss | NA | 58.1% | Correct | 5 | Correct |
| 23 | Near-Miss | NA | 76.3% | Correct | 8 | Correct |
| 24 | Near-Miss | NA | 71.6% | Correct | 8 | Correct |
| 25 | Near-Miss | NA | 56.1% | Correct | 4.5 | Correct |
| 26 | Near-Miss | NA | 78.4% | Correct | 8.5 | Correct |
| 28 | Near-Miss | NA | 65.5% | Correct | 6 | Correct |

## PRACTICAL APPLICATION

We recognized that explaining and applying a GLM in practice would be cumbersome, especially for unfamiliar with the modeling technique. Thus, we used the coefficients from the GLM as weightings to create a simplified scorecard. By compromising precision (and potentially accuracy), we vastly increased usability. As one may note from reviewing the GLM equation, the coefficients multiplied by each principal factor $X_1$, $X_2$, X3, and $X_4$ are conveniently 0.20, 0.56, 0.46, and 0.24, respectively. Numerically, this can be modeled as an approximate 2:1 ratio for the coefficients. In other words, rather than use the complex model in practice, a less precise but far simpler prediction can be made multiplying $X_2$ and $X_3$ by 2 and $X_1$ and $X_4$ by 1. To complete the assessment, the weighted precursor scores are added and compared against the threshold of 4, which corresponds to the 50% threshold previously discussed. The scorecard is provided in Figure 9.

***Mark the presence of each Factor using the numeric scale below:***

$1 = Precursor\ is\ Present$ $\quad \frac{1}{2} = Precursor\ is\ Partially\ Present$ $\quad 0 = Precusor\ is\ NOT\ Present$

| | Factor Presence | Weight | Weighted Score |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Crew Members are Unaware of Standard Work Procedure | | x1 | |
| No/Poor Plan to Address Work Changes | | x1 | |
| No/Poor Pre-Task Plan or Discussion Specific to Work | | x1 | |
| Significant Overtime | | x2 | |
| Fatigue | | x2 | |
| Schedule/Productivity Pressure | | x2 | |
| Prior Safety Performance is Poor | | x2 | |
| Crew Members are NOT Active in Safety | | x2 | |
| Lack of Control Barrier and/or Visual Warning | | x2 | |
| Line of Fire is Uncontrolled | | x2 | |
| Improvisation | | x2 | |
| Limited Safety Supervision | | x1 | |
| Poor Quality or Inexperienced Foreman | | x1 | |
| Distracted Workers | | x1 | |
| Working Alone | | x1 | |
| Congested Workspace/Crowding | | x1 | |
| Total Score (if score equal to or greater than 4, HILF is Predicted) | | | |

***Figure 9: Simplified Precursor Assessment Scorecard***

Much like the GLM, the predictive skill of the scorecard was assessed on the 19 original cases and the 10 validation cases. In total, the simplified scorecard correctly predicted 27 of the potential 29 case studies. The two incorrect predictions were 'false alarms' where a successful work scenario was identified as a failure. Thus, this preliminary evidence suggests that the scorecard is conservative. As with the GLM, a permutation test confirmed that the scorecard performed far better than random ($p < 0.01$). The performance of the simplified scorecard is also provided in Figure 4.

## CONCLUSION AND RECOMMENDATIONS

As the construction industry continues to pursue zero fatalities, new methods of predicting and preventing fatalities are required. This study offers a new approach to fatality prediction consistent with the term precursor analysis used in other industries. We used the underlying theory that anomalous but observable leading conditions can predict the occurrence of high-impact events. The overall study was comprised of two parts. First, in the companion paper, an expert team was formed to identify potential precursors, establish a precursor data collection protocol, collect actual cases, and test their predictive validity through an experiment. The process was also validated with less experienced construction professionals. The defining characteristic of this initial phase was the use of the responses obtained via the protocol and judgment to make a prediction. This less sophisticated method is important because practitioners often must scan an environment without sophisticated tools. However, when available and feasible, objective methods for precursor analysis can be very powerful because of their accuracy and precision. Thus, the present paper focused on a research process implemented to identify the most important precursors, organize them into an objective predictive model, and validate the model with new data. The results returned very promising data as the resulting model predicted all cases correctly. Although the sample sizes are relatively small, the predictive accuracy is extremely high with very strong statistical significance.

This study is not without its limitations. First, the sample size for model creation and validation was 29 cases. Although the results returned statistical validity and sufficient degrees of freedom were available for all analyses performed, the models can certainly become more accurate and precise with additional training data. Second, the input data for the models requires the judgment of an investigator. Specifically, an investigator must obtain responses of workers to the questions in the precursor analysis protocol and then assess if each precursor was present, partially present, or not present. Although we provide detailed guidance from an expert panel on how to make these assessments, the process is still subject to the individual biases of the investigators who apply the methodology. Thus, until further validation can be performed, we suggest that investigations are performed in teams and/or conservative estimates are made. Finally, the validation dataset included mostly near miss cases in an effort to measure if the GLM would have correctly predicted the occurrence of an event. We suggest that future researchers replicate our work and use a higher proportion of fatal and success cases. One should note that collecting fatality cases using leading information is very challenging as the events are (fortunately) rare and subject to legal scrutiny.

Despite its limitations, this study yielded a strong starting point for precursor analysis for construction, advancing the industry toward the types of methods employed by NASA, the nuclear industry, and the aviation industry. These existing programs are in operation and yield warnings when known precursors are present. We anticipate that, with an increased volume of data and validation, the model and methodology presented here can be applied to identify precursors of fatal and disabling events, which can trigger proactive safety response. As such a program matures, researchers are encouraged to explore the root system and managerial causes of precursors to prevent their occurrence.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the generous funding of the Construction Industry Institute, which supported this research effort and the participation of the members of Research Team 321. The opinions expressed in this article are solely those of the authors and do not necessarily reflect the opinion of the Construction Industry Institute or its member.

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# CHAPTER 4: ENERGY-BASED SAFETY RISK ASSESSMENT: DOES MAGNITUDE AND INTENSITY OF ENERGY PREDICT INJURY SEVERITY?

## ABSTRACT

Recent research has focused on risk-based approaches to proactively manage safety. Although the quantity and quality of safety risk data have improved in recent years, available data do not link directly to natural principles and are, therefore, limited in their application and scientific extension. The present study aims to test the hypothesis that the quantity and intensity of energy observable prior to an incident predicts variability in the severity of the incident. The hypothesis is built upon the theory that energy is translated to an injury through uncontrolled release of the energy, transfer of the energy to the human body, and the vulnerability of the body and associated protective equipment. To test the hypothesis, a multi-phase experiment was conducted. First, over 500 injury reports were gathered from national databases and private companies for fall and struck-by injuries involving either potential or kinetic energy. For each report, the leading information describing the work operations and environment and the lagging information describing the injury were extracted, separated, and isolated. Second, the magnitude of the energy was estimated by a group of engineers who were only given leading information. Once energy magnitude was quantified, the distribution of energy magnitude was compared across injury severity levels using analysis of variance tests, which revealed significant differences across severity levels. As hypothesized, energy magnitude is a strong predictor of injury severity. Although more computationally intensive, energy intensity, defined as the magnitude of energy divided by the area of contact between an object and the human body, showed even stronger predictive validity. This research indicates that energy-based safety risk analysis has predictive validity and is a promising line of scientific inquiry that has the potential to increase our understanding of the natural phenomena that contribute to injuries.

## INTRODUCTION

The construction industry's disproportionate fatality and serious injury rate has been an ever-present trend. Until the creation of the Occupational Safety and Health Act of 1970 these incidents were largely viewed as an inherently unavoidable characteristic of the work being performed (Bureau of Labor Statistics 2014; Cameron et al. 2008; Roudsari and Ghodsi 2005). Fortunately, perspectives have changed. Many organizations have invested significant resources in pursuit of zero injury goals (J. Hinze, 2001; Liska, Goodloe, & Sen, 1993). Mature organizations even consider safety is an indicator of effective design, planning, training, and work execution.

To reduce the frequency of injuries and fatalities, a plethora of programs have been introduced such as project-specific training and safety meetings, frequent worksite inspections, and worker safety and health orientation. However, the effectiveness of these traditional injury prevention approaches is limited due to their reactive and regulatory-based nature. Additionally, most existing strategies have reached saturation in terms of new adoption, suggesting that new, perhaps untraditional, avenues of research and development for construction safety is critical for future improvement (Esmaeili and Hallowell 2012). In response to these limitations and trends, researchers have begun to explore risk-based practices as a means for safety innovation.

Conventional safety risk management methods are built on the assumption that work can be decomposed into its constituent parts (Lingard 2013), ranging from trades (Baradan and Usmen 2006) to specific construction activities such as concrete formwork placement (Hallowell and Gambatese 2009). The drawback of this approach is that the decomposition of a complex construction site is of limited value when the work elements are in constant dynamic interaction (Cooke-Davis, et al. 2007). As a result, conventional construction safety risk units of analysis are limited in terms of both their current application and potential for future scientific development. Safety risk analysis is also limited by data sources and, as a result, most studies use opinion-based data (Esmaeili 2012). It is widely accepted that humans have poor ability to quantify risk as we are susceptible to an abundance of cognitive biases (Gustafson, 1998; Kahneman and Tversky, 1982; Sjöberg, 2000). As a result, empirical data are needed for truly reliable risk assessments.

The objective of this study is to address the current limitations in safety risk analysis by offering and testing a new, energy-based approach to predicting the potential severity of injuries. The specific goal is to test the hypothesis that *the quantity and intensity of energy observable prior to an incident predicts variability in the severity of the incident.* If this hypothesis is correct, an elegant and scientific method for assessing the severity component of safety risk may emerge that may be operationalized as a more robust safety risk assessment technique for industry.

## LITERATURE

Applying the concept of energy to explain variability in the severity of construction injuries requires a description of our epistemological positions on both safety risk analysis and safety energy. Also, we must explain the scientific basis for our proposed extension of the energy theory. Thus, we dedicate this background to reviewing perspectives of and approaches to safety risk analysis, the theory of safety energy, and comparable scientific approaches to risk modeling from the field of natural disaster research. We use this background to frame our theoretical point of departure and our contributions to the body of knowledge.

### Safety risk analysis

At its essence, risk can be defined as a potential event that results in an outcome that is different from what is planned. Researchers have consistently calculated safety risk using Equation 1, which expresses the quantity of safety risk as the product of injury frequency and severity (e.g. Jannadi and Almishari, 2003; Baradan and Usmen 2006; Hallowell and Gambatese 2009). Unfortunately, traditional safety risk analysis techniques are severely limited because of bias toward the frequency component of risk, inadequate data sources, and units of analysis that compromise generalizability (Hallowell, et al., 2011).

$$[1] \quad Unit\ Risk = (Frequency)\ x\ (Severity)$$

***Approaches to safety risk quantification.***

Most safety risk analyses have focused exclusively on quantifying the frequency of particular injuries. For example, Huang and Hinze (2003) quantified the rate of fall incidents using statistical data from OSHA and the Bureau of Labor Statistics (BLS) and Everett (1999) quantified the risk of overexertion injuries for various trades by computing the rate at which they occur. Researchers have focused on frequency because the data are typically accessible through databases such as the BLS. Although the severity component of risk is equally important in a mathematical sense, its quantification has received comparatively little attention due to reliance on the widely-used *Safety Pyramid* (Heinrich, 1931) assumption to explain injury severity distribution.

In contrast to advances achieved in risk analyses for other project management functions like cost control, the development of safety risk analysis has lagged because of inadequate data sources. Since it is challenging to access large volumes of sensitive empirical safety data, many researchers have resorted to opinion-based ratings of safety risk (Jannadi and Almishari, 2003; Brauer, 2005; Everett, 1999; Hallowell et al., 2011). Unfortunately, human ratings of risk are vulnerable to biases in judgment that often render the data invalid (Gustafson, 1998; Kahneman and Tversky, 1982; Sjöberg, 2000). Fortunately, recent advancements in injury reporting and data collection have enabled researchers to leverage high quantities of data from private companies to perform empirical risk analyses (Desvignes (2014), Prades (2014), and Esmaeili et al. (2015a;b)). These studies involved forecasting likelihood of various injury types based upon the physical attributes of the work environment. Although physical attributes of the work environment can be used to assess the likelihood component of risk, they do not predict the severity of an injury better than random (Tixier 2016). Although this is consistent with Heinrich's (1950) axiom that the severity of an injury is largely fortuitous, we challenge this assumption with a new scientific method of severity prediction.

### *Units of safety risk analysis.*

Past safety risk studies vary in the units of analysis, which have a great impact on the generalizability and practicality of the risk ratings. All past safety risk researchers have assumed that the work can be decomposed into its constituent parts to address the variability of work activities and environments (Lingard, 2013). The decomposition has resulted in a great variety of units ranging from high-level studies that compare risk among trades (Baradan and Usmen, 2006; Fung, et al. 2010) and injury types (Hinze et al., 2005) to detailed studies looking at specific work activities and the risk associated with specific tasks (Everett, 1999; Hallowell and Gambatese, 2009; Jannadi and Almishari, 2003). The limitations arise from the fact that the units are either so overly broad that they have limited application to individual projects or are so specific that any new work methods or variation upon existing methods requires a laborious research process to collect new data. Very recently, Esmaeili et al. (2015a) introduced attribute level risk analysis, which focuses on elemental characteristics of the work that are independent of any task or environment (e.g., uneven surfaces, work at height, etc.). Although this new framework allows researchers to quantify the risk of injury for virtually any environment, risk forecasts have shown to only have moderate validity (Esmaeili et al. 2015b).

To address limitations associated with data source and unit of analysis, the present study introduces and tests a new safety risk analysis framework based on the theory that all injuries are caused by the unwanted release of energy. The theory is independent of any work environment and focuses on a fundamental natural condition. If true, the energy risk theory may prove to be a basic method for predicting injury severity and conceptualizing safety risk.

## Energy release theory

The inspiration for an energy-based approach to safety risk analysis originated with Haddon's (1968) etiologic basis for describing injury severity. Using medical diseases and symptoms as an analogy, Haddon

(1968) argued that injuries are not caused by the seemingly infinite and random collaboration of causal factors that describe the specific circumstances of the accident (i.e. symptoms). Rather, he claims that injuries should be defined by their fundamental cause, hazard energy (i.e. disease), or more specifically, the release of hazard energy and contact by an individual. Under this etiologic explanation, there must be a form of energy exchange in excess of the body's vulnerability in order for an injury to be sustained. Approximately ten years later, Haddon (1980) further expanded upon this etiological theory by introducing the concept that injury prevention should focus on the removal, reduction, isolation, or control of hazard energy.

Fleming (2009) contributed to the theory by defining various energy sources that cause injury. His argument was that industry application of the energy theory requires focus on the management of specific types of hazard energy sources (e.g., gravity, motion, electrical). Most recently, principles of the energy release theory were organized into a ten-energy-source mnemonic, which was then field-tested in an effort to measure its impact on hazard recognition skills (Albert et al. 2014a;b;c). The results of the multiple baseline test indicate that the mnemonic based learning increases hazard recognition skills by approximately 30% when compared with traditional safety planning activities alone (e.g., job safety analyses and checklists). Despite these significant advancements, there is still a dearth of research that investigates the scientific extension and practical application of hazard energy within occupational safety.

**Parallels between energy release theory and natural disaster research**

Our concept of energy-based safety risk analysis parallels modern theory of natural hazard risk assessment techniques. In essence, predicting the impact of a natural hazard relies on three fundamental factors: 1) the potential for a natural hazard; 2) the natural hazard's impact intensity; 3) and the vulnerability of the affected community (Lindell & Prater, 2003). Similar to occupational injuries, the impact (severity) of a natural hazard is very difficult to predict because it may be comprised of several hazards that may inflict damage on a particular area (Lindell & Prater, 2003). For example, one agent, such as a hurricane, may inflict casualties and damage through wind, rain, storm range, and inland flooding (Bryant, 1991). For this reason, the impact intensity of a natural hazard can generally be defined in terms of the physical materials involved (i.e. liquid in a flood or solid material in a landslide) and the energy these material impart (Lindell & Prater, 2003). Whether the goal is to predict the potential impact of landslides using the mass and velocity of a potential landslide area (Cardinali et al., 2002) or predict the potential impact of a hurricane by measuring wind speed (Moon, et al., 2007), using a natural hazard's energy allows the potential impact of various natural hazards to be expressed in one universally relatable metric (Lindell & Prater, 2003). We postulate that the same theory holds true for safety, where many sources of energy can contribute to the potential severity of an event.

The second portion of any natural hazard risk assessment is the vulnerability of an affected community and the community's ability to withstand a natural hazard. The majority of natural hazard risk analysis research studies vulnerability. For example, several studies have created models to assess the vulnerability of potentially affected areas based on variables ranging from a country's Gross Domestic Product (Kahn, 2005), the money invested in mitigation and emergency practices in the area (Lindell & Prater, 2003), the density of population and complexity of commercial infrastructure (Wei, Fan, Lu, & Tsai, 2004), or the area's reliance on the surrounding ecosystem (Tang, Li, Lei, Wang, & Shen, 2015).

**Proposed new theory: energy-based safety risk analysis**

Utilizing elemental concepts of energy release theory, we postulate that: ***the severity of a potential injury is determined by the ratio between energy intensity and the vulnerability of the human body part to which the energy is transferred***. Furthermore, a hazard's energy intensity is defined ***as the ratio between the hazard's energy magnitude and the mechanism by which energy contacts the human body***. The likelihood component of risk is, in turn, defined as the human, managerial, political, social, and stochastic factors that define the probability that energy will be released and will contact a worker. Figure 1 illustrates the proposed relationships among these factors organized in to parallel prevailing natural disaster models presented by Lindell and Prater (2003). Here, the energy transfer mechanics refer to the shape and size of the object possessing energy, which may contact the human body (e.g., a sack of concrete, tape measure, mobile equipment).

Because the vulnerability of the human body is highly variable among subjects and difficult to observe in a leading manner, the focus of this paper will be on hazard energy magnitude and intensity. Specifically, we aim to assess the extent to which energy magnitude and energy intensity predicts injury severity. Since we postulate that energy intensity is a better predictor of injury severity, we show this relationship in Figure 11.

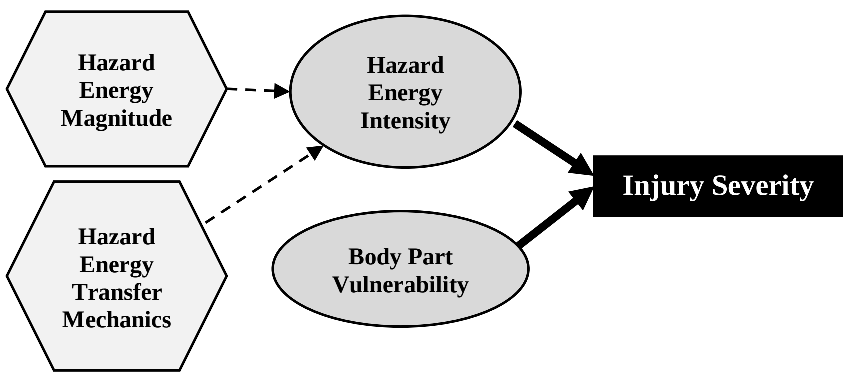


***Figure 10:*** **Proposed Energy-Based Occupational Safety Risk Analysis Framework**

***Hazard Energy Magnitude***

In order to compute energy intensity, one must first measure *energy magnitude*. Since a variety of energy sources exist in occupational environments (e.g., gravitational, kinetic, radiation), there are various methods of computing energy magnitude. For example, using basic physics, gravitational potential energy (PE) can be directly measured by finding the product of the mass of an elevated object, the height of the object, and the gravitational constant (Equation 2).

$$[2] \qquad PE = mgh$$

*where m = mass; g = gravitational constant; and h = height that the object or subject could fall.*

In a practical sense, the computation of PE is quite simple as it only requires the measurement of height and mass along with the knowledge that when either increases, the quantity of PE increases proportionally. However, translating energy magnitude to potential injury severity can be abstract without formal analysis.

Take, for example, the conditions where both a 0.5 kg tape measure and a 7 kg sledgehammer are dropped from a height of 2 meters. It is obvious that, due to the difference in mass, the sledgehammer possesses a greater quantity of energy than the tape measure. Also, it may seem intuitive that the sledgehammer has the potential to inflict greater damage and result in a more severe injury. However, it becomes comparatively difficult to intuit energy magnitude and make comparisons in extremes when more than one variable changes at a time or when different energy types are compared. For example, assessing the comparative energy between a 0.5 kg tape measure dropped from 10 meters and a 7 kg sledgehammer dropped from 2 meters is not as easy. In such cases, formal energy computations with consistent units and reliable predictive models could allow for an objective assessment of risk. In other words, formal analyses would help a person to evaluate the quantity of the energy and interpret the risk associated with the energy without judgment biases.

***Hazard Energy Intensity***

Synonymous with natural hazard risk analysis, we postulate that the actual danger associated with a hazard energy source depends not only on energy magnitude but also on the physical characteristics of the hazard itself. In order to be theoretically transferable to any hazard energy source, the term, ‘relation’, used within the definition of energy intensity references two scenarios: 1) a scenario in which a greater transfer mechanism value will increase the likelihood an individual is severely injured and be expressed in a unit of time (i.e. radiation, sound, and chemical); 2) and a scenario in which a smaller energy transfer mechanism value will result in a more severe injury and be expressed in a unit of area (i.e. pressure, gravity, and motion). Equations 3 and 4 present the respective relationships above scenarios, respectively. From a scientific standpoint, the second scenario is analogous to pressure and the translation of energy to force through Newton's Second Law of Motion. The second scenario will be the focus of the experimental portion of this study; however, the proposed theory can apply to any hazardous energy source.

$$[3] \quad Hazard\ Intensity = (Energy\ Magnitude) * (Energy\ Transfer\ Period)$$

$$[4] \quad Hazard\ Intensity = \frac{Energy\ Magnitude}{Energy\ Transfer\ Area}$$

To better illustrate the relationship between energy intensity and the severity of a sustained injury for the second scenario, a comparison between a 0.5 kg tape measure and a 0.5 kg. concrete chisel dropped from 3 meters provides a compelling example. The concrete chisel has a minimum contact area at its tip of approximately 0.6 $cm^2$ while a standard tape measure on its smallest edge is approximately 12.9 $cm^2$. Assuming that both objects strike a person with the identical impact duration and velocity (i.e., 0.05 seconds and 7.67 m/s), the pressure of the tape measure and concrete chisel are 59.5 kPa. and 1279 kPa., respectively. Although the tape measure and concrete chisel possess an equivalent amount of potential gravitational energy (14.7 joules), the disparity in impact area between the objects causes dramatic differences in pressure and injury.

Because the impact duration needed to calculate the rate of force transfer (i.e. impulse) cannot be readily measured in a leading fashion, we simplify the computation to energy intensity, which, for the example, would be 1.14 joules/$cm^2$ for the tape measure and 24.5 joules/$cm^2$ for the concrete chisel. The concept of energy intensity provides a reasonable compromise between the scientific validity and practicality, using variables that are readily observed in the field.

***Vulnerability of the human body***

Returning to the analogy of natural hazard modeling, the magnitude of a natural disaster, such as a hurricane, does not fully predict the magnitude of damage. For example, due to differences in infrastructure, a hurricane striking the coast developing country would presumably inflict more human casualties than a hurricane of the same magnitude striking a developed country. This concept, referred to as vulnerability, also applies in the context of energy-based safety risk where the extent of injury caused by a particular hazard varies depending upon the vulnerability of a particular body part to which the energy is transferred. For example, in the unfortunate case of the New Jersey construction worker being struck by a falling tape measure (Santora, 2014), the injury most likely would have not been fatal had the tape measure stuck the worker in the shoulder rather than his head. Additionally, personal protective equipment (PPE) items, such as a hard hat or padded gloves, can improve the body's resistance to injury and reduce vulnerability to impact by dispersing the energy across its surface. Although we theorize that the vulnerability of the impacted body part heavily influences the severity of injury suffered, it is difficult to evaluate this factor in a predictive sense due to the speculative nature of estimating variables such as the variations in worker actions and body position. These values are often impossible to quantify accurately from second-hand accounts in injury reports. For these reasons, vulnerability was omitted from analysis with the caveat that inclusion of this variable in future research may improve the overall scientific validity of the theory.

## HYPOTHESES

Based upon the new theory discussed above, we formed the following two priori null hypotheses:

> ***Null Hypothesis 1:*** Variability in energy magnitude measureable prior to an incident does not predict variability in injury severity better than random

***Null Hypothesis 2:*** Variability in energy intensity measureable prior to an incident does not predict variability in injury severity better than random.

In order to test these two null hypotheses, the leading information describing the circumstances on an injury from which energy magnitude and intensity could be computed was decoupled from the lagging information regarding the severity of each injury. In addition to testing the two primary hypotheses, we aimed to measure the extent to which energy magnitude and energy intensity distinguish between low severity injuries (i.e., non-fatal injury) and high severity injuries (i.e. fatalities) in an effort to define a "high energy" threshold. This was important from a practical perspective because industry practitioners are beginning to use the term "high energy" without a precise definition or threshold.

## COMPUTING ENERGY MAGNITUDE AND ENERGY INTENSITY

In this study, motion and gravity hazards were analyzed. We limited our scope to the unwanted released of gravity and motion energy sources contribute to three of the four leading classified causes of construction injuries according to the latest Bureau of Labor Statistics Occupational Injury data within construction (BLS 2015). Additionally, these two energy sources proved to be readily available for robust statistical hypothesis testing. As shown in equations 5 and 6, we needed the following independent variables to compute energy magnitude and energy intensity: the weight, height, speed, and contact area of an object or person possessing the energy. These variables are leading in that they are observable prior to an incident and objectively measurable.

Although we hypothesize that energy intensity has stronger predictive validity than energy magnitude, we recognize that, in practice, the probabilistic assessments of contact area are abstract and unrealistic. Energy magnitude, however, only requires the observation of height, weight, and velocity, which are, typically, easily estimated. Table 10 illustrates several case examples of the data needed to compute energy magnitude and energy intensity from gravity and motion.

$$[5] \qquad Energy\ Magnitude = mgh = \frac{1}{2}mv^2$$

$$[6] \qquad Energy\ Intensity = \frac{Energy\ Magnitude}{Contact\ Area} = \frac{mgh}{A} = \frac{\frac{1}{2}mv^2}{A}$$

*where m = hazard mass; g=gravitational acceleration constant; h= height of the hazard; v = velocity of hazard; and A= contact area (i.e., "sharpness" of hazard)*

***Table 9:*** **Proposed energy-based safety risk analysis computational framework with examples**

| | *Input variables* | | | | *Output Variables* | |
|---|---|---|---|---|---|---|
| | **Weig ht (kg)** | **Height (m)** | **Speed (m/s)** | **Contact Area ($cm^2$)** | ***Energy Magnitude* (joules)** | ***Energy Intensity* ($\frac{Joules}{cm^2}$)** |
| ***Computation*** | **A** | **B** | **C** | **D** | $A * B$ or $\frac{1}{2} * \left(\frac{A}{g}\right) * C^2$ | $(A * B)/D$ or $\left(\frac{1}{2} * \left(\frac{A}{g}\right) * C^2\right)/D$ |
| *Tape measure dropped from 50 stories* | 0.5 | 152.4 | - | 12.9 | 747.5 | 57.9 |
| *Bag of cement mix dropped from 1 story* | 22.7 | 3.0 | - | 232.3 | 668.1 | 2.88 |
| *Tape measure dropped from 1 story* | 0.5 | 3.0 | - | 12.9 | 14.7 | 1.14 |
| *Concrete chisel dropped from 1 story* | 0.5 | 3.0 | - | 0.65 | 14.7 | 22.6 |
| *Nail fired from pneumatic nail gun* | 0.001 | - | 30.5 | 0.008 | 0.47 | 58.14 |

## RESEARCH METHODS

The proposed hypotheses were tested by investigating the relationship between the severity of worker injury and the characteristics of the energy present before the injury was sustained. Energy magnitude and energy intensity were computed from information contained in detailed accounts of past injuries. The severity of each injury was entered into an event management system and classified according to the guidance provided by Hallowell and Gambatese (2009b). The injury severity classifications are listed in Table 11 along with their respective definitions.

***Table 10:*** **Injury classification system used during data analysis**

| Classification | Definition | Reports Analyzed |
|---|---|---|
| **1st Aid** | Any treatment of minor scratches, cuts, burns, etc. where the worker is able to return to work the same day following first-aid treatment. | 55 |
| **Medical Case** | Any work-related injury or illness requiring medical care or treatment beyond first-aid where the worker is able to return to work the following day. | 113 |
| **Lost Work Time & Permanent Disability** | Any work-related injury or illness that prevents the worker from returning to work the following day.<br><br>Any work-related injury or illness that results in permanent aliment. | 280 |
| **Fatality** | Any work-related injury or illness that results in death. | 57 |

Injury reports were obtained from three databases: (1) donation by a consortium of 281 private construction organizations over a three year span; (2) the Fatality Assessment and Control Evaluation (FACE) reports provided by the National Institute for Occupational Safety and Health (NIOSH); (3) and the Worker's Compensation Board of British Columbia (WorkSafeBC). In total, 505 reports of injuries related to gravity and motion energy sources were obtained. The distribution of injury reports within each injury classification can be viewed in Table 11.

Processing the injury report data first involved decoupling the independent predicting variables, *hazard energy magnitude* and *hazard energy intensity*, from the dependent variable, *injury severity*. Using only descriptions contained within the written injury reports, a team of three engineering students with training in Newtonian energy principles computed hazard energy magnitude and hazard energy intensity by estimating height, weight, speed, and physical characteristics of the equipment, tools, material, and workers. Importantly, the estimation of the independent variables was performed without knowing the outcome of each case. Then, statistics were applied in order to test our hypotheses. Figure 12 illustrates the described research process.

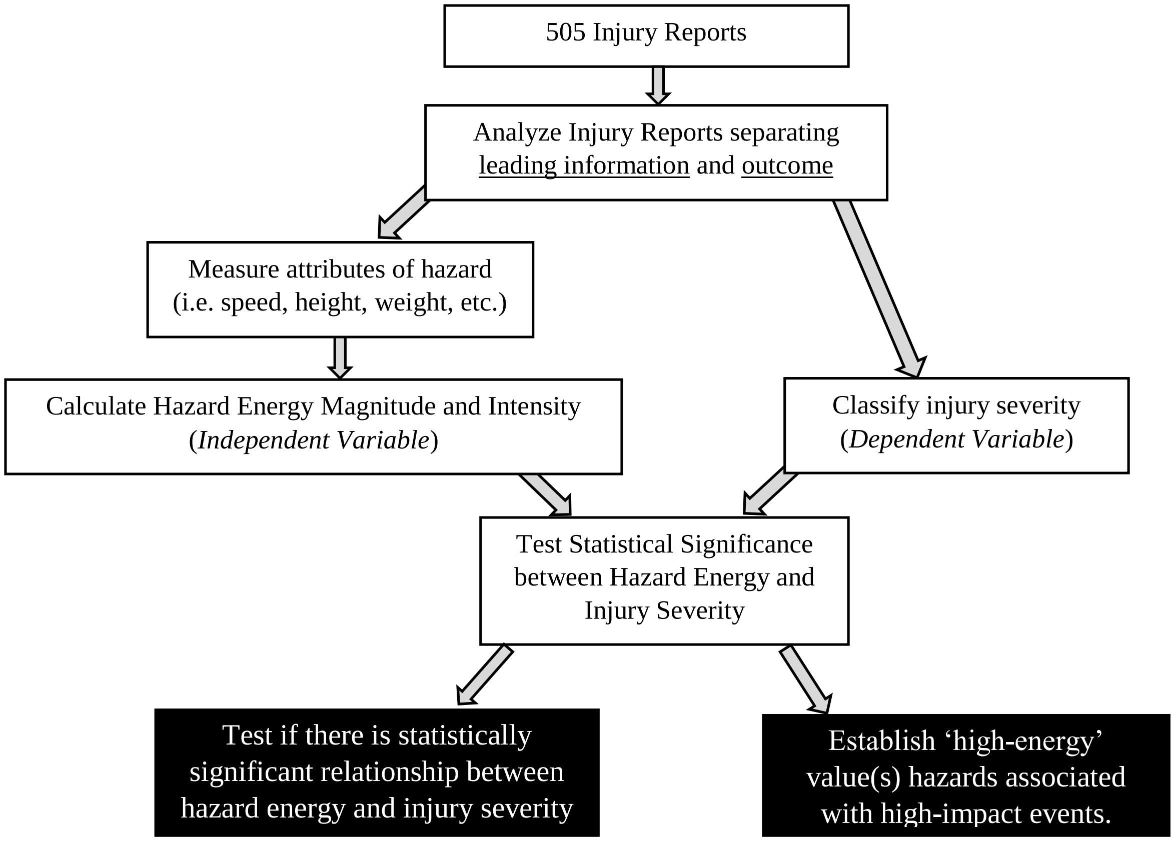


***Figure 11:*** **Diagram of Research and Analysis Process**

## RESULTS AND ANALYSIS

### Testing Statistical Significance among All Injury Severity Levels

The goal of the analysis was to measure the extent to which energy magnitude and energy intensity predict injury severity better than random. In other words, we aimed to answer the question: ***does magnitude and intensity of energy predict injury severity?*** To make this assessment, the distribution of energy magnitude for each severity level was first plotted and compared statistically. In order to visualize the distributions across the severity levels, a series of boxplots were created. In addition, approximate probability density functions (PDF's) were mapped with respect to each injury classification to visually represent the distributions of each boxplot.

It is apparent from examination of Table 12 and Figure 13 that the distribution of energy magnitude is starkly different across the severity levels (note the log scales). Because injury severity is typically observed and quantified as a step function rather than a continuous scale, the presentation of the data and the statistical metrics used to compare the groups were categorical. Furthermore, a logarithmic scale was used to facilitate visual comparison among the injury severity levels. The high energy threshold is depicted in Figure 13; however, the underlying rationale to determine the threshold will be explained in subsequent sections.

To test for differences in the energy magnitudes across severity classifications, a single-factor analysis of variance (ANOVA) test was performed. As one can see, the assumptions of approximately normally distributed data to use the ANOVA test were met. The ANOVA test indicates, and the distributions suggest, there is a significant statistical difference across all severity levels (p-value < 0.01). These results indicate that null hypothesis 1 should rejected.

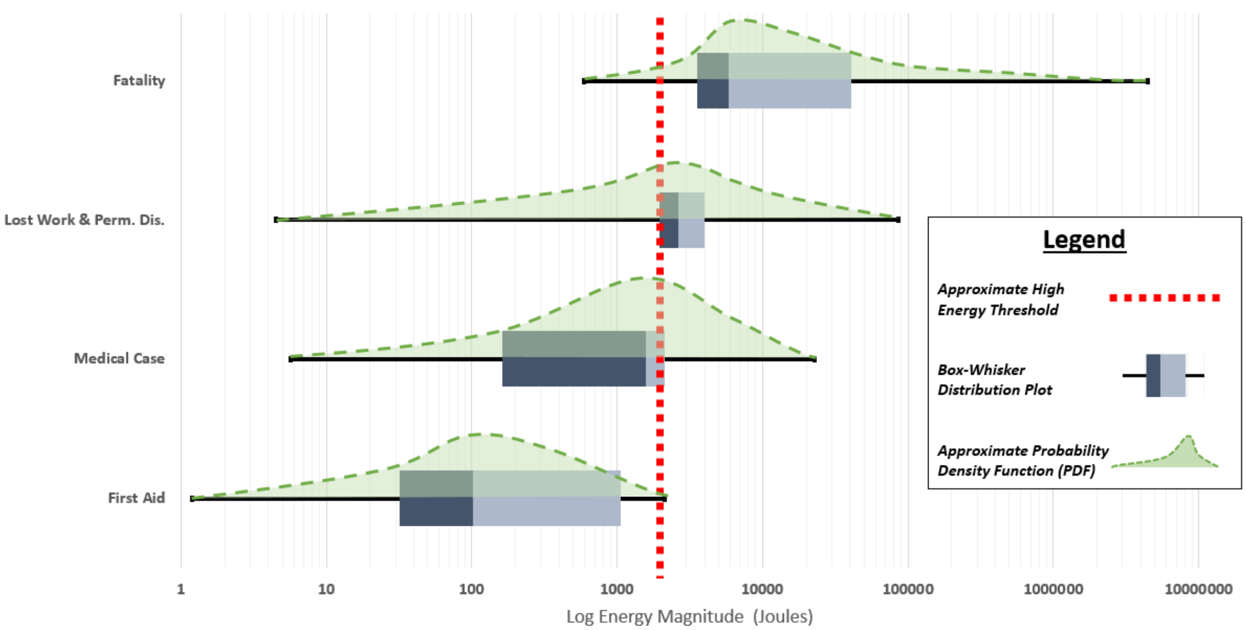


***Figure 12: Boxplot distributions of energy magnitude with respect to injury severity***

***Table 11: Demographic statistics for energy magnitude***

| | Fatality | Lost Work & Permanent Disability | Medical Case | First Aid |
|---|---|---|---|---|
| **Number of Reports** | 57 | 288 | 134 | 57 |
| **Min. (*joules*)** | 590 | 5 | 6 | 1 |
| **Quarter 1 (*joules*)** | 3,580 | 1,952 | 162 | 32 |
| **Median (*joules*)** | 5,859 | 2,645 | 1,587 | 103 |
| **Quarter 3 (*joules*)** | 40,689 | 3,967 | 2,116 | 1,058 |
| **Max (*joules*)** | 4,433,408 | 85,853 | 22,652 | 2,121 |

***ANOVA (Single Factor) p-value < 0.01***

The same analyses were performed using energy intensity values for each injury classification. A similar boxplot format was employed to graphically compare the energy intensity distributions (see Figure 14). The salient values are shown in Table 13. Again, the high energy threshold is shown in Figure 4 but will be explained in following sections. When compared with the distributions for energy magnitude, energy intensity showed significantly less variability among the severity groups (i.e., the variability decreased significantly by adding the variable contact area). Accounting for contact area reduced both the variance within each severity level and overlap among severity levels. This indicates that energy intensity predicts injury severity better than energy magnitude. Similar to the analysis performed with energy magnitude, a single-factor ANOVA statistical test was performed, yielding a p-value < 0.01. These results indicate that null hypothesis 2 should also be rejected.

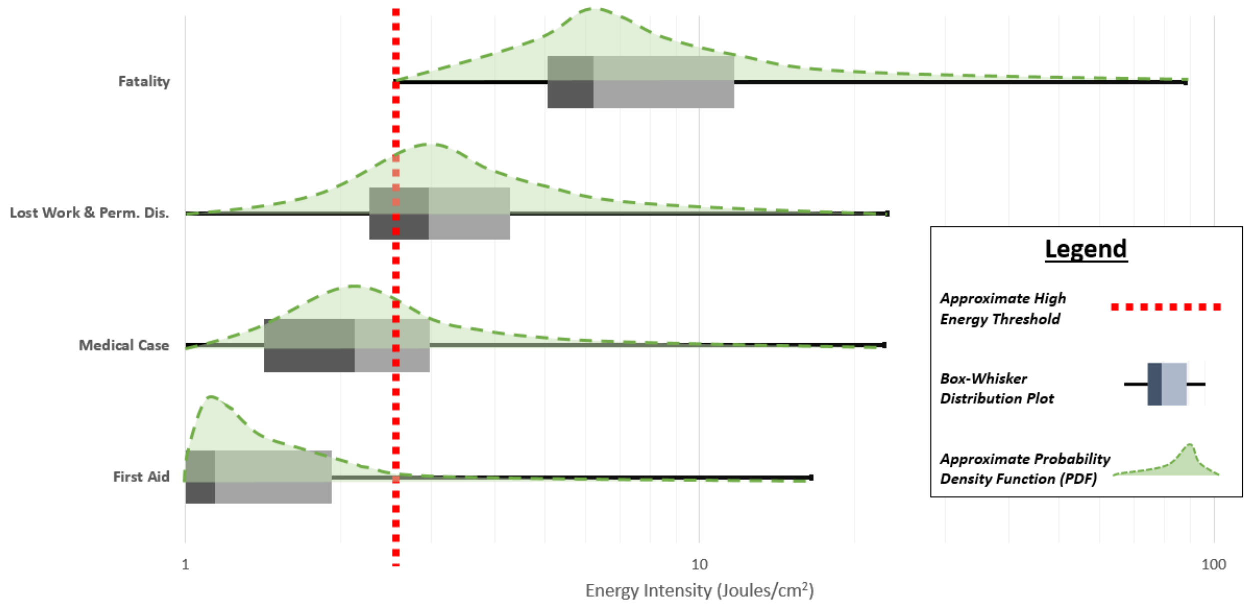


***Figure 13: Boxplot distributions of energy intensity with respect to injury severity***

***Table 12: Demographic statistics for energy intensity***

| | Fatality | Lost Work & Permanent Disability | Medical Case | First Aid |
|---|---|---|---|---|
| **Number of Reports** | 56 | 280 | 113 | 55 |
| **Min.** ***(joules/cm²)*** | 2.6 | 0.35 | 0.27 | 0.092 |
| **Quarter 1** ***(joules/cm²)*** | 5.1 | 2.3 | 1.4 | 0.60 |
| **Median** ***(joules/cm²)*** | 6.2 | 3.0 | 2.1 | 1.1 |
| **Quarter 3** ***(joules/cm²)*** | 11.7 | 4.3 | 3.0 | 1.9 |
| **Max** ***(joules/cm²)*** | 88.3 | 23.2 | 22.9 | 16.5 |

***ANOVA (Single Factor) p-value < 0.01***

## Defining a "high energy" threshold

As previously indicated, one goal of our analysis was to help practitioners to distinguish conditions that may lead to a fatality from non-fatal events. In other words, we aimed to define the "high-energy threshold." The implication is that, if the potentially fatal conditions can be identified before an event occurs, targeted and potentially costly prevention efforts can be implemented with confidence grounded in empirical evidence.

To measure this threshold, a standard t-test was performed comparing energy magnitude and intensity for fatal and non-fatal events. The results indicate very strong differences in energy between fatal and non-fatal events (p-values for hazard energy magnitude and hazard energy intensity of 0.06 and 0.00007, respectively). Figure 15 and 16 present the distribution of hazard energy of high impact events and low impact events for both hazard energy metrics.

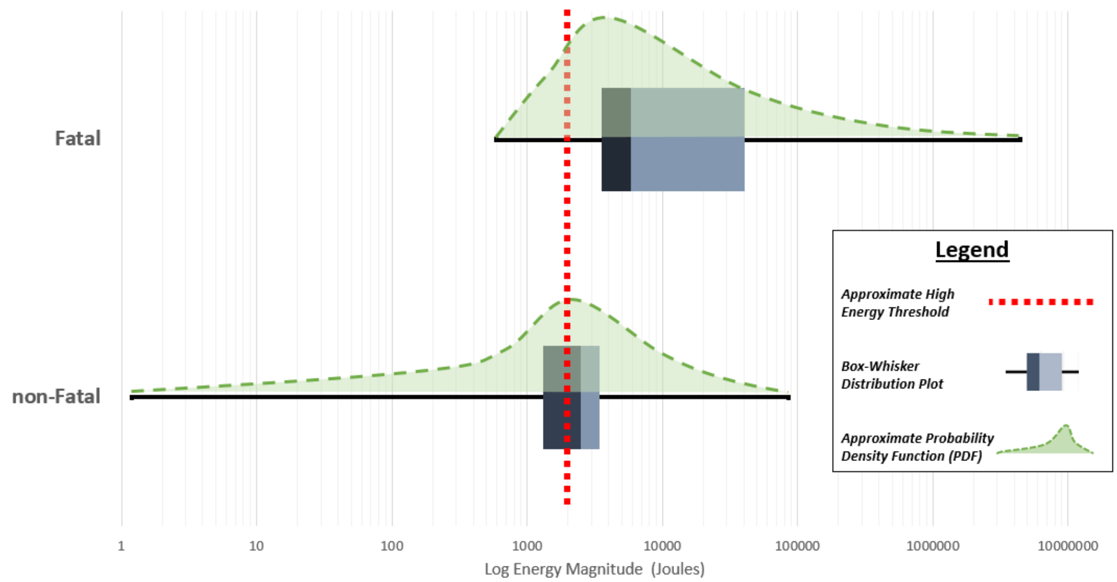


***Figure 14: High and Low Impact Event Energy Distributions for Hazard Energy Magnitude***

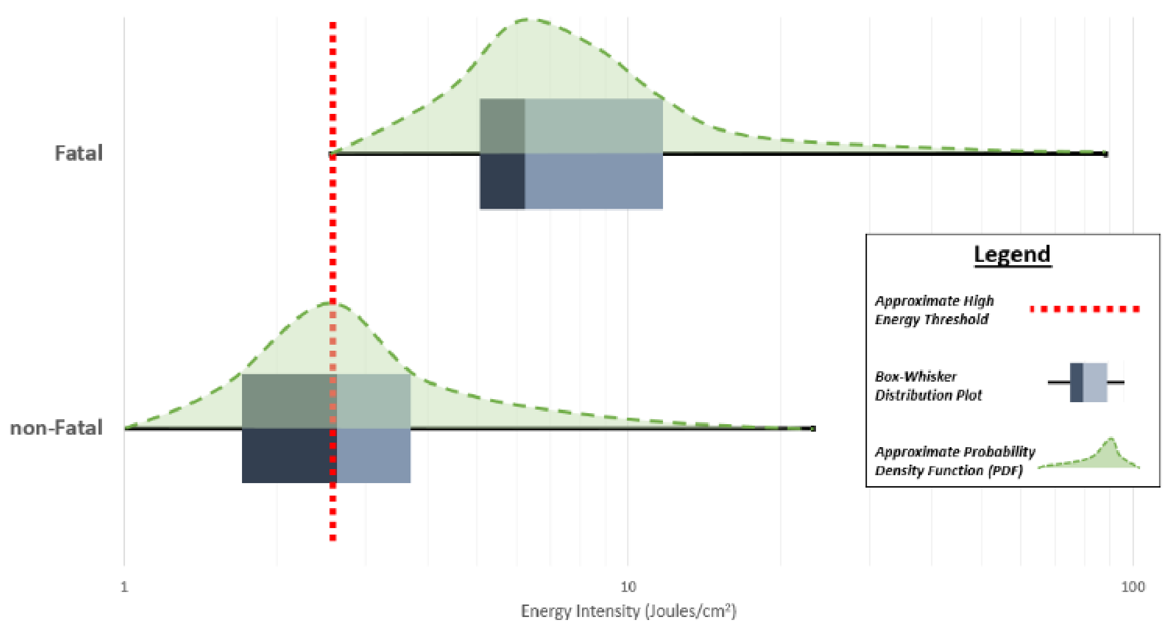


***Figure 15: High and Low Impact Event Energy Distribution for Hazard Energy Intensity***

# DISCUSSION AND INTERPRETATION

## Explaining the variability and extreme values

Wide variability within the data can be seen within each injury classification, which causes modest overlap between the differing injury severity distributions. To study this variability, extreme cases were examined. Such an examination also provided insight as to why energy intensity was, indeed, a better predictor of injury severity than energy magnitude. The examination for these extreme cases revealed that much of the variability can be explained using the previously explained concepts of impact area (i.e., "sharpness") and the vulnerability of the affected body part. When computing energy magnitude alone, the impact area is neglected, which does not account for sharp objects that cause a plethora of injuries. For example, one injury involved a worker who fell 0.7 meter and landed on a flat surface on his back and another report described a worker being struck in the head by a corner of oriented strand board (OSB) sheathing panel. Both incidents involved approximately 600 joules of energy; however, the worker who fell on his back sustained only minor contusions (first aid) while the worker who was struck by OSB sheathing was killed. The worker struck by the OSB sheathing unfortunately sustained fatal injuries despite the relatively low magnitude of energy because he was struck by a relatively sharp object at a vulnerable part of his body. In contrast, the other worker sustained only minor injuries because he fell on a flat surface and contacted a more resilient part of his body.

In order to better understand the role that impact area and body resilience affect injury severity, these variables were isolated and anomalous conditions (e.g., cases in the overlap among distributions) were studied. Table 14 provides several example injury reports of similar *energy magnitude* where the injury severity varied greatly. For each case, the estimated contact area of the object-person interaction is provided. One can easily see from these cases why energy intensity was a better predictor of injury severity than energy magnitude alone. It should be noted that these cases were used because they represent situations where the various distributions shown in Figure 13 overlap.

***Table 13: Examples of injury reports in which contact area affected the severity of injury sustained***

| **Injury Severity** | **Verbatim Injury Report** *(Described Units Converted to Metric)* | **Impact Area** | **Approximate Energy Magnitude** | **Approximate Energy Intensity** |
|---|---|---|---|---|
| **Fatality** | A worker was crushed by a lift of OSB sheathing when it slipped off the forks of a skid steer loader, falling approximately 8 feet. | ~ 29 $cm^2$ | 590 *joules* | 21.8 $joules/cm^2$ |
| **Permanent Disability or Lost Work Time** | A worker was on the third rung of a 6-foot stepladder that was set up leaning against the side of a flatbed trailer. The worker slipped off the ladder and fell to the ground (about 3 feet). | ~ 155 $cm^2$ | 793 *joules* | 5.13 $joules/cm^2$ |
| **Medical Case** | The turned on the foot bridge and walked off into the excavation (3-4 ft.) where the worker struck his head and shoulder on some wooden forming materials. | ~ 465 $cm^2$ | 793 *joules* | 1.70 $joules/cm^2$ |
| **First Aid** | A worker fell 3 feet from an aluminum sawhorse, landing squarely on his back. | ~ 929 $cm^2$ | 793 *joules* | 0.84 $joules/cm^2$ |

As expected, the energy intensity values for the examples listed in Table 15 appear to appropriately correlate with the severity of injury sustained due to the fact that energy intensity accounts for the impact area of a hazard. Consequently, the inclusion of impact area resulted in less variability and overlap between injury severity distributions within the energy intensity data; however, despite the increase in accuracy, the energy intensity distributions still overlap to a modest extent (see Figure 14). This residual variability can be primarily attributed to the vulnerability of the body part affected. For example, one injury classified as Permanent Disability involved a worker falling 2.4 meters (8 feet) off of a stepladder, which had approximately the same level of energy intensity as a Medical Case injury which involved a non-structural steel member falling 3 meters (10 feet). The disparity in injury severity can be explained when one considers the vulnerability of the body part impacted. In the 'Medical Case', the beam struck the worker's shoulder, arm, and hand whereas the more serious injury involved an impact to the head and back. Table 15 lists example injury reports in which body vulnerability had an effect on the injury severity. Looking at the listed injury report examples in addition to the analysis results, it appears that energy magnitude and energy intensity are equally susceptible to inaccuracies due to body vulnerability.

***Table 14: Examples of injury reports in which body vulnerability impacted injury severity***

| Injury Severity | Injury Report | Impact Area | Body Part Impacted | Approximate Energy Magnitude | Approximate Energy Intensity |
|---|---|---|---|---|---|
| **Fatality** | "A 37-year-old male laborer fell approximately 13.5 feet from a residential roof to a concrete driveway; he died immediately from his injuries." | ~ 929 $cm^2$ | Head & Back | 3580 *joules* | 3.85 $joules/cm^2$ |
| **Permanent Disability or Lost Work Time** | A worker was standing on an 8-foot stepladder while installing a vent in an 11-foot ceiling. The worker fell to the ground. | ~ 929 $cm^2$ | Head & Back | 2117 *joules*. | 2.27 $joules/cm^2$ |
| **Medical Case** | "…The clamp supporting the beam slipped and the beam fell about 3 meters, striking the worker at ground level." | ~ 929 $cm^2$ | Shoulder, Arm, & Hand | 2592 *joules* | 13.3 $joules/cm^2$ |
| **First Aid** | "Employee received a contusion to the left foot after a belly liner weighing approximately 300 pounds fell approximately one foot striking the employee on the left foot." | ~ 155 $cm^2$ | Foot | 407 *joules* | 2.63 $joules/cm^2$ |

## Defining 'high energy' hazards

The comparisons between serious injuries and less serious injuries using the high and low thresholds was performed with the ultimate goal of identifying values for energy magnitude and energy intensity that distinguish high-impact events (i.e. fatal injury) from low-impact events (i.e. non-fatal). Unfortunately, due to the explained variability within each severity classification, a clear and distinctive value did not arise from the data. Therefore, values using deterministic and probabilistic logic for each metric are presented below.

***Deterministic High Energy Threshold***

Initially, the ‘high energy’ criterion was chosen to be the minimum *energy magnitude* and *energy intensity* values for high impact events, which, in the context of this study, was fatal injuries. These values were 590 joules and 2.56 joules/cm.$^2$, respectively. Although the 2.56 joules/cm.$^2$ ‘high energy’ threshold for *energy intensity* includes approximately 50% of the non-fatal injuries and 25% of the injuries classified as ‘Medical Case’ or ‘First Aid’, this value, upon further investigation, appears to be a reasonable threshold. In assessing the low-impact injuries that contained an *energy intensity* greater than 2.56 joules/cm.$^2$, it was determined using the judgement of the researchers that most of these injuries could have reasonably resulted in a fatality (e.g. several falls from 6 meters or higher, 24” concrete pipe weighing 318 kg. landing on a worker’s leg, a nail fired from a pneumatic nail gun into a worker’s leg, etc.).

Contrarily, the use of the minimum *energy magnitude* value to establish the ‘high energy’ criteria proved to be of limited value. As one can see in Figures 3 and 5, the ‘high energy’ threshold of 590 joules overlaps an even larger portion of less severe injuries (e.g. low-impact injuries). One of the primary flaws in using *energy magnitude* was the notable inaccuracies implicated with smaller hazards. For instance, the value of 590 joules initially chosen to be a criterion for ‘high energy’ represents the minimum value evaluated for a fatality and involved an OSB board striking a worker’s skull. In a different context, the *energy magnitude* present within this fatality is roughly equivalent to a worker falling from a height of 0.7 meters. Taken literally, using 590 joules as the criterion indicates any work being performed where a worker is located 0.7 meters above the ground is ‘high energy’ and has potential to be fatal. Certainly this is not the case and the *energy magnitude* threshold of 590 joules needed adjustment.

During analysis, *energy magnitude* proved to be an accurate predictor of hazards that were neither sharp nor small, such as falls from height or impacts from large vehicles. Therefore, in order to establish a new, more accurate criterion for 'high energy' using hazard *energy magnitude*, only the injuries that could be accurately depicted were considered. Following this realization, the new 'high energy' criterion for energy magnitude became approximately 2000 joules and was obtained from a worker who tragically sustained fatal injuries after falling form height of 2.44 meters. This value represents the minimum *energy magnitude* for fatal injuries that could be accurately predicted using energy *magnitude* metric. Although the new 'high energy' criterion for *energy magnitude* is not a comprehensive value in that it does not include all HILF injuries, it provides a more practical and useful benchmark in evaluating 'high energy'. Table 16 lists examples of hazards evaluated in the data that contained roughly equivalent *energy magnitude* and *energy intensity* values to the established 'high energy' criteria. The 'high energy' criteria for each metric has also been marked and labeled on Figures 13, 14, 15, and 16 as well.

***Table 15: Deterministic 'High Energy' Criteria with approximate examples***

| | **'High Energy' Criterion** | **Example 1** | **Example 2** |
|---|---|---|---|
| **Energy Magnitude** | 2000 joules | A worker falling from a height of 2.4 meters. | A standard scaffolding board (approximately 20 kg.) falling 3 stories |
| **Energy Intensity** | 2.56 joules/cm$^2$ | A worker falling 2.4 meters. and landing on back | A framing hammer being dropped from a height of 2.4 meters. |

**Note: Contact area was estimated for energy intensity values; the 'high energy' criterion is not absolute.*

***Probabilistic "High Energy" Threshold***

Similar to techniques used in fields such as earthquake engineering that utilize deterministic and probabilistic approaches to hazard assessment (Villaverde, 2009), a probabilistic approach to evaluating hazard risk was used to compliment the deterministically established high energy criterion of 2000 joules and 2.56 joules/cm$^2$. To accomplish this task, *logit* regression models were fit to the data using each respective hazard energy metric as the predicting variable and the injury severity (fatal or non-fatal) as the dependent variable. The resulting regression equations are provided below for each hazard energy metric using two arrangements and provide a means to predict the probability of a high-impact event's occurrence. Equation 8 and 9 will output the probability of a high-impact, fatal event occurring for any given hazard energy value, X. For example, a hazard possessing 2000 joules would have a 6% chance of resulting in a fatal injury. Equation 10 and 11 allows for the reverse calculation to take place in which a desired probability for high-impact injury, in decimal format, could be inputted for $P$ to calculate a resulting hazard energy threshold. This would allow a user to set a desired high energy criterion based on probabilistic data in place of the deterministic value of 2000 joules or 2.56 joules/cm$^2$.

**Hazard Energy Magnitude Probabilistic Equations**

[8] $$P(x = Energy) = \frac{e^{-2.9768+0.00016(X)}}{e^{-2.9768+0.00016(X)} + 1}$$

[10] $$X_{Energy} = \frac{\ln\left(\frac{P}{1-P}\right) + 2.9768}{0.00016}$$

**Hazard Energy Intensity Probabilistic Equations**

[9] $$P(x = Energy) = \frac{e^{-3.9065+0.386(X)}}{e^{-3.9065+0.386(X)} + 1}$$

[11] $$X_{Energy} = \frac{\ln\left(\frac{P}{1-P}\right) + 3.96065}{0.386}$$

## CONCLUSION

The fundamental purpose of the research was to test the hypothesis that the variability in energy magnitude and intensity predict the severity of an injury better than random. In testing the null hypothesis, a theory was presented based on the concepts of energy, pressure, and body vulnerability. This theory, energy-based safety risk assessment, was inspired by natural hazards research. The theory was tested using data from 505 information-rich injury reports gathered from multiple data sources. Two metrics were successfully used to represent hazard energy: magnitude and intensity. Energy magnitude offers a simplistic evaluation of safety risk at the expense of certain inaccuracies; in particular, inaccuracies involving sharp or small hazards. These inaccuracies ultimately led to large data variability that, at times, compromised the predictive value of energy magnitude. Energy intensity proved to be a better predictor of injury severity but is also more burdensome and computationally intensive. Thus, practitioners must weigh the benefits of increased accuracy against the drawbacks of additional computation.

Although the concept of predicting injury severity from energy may seem logical and obvious, this concept has never been formally defined or analyzed. This corresponds with inconsistent and unscientific use of the term energy as it applies to safety. There was a lack of knowledge of what constitutes high energy, i.e., enough energy to cause serious or fatal injuries. The implication of a formal analysis of energy magnitude and energy intensity is that these variables can be measured and tracked as projects progress and worksites are designed to identify and empirically analyze vulnerability. Such analysis offers the opportunity to identify and monitor energy sources in design, model energy in technological systems like Building Information Models, and alert workers using proximity sensing technology. Simply, this theory and the associated analysis offers a new way of empirical measurement of workplace hazards and risks.

Albert et al. (2014), who utilized the concept of hazard energy, was able to improve deficiencies in worker hazard recognition by creating a universally applicable mnemonic system that is independent of any specific work scenario. The proposed energy-risk based analysis technique would enjoy similar benefits within the context of safety risk analysis, advancing the practical application of Haddon’s (1968) original etiological approach to injury prevention. Hazards can be dissected to their most elemental form that, when combined with probability, can be theoretically applied with relative ease to nearly every construction project or activity and addresses a significant limitation in the current state of safety risk analysis within construction safety. Initial data presented in this study demonstrates that energy-based safety risk analysis possesses significant promise in becoming a much improved and more universally accessible technique for safety risk analysis.

To the knowledge of the authors, this is the first significant study relating injury severity to hazard energy and, as expected, initial limitations were revealed. Most notably, it was discovered that the energy intensity metric could not accurately depict ‘mechanical’ hazard energy sources (i.e., saws, grinders, etc.).

Mechanical hazards resulted in outlying values for energy intensity predicting much higher injury severity than what actually resulted. As anticipated, the explanation for this discrepancy relies on the concept of body vulnerability. Similar issues were encountered for biological and chemical hazards where severity seems to be predicted in a more dichotomous fashion. For example, a particular biological agent like a bee or a snake either causes great harm in normally encountered situations or causes little to no harm, depending on the agent. These other forms of energy offer opportunity for future research.

Another important limitation of the study is the presented energy values can only be compared relative to one another. Approximate values for worker mass and hazard impact area were used and, if altered, would change the resulting energy values. This makes outside comparisons of hazard energy sources potentially inaccurate if differing values are used. As a result, these values must be kept consistent during analysis until definitive computational hazard values can be established.

Despite the limitations, this study has advanced knowledge and formalized the theory of energy transfer. Just as researchers in natural hazard prediction have become adept in natural hazard risk analysis due to an energy-based approach for natural hazard modeling, a similar understanding from the perspective of safety can improve proficiency in safety risk analysis. To build upon our research we suggest three areas: 1) utilizing body vulnerability in predicting injury severity; 2) analyzing other hazard energy forms; and 3) establishing a definitive set of computational values to be used in analysis to establish universal hazard energy values. Residual variability present within both metrics was, in large part, attributed to the body part where the injury was inflicted. Although implications were discussed, empirical investigation of injury severity in relation to body vulnerability remains to be extensively investigated. Furthermore, analysis using energy magnitude and energy intensity was respectively limited to two (i.e., gravity and motion) of the ten identifiable energy forms on a construction site due to sample size limitations. Supplementary exploration is needed regarding the other hazardous energy sources to further validation of this study's results. Lastly, a significant limitation of this study was the fact the hazard energy values can only be used in relative comparisons due to potential discrepancies among approximated values used during analysis. An important step in advancing energy-based safety risk analysis will be the establishment of standard computational values that will, over time, allow universal values for hazard energy to be established.


## ACKNOWLEDGEMENTS

The authors would like to acknowledge the generous funding from the Construction Industry Institute, which supported this research effort and the participation of the members of Research Team 321. The opinions expressed in this article are solely those of the authors and do not necessarily reflect the opinion of the Construction Industry Institute or its members.


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# CHAPTER 5: EXECUTIVE SUMMARY

## SUMMARY

Over the past few decades total recordable injury rates have shown great improvement. However, recent data reveal that, although the annual rate of lower severity injuries has improved, the rate of fatalities appears to have plateaued. Studies of catastrophic incidents in other industries have revealed that fatal and disabling events are preceded by events or conditions that can be detected and, if acted upon, can prevent the fatal and disabling incident. Although the precursors present in each industry are often unique because of the nature of work, the methods implemented to identify and analyze precursors in each industry are consistent.

Using a combination of literature review, input from industry experts, empirical data collection, a series of randomized and blinded experiments, and objective multivariate statistical analyses, the research was able to achieve the aforementioned goal and exceed original expectations. This project yielded the construction industry's first valid and reliable method for identifying leading conditions that predict fatal and disabling injuries. Figure 17 is the most elegant summary of the results. As the figure shows, one must first assess energy magnitude. If energy is high (>1,500 ft-lb), the precursor analysis protocol should be deployed and the results should be assessed. If the results of the precursor analysis indicate that the workers are at high risk (i.e., score of 4 or greater on the protocol), the work should be stopped immediately and not released until corrective action is taken. A precursor score of 4 or above in a high energy situation indicates that there is high risk of a fatal and disabling injury occurring *and* key elements of vulnerability present, which is an extremely concerning couplet. This guidance is based on empirical data, scientific experimentation, and conservative recommendations from experts in construction safety.

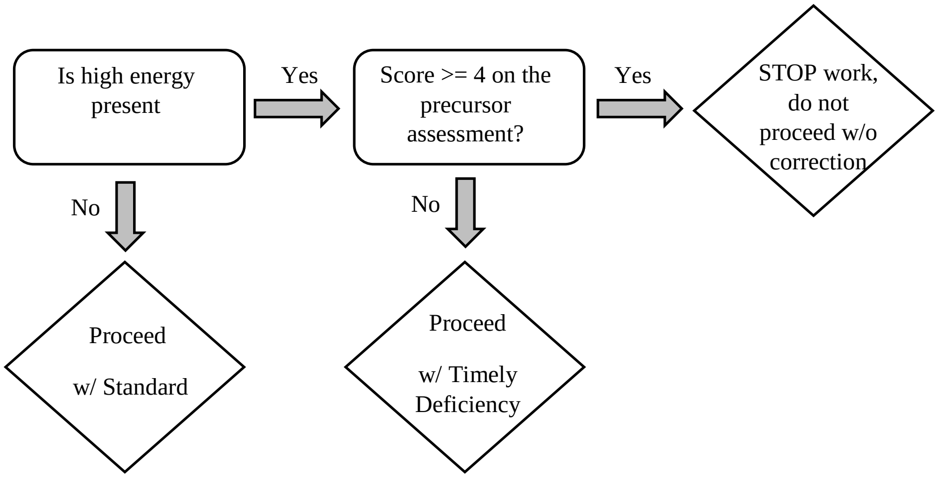


***Figure 16: Recommended precursor analysis process***

## KEY FINDINGS

1. **The process of predicting a fatal and disabling injury is <u>far</u> more difficult than conducting a retrospective root cause analysis.** The construction industry is relatively adept at performing retrospective root cause analyses of safety events. However, the transition from a retrospective analysis to a predictive analysis proved to be extremely difficult, even for the industry-leading experts on this team. With the precursor analysis protocol the approach became methodical, efficient and, most importantly, accurate with predictions far outperforming original goals.

2. **Precursors are different than leading indicators, and precursor analysis is different than monitoring and evaluating leading indicators.** Prior CII research (RT284) exposed the importance of identifying and monitoring leading indicators of safety performance. Although leading indicators provide a means to assess overall safety performance on a project, precursors indicate the likelihood of an injury incident occurring during a specific work operation. Precursor analysis is also designed to be conducted at the work face to assess planned or on-going work operations at the worker and task levels. Both monitoring of leading indicators and precursor analysis are essential.

3. **The quantity of energy present in a work operation or condition before an incident occurs is a direct predictor of the severity of an injury.** It is not feasible to conduct a precursor analysis for all construction tasks on every project. The time and resources required are simply too burdensome. Thus, the industry needed guidance on when to initiate the precursor analysis process. The philosophy was that a precursor analysis should be conducted any time the work situation has the potential to be fatal or life-altering. In order to objectively assess this potential, we tested the hypothesis that the quantity of energy present before an incident occurs directly predicts the severity of an injury. An analysis of 505 cases showed that energy magnitude does, indeed, predict injury severity and a threshold of 1,500 ft.-lbs. defines a boundary above which a fatal and disabling injury is very likely.

4. **Professionals are able to use the precursor analysis protocol developed in this research and their intuition to correctly predict the occurrence of fatal and disabling events significantly better than random.** Not all high-energy situations involve injury. The core of our research involved a blind, randomized experiment designed to measure the extent which professionals with varying levels of expertise could distinguish between fatal and disabling cases and success cases when presented only with leading information obtained through a conversation with workers prior to or during the work. The results showed that industry professionals with 5 or more years of safety experience are able to predict the correct outcomes and distinguish fatal and disabling injury cases from success cases far better than random ($p$-value $< 0.01$).

5. **Errors made in prediction were most often conservative.** When using intuition to distinguish between successful and fatal and disabling injury cases, all errors involved the prediction of fatal and disabling injury events when the scenario was actually successfully completed without an injury. Despite a limited sample size, there were no instances where the majority of participants incorrectly predicted success for an actual fatal and disabling injury.

6. **Mathematical models provide a valid, reliable, and objective method for predicting the occurrence of fatal and disabling injuries.** The gold standard for this research was the creation of a data-driven objective method for predicting fatal and disabling injury events that complements intuition and experience. Using the data extracted during the iterative experiment and the known outcomes, a generalized linear model was created that is able to predict the outcomes of new cases with nearly perfect skill. This model was translated into a user-friendly scorecard.

7. **The precursors for fatalities and severe injuries are indistinguishable from those that were involved in high-energy near misses.** Many industry professionals are beginning to share the sentiment that near misses should be analyzed and treated as if they were events that resulted in actual injuries. This research revealed that there is no significant statistical distinction between the precursors for events that result in fatalities, disabling injuries, and the precursors of high-energy near misses (p-value = 0.21). This is empirical evidence that high-energy near misses are, in their essence, fatal and disabling injury events and should be treated the same as actual fatalities. They should trigger serious organizational investigations and be used as vital data for bolstering precursor analysis and other safety programs.

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