Safety Risk Management for Electrical Transmission and Distribution Line Construction

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Abstract

Prior research has established that electrical contractors involved in the construction and maintenance of electrical transmission and distribution (T&D) lines are at extremely high risk of electrocution. The result of inadvertent contact with T&D lines often is death or severe injury that involves damage to internal organs, musculoskeletal disorders, neurological damages and severe burns. The International Electrical Safety Foundation has demonstrated that contact with overhead power lines has been the single largest cause of electrical fatalities over the last decade. To reduce this disproportionate injury rate, electrical contractors implement many strategies such as the use of rubber insulating equipment, and locking devices. Unfortunately, these strategies are often cost-prohibitive in certain construction and maintenance scenarios. Therefore, electrical contractors are faced with complex decisions that involve comparing the cost of injury prevention with the expected safety benefit. This paper presents research that objectively evaluated the risk associated with common T&D construction tasks and the effectiveness of specific injury prevention techniques. The research team then developed a decision support framework that provides electrical contractors with objective safety and cost feedback given specific project characteristics. The results indicate that many of the effective strategies implemented to reduce T&D electrical injuries are very costly (e.g., de-energizing lines). Consequently, under most conditions, the costs of injury prevention far outweigh the cost savings associated with the reduction of injury rates. The implication of these findings is that T&D electrical contractors must highly value the non-monetary benefits of injury prevention in order to improve safety in their sector.
According to the U.S. Energy Information Administration (2010), more than 4 billion mWh of electricity is generated annually in the United States to serve more than 300 million people. This electricity is transmitted for consumption through electrical transmission and distribution (T&D) lines. The nominal voltage in bulk transmission lines can be as high as 750 kV (Short, 2004). Electric contractors involved in the construction and maintenance of these electrical T&D lines are at extremely high risk of electrocution. In fact, according to the International Electrical Safety Foundation (2010), contact with overhead power lines has been the single largest cause of electrical fatalities every year between 1992 and 2009. Furthermore, the Bureau of Labor Statistics estimates that among the 192 recorded electrocution fatalities in 2008, 53% involved overhead power lines and the National Institute for Occupational Safety and Health (2009) documented that 80% of fatalities among linemen have occurred due to direct contact with T&D power lines. Such a disproportionate injury rate caused the Bureau of Labor Statistics (2010-2011) to classify T&D line construction and maintenance as one of the most dangerous jobs in the American economy.

The impacts of T&D electrical injuries are substantial. The result of inadvertent contact with T&D lines is often death or severe injury that involves damage to internal organs, musculoskeletal disorders, neurological damage, and severe burns (Lee et al., 2000). Such injuries cause long-term physical and emotional distress to workers and their families. In addition, these injuries and fatalities result in substantial economic expenses such as: higher insurance premiums, medical cost, compensations, lost productivity, administrative costs, and others (Everett et al., 1996; Ferret and Hughes, 2007; Oxenburg and Marlow, 2005; Tang et al., 2004). According to Waferer et.al (2007), the construction private sector accounted for $11.5 billion in fatal and non-fatal injuries in the year 2002. The electrical T&D sector contributed greatly to these statistics. In fact, the average cost of each electrical fatality was $4 million and the cost of each lost work time injury was $42,207. Despite the high injury and fatality rates and their severe financial and personal impacts, the electrical T&D industry continues to grow at an alarming rate.

Research in the electrical T&D sector has predicted that recent technological advances will force utility companies to construct new lines, maintain existing lines, and upgrade their performance (PNNL, 2002). It has also been estimated that the demand for electricity will increase by more than 1 trillion kilowatt-hours from the years 2003 to 2020 Further, studies by the Edison Foundation (2008) have shown that, the electrical utilities will have to make an investment of $1.5 to $2.0 trillion by the year 2030 to keep up with the pace in demand. These investments to enhance the T&D infrastructure will likely increase the volume and complexity of T&D electrical line work over the next 20 years (ESFI, 2010). Electrical utilities and contracting companies clearly need to consider injury prevention strategies that reduce the frequency and severity of injuries and their associated monetary and non-monetary costs. When addressing this issue, electrical

Introduction
contractors and utility companies are faced with complex decisions involving weighing the cost of injury prevention against the expected safety benefit.

The purpose of this study was to objectively evaluate the costs and benefits of safety management techniques in the electrical T&D sector of the US construction industry for commonly-encountered work scenarios. The associated objectives of this research study were to: (1) identify common work tasks performed around T&D lines and safety strategies used by utility companies to prevent injuries; (2) quantify the safety risk associated with each work task using a combination of opinion-based and empirical data; (3) quantify the percent risk reduced by the various injury prevention strategies; and (4) apply a risk-based contingent liability model developed by Hallowell (2011) to analyze the cost-benefit of the injury prevention strategies under specific work scenarios. The result is a stable, valid, and reliable decision support tool that provides critical safety and cost feedback that practitioners can use to make informed decisions that enhance both safety and financial performance.
To provide context for this study and better understand the unique features of the electrical T&D sector, the writers reviewed literature on the topics of electrical T&D operation, the effect of high voltage electrical current on the human body, safety risk quantification, and safety risk mitigation. Though a thorough review revealed no research that had specifically quantified safety risks in the T&D sector or the impacts of commonly implemented injury prevention strategies, guidance from similar studies in other industry sectors were used as guidance. The results of this literature review are summarized briefly below.

2.1 Electricity Transmission and Distribution (T&D) Operation

Electricity is generated by the conversion of the stored energy in gas, oil, nuclear fuel or water position (Karady, 2006). The voltage at the point of generation is usually between 15 to 25 kV, which, unfortunately, is not ideal for transmission due to losses that may occur. In order to reduce power losses during transmission, a transformer is used to step up the voltage in the transmission line to 230-750 kV. Subsequently, the voltage is reduced at a substation preceding the sub-transmission lines between 69 to 169 kV, which leads to the primary distribution line where the voltage is maintained between 4 to 35 kV (Short, 2004). Finally the distribution transformer reduces the voltage to 120 and 240V, which is supplied to consumers through the secondary distribution lines.

2.2 Impacts of High Voltage Electrical Current on the Human Body

The effect of contact of electricity with the human body is highly random and often manifests itself in a number of ways. Electrical injuries are usually induced primarily through hazards such as shock, arc and blast (Cadick et al., 2005). In the case of an electric shock, the degree of the injuries is typically a function of the intensity of current, current flow path, the duration of contact with the source, and the voltage magnitude (Lee 2000). The nervous, musculoskeletal, cardiovascular and the pulmonary system can be adversely affected due to the flow of electricity (Spies and Trohman, 2006). Gordon and Cartelli (2009) recently categorized electrical injuries as:

- Immediate effects on the nervous system from shock currents, including life threatening effects on the heart, breathing, and brain;
- Stimulus of the muscles from current flowing through the body, including reflex action and being “frozen” to the circuit;
- Burns to the body from hot conductors caused by high currents flowing through metal conductors, does not necessarily involve a shock;
Internal tissue damage from shock currents flowing through the body that ranges from mild cellular damage to major damage to organs and limbs; and

External burns and other physical injury due to an arc, creating an arc flash (thermal energy) and/or an arc blast (including acoustic and kinetic energy).

As mentioned above, apart from complexities such as asphyxia (Shoemaker, 2009), arrhythmias, asystole, and myocardial injury (Spies and Trohman, 2009), fatalities or injuries may result even when there is no electrical current flow through the body (e.g., electrical ignition fire, blast, fall) (Cadick et al., 2005). Although very little can be done to reduce the severity of electrical contact (Soelen, 2007), much can be done to reduce workers exposure to electrical current and to reduce the frequency of injuries incurred.

2.3 Safety Risk Quantification

Quantifying occupational safety risks for the purpose of resource allocation is becoming increasingly popular in the academic and professional research communities. Risk is defined as, a measure of the probability of occurrence of an incident and the severity of the adverse consequence that results from an exposure to a hazard (ANSI, 2000; Lowrance, 1976; NFPA1500, 2002; NSC, 2009). These adverse effects (such as an injury) often result in cost overruns, schedule delays, and poor performance (Sun et al., 2008). In the past, researchers have undertaken diverse approaches to assess safety risk in construction and infrastructure projects. For example, Lee and Halpin (2003) utilized fuzzy mathematical techniques and expert inputs to assess factors influencing accident potential in the context of trenching operations, Gürcanli and Mügen (2009) proposed a fuzzy rule-based analysis methodology to assess safety risk with linguistic variables, and Sun et al (2008) using expert ratings and the analytical hierarchy process (AHP) in their quantification of safety risks. Other researchers have used more formal frameworks and independent quantification of frequency, severity and exposure in their evaluation of safety risks (e.g., Baradan and Usmen, 2006; Jannadi and Almishari, 2003; Hallowell and Gambatese, 2009). These studies identify risk as a function of the frequency of incidents; severity of injury; and exposure duration. Equation 1 shows the relationship between the components of unit risk and Equation 2 shows the relationships among the components of cumulative risk. Cumulative risk is also known as expected value.

**Equation 1**

\[ UR = f \times s \]

Where UR is unit risk measured in $ per w-h; \( f \) is frequency measured in injuries per w-h, \( s \) is severity measured in $ per injury.

**Equation 2**

\[ CR = UR \times e = f \times s \times e \]

Where CR is cumulative risk measured in $ and \( e \) is exposure duration measured in w-h

In the above equation, frequency is indicative of the prospect of making contact with the hazard per unit time; severity refers to the probable outcomes (e.g., fatalities, injuries, damages and lost work-time due to accidents); and exposure signifies the time period spent in proximity to the hazard (e.g., days). This equation has been used by Soelen (2007) to
demonstrate the high risk profile associated with work on power lines. Though the frequency of contact is low, exposure can be high and the severity of contact is very extreme.

2.4 Safety Risk Management and Mitigation

The US Occupational Safety and Health Administration (OSHA) holds both the employer and the employee responsible for safety related issues in the work place. The employer is to provide the workforce with a place free from any recognized hazard (Wilson and Koehn, 2000), personal protective equipment, and training to enhance safety performance (Spellman, 1998) and employees must comply with the regulations set by the employer and relevant regulatory bodies.

Employers have recognized that the first step in safety risk management is to identify dormant and active hazards which may exist or may be invoked by worker behavior at the worksite (MacCollum, 2006). This is often accomplished through reviewing the scope of projects, schedules and other relevant documentation to identify possible hazards. According to OSHA (2002, p.11), most hazards in the T&D industry result due to “unsafe equipment or installation; unsafe environment; and unsafe work practices”. Having identified the potential hazards, risk mitigation techniques are implemented in order to control the frequency, severity and exposure level of injuries. This is typically accomplished by the use of electrical safety equipment (e.g., PPE, barriers); and safety procedures and methods (e.g, grounding, de-energizing power lines) (Cadick et al., 2005). OSHA (2002) suggests measures such as insulating conductors by the use of glass, mica, rubber, or plastic; guarding energized parts to avoid accidental contact; grounding of conductors and equipment to avoid voltage surges; use of circuit protection; and other safety work practices.

Although publications by regulatory bodies set the standards and encourage the use of risk mitigating techniques, utility decision makers often are drawn towards regulatory compliance, thereby minimizing safety investment to that which is only demanded by law (Soyka and Feldman, 1998). Their resistance can be ascribed to the assumption that expending resources on safety, compromises profit potential by increasing the cost of the project. Despite this attitude, Lancaster et al. (2003) argued that investments in injury prevention results in economic benefits. Several other studies show similar evidence for the cost-effectiveness of injury prevention in certain work scenarios (e.g., Hallowell, 2010; Jaselskis et.al., 1996; Hallowell and Gambatese, 2009; Jervis and Collins 2001; Smallman and John 2001). However, despite the high injury rate in the electrical T&D industry, no research has specifically examined the relation between injuries and benefits of expending towards enhancing safety. The present study has been conducted with the aim addressing this gap in knowledge.
The research process involved two distinct phases, each designed to achieve individual but related objectives. The purpose of the first phase was to obtain contextual information regarding the work that contractors typically perform on electrical T&D lines and the methods that they use to prevent injuries. This contextual information was then used in the second phase of the research where an expert panel rated the relative risks of the common tasks and the risk reduced by the various injury prevention strategies. The results were finally compiled into a decision support system using a risk-based contingent liability model. The details of these phases are provided below.

3.1 Phase 1: Exploratory Interviews

To initiate this two-year research effort, exploratory interviews were conducted with leaders in the electrical T&D sector in order to identify common T&D construction activities and injury prevention strategies. These data would serve as the underlying framework for the subsequent phase. Semi-structured interviews were selected for this initial effort because, in comparison to surveys, they provide more flexibility for exploration and deeper understanding of the subject (Fowler and Mangione, 1990). Interviews, as opposed to questionnaires, also allow for clarification, detailed insight, and have been shown to have higher response rates (Bryman, 2004).

Interviewee contacts were assembled from ELECTRI International’s Electrical T&D Committee, member organizations of the Construction Industry Institute (CII), and other prominent utility and contracting company contacts held by the research team. Of the 17 potential interviewees contacted, four electrical contractors and six utility representatives agreed to participate. This number of experts was adequate to provide theoretical saturation and repeated evidence (Strauss and Corbin, 1990). To initiate the interview process, the participants were contacted via phone and the purpose of the interviews was described. Prior to the actual interview date, the participants were encouraged to review project schedules, job hazard analyses, and other relevant documents that would aid them in their responses. In total, twenty-five salient work tasks and sixteen injury prevention strategies were identified from these interviews. The tasks are listed and described in Table 1 (next page) and the mitigation strategies are listed and described in Table 2 (page 11).

3.2 Phase 2: Quantification of Safety Risks and Risk Mitigation Impacts

The objectives of the second research phase were to (1) quantify the relative risk of the common work tasks and (2) quantify the proportion of risk mitigated by typical injury prevention strategies. Because archival and empirical data do not exist for these tasks and safety strategies, the research team decided to address these objectives using a detailed survey of industry experts as a primary data collection effort based on past industry empirical performance data. In order to
Table 1: Transmission and Distribution Construction/Maintenance Activities

<table>
<thead>
<tr>
<th>Task</th>
<th>Brief Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operate equipment near energized lines</td>
<td>Use tools and equipment to organize and stage material used for electrical facilities</td>
</tr>
<tr>
<td>Energize lines/equipment—put in service</td>
<td>Place electrical lines and equipment in service for distributing power to end users</td>
</tr>
<tr>
<td>Excavate/trench and install foundation</td>
<td>Excavate and construct the foundation to place electric facilities in position to distribute electric power to customers</td>
</tr>
<tr>
<td>Climb pole/operate on aerial lifts</td>
<td>Position workers to physically work on electric circuits</td>
</tr>
<tr>
<td>Grounding/removing grounding</td>
<td>Use tools to bond on to existing circuits creating an electrical path to ground (creating a “short circuit”)</td>
</tr>
<tr>
<td>Framing of temporary and permanent structures</td>
<td>Use tools and equipment to assemble material to be used in establishing and maintaining electric systems</td>
</tr>
<tr>
<td>Inspect/troubleshoot power lines/equipment</td>
<td>Observe present conditions of existing electrical facilities</td>
</tr>
<tr>
<td>Splice, repair, and install conductors and wiring</td>
<td>Using tools and equipment to effectively add on to or repair material used to conduct electricity</td>
</tr>
<tr>
<td>Clear/trim trees and bushes</td>
<td>Use tools and equipment to remove vegetation from areas where electrical power facilities exist</td>
</tr>
<tr>
<td>Move energized conductor</td>
<td>Use tools &amp; equipment to change position of energized electric equipment</td>
</tr>
<tr>
<td>Assemble/repair equipment and hardware</td>
<td>The process of creating and maintaining electrical facilities.</td>
</tr>
<tr>
<td>Traffic control</td>
<td>Aid in the flow of pedestrian &amp; vehicle traffic in the interest of public safety</td>
</tr>
<tr>
<td>Hang and install transformers &amp; vaults</td>
<td>Use tools and equipment to install transformers and transformer vaults</td>
</tr>
<tr>
<td>Installation and connection of busses, switches, circuit breakers, and regulators</td>
<td>Use tools and equipment to install operational components such as busses, switches, circuit breakers, and regulators</td>
</tr>
<tr>
<td>Install conduit or cable trough</td>
<td>Use tools and equipment to install conduits or cable trough</td>
</tr>
<tr>
<td>Install insulators</td>
<td>Install insulators to support conductors and provide insulation</td>
</tr>
<tr>
<td>Assemble and erect substation</td>
<td>Use tools and equipment to install and erect substations to transform voltages</td>
</tr>
<tr>
<td>Remove/replace existing line</td>
<td>Removal or replacement of electrical lines during routine maintenance</td>
</tr>
<tr>
<td>Install lightning arrestors</td>
<td>Install devices on power systems to protect insulation and other damages that can be caused by lightning</td>
</tr>
<tr>
<td>Sagging to provide clearance between wires</td>
<td>The process of adjusting the tension in overhead power lines</td>
</tr>
<tr>
<td>Attach/replace insulators</td>
<td>Provide insulation after splicing conductors or regular maintenance work</td>
</tr>
<tr>
<td>Replace shield wire</td>
<td>Replace the shield wires during routine maintenance</td>
</tr>
<tr>
<td>Install/remove dampers</td>
<td>Install dampers to control vibrations in the cables that may be caused by winds</td>
</tr>
<tr>
<td>Install/remove spacers</td>
<td>Use tools and equipment to install spacers to avoid contact power lines</td>
</tr>
<tr>
<td>Meter/test/measure</td>
<td>Use tools and equipment to monitor the performance of electric facilities</td>
</tr>
</tbody>
</table>
obtain valid and reliable data, it was of the utmost importance that the survey participants had a significant amount of practical experience in the electrical T&D sector.

In order to be qualified as an 'expert' for the second phase, a participant must be designated as a safety professional in an organization involved in the T&D industry and have a minimum of 10 years of professional experience in occupational safety.

Table 2: Injury Prevention Methods

<table>
<thead>
<tr>
<th>Injury Prevention Methods</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber insulating personal protective equipment</td>
<td>Use of rubber insulating equipment such as rubber gloves, sleeves, line hose, blankets, covers, and mats that comply with ASTM requirements</td>
</tr>
<tr>
<td>Using hot sticks</td>
<td>Use of insulated hot stick poles that allow workers to manipulate and move energized lines from a safe distance</td>
</tr>
<tr>
<td>Follow safety procedures</td>
<td>Following safety procedures as provided by regulatory bodies/electrical standards (e.g. NEC, NFPA 70E, NESC, OSHA) and general industry safety practices</td>
</tr>
<tr>
<td>Inspection of equipment prior to work</td>
<td>Conducting detailed inspection of all electrical safety equipment prior to work to ensure its effectiveness to prevent/minimize hazards and accidents</td>
</tr>
<tr>
<td>Placement of safety grounds</td>
<td>Connecting the circuit to the ground to prevent the building-up of line/lightning surges, static electricity, etc. when work is being carried out</td>
</tr>
<tr>
<td>Job hazard analysis</td>
<td>A technique in which schedules and activities are reviewed with the purpose of identifying hazards before they occur</td>
</tr>
<tr>
<td>Insulated hard hats with electrical insulation</td>
<td>Use of hard hats with electrical insulation which complies with the requirements of ANSI Standard Z 89</td>
</tr>
<tr>
<td>Use of barriers and signs</td>
<td>Use of barriers and signs to inform personnel of the existence of an active/dormant hazard</td>
</tr>
<tr>
<td>Safety tags or lock-out-tag-out</td>
<td>Use of safety tags, locks and locking devices to secure and mark lines and devices to avoid accidental energization</td>
</tr>
<tr>
<td>Use of voltage measuring instruments</td>
<td>Use of voltage measuring devises to ascertain the status of electric lines and equipment prior to be worked on</td>
</tr>
<tr>
<td>Safety grounding equipment</td>
<td>Using of rated safety ground equipment to protect workers by short circuiting and grounding de-energized conductors</td>
</tr>
<tr>
<td>Fall arrest or other restraint systems</td>
<td>Use of systems to protect workers from the risk of falls and coming in contact with energized lines in the proximity during a fall</td>
</tr>
<tr>
<td>Bonding conductors to create equipotential</td>
<td>Maintaining worker in an equipotential zone by connecting all metallic parts to form electrical continuity to avoid zones of potential difference within his reach</td>
</tr>
<tr>
<td>De-energizing T&amp;D lines</td>
<td>This involves the shutting down of the flow of electricity through the lines during work</td>
</tr>
<tr>
<td>Cradle to cradle use of rubber gloves and sleeves</td>
<td>Use of rubber gloves and sleeves anytime the lineman moves the bucket/boom out of the cradle when there is a possibility of approaching energized circuits with the bucket</td>
</tr>
<tr>
<td>Use of proper flash/thermal rated clothing</td>
<td>Use of flash/thermal protective equipment when working within the flash boundary distance</td>
</tr>
</tbody>
</table>
safety. Potential participants were identified from the original panel in Phase 1, members of the Edison Electric Institute (EII), and the National Electrical Contractors Association (NECA). In total, twenty-one experts qualified as ‘experts’ and agreed to participate in the study. In addition to the requisite qualifications needed to achieve expert status for this study, eight of these individuals are Certified Safety Professionals (CSP), four are certified Construction Health and Safety Technicians (CHST), and twelve hold advanced degrees in fields related to occupational safety. Such an expert panel enhances research validity when obtaining a large number of samples is unrealistic (Patton, 1990). Fortunately the panel was both professionally and geographically dispersed. Ten of the experts represented utility companies, eleven represented electrical T&D contractors, and every major region of the US was represented.

After identifying qualified experts, the survey package was mailed to each potential participant, which included the results from Phase 1; an explanation of the purpose, method, and implications of the study; and the structured survey. As an initial step, the participants were asked to verify the completeness of the results from Phase 1 to ensure that all salient tasks and risk mitigation strategies were identified. The participants were then asked to complete the survey, which included both risk ratings for the tasks and risk mitigation ratings for the safety strategies.

When rating the risk of each of the 25 tasks, the participants were instructed to (1) provide an estimate of the actual frequency of injuries that occur per 200,000 worker-hours for each of the following severity levels: first aid, medical case, lost work time, and fatality and (2) provide the typical cost in dollars for each task and severity level. For example, the panel was asked to provide both the frequency (injuries per 200,000 worker-hours) and costs ($) of first aid, medical case, lost work time, and fatal injuries associated with operating equipment near energized lines. When providing cost data, the experts were asked to consider both direct costs (e.g., actual medical expenses, material damage) and indirect costs (e.g., productivity losses, overtime, temporary employee replacement costs). A total of 200 ratings (25 tasks x 4 severity levels x 2 risk components) were solicited in this first section of the survey.

In the second section of the survey, the expert participants were asked to rate the proportion of risk mitigated by each injury prevention strategy for each task on a 0-100% scale. For example, an expert was asked to rate the proportion of risk mitigated by using ‘hot sticks’ for each of the 4 severity levels. Experts were also asked to provide the typical costs of implementing each of the 16 injury prevention strategies per worker-week. In total, 80 ratings (16 mitigation strategies x 4 severity levels + 16 costs) were solicited from each expert in this second section. For both sections of this survey, the expert participants were asked to review OSHA 300 logs and company data when providing ratings.
Results and Discussion

The research process resulted in a large volume of high quality data. In fact, 280 ratings were obtained from each of the 21 expert participants for a total of 5,880 ratings. As suggested by Heath and Tindale, (1994), Field (2005), and Mann (2003); the median ratings rather than mean ratings were reported to minimize effects of cognitive biases such as recency, primacy, and contrast and to reduce the impacts of extreme outliers. The results of the risk quantification for the 25 electrical T&D construction tasks are provided in Table 3 (next page) and are sorted by total risk.

The table indicates that first aid injuries (5.41 injuries per 200,000 w-h) are the most common in T&D worksites, followed by medical case injuries (2.74 per 200,000 w-h), lost work time (1.20 per 200,000 w-h) and fatalities (0.004/200,000 w-h). This is in agreement with literature that suggests that low severity injuries (first aid and medical case) are more frequent in comparison to high severity incidents (lost work time and fatalities) (Hallowell, 2010).

Once the unit risk of the activities are computed by multiplying the frequency by the cost for each severity level, one can see that the activity with the highest risk is operating equipment near energized power lines ($9,295.00 per 200,000 w-h). This is not surprising, as other studies have shown the significance of considering safety while working with equipment in the vicinity of power lines (e.g., Hinze and Bren, 1996; Homce et al., 2001; Still et al., 1997). According to Hinze and Bren (1996), about 60% of accidents occur when equipment comes in contact with power lines. Other high risk tasks include energizing lines and equipment prior to service ($5,924.00 per 200,000 w-h); excavation/trenching and installing foundations ($4,402.50 per 200,000 w-h); and climbing poles and operating on aerial lifts ($3,545.00 per 200,000 w-h). On the other hand, activities such as metering, testing or measuring the voltage and current ($178.75 per 200,000 w-h) and installing or removing spacers and dampers ($180.50 per 200,000 w-h) are relatively low risk.

The data from the second part of the expert survey provides insight to the most effective injury prevention strategies for electrical T&D line construction. Table 4 (page 16) provides the complete results from the second survey step including the risk mitigated for each severity level for each task and the cost of implementation. When the percent decrease in safety risk is considered for a typical project involving all the activities (i.e., a project with total risk as shown in Table 3), the most effective strategies are: following safety procedures and regulations set by regulatory bodies (NEC, NFPA, NESC, OSHA) (91%), De-energizing T&D lines (86%) and the use of hot sticks (81%). The most costly strategies are de-energizing the lines prior to work ($800 per worker per week) and placement of grounds ($125 per worker per week). The least expensive strategies are the cradle to cradle use of rubber insulated material and fire resistant clothing ($20 per worker per week). The writers have not provided a computation for the cost-effectiveness of these strategies because these values depend on the tasks being performed as will be discussed in the analysis section.
Table 3: Activity Level Risk Quantification

<table>
<thead>
<tr>
<th>Task</th>
<th>F</th>
<th>S</th>
<th>UR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating equipment near energized lines</td>
<td>1.00</td>
<td>$25.00</td>
<td>$25.00</td>
</tr>
<tr>
<td>Energize lines/equipment-put in service</td>
<td>0.40</td>
<td>$22.50</td>
<td>$9.00</td>
</tr>
<tr>
<td>Excavation/trenching &amp; installing foundation</td>
<td>0.50</td>
<td>$25.00</td>
<td>$12.50</td>
</tr>
<tr>
<td>Climbs pole/operates on aerial lifts</td>
<td>1.00</td>
<td>$25.00</td>
<td>$25.00</td>
</tr>
<tr>
<td>Grounding/removing grounding</td>
<td>0.09</td>
<td>$22.50</td>
<td>$2.12</td>
</tr>
<tr>
<td>Framing of temporary and permanent structures</td>
<td>0.10</td>
<td>$22.50</td>
<td>$2.25</td>
</tr>
<tr>
<td>Inspect/troubleshooting power lines/equipment</td>
<td>0.10</td>
<td>$22.50</td>
<td>$2.21</td>
</tr>
<tr>
<td>Splice, repair, and install conductors and wiring</td>
<td>0.50</td>
<td>$25.00</td>
<td>$12.50</td>
</tr>
<tr>
<td>Clearing/trimming trees and bushes</td>
<td>0.10</td>
<td>$25.00</td>
<td>$2.50</td>
</tr>
<tr>
<td>Move energized conductor</td>
<td>0.10</td>
<td>$25.00</td>
<td>$2.50</td>
</tr>
<tr>
<td>Assembling/repairing equipment and hardware</td>
<td>0.04</td>
<td>$25.00</td>
<td>$1.00</td>
</tr>
<tr>
<td>Traffic control</td>
<td>0.02</td>
<td>$25.00</td>
<td>$0.50</td>
</tr>
<tr>
<td>Hanging and installing transformers &amp; vaults</td>
<td>0.10</td>
<td>$27.50</td>
<td>$2.75</td>
</tr>
<tr>
<td>Installation and connection of busses, switches, circuit breakers, and regulators</td>
<td>0.40</td>
<td>$22.50</td>
<td>$9.00</td>
</tr>
<tr>
<td>Installing conduit or cable trough</td>
<td>0.55</td>
<td>$37.50</td>
<td>$20.63</td>
</tr>
<tr>
<td>Installing insulators</td>
<td>0.02</td>
<td>$25.00</td>
<td>$0.50</td>
</tr>
<tr>
<td>Assembly and erection of substation</td>
<td>0.10</td>
<td>$25.00</td>
<td>$2.50</td>
</tr>
<tr>
<td>Remove/replace existing line</td>
<td>0.05</td>
<td>$25.00</td>
<td>$1.18</td>
</tr>
<tr>
<td>Installing lightning arrestors</td>
<td>0.02</td>
<td>$25.00</td>
<td>$0.50</td>
</tr>
<tr>
<td>Sagging and providing for clearance between wires</td>
<td>0.01</td>
<td>$25.00</td>
<td>$0.25</td>
</tr>
<tr>
<td>Attaching/replacement of insulators</td>
<td>0.02</td>
<td>$25.00</td>
<td>$0.50</td>
</tr>
<tr>
<td>Replacing shield wire</td>
<td>0.05</td>
<td>$25.00</td>
<td>$1.25</td>
</tr>
<tr>
<td>Installing/removing dampers</td>
<td>0.02</td>
<td>$25.00</td>
<td>$0.50</td>
</tr>
<tr>
<td>Install/remove spacers</td>
<td>0.02</td>
<td>$25.00</td>
<td>$0.50</td>
</tr>
<tr>
<td>Metering/testing/measuring</td>
<td>0.10</td>
<td>$37.50</td>
<td>$3.75</td>
</tr>
<tr>
<td>Total</td>
<td>5.41</td>
<td>140.87</td>
<td></td>
</tr>
</tbody>
</table>

F = Injuries per 200,000 w-h  
S = Cost per injury  
UR = Cost per 200,000 w-h
<table>
<thead>
<tr>
<th>Medical Case</th>
<th>Lost Work Time</th>
<th>Fatality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F</strong></td>
<td><strong>S</strong></td>
<td><strong>UR</strong></td>
</tr>
<tr>
<td>1.00</td>
<td>$5,000.00</td>
<td>$5,000.00</td>
</tr>
<tr>
<td>0.20</td>
<td>$5,000.00</td>
<td>$1,000.00</td>
</tr>
<tr>
<td>0.10</td>
<td>$2,000.00</td>
<td>$200.00</td>
</tr>
<tr>
<td>0.10</td>
<td>$2,500.00</td>
<td>$250.00</td>
</tr>
<tr>
<td>0.05</td>
<td>$3,750.00</td>
<td>$187.50</td>
</tr>
<tr>
<td>0.09</td>
<td>$3,000.00</td>
<td>$282.00</td>
</tr>
<tr>
<td>0.10</td>
<td>$1,750.00</td>
<td>$175.00</td>
</tr>
<tr>
<td>0.14</td>
<td>$5,000.00</td>
<td>$710.00</td>
</tr>
<tr>
<td>0.10</td>
<td>$2,000.00</td>
<td>$200.00</td>
</tr>
<tr>
<td>0.05</td>
<td>$1,750.00</td>
<td>$82.25</td>
</tr>
<tr>
<td>0.03</td>
<td>$2,250.00</td>
<td>$67.50</td>
</tr>
<tr>
<td>0.10</td>
<td>$3,750.00</td>
<td>$375.00</td>
</tr>
<tr>
<td>0.10</td>
<td>$3,500.00</td>
<td>$350.00</td>
</tr>
<tr>
<td>0.14</td>
<td>$2,000.00</td>
<td>$284.00</td>
</tr>
<tr>
<td>0.09</td>
<td>$3,500.00</td>
<td>$315.00</td>
</tr>
<tr>
<td>0.10</td>
<td>$2,000.00</td>
<td>$200.00</td>
</tr>
<tr>
<td>0.10</td>
<td>$1,750.00</td>
<td>$175.00</td>
</tr>
<tr>
<td>0.02</td>
<td>$2,750.00</td>
<td>$55.00</td>
</tr>
<tr>
<td>0.02</td>
<td>$1,750.00</td>
<td>$35.00</td>
</tr>
<tr>
<td>0.01</td>
<td>$2,250.00</td>
<td>$22.50</td>
</tr>
<tr>
<td>0.01</td>
<td>$2,250.00</td>
<td>$22.50</td>
</tr>
<tr>
<td>0.03</td>
<td>$2,500.00</td>
<td>$75.00</td>
</tr>
<tr>
<td>0.02</td>
<td>$2,500.00</td>
<td>$50.00</td>
</tr>
<tr>
<td>0.02</td>
<td>$2,500.00</td>
<td>$50.00</td>
</tr>
<tr>
<td>0.01</td>
<td>$2,250.00</td>
<td>$22.50</td>
</tr>
</tbody>
</table>

2.74 | 10185.75 | 1.20 | 25855.00 | 0.004 | 3680.00 | 39861.62

CR = Sum of unit risks across all severity levels for a particular task
Table 4: Cost and Risk Mitigated by Injury Prevention Methods

<table>
<thead>
<tr>
<th>Injury Prevention Methods</th>
<th>Cost*</th>
<th>% Decrease In Risk</th>
<th>First Aid</th>
<th>Medical Case</th>
<th>Lost Work Time</th>
<th>Fatality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber insulating personal protective equipment</td>
<td>$100.00</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Using hot sticks</td>
<td>$75.00</td>
<td>45</td>
<td>68</td>
<td>85</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Follow safety procedures</td>
<td>$25.00</td>
<td>80</td>
<td>90</td>
<td>90</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Inspection all equipment prior to work</td>
<td>$25.00</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Placement of safety grounds</td>
<td>$125.00</td>
<td>43</td>
<td>58</td>
<td>68</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Job hazard analysis</td>
<td>$100.00</td>
<td>20</td>
<td>30</td>
<td>60</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Insulated hard hats—providing electrical insulation</td>
<td>$20.00</td>
<td>10</td>
<td>20</td>
<td>25</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Use of Barriers and signs</td>
<td>$60.00</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Safety tags or lock-out-tag-out</td>
<td>$25.00</td>
<td>43</td>
<td>63</td>
<td>73</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Use of Voltage measuring instruments</td>
<td>$30.00</td>
<td>10</td>
<td>50</td>
<td>60</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Safety grounding equipment</td>
<td>$100.00</td>
<td>10</td>
<td>75</td>
<td>75</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>Fall arrest or other restraint systems</td>
<td>$100.00</td>
<td>10</td>
<td>30</td>
<td>60</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Bonding to the conductor to create equipotential</td>
<td>$100.00</td>
<td>10</td>
<td>50</td>
<td>50</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>De-energizing T&amp;D lines</td>
<td>$800.00</td>
<td>65</td>
<td>78</td>
<td>88</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Cradle to cradle use of rubber gloves and sleeves</td>
<td>$20.00</td>
<td>0</td>
<td>50</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Use of Proper fire Rated Clothing in Energized Areas</td>
<td>$20.00</td>
<td>10</td>
<td>30</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

*denotes cost per worker per week
Data Analysis and Application

The data collected in this study can be incorporated into a risk-based contingent liability model developed by Hallowell (2011), which allows a user to: (1) identify the most effective injury prevention strategies given specific work scenarios (i.e., the selection of appropriate tasks for a project); (2) quantify the original risk of the work environment; (3) quantify the benefit derived from implementing selected injury prevention strategies (i.e., amount of risk reduced); (4) quantify the cost of the selected strategies; and (5) compute the cost-benefit of the collective program. Such analyses are critical to the cost-effective implementation of safety strategies in the high risk electrical T&D line construction environment. With the data presented in this paper, the only required user inputs are the total number of worker-hours expected for each task based on the schedule and a selection of appropriate safety strategies based on the initial feedback of the model. The computational model and the integration of the aforementioned data are discussed in detail below.

5.1 Step 1: Calculate Base Level Risk Demand

The first step in the decision analysis procedure involves the calculation of the base-level risk (i.e., the condition that would exist without additional safety strategies). In order to compute this value for a project, the expected tasks must be identified and their approximate durations must be recorded. These durations represent the exposure durations in the risk computations. Once the task durations have been recorded, the cumulative risk (i.e., expected value) for each task can be computed using Equation 2 and the total risk for the project can be computed using Equation 3. As a reminder, these are the values one could expect without the selection of additional safety strategies.

\[
TR = \sum_{i}^{25} CR_i
\]

Where, TR is total risk measured in $ and CR_i represents the cumulative risk for each of the 25 tasks measured in $ and computed using Equation 2.

5.2 Step 2: Select Injury Prevention Methods to be Implemented

Following the entry of task durations, the cost-benefit of the available injury prevention strategies can be quantified and the most cost-effective strategies can be selected. To compute the cost-effectiveness values for each available strategy, the reduction in risk must be computed and divided by the cost of the strategy from Table 4. The risk reduction can be computed using Equation 4 (next page) and the cost effectiveness can be computed using Equation 5 (next page). The user should select the strategy with the highest cost-effectiveness rating, CEj
Equation 4
\[ RR_j = \sum_m CR_m \times rr_j \]
Where, \( RR_j \) is the risk reduction for strategy \( j \) measured in $, \( CR_m \) is the cumulative risk for all selected activities combined for severity level \( m \) and \( rr \) is the percent risk reduction for strategy \( j \).

Equation 5
\[ CE_j = \frac{RR_j}{I_j} \]
Where \( CE_j \) is the cost-benefit of safety strategy \( j \) measured as a unitless ratio and \( I_j \) is the cost of safety strategy \( j \).

5.3: Step 3: Calculate the total investment required to support selected safety program and residual risk

Once the safety strategies that will comprise the safety program have been selected, the total cost of the safety program (TC) can be simply calculated by summing the costs of the selected strategies, \( I_j \) as shown in Equation 6. The residual risk (Res) can be computed by applying Equation 7.

Equation 6
\[ TC = \sum_{i=1}^{9} I_i \]

Equation 7
\[ Res = TR - \sum_{j=1}^{6} RR_j \]

5.4. Illustration through a case example

To illustrate the application and the contribution of this study, a case example is considered and provided as Table 5. The following input assumptions are made: (1) the project involves the erection of a new transmission and distribution line segment, which includes all the tasks in Table 3; (2) the project requires a total of 5 labors working for a period of 4 weeks, (3) each work week consists of 40 worker-hours, (4) the project will require a total of 800 worker-hours. Based on the initial feedback, following safety procedures, use of rubber insulating personal protective equipment, and safety grounds were selected as the injury prevention strategies.

In Table 5 the safety strategies are implemented in their sequence of cost-effectiveness. That is, the first injury prevention method to be introduced is ‘following safety procedures’ followed by the other two strategies. The table shows that the implementation of following safety procedures’ would reduce the risk by 90.71%. Subsequently, the introduction of the use of rubber insulating equipment and the placing of safety grounds would further decrease the safety risk by 64.57% and 63.81%, respectively. Although the introduction of strategies decreases the expected value of injuries, the implementation of the safety program increases the total cost of the project because the cost of implementing the strategy is higher than the economic returns obtained. This implies that the T&D industry value non-monetary benefits that are obtained through reduced injury rates. In this case example, the introduction of safety procedures provides a return of $0.29 for each dollar invested, whereas the safety program involving the three strategies returns $0.03 for every dollar.
Table 5: Case Example Showing Residual Risk

<table>
<thead>
<tr>
<th>Injury Prevention methods</th>
<th>Residual risk</th>
<th>Risk mitigated</th>
<th>% reduction in residual risk</th>
<th>B-C</th>
<th>UF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First Aid</td>
<td>Medical case</td>
<td>Lost work time</td>
<td>Fatality</td>
<td>Cumulative risk</td>
</tr>
<tr>
<td>Base-level risk</td>
<td>$0.56</td>
<td>$40.74</td>
<td>$103.42</td>
<td>$14.72</td>
<td>$159.45</td>
</tr>
<tr>
<td>Follow safety procedures</td>
<td>$0.11</td>
<td>$4.07</td>
<td>$10.34</td>
<td>$0.29</td>
<td>$14.82</td>
</tr>
<tr>
<td>Rubber insulating</td>
<td>$0.08</td>
<td>$2.04</td>
<td>$3.10</td>
<td>$0.03</td>
<td>$5.25</td>
</tr>
<tr>
<td>personal protective</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Placement of safety</td>
<td>$0.04</td>
<td>$0.86</td>
<td>$0.99</td>
<td>$0.00</td>
<td>$1.90</td>
</tr>
<tr>
<td>grounds</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

B-C = Benefit to cost ratio  
UF = measure of investment required to obtain a return of $1
Conclusion

The objective of this study was to quantify safety risk for projects involving the construction and the maintenance of transmission and distribution lines at the activity level and to evaluate various injury prevention techniques used in the industry. Interviews and questionnaire surveys were conducted to populate the data and to validate the study. A decision support framework was developed that provides electrical contractors and utility companies with objective safety and cost feedback given specific project characteristics.

The analysis computed the safety risk associated with each task and suggests that operating equipment near energized lines pose the highest risk among the activities done on or near T&D lines. Other tasks with high risk profiles include energizing line and equipment prior to placing in-service; excavation/trenching and installing foundations; and climbing poles and operating on aerial lifts. Among the injury prevention methods, following safety procedures and regulations and de-energizing lines and equipment prior to work were highly effective, although certain strategies are cost-inefficient. The framework also allows the evaluation of the cost effectiveness of the strategies in controlling injury rates. Finally, the study indicates that the economic returns obtained in the T&D industry by the implementation of injury prevention strategies is lesser in comparison to the general construction industry. This indicates that the T&D industry has a higher cost-utility (i.e., investment into safety interventions exceed economic returns), which values non-monetary benefits and aims to reduce social costs associated with injuries.

The results of this study will allow electric utilities and contractors to evaluate risk levels associated with various projects based on the tasks involved and in designing efficient safety programs based on injury prevention capability. Enhanced resource allocation to control injuries while performing activities with high risk profiles will be facilitated based on the risk quantification concept. For instance, while operating equipment in the vicinity of power lines, the use of barriers and signs may serve as an indicator of the presence of an active hazard which may help prevent incidents. The framework created for decision making, also incorporates the cost of the strategies, which will allow for rational decisions based on the resources available and the financial implication of injury prevention measures.

Finally, several researchers have proposed that tasks executed concurrently in a worksite may increase the base-level risk (Lee and Halpin, 2003; Sacks et al., 2009; Rozenfeld et al., 2010; Hallowell et al., 2011) and likewise the synergistic effect of injury prevention methods may enhance safety performance (Hallowell et al., 2011). Thus, it is suggested that future research be conducted in establishing the risk interactions between different activities and injury prevention methods. Also, studies that include the social benefits obtained through injury prevention may need to be explored in the design of safety programs.
Appendix A

Safety DashBoard

Electrical contractors involved in the construction and maintenance of electrical transmission and distribution (T&D) lines are at extremely high risk of electrocution. In order to manage risk and prevent injuries associated with line work, various physical and procedural barriers are typically implemented. Unfortunately, these strategic techniques are often cost-prohibitive and difficult to improvise in certain scenarios. Thus, electrical contractors and utility companies face complex decisions involving weighing the cost of injury prevention against the expected safety benefit. To assist with making such informed managerial decisions, the Safety DashBoard was developed. The DashBoard is a valid and reliable decision support system that provides practitioners with objective safety and cost feedback given specific project characteristics. This tool was developed based on research that quantified risk at the activity level and the proportion of risk mitigated by industry prevalent injury prevention techniques. The tool utilizes a risk-based contingent liability
model to analyze the cost-benefits of implementing individual injury prevention strategies and assists in the design of an effective safety program. The only required inputs are the total number of worker-hours associated the project, the tasks involved in the project, and selection of appropriate strategies based on the initial feedback of the tool. The tool then allows the user to: (1) identify the most effective injury prevention strategies given specific work scenarios (i.e., the selection of appropriate tasks for a project); (2) quantify the original risk of the work environment; (3) quantify the benefit derived from implementing selected injury prevention strategies (i.e., amount of risk reduced); (4) quantify the cost of the selected strategies; and (5) compute the cost-benefit of the collective program.

The Safety Dashboard is available online at http://electri.org/safetydashboard
Appendix B

References


