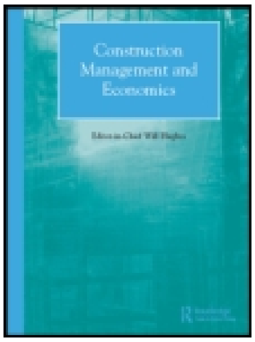

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Safety risk interactions among highway construction work tasks

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Recent research has produced frameworks for integrating safety risk data into project schedules, visual models and other construction planning tools. Unfortunately, only a few studies have attempted to quantify base-level safety risk for construction tasks and no study has attempted to quantify the degree to which spatial and temporal interactions among tasks contribute to the potential for injury. A research study was performed to quantify the impact that pair-wise spatial and temporal interactions have on the base-level risk of 25 common highway construction work tasks in the United States. Six hundred risk interactions were quantified by obtaining and aggregating over 23 500 individual ratings from certified experts using the Delphi method. The results indicate that incompatible tasks may increase the base-level risk up to 60%. The most incompatible highway construction tasks are: (1) installing curbs and gutters and installing rigid pavement; and (2) construction zone traffic control and installing rigid pavement. Additionally, watering and dust palliatives and pavement marking is the one compatible task pair and there are 45 neutral task pairs. The resulting database and analysis have the potential to increase the efficacy of existing frameworks for integration of safety risk data with project planning tools.

Keywords: Project management, risk analysis, safety.

Introduction

Over the last 40 years the construction industry has accounted for an injury and fatality rate that is nearly five times greater than the all-industry average (Bureau of Labor Statistics, 2010). Although injury rates have declined dramatically in this time, in each of the past 15 years the construction industry has accounted for over 1200 deaths and 460 000 disabling injuries in the United States (National Safety Council, 2009). In addition to physical pain and emotional suffering experienced by the victims and their families, these incidents have substantial societal costs totalling an estimated $15.64 billion annually (National Safety Council, 2009). Furthermore, it has also been shown that injuries alone account for 7.9% to 15% of the costs of new construction (Everett and Frank, 1996). These costs cripple entrant firms and have a strong, negative impact on the gross domestic product (GDP).

Following the Occupational Safety and Health Act of 1970, numerous attempts have been made to improve understanding of construction safety. For example, Bernold and Guler (1993) identified common activities and physical motions that contribute to back injuries; Hinze *et al.* (1998) suggested a new classification method for identifying root causes of injuries; Chi *et al.* (2005) identified key contributing factors to fall incidents; Hinze *et al.* (2005a) studied the root causes of struck-by accidents; Sobeih *et al.* (2009) identified causes of musculoskeletal disorders; Lombardi *et al.* (2009) evaluated factors affecting workers' perception of risk; and Mitropoulos and Guillama (2010) suggested a protocol to evaluate the potential for injury when constructing residential framing. Though the contributions of these previous studies are considerable, they are limited in application because they evaluate injuries, activities and preventive measures as individual issues and isolated subjects (Sacks *et al.*, 2009).

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Construction projects are characterized by complexity and uncertainty which stems from an ever-changing environment. The dynamic nature of construction projects requires safety measures to be adapted to new situations. Consequently, many experts believe that injury prevention activities should be conducted early in the project life cycle (Hinze, 1997). One emerging proactive safety management strategy is to integrate safety information into project schedules (Kartam, 1997; Chantawit *et al.*, 2005; Hinze *et al.*, 2005a). Recently, Yi and Langford (2006) and Sacks *et al.* (2009) developed techniques for 'safety loading' safety risk data into critical path method (CPM) schedules. According to Yi and Langford (2006), the quantity of safety risk varies during the project schedule and limited resources should be allocated to projects in proportion to their safety risk at any given time. To analyse temporal safety risk, both studies concluded that safety risk data should be numerically integrated into the project schedule. Prior to these efforts, resource allocation for safety management was inefficient because resources (e.g. safety personnel) were assigned to projects for longer periods than they were actually required for (Sacks *et al.*, 2009).

In order to effectively integrate safety risk data with project schedules, managers must identify and quantify safety risk for all scheduled tasks. Though the framework for schedule integration established by Yi and Langford (2006) only requires base-level risk data for the performance of individual tasks, in isolation, under typical circumstances, several authors have postulated that the actual risk of construction operations also depends on the interactions that occur among tasks throughout space and time (Lee and Halpin, 2003; Sacks *et al.*, 2009; Rozenfeld *et al.*, 2010). These studies argue that interactions among incompatible tasks may contribute to a greater risk than the sum of the base-level task risks alone. Unfortunately, no study has quantified these potential interactions.

The objective of the present study was to quantify the impact that the interactions of common highway construction tasks have on base-level safety risk levels. Risk interactions are defined as the pair-wise impacts that tasks have on each other due to task compatibility or incompatibility. Interactions were measured as the *percentage increase or decrease in safety risk resulting from the concurrent performance of the tasks in the same physical workspace*. The research focused on the highway construction sector because this is one of the most dangerous in the construction industry (Bai, 2002; Bureau of Labor Statistics, 2010) and highway construction tasks are limited in number and well defined (Pandey, 2009).

Literature review

Spatial and temporal interactions

Traditionally, safety has not received the attention that it deserves in comparison with other objectives in jobsite planning (Anumba and Bishop, 1997). Recently, however, researchers have begun to study the impact of site layout schemes on safety performance. For example, Shapira and Lyachin (2009) showed that crowded jobsites, resources constraints and overlap of activities may increase safety risks. In an effort to integrate safety into site layout planning, Elbeltagi *et al.* (2004) presented a method of modelling safety zones around temporary facilities. They used genetic algorithms to optimize the distances between facilities in order to minimize their negative interactions. Similarly, El-Rayes and Khalafallah (2005) suggested a model to consider the influence of crane operations, hazardous materials and travel routes on safety. Navon and Kolton (2006) took a different approach and showed how interactions among site layouts and planned tasks can produce fall hazards. This body of literature confirms the importance of studying risk interactions but has two main limitations: (1) the models are conceptual and are not based upon an underlying database; and (2) the interactions among tasks were ignored in the quantitative analyses.

While spatial safety management typically occurs during site layout planning, temporal safety management typically involves safety–schedule integration. Kartam (1997) made the first attempt to integrate safety data into schedules; however, as Hinze *et al.* (2005b) recognized, there was not an actual relation between schedule and safety resources in Kartam's model. Consequently, Hinze *et al.* (2005b) developed software called SalusLink which allows safety personnel to load safety components into the schedule of a project. Taking schedule integration a step further, Yi and Langford (2006) suggested a framework to integrate safety risk into schedules using a similar method to resource loading (i.e. assigning a safety risk quantity to each scheduled activity). This framework can be used to identify periods with a relatively high level of safety risk and allows managers to use resource levelling techniques to level the safety risk in a schedule. Similar to the spatial modelling of safety, these schedule-based techniques are not based on robust underlying data nor do they consider the interactions among tasks.

Sacks *et al.* (2009) recently proposed CHASTE, a model that simultaneously considers spatial and temporal interactions of work tasks. By using information available in 4D geographic models and user-provided data for 'loss-of-control events', the method can be used to produce a 4D view of the regions of the worksite with high levels of safety risk (Sacks *et al.*, 2009). The most significant limitation of this framework is that, in order to quantify the risk for 'loss-of-control events', the hazards related to each task must be identified and quantified by the user, which can be time intensive and laborious. As discussed by Jannadi and Almishari (2003), quantifying these risk values is not practical for most firms. To address the limitations in the current body of literature and to enhance the efficacy of the aforementioned safety integration models and frameworks, a database of task interactions was created.

Safety risk quantification

The prevailing methods of injury risk assessment typically involve qualitative risk ratings on either linguistic or numerical scales (e.g. Hallowell and Gambatese, 2009). Typically, injury risks are evaluated using a combination of frequency ratings, severity ratings and exposure durations. When sufficient historical data are available, safety risk can be calculated by finding the product of likelihood of occurrence and magnitude of impact (Baradan and Usmen, 2006; Navon and Kolton, 2006). To date, no research has evaluated the impact of risk interactions in risk assessment. Rather, base-level task risks are evaluated individually and are rarely aggregated.

The methods used to obtain risk data and the units of analysis are diverse in existing literature. For example, Jannadi and Almishari (2003) considered risks posed by construction activities, equipment, hazardous substances and external stimuli to estimate total safety risk on worksites; Baradan and Usmen (2006) used American Bureau of Labor Statistics (BLS) data to analyse safety risk in 16 different construction trades; Hallowell and Gambatese (2009) quantified risk at the activity level using the Delphi method; Gürcanli and Müngen (2009) proposed a fuzzy rule based system to analyse safety risk with linguistic variables; and Rozenfeld *et al.* (2010) used a technique similar to job hazard analysis to identify loss of control events for 14 construction activities. As previously indicated, one of the major limitations of this previous work is that risk analyses consider activities, tasks and processes to be independent. That is, safety risks are quantified for individual tasks in isolation without considering the impacts of other concurrent tasks.

Research method

In order to develop an appropriate scope for data collection, clear definitions of common highway construction work tasks were needed. Recently, Pandey (2009) used data from literature, project schedules and interviews to identify and describe 25 common highway construction tasks (see Table 1). As will be described in detail, the interactions among these 25 highway construction tasks were quantified using the Delphi method.

The Delphi method is a systematic and interactive research strategy for achieving consensus among a panel of experts. With this technique, panellists are selected according to specific guidelines and are invited to participate in two or more rounds of structured surveys. After each round, an anonymous summary of the experts' input from the previous survey is provided as feedback to the panel. In each subsequent round, participants are encouraged to review the feedback provided by the other panellists and consider revising their previous response. The process is concluded after a pre-defined criterion (e.g. number of rounds or the achievement of consensus) is achieved.

The Delphi method was selected over alternative research methods because archival data are incomplete (Bureau of Labor Statistics, 2010; Shapira and Lyachin, 2009; Rozenfeld *et al.*, 2010), empirical data could not be obtained during a realistic timeframe, and because the Delphi method is preferred when attempting to obtain complex data that cannot be separated from project context due to confounding factors (Linstone and Turoff, 1975). Furthermore, the Delphi method has seen increased use over the past decade for construction engineering and management research (Hallowell and Gambatese, 2010). In fact, this method has been successfully employed to enhance bridge condition assessments and predict remaining service life (Saito and Sinha, 1991), select procurement systems for construction projects (Chan *et al.*, 2001), identify and evaluate factors affecting international construction (Gunhan and Arditi, 2005), identify components and characteristics of supply change flexibility (Lummus *et al.*, 2005), quantify indicators for measuring partnering performance (Yeung *et al.*, 2008), and to select contractors using qualitative measures (Manoliadis *et al.*, 2009).

Expertise requirements

The careful selection of expert panellists is one of the most important aspects of the Delphi method. A well-qualified, well-rounded and diverse panel of experts is essential to ensure minimal bias and maximum internal and external validity. A review of literature reveals various methods to qualify an individual as an 'expert' using objective criteria. Though Rogers and Lopez (2002) and Linstone and Turoff (1975) are the two most commonly cited references when selecting expertise requirements, these publications offer very

Table 1 Highway reconstruction work tasks and descriptions (after Pandey, 2009)

Work tasks in highway reconstruction	Description
Clear and grub	Clearing vegetation, debris and existing structures (e.g. abandoned utility services)
Excavation	Excavating and constructing embankments and the construction of erosion control devices
Demolition of existing pavement	Removing existing pavement
Landscape	Preparing soil, mulching and constructing irrigation systems
Watering and dust palliatives	Applying water for density and moisture control of soil, applying palliatives for dust control, and soil stabilization
Reset structures	Installing guardrails, fencing, cattle guards, delineators and lighting
Lay aggregate base course	Furnishing and placing one or more courses of additives on a prepared sub grade
Recondition bases (compaction)	Blading, shaping, wetting and compacting the existing sub grade
Installing flexible pavement/ patching	Laying hot mix asphalt and installing geosynthetics beneath pavements
Install rigid pavement (concrete)	Forming, pouring, floating and finishing rigid pavement
Heat and scarifying	Recycling the top portion of existing bituminous pavement by cleaning, heating, scarifying, re-levelling, compacting and rejuvenating existing pavement
Recycle cold bituminous pavement	Pulverizing the existing bituminous pavement, surfacing to the required depth and mixing a recycling agent with water
Prime, coat, rejuvenate pavement	Preparing and treating an existing pavement surface with bituminous and blotter materials
Seal joints and cracks	Furnishing and placing hot-poured joint and crack sealant in properly prepared cracks in asphalt pavements
Install cribbing	Installing concrete cribbing, rip rap and paving slopes/ditches
Install culverts, subsurface drains and maintain sewers	Constructing culverts, sewers, storm drains, under drains, edge drains, geocomposite drains and French drains
Install curb and gutters	Installing curb and gutters, constructing sidewalks and bikeways and installing median cover material
Install traffic control devices	Constructing signs, signals, street markings and other restriction systems that regulate and guide traffic
Install water control devices	Constructing water and erosion control devices
Install culvert pipe and water lines	Constructing culvert pipe and installing of water lines
Install field facilities	Installing field offices, laboratories and sanitary facilities on the worksite
Survey	Surveying the worksite during planning, construction and operation
Mobilization/demobilization	Mobilizing and demobilizing personnel and equipment
Pavement marking	Furnishing and applying pavement markings and removing existing markings
Construction zone traffic control	Preparing or removing lane closures, flagging, traffic diversions, cones, delineators, barricades, sign stands, flashing beacons, flashing arrow trailers and changeable message signs

different sets of requirements. To address these inconsistencies, Hallowell and Gambatese (2010) created a new set of objective and flexible requirements that can be used when certifying potential panellists as 'experts' in the field of construction engineering and management. According to this study every panellist must score at least 12 total points in the related field of research using the point system shown in Table 2 to qualify.

To ensure that the panel is well rounded and professionally oriented every panellist was required to have at least eight years of professional experience in the architecture, engineering and construction (AEC) industry. It was expected that safety managers, project managers, safety officers, Occupational Safety and Health Administration (OSHA) representatives, construction safety and health researchers and representatives from workers compensation insurance providers would be the most highly qualified panellists.

More than 500 potential experts in the field of highway safety risk management were identified. Contact information for potential experts was gathered mainly from The National Work Zone Safety Information Clearinghouse website (www.workzonesafety.org),

Table 2 Flexible point system for the qualification of expert panellists (after Hallowell and Gambatese, 2010)

Achievement or experience	Points (each)
Professional registration	3
Year of professional experience	1
Conference presentation	0.5
Member of a committee	1
Chair of a committee	3
Peer-reviewed journal article	2
Faculty member at an accredited university	3
Author/editor of a book	4
Author of a book chapter	2
Advanced degrees:	
BS	4
MS	2
PhD	4

OSHA, Departments of Transportation (DOTs), the Federal Highway Administration (FHWA), Associated General Contractors (AGC) and university websites. Invitation e-mails that included basic information for the project and estimated time commitments were sent to all potential experts. Of the initial pool of 500 potential experts, 57 individuals agreed to participate. All 57 potential experts were asked to fill out an introductory survey that solicited information that was later used to assess each individual's level of expertise. Of the 51 introductory surveys that were received, 37 individuals were certified as experts using the aforementioned criteria and were randomly assigned to one of three panels.

The 37 experts had an average of over 21 years of professional experience with highway work zone safety management. Approximately 80% of the respondents are professional engineers (PE), certified safety professionals (CSP), or have at least a bachelor's degree in a related field. In addition to the professional experience of respondents, the panel has collectively authored 457 conference papers and 45 peer-reviewed journal articles on safety or risk-related topics. Moreover, the panel was geographically dispersed including all major regions of the United States except for Alaska and Hawaii (i.e. the contiguous United States).

Number of panellists

The number of panellists has varied in previous studies from 3 to 80 (Rowe and Wright, 1999). In fact, the number of panellists is affected by the volume of data targeted, timeframe of the research, number of accessible experts in the field and the capability of the facilitator to handle the panellists (Linstone and Turoff, 1975). The relationship between the number of panellists and accuracy of the results was investigated by Brockhoff (1975) and Boje and Murnighan (1982). These studies found that optimum number of panellists ranges from 8 to 15. A range between 10 and 13 was targeted for this study because this number ensures an adequate population if a member defaults during the process, is easily manageable and ensures a high level of internal and external validity (Rajendran and Gambatese, 2009).

Owing to the great volume of data required for this study (i.e. aggregated ratings of 600 interactions), the authors elected to conduct the study using three independent panels with 12 or more panellists each. Two panels were responsible for quantifying the pair-wise interaction among eight tasks (i.e. 192 ratings) each while the third panel quantified the pair-wise interactions among nine tasks (i.e. 216 ratings). The task interactions were randomly assigned to each panel using a pseudo random number generator in Microsoft Excel.

Number of iterations and feedback process

There are two prominent reasons to conduct multiple iterations of surveys during the Delphi process: reaching consensus by reducing variance and improving precision (Hallowell and Gambatese, 2010). The number of rounds and methods used to measure consensus has been seen as an indicator for accuracy of the Delphi method. The number of iterations in previous large-scale studies ranged from two to six (Dalkey, 1972; Linstone and Turoff, 1975; Gupta and Clarke, 1996). Over half of these studies found acceptable convergence after three or fewer iterations. Hallowell and Gambatese (2010) suggested that a study with three iterations is ideal because expert panellists may review reasons for outlying responses in the third and final round thereby minimizing several forms of cognitive bias. Thus, this Delphi study was designed to include three initial rounds of data collection and a fourth round to cross-validate the results. A description of each round is provided in Table 3.

A feature of the Delphi method that distinguishes it from other similar methods is providing anonymous feedback to decrease the potential impacts of cognitive bias. Providing anonymous feedback facilitates indirect communication among panellists in an effort to reach a high level of consensus (Linstone and Turoff, 1975; Chan *et al.*, 2001). Research has been conducted to evaluate the effects of different forms of feedback on accuracy of final results (Best, 1974; Rowe and Wright, 1999). These studies found that Delphi studies lead to more accurate results when reasons and simple statistical summaries are included in feedback. For the present study, medians and reasons for outlying

Table 3 Iterations of the Delphi process

	Duration (days)	Description
Introductory survey	15	Individuals were asked to fill out introductory surveys that solicited information used to objectively qualify potential panellists as experts.
Round 1	30	Panellists were asked to rate the pair-wise interactions among randomly assigned tasks (i.e. the increase or decrease in base-level safety risk resulting from compatibility or incompatibility of work tasks).
Round 2	30	Medians responses and personal ratings from round 1 were provided as feedback for round 2. Panellists were asked to provide written reasons for round 2 ratings that they believe were ≥10% greater or less than the median response from round 1.
Round 3	30	In addition to medians and personal ratings from round 2, reasons supplied by experts for outlying responses were included for consideration. Panellists were given the opportunity to review medians and reasons for outlying responses. The median ratings from this round represented the final aggregated rating.
Round 4 (validation)	30	Panellists were asked to evaluate the median responses provided by one of the other panels. Panellists had the opportunity to accept the medians provided by other panellists or choose a new rating.

responses have been chosen as feedback because median responses are impacted on very little by biased responses and reviewing and providing reasons for outlying responses requires deeper thinking about more complex interactions. The specific feedback provided in each round is provided in Table 3.

Methods to minimize bias

The research team held the minimization of cognitive bias paramount because the validity and reliability of the Delphi process depends on the unbiased judgment of its experts. Various sources of bias may exist despite the panellists' status as certified experts. Identifying potential cognitive biases that affect one's ability to accurately rate risk values is essential because it allows the research team to strategically design the Delphi process in such a way that potential biases are minimized. Any panellist is likely to be susceptible to one or more of the following eight forms of judgment-based bias during the Delphi process: collective unconscious, contrast effect, neglect of probability, Von Restorff effect, myside bias, recency effect, primacy effect and dominance (Hallowell and Gambatese, 2010). Literature suggests several different methods to avoid the cognitive biases listed above. Specific controls that apply to this study include: (1) maintaining the anonymity of the respondents; (2) providing reasons as a part of the controlled feedback; (3) reporting results as medians rather than means; (4) randomizing the question order of the surveys. It was expected that these controls would reduce the potential effects of cognitive bias thereby enhancing the reliability and validity of the results.

Results

In each round of the Delphi process, experts were asked to provide 192 or 216 ratings, depending on their panel assignments. Of the 37 experts who agreed to participate in this research effort, 28 completed all survey rounds resulting in an ultimate Delphi response rate of 76%. In total, over 5900 ratings were obtained per round resulting in a total of 17 776 ratings after the three rounds of initial data collection. The validation effort conducted in the fourth round required an additional 5900 ratings.

One of the goals of the Delphi process is to reach consensus; however, measures of consensus are not consistent in previous studies. Lummus *et al.* (2005) compared changes in standard deviations between rounds and conducted t-tests to measure level of significance. Another test that has been used to assess level of agreement between panellists in Delphi research is Kendall's coefficient of concordance (W) (Chan *et al.*, 2001; Yeung *et al.*, 2007, 2008; Hon *et al.*, 2010). Using Kendall's coefficient to measure consensus is not appropriate for this study because the test is designed to measure the level of concordance among rankings with few ties within the resulting database. The data targeted, however, are ratings of pair-wise influence. Ties among ratings were welcomed for interactions of the same magnitude. Thus, the absolute deviation (i.e. average deviation from the median) alone was used as a measure of consensus, which is consistent with Delphi studies with similar data profiles (e.g. Hallowell and Gambatese, 2009).

Prior to initiating the Delphi process, the research team set the goal to reach an absolute variance of less than 5% for all three Delphi panels after the third

Table 4 Absolute variance of responses for panels in different rounds (percent deviation)

	Round 1	Round 2	Round 3
Panel 1	14.67%	5.71%	4.95%
Panel 2	30.39	9.94	4.22
Panel 3	34.31	6.42	1.35

round with a 95% agreement in the validation ratings. The absolute variance for each panel after each round is shown in Table 4. It can be seen that the target consensus of <5% was achieved for all panels after the third round of Delphi surveys. Notably, medians did not change from round 2 to round 3.

The resulting dataset (after round 3) is shown in Table 5. Each median rating in Table 5 represents the aggregate of at least eight expert panellists' ratings. These ratings are the percentage increase or decrease in effectiveness that result from the concurrent performance of two tasks in a proximate physical space. One should note that for each interaction, two different ratings exist in the database. Two ratings are provided for each interaction because the effect of activity A on activity B is not necessarily equal to the effect of activity B on A. For example, when laying aggregate base course and installing rigid pavement are performed simultaneously in overlapping physical work spaces, the base-level safety risk of laying aggregate base course increases by 40% while the base-level safety risk of installing rigid pavement increases by only 20%. The range of the interactions is from –5% up to 60%. The only compatible interaction is the effect of pavement marking on watering and dust palliatives (–5%). This shows that performing different activities at the same time will usually increase safety risk. For some activities, the interaction is zero, which means that there is no risk interaction when the task pairs are concurrently implemented.

As indicated, experts were asked to provide reasons for outlying responses during the Delphi process. Though there was a high degree of consensus after the three rounds of surveys, several respondents provided compelling reasons for outlying responses. For example, a few experts believed that safety risk interactions among specific tasks (e.g. mobilization and demolition of existing pavement) should be rated higher because of the concurrence of equipment intensive tasks, using heavy and noisy machinery and changing of traffic patterns. Overlap between such attributes was thought to increase the chance of spatial interference and, consequently, safety risk. Another example involved the interaction between tasks with heavy materials and noisy machinery. Such tasks were thought to impact on other tasks more than the median rating because communications among workers becomes more difficult. Finally, construction zone traffic control was expected to increase the risk of other tasks because of changing of traffic patterns.

In addition to the increases in risk interactions, some experts provided reasons why some interactions should have lower ratings. For example, one of the experts stated that resetting structures takes place primarily beyond the shoulder of the road while prime, coating and rejuvenating pavement would occur on the roadway. Consequently, it is unlikely that these tasks would have a spatial interaction. Similarly, watering and dust palliatives and pavement marking are very unlikely to be performed concurrently in the same location on a project. Other experts noted that it would be very unrealistic for some tasks to be performed concurrently due to typical construction sequencing. However, the research team purposefully did not remove any task interactions from the analysis to minimize the potential for bias from the research team and to preserve a comprehensive dataset.

Analysis

By summing the rows and columns of this matrix (Table 5), one can evaluate the impacts that each task has on the others and the extent to which each task is affected by the presence of others. The results of this analysis are provided in Table 6. It should be noted that the measures in this table are a unit-less relative measure of influence. Three activities: construction zone traffic control (7.10), installing flexible pavement/ patching (6.20) and excavation (6.10) have the greatest impact on the other activities. Thus, when performing these tasks simultaneously with other tasks, there is a great increase in the base-level risk of the other activities. Additionally, the base-level safety risk installing rigid pavement (concrete) (6.20), demolition of existing pavement (6.10) and recondition bases (compaction) (5.90) are affected most by the presence of other activities. Another interesting finding is that construction zone traffic control has the most significant impact on base-level risk of all tasks and yields the most unstable work environment. Alternatively, installing field and facilities is the most stable task because it is affected the least by presence of other tasks and has the lowest effect on other tasks.

An analysis of the distribution of interaction ratings produced interesting results. The average, median and standard deviation of all ratings were 0.17, 0.2 and 0.14 respectively. Twenty-nine per cent of the ratings were between 0.0 and 0.1, 40% were between 0.2 and 0.3 and 11% were between 0.4 and 0.5.

Another analysis was performed to identify the most significant two-way interactions. The magnitude of

Table 5 Median safety risk interaction after round 3 (percent increase in base-level risk)

Tasks: Effect of ↓ / Effect on →	Clear and grub	Excavation	Demolition of existing pavement	Landscape	Watering and dust palliatives	Reset structures	Lay aggregate base course	Recondition bases (compaction)	Installing pavement/patching	Install rigid pavement (concrete)	Heat and scarifying	Recycle cold bituminous pavement	Prime, coat, rejuvenate pavement	Seal joints and cracks	Install cribbing	Install culverts, drains and sewers	Install curb and gutters	Install traffic control devices	Install water control devices	Install culvert pipe and water lines	Install field facilities	Survey	Mobilization/demobilization	Pavement marking	Construction zone traffic control
Clear and grub		20	20	10	0	10	20	20	10	0	0	0	0	0	40	10	0	0	20	20	0	20	0	10	0
Excavation	40		40	40	40	30	20	20	20	20	20	20	20	20	40	40	20	30	20	40	10	20	0	20	20
Demolition of existing pavement	20	20		20	20	40	20	20	20	40	40	20	20	0	0	20	30	30	20	20	0	20	0	10	40
Landscape	40	40	10		20	0	20	0	20	0	0	0	0	0	20	20	0	0	20	20	0	10	0	20	0
Watering and dust palliatives	0	20	20	0		20	20	20	0	0	20	0	0	0	0	10	0	10	0	0	0	10	0	0	0
Reset structures	20	20	40	20	20		20	20	20	60	40	30	60	20	0	20	30	20	20	20	0	20	0	20	40
Lay aggregate base course	0	20	30	10	0	20		30	20	40	30	50	20	0	0	20	30	30	20	40	0	20	0	10	40
Recondition bases (compaction)	20	20	30	20	20	20	20		20	40	20	30	30	0	20	20	30	40	20	20	0	20	0	20	20
Installing pavement/patching	0	20	20	20	20	40	20	50		50	40	50	50	40	20	20	20	40	10	20	0	10	0	20	40
Install rigid pavement (concrete)	0	20	20	10	20	20	20	40	20		40	40	15	0	0	20	60	30	20	20	0	10	0	20	60
Heat and scarifying	0	20	20	10	20	20	10	30	20	20		30	20	20	0	10	30	30	20	20	0	10	0	20	20
Recycle cold bituminous pavement	0	20	30	20	10	10	20	40	20	20	20		40	20	20	20	30	20	20	40	0	10	0	10	35
Prime, coat, rejuvenate pavement	0	0	20	10	0	20	20	40	20	30	40	30		20	0	20	30	20	10	20	0	20	0	20	40
Seal joints and cracks	0	0	30	0	0	30	20	20	20	40	20	40	40		0	20	10	20	10	20	0	0	20	20	40
Install cribbing	20	20	20	20	20	20	10	0	20	20	0	20	0	0		20	10	10	20	20	0	10	0	20	20
Install culverts, drains and sewers	20	40	40	20	20	30	20	40	20	30	0	0	20	20	20		40	10	20	20	0	20	0	20	20
Install curb and gutters	0	20	40	20	20	30	20	40	20	60	40	40	20	20	0	30		30	20	20	0	20	0	20	20
Install traffic control devices	0	20	20	20	20	0	20	40	30	30	60	10	20	20	0	30	40		20	20	0	10	20	30	40
Install water control devices	20	40	20	20	20	10	10	10	0	20	0	10	0	0	20	20	30	10		20	0	0	0	10	20
Install culvert pipe and water lines	40	40	40	20	20	20	20	30	20	30	10	20	20	20	20	30	30	0	20		0	20	20	20	20
Install field facilities	0	0	10	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	20	0	0
Survey	0	20	20	10	0	0	20	0	10	0	20	0	20	0	0	0	0	0	20	0	0		10	0	0
Mobilization/demobilization	0	0	10	10	0	0	20	10	10	0	0	0	0	0	0	20	0	0	10	0	0	0		20	0
Pavement marking	0	0	20	10	–5	20	10	30	20	20	40	40	30	45	0	10	30	30	0	20	0	20	0		20
Construction zone traffic control	0	20	40	0	30	20	40	40	50	50	50	50	20	60	0	20	30	60	20	20	0	30	20	40	

Table 6 The cumulative effect of activities on each other (relative unit-less measure)

Tasks	Total effects of the activity on other activities	Total effects of other activities on the activity
Clear and grub	2.30	2.40
Excavation	6.10	4.60
Demolition of existing pavement	4.90	6.10
Landscape	2.60	3.40
Watering and dust palliatives	1.50	3.35
Reset structures	5.80	4.50
Lay aggregate base course	4.80	4.40
Recondition bases (compaction)	5.00	5.90
Installing flexible pavement/patching	6.20	4.30
Install rigid pavement (concrete)	5.05	6.20
Heat and scarifying	4.00	5.50
Recycle cold bituminous pavement	4.75	5.30
Prime, coat, rejuvenate pavement	4.30	4.65
Seal joints and cracks	4.20	3.25
Install cribbing	3.20	2.20
Install culverts, drains and sewers	4.90	4.50
Install curb and gutters	5.50	5.30
Install traffic control devices	5.20	4.70
Install water control devices	3.10	3.80
Install culvert pipe and water lines	5.30	4.60
Install field facilities	0.50	0.10
Survey	1.50	3.30
Mobilization/demobilization	1.10	1.10
Pavement marking	4.10	4.00
Construction zone traffic control	7.10	5.55

these two-way interactions was calculated by summing both interactions for each pair. For example, if demolition increases the base-level risk of excavation by 20% and excavation increases the base-level risk of demolition by 40%, the magnitude of the two-way interaction for this pair would be 60. This two-way interaction value is a relative, unit-less measure that quantifies the relative magnitude of a two-way interaction between two tasks. Of these two-way interactions, the most significant are installing rigid pavement and installing curb and gutters (120); installing rigid pavement and construction zone traffic control (110); construction zone traffic control and sealing joints and cracks (100); construction zone traffic control and installing traffic control devices (100); construction zone traffic control and installing pavement and patching (90); and installing traffic control devices and heating and scarifying (90). Interestingly, there were 45 two-way interactions with a magnitude of zero indicating that there are a significant number of neutral interactions. Finally, there was one two-way interaction, pavement marking and watering and dust palliatives (–5), that is compatible indicating that overlapping these two tasks in the project schedule *decreases* the base-level safety risk. It should be noted that the actual impact that these two-way interactions have on site safety depends on the magnitude of the base-level risks.

Validation

As previously stated, the members of three distinct panels of experts and each panel were asked to provide safety risk interaction ratings for 196 or 216 interactions. The first three rounds focused on obtaining initial interaction ratings while the fourth or final round was used to cross-validate the resulting matrix. To perform this validation, surveys similar in structure to the initial Delphi surveys were distributed. In the validation round, experts were asked to review the round 3 responses from a different panel that rated a completely different set of interactions. Panellists were given the option to agree with the other group's collective assessment or provide a new rating. In order to decrease bias, surveys were randomly assigned to the panellists. The only limitation was that no panellist was allowed to rate the same interactions that they were assigned during the initial Delphi process. Of the 28 surveys that were sent, 27 surveys were returned resulting in a 96% response rate for the validation. One month was allocated for this validation process and a total of 5276 ratings were obtained. Absolute variance of responses for each panels have been calculated 0.6, 1.13 and 0.9% for panel 1, 2 and 3, respectively. Additionally, medians from validation were the same as medians of each panel, which is evidence of strong validation.

Application of results

There are several potential applications of this database to safety management and planning, which served as the impetus for this research effort. One of the most important aspects of the interaction database is its application to project schedule integration. Previously, researchers have developed a model for integrating safety risk data into project schedules (Yi and Langford, 2006; Sacks *et al.*, 2009). This technique involves safety-loading the risk data with the project schedule using the same strategy as resource loading a schedule. This framework is mathematically summarized in Equation 1.

$$\left[SF\right]_{1\times n}=\left[R_{Individual}\right]_{1\times 25}\times\left[X_{Schedule\,\&\,Time}\right]_{25xn} \qquad (1)$$

where:

$[SF]$ is an ultimate safety risk matrix and its members are total safety risk for each time unit (day, week and month);

$[R_{Individual}]$ is a matrix which includes safety risk values related to performing each task individually;

$[X_{Schedule\ \&\ Time}]$ is a matrix which includes just 0 and 1. If in time t, activity i is performing, then X_{it} = 1, otherwise X_{it} = 0.

Unfortunately, this model and available safety risk data only allow one to model the independent, base-level risks associated with various work tasks and does not account for the influence that multiple concurrent work tasks can have on one another. With the new dataset in Table 5, each task risk can be adjusted by multiplying the base-level risk by all interaction values for all concurrent tasks. The new data from Table 5 can be incorporated into a schedule analysis using a modification of Yi and Langford's (2006) framework shown in Equation 2.

$$\left[SF_{Task}\right]_{1\times n}=\left[R_{Individual}\right]_{1\times 25}\times\left(\left[R_{Interaction}\right]_{25\times 25}\times\left[X_{Schedule}\right]_{25\times n}\right) \qquad (2)$$

where:

$[SF_{Task}]$ is a safety risk matrix resulting from performing tasks by considering interaction among them and its members are total safety risk for each time unit (day, week and month);

$[R_{Individual}]$ is a matrix which includes safety risk values related to performing each task individually;

$[R_{Interaction}]$ is a matrix (Table 5) which includes impact of performing each task simultaneously with other tasks on safety risk values of other tasks;

$[X_{Schedule}]$ is a matrix which includes just 0 and 1. If in time t, activity i is performing, then X_{it} = 1, otherwise X_{it} = 0.

In this new framework, the safety risk data, which include spatial and temporal interactions of work tasks, can be simply integrated with the schedule and the safety risk can be plotted over time. This method can be used to identify high risk periods that may not be identified intuitively. In response, contractors can attempt to consume float to level risk, take extra precautionary measures during these high risk periods (e.g. lane closure), inform workers of high risk periods and strategically design injury prevention strategies to focus on high risk tasks. When the risk profiles for multiple concurrent projects are overlaid in the same plot a manager can identify when and where safety resources should be deployed and could evaluate the risk profile for the company's portfolio simply by computing the cumulative risks for all projects in the company's programme and plotting the risk over time.

In addition to integrating these safety data into schedules, risk interaction values can be applied to information models. For example, safety risk data for specific construction tasks and the task interaction data can be assigned to temporal and spatial elements of the model in the same way as cost, duration, quality, material and other data. These data are essential to identify high risk locations and time periods based on the planned sequence and location of tasks. The collection and dissemination of the risk data presented takes a major step towards the creation of a safety information model. Though the dataset presented does not include tasks associated with building construction tasks as would be necessary to integrate with building information models, the research methods and framework could be applied to a future study on the topic.

Several limitations to the application of the results should be noted. First, the interaction data may only be applied to the highway work tasks as they are described in Table 1. Though these task descriptions are representative of typical work scenarios, as described by Pandey (2009), the data presented are not representative of any deviations from these standard procedures. For example, if a crane were used to install field facilities or if excavations were unusually deep, the magnitude of any task interactions associated with these deviations may no longer be accurate. This limitation was essential because adding new criteria to the Delphi survey would have resulted in an overwhelming burden to the panellists, each of whom had already been asked to provide 1800 ratings over the course of three rounds of surveys. Because of this limitation, the writers suggest future research on the impacts of relevant subtasks, alternative means and methods, and specialty equipment. The second major limitation is that these data should only be applied to daytime construction on projects in the contiguous United States. The limitation must be imposed because the Delphi panellists only had significant experience in the contiguous United States and construction deviates significantly from standard means and methods when work is performed at night. Finally, the data must be applied with the understanding that the task descriptions are general in nature and do not reference specific design features, environmental conditions, crew capabilities and competencies, or any other project-specific characteristics.

Conclusions and study limitations

The research objective was to quantify the pair-wise safety interactions among 25 highway construction work tasks that result from task compatibility or incompatibility using the Delphi method. After three iterations of Delphi surveys with three separate panels, consensus was achieved. In a fourth and final round, the results were successfully cross-validated.

The results of this research indicate that construction zone traffic control, installing flexible pavement/patching and excavation have the greatest impact on the base-level risk of other construction activities. In contrast, installing rigid pavement (concrete), demolition of existing pavement and reconditioning bases (compaction) are affected most by other concurrent activities. Though the pair-wise data are interesting and valuable on their own, the most significant contribution is that these data can be effectively integrated with cost, schedule and quality planning. As discussed, the database produced can be attached, along with base-level safety risk data to common highway construction work tasks in a project schedule thereby allowing a manager to 'safety-risk-load' a project schedule in the same way one would resource load a schedule. The risk interaction data can be used to more accurately quantify temporal safety risk on projects with many concurrent tasks. The resulting temporal plot includes the base-level safety risk and the influence that multiple concurrent work activities have on each other's risk level. Though it may be unrealistic to separate concurrent construction tasks, such an analysis may yield more accurate and reliable temporal risk analyses. Being able to proactively identify high risk periods and communicate risks with construction crews is very important for successful safety management.

There are several limitations of this research. First, though several controls were implemented to enhance the rigour of the study and to promote the validity and reliability of the results, there are inherent limitations associated with quantifying risk-related information using expert ratings. Second, the pair-wise interaction database is limited to only 25 tasks (600 interactions). The creation of a sufficiently representative and robust database would require the quantification of many more task interactions, including building construction tasks. Thus, additional research in this area is suggested. Third, these task interactions apply to the construction environment at the time that the study was conducted. Therefore, if common construction tasks were to change due to the implementation of technological innovations or new means and methods the pair-wise interactions and base-level risk must be re-evaluated. Fourth, the assumption made in this research is that the tasks are performed as described in Table 1 and that this performance is consistent throughout the industry. Satisfying this assumption requires competent and capable crews with sufficient leadership and management control. The authors recognize, however, that construction sites are composed of a spectrum of crews with different levels of safety experience, competencies and capabilities. Therefore, the safety interaction risks presented here are average for the industry and can be varied for different projects and crews. Finally, this research does not consider the impacts of environmental risk factors such as weather or light conditions, the safety programme of the contractor or productivity pressure from top managers. Despite these limitations, the resulting database makes a significant contribution to the body of knowledge which can be used to enhance project management capabilities through the integration of safety with other project management functions.

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