ASSE ACADEMICS PRACTICE SPECIALTY

VOLUME 11, ISSUE 1 • 2015

Journal of Safety, Health & Environmental Research

THIS ISSUE

186-194 Management Commitment to Safety & Risk of Workplace Injury: A Workers' Compensation Insurance Perspective

195-200 Validation of a Simple Seat Satisfaction Questionnaire

201-210 Evaluation of Fuzzy Linguistic Modeling Performance to Predict Health Effects of Occupational Vibration Exposure

211-221 A Literature Review of the Ambient Air Asbestos Concentrations

222-231 Safety Performance Assessment of a Construction Site Using Construction Safety Index: Evidence From Indian Construction Industry

AMERICAN SOCIETY OF SAFETY ENGINEERS • www.asse.org

Journal of Safety, Health and Environmental Research ISSN 2168-1368

ASSE ACADEMICS PRACTICE SPECIALTY VOLUME 11, ISSUE 1 • 2015

Journal of Safety, Health & Environmental Research

Mission: The mission of the *Journal of Safety, Health and Environmental Research* (JSHER) is to peer review theoretical and empirical manuscripts, reviews and editorials devoted to a wide variety of SH&E issues and practices.

Scope: As such, JSHER accepts theoretical and empirical papers committed to concepts, analytical models, strategy, technical tools and observational analyses that enhance the decision-making and operating action capabilities of SH&E practitioners and provide subject matter for academics. JSHER is an online journal intended to be of interest to SH&E academics and to field practitioners concerned with SH&E science, emergency and disaster preparedness, fire and homeland security, corporate sustainability and resiliency, economic evaluation of SH&E programs or policies, risk-loss control, engineering and other legal aspects of the SH&E field.

Submission Guidelines: Each submission to JSHER will be blind peer reviewed by at least two reviewers. Submission of a manuscript to JSHER indicates that the effort expressed has not been published previously and that it is not currently under consideration for publication elsewhere.

Manuscripts that are in agreement with the mission and scope of JSHER should be crafted carefully and professionally written. They should be submitted as an attachment within an e-mail message. Specifically, they should:

- be submitted as an MS Word file(s) with no author identifiers;
- be 8 to 20 double-spaced pages with 1-in. margins all around (approximately 3,000 to 8,000 words including references, but not including illustrations, tables or figures that are not included in the text);
- include a separate document indicating the title, coauthors and the person to whom correspondence should be directed, including that person's name, title, employer, phone number, fax number and e-mail address, and a short (50-word) bio of each author indicating at least the author's current position, highest degrees earned and professional certifications earned;
- include an abstract of no more than 200 words that states briefly the purpose of the research, the principal results and major conclusions, including a short list of key words;
- include a reference section at the end of the manuscript, using APA style to cite and document sources;
- number pages consecutively and clearly indicate new paragraphs;
- document and acknowledge facts and figures;
- present tables and figure legends on separate pages at the end of the manuscript, but indicate where in the manuscript the table or figure should go;
- ensure that graphics, such as figures and photos, are submitted as separate files and are not embedded in the article text;
- for empirical research, at a minimum, the text should include introduction, methods, results and discussion main sections in the text;
- for all submission types, section headers that describe the main content of that portion of the manuscript are advisable.

Copyright: Authors are requested to transfer nonexclusive copyright to ASSE.

All submissions should be sent as an MS Word e-mail attachment to:

Sang Choi, Ph.D., CSP
JSHER Editor
Professor of OESH
University of Wisconsin-Whitewater
3509 Hyland Hall
Whitewater, WI 53190
Phone: (262) 472-1641
chois@uww.edu

Editorial

It is with my great honor to present summaries of the truly impressive articles in the first issue of 2015 of ASSE's *Journal of Safety Health and Environmental Research (JSHER)*.

First, authors Schofield, Alexander, Gerberich and Ryan explored workers' compensation data coupled with OSH professionals evaluation surveys to explore the association between management commitment and risk of employee injury. These approached the analysis in a unique way: from an outside entity's perspective and with workers' compensation data. The ability to accurately detect an association between management commitment and employee risk can have both injury prevention and financial implications in the insurance industry, and beyond. The authors aimed to explore if OSH professionals perception of poor commitment is related to increased risk of employee injury and severity. Significant elevation of risk was detected for some trade-specific rates. Interestingly, companies were also at increased risk of injury during the time prior to initial OSH professionals' rating visits.

The findings support the conclusion that outside perception of management commitment does not appear to be wholly indicative of risk of injury within a company, but may be predicative for some construction trades or potentially in combination with other measures. Continued exploration of valuable workers' compensation data sources may help refine this measure. As with all research involving workers' compensation data, the prevalence of underreporting of injuries, especially non-random underreporting should be taken into consideration. Utilizing these often low-cost or free services from workers' compensation insurers could be an excellent resource and avenue for employers to reduce injuries in their workforce.

In the next article, Radwan, et al., developed a 16-item simple seat satisfaction questionnaire (SSSQ) that assesses ergonomic quality of seats. A scoring system for the questionnaire was proposed by the authors utilizing a Likert-scale-based scoring system. The authors validated their questionnaire through testing its internal consistency among 220 volunteers from an educational institute and the results were compared to independent ergonomic analysis of seats. The questionnaire was deemed statistically consistent and valid with overall Cronbach's alpha reliability coefficient of .85. Fifty percent of the sample that took the questionnaire had pain claimed to be related to seats, especially among females. Similarly, complaints and dissatisfaction with seats were greater among students than instructors and staff. According to the proposed scoring system, 30% of examined seats needed some sort of ergonomic adjustments.

The proposed SSSQ is a valid and reliable tool that can be used to assess the overall ergonomic quality of a chair. It is a graphically enhanced questionnaire that incorporates ergonomic education of the proper seating aspects while measuring seat satisfaction. The questionnaire is user friendly and can be conveniently completed in as little as 5 minutes and does not need prior knowledge of ergonomics to complete.

In the third article, Moayed and Cheng hypothesized that descriptive and qualitative information provided by employees about their perceived level of exposures to hazards and the effects of such hazards on their heath can be used to assess or even predict the most probable outcome of exposures by developing fuzzy linguistic models. This method can be significant to safety expert who rely on surveys and historic data for safety evaluation and assessment in various industries. The authors conducted a secondary data analysis on a dataset (historic data) about occupational vibration exposure and its health effects on stone cutting workers in Taiwan. The authors identified the data trends and used expert opinion and developed fuzzy linguistic models to predict the most probable health effects of occupational vibration exposure. The linguistic models developed by Moayed and Cheng were basically a series of if-then rules that determines the possible health effect of vibration exposure based on the level of exposure determined by subjects. The authors then decided to compare the results of their fuzzy linguistic models with logistic regression models that are considered an acceptable method suitable for analyzing categorical data in order to predict the possible health effects.

The performance of both types of models was compared with one another by using root-mean-square-error of predicted values for health effects of vibration and the t-test result showed fuzzy linguistic models performed better in predicting the outcomes. The authors were able to show that the initial hypothesis was true, in which the descriptive and qualitative information about perceived level of exposures to hazards and the effects of such hazards on workers' heath can be used to assess or even predict the most probable outcome by developing fuzzy linguistic models.

Next, Anderson, Parr and Boyd reviewed publications from the archives of the scientific literature and governmental bodies that evaluated ambient air asbestos concentrations. The authors focused on determining whether original sampling was performed and identified the analytical methodologies utilized for this sampling, as well as the location in which the samples were collected and the concentrations reported. Sampling methodologies utilized in earlier studies were collected as total mass or respirable mass of particulate per volume of air, which did not provide information as to the size distribution of the particulates, whether fibers were present and, if so, the identification of fibers was not possible. Many of the studies analyzed the sampling results utilizing phase contrast microscopy (PCM), which cannot definitively identify fibers as asbestos or other types of materials, but simply counts all fibers greater than or equal to 5 µm in length, with a 3:1 aspect ratio of the length to width and a diameter of at least 2.5 µm. The preferred analytical method to identify and distinguish asbestos fibers from other fiber types is transmission electron microscopy (TEM).

The authors noted that a range of ambient air asbestos concentrations were determined and that those concentrations varied widely between ambient air asbestos samples collected in rural areas compared to those in urban settings, or those collected near naturally occurring asbestos locations. Given that the reported results have served in part as the basis for public health policy and regulations involving asbestos, public health officials should utilize ambient air asbestos concentration sampling results from studies where sampling was performed that preferably were analyzed utilizing TEM. A concentration range of 2.0 x 10^{-5} f/mL to 1 x 10^{-2} f/cc, based on publications in the scientific literature that conducted original sampling and performed TEM analysis, was found by the authors.

Finally, Pathak and Jha proposed a model in the form of safety performance evaluation (SPE) sheet for assessing the safety of construction sites. The authors have evaluated priorities for potential attributes that affect construction sites' safety on the basis of weight-age calculated with the help of analytical hierarchy process. The authors used a three-level hierarchy. The SPE sheet has devised to evaluate the safety of a construction site in the form of construction safety index (CSI).

The authors accomplished their research by conducting two questionnaires among Indian construction professionals. The first stage questionnaire is designed to get the relative weight-age of first-level factors and second-level attributes along with the relative importance for third-level attributes. The objective of second questionnaire is to validate the devised SPE sheet via surveys conducted for 30 construction sites. Accident statistics for those sites were collected as a part of the second questionnaire in order to assess the validity of CSI and to explore the possible correlation of CSI with various site safety indicators. The authors also took into consideration the *t*-test for checking the significance of correlation coefficient between CSI and safety indicators.

The findings verify strong association of CSI with safety indicators such as lost-time injury frequency rate and lost-time injury incident rate, which shows that the safety performance of a construction site can be presented in terms of CSI scores. The CSI score can act as an objective tool to measure the effectiveness of safety management system, which further could be utilized by the management for appraisal purposes and the SPE framework may be used by safety managers for making decisions to improve safety performance.

I hope that you will enjoy these articles. As always, I look forward to hearing from you and welcome your submission of manuscripts to *JSHER*.

Yours sincerely,
Sang D. Choi, Ph.D., CSP
Managing Editor, *JSHER*

Management Commitment to Safety & Risk of Workplace Injury: A Workers' Compensation Insurance Perspective

Katherine E. Schofield, Bruce H. Alexander, Susan Goodwin Gerberich and Andrew Ryan

Abstract

Management commitment to safety has been identified as a factor in employee injury prevention, but has not been evaluated solely from an outside entity perspective to predict injury risk. We evaluated workers' compensation claims from construction companies to explore the association between OSH professional evaluations of management safety commitment and different types of injury rates. Employee hours and claim data were used to calculate injury rates. OSH professionals rated employer management commitment as good or poor; good was used as the comparison group. A Poisson model was used and generalized estimating equations accounted for correlated data. Rate ratios and 95% confidence intervals were estimated for injury rates. Models included covariates of company premium-size, union status, and trade. Results of total, lost-time and medical injuries revealed limited differences on an aggregate level between companies having a good or a poor management commitment. Significant elevation of risk was detected for some trade-specific rates. Employers were also at increased risk during the time prior to OSH professionals rating visits. Further investigation into data combinations providing predictive capabilities, or OSH professional guidance to improve management commitment may be warranted.

Keywords
workers' compensation, insurance, injury, construction, occupational, Poisson, management commitment, safety culture, safety climate, safety professional

Introduction

Ongoing efforts to advance occupational safety and employee injury reduction have increased the focus of safety and health to include organizational factors. Two terms used to describe organizational factors related to safety are safety culture; an organization's norms, beliefs, roles, attitudes, and practices concerned with minimizing exposure of employees to workplace hazards, and safety climate; a snapshot of the prevailing state of safety in the organization at a discrete point in time (Choudhry, Fang & Mohamed, 2007; Flin, Mearns, O'Connor, & Bryden, 2000; Gillen, Baltz, Gassel, Kirsch & Vaccaro, 2002; Huang, Ho, Gordon & Chen, 2006; Turner, 1991). Studies of climate, culture and perception have identified management commitment as one effective and important way to achieve a positive safety culture or safety climate. Management commitment, broadly defined, is management's involvement, participation in, promotion, and enforcement of the safety culture and safety programs across all levels of an organization (Choudhry, et al., 2007; Flin, et al., 2000; Gillen, et al., 2002; Huang, et al., 2006; Lehtola, et al., 2008; Wirth & Sigurdsson, 2008; Zohar, 1980). The safety culture or climate of a company, and management commitment, are believed to play a role in risk of employee injury (Huang, et al., 2006). One study on management commitment showed a large reduction in lost-time injury rates (Garrett & Perry, 1996). Another hospital-based study indicated that management commitment was one of six management practices that, together, significantly predicted employee injury ($p < .1$), but was not by itself a significant predictor (Vredenburgh, 2002). Company culture is an influential and a powerful motivator, but may take time to change or modify as employees may resist change (Kletz, 1993, 1985). Statements and policies on management commitment are not enough; if supervisors do not convey commitment (Hofmann & Stetzer, 1996) or behaviors and activities do not adequately reflect commitment (Hofmann, Jacobs & Landy, 1995), employees may not think safety is important.

Much of the research on management commitment has been centered on internal company factors and employee

Katherine E. Schofield, Ph.D., CSP, ARM, CHST, CSRM, earned her doctoral degree from the University of Minnesota and is a risk consultant at SFM-The Work Comp Experts in Bloomington, MN. She can be reached at kteschofield@hotmail.com.

Bruce H. Alexander, Ph.D., is a professor and head of the Division of Environmental Health Sciences at the University of Minnesota. He is director of the Upper Midwest Agricultural Safety and Health Center, director of the Occupational and Environmental Epidemiology training program and co-director of the Occupational Injury Prevention and Research training program.

Susan Goodwin Gerberich, Ph.D., is the Leon S. Robertson Professor in Injury Prevention, a Mayo Professor in the Division of Environmental Health Sciences, School of Public Health, University of Minnesota, and director and principal investigator of the Midwest Center for Occupational Health and Safety Education and Research Center.

Andrew Ryan, M.S., is a senior research fellow in the Division of Environmental Health Sciences, School of Public Health at the University of Minnesota.

perceptions. Equally important, is insight if this relationship between management commitment to safety and effect on injury continues to hold true when based on an outside observer's perception. This would be of interest for any outside occupational safety and health professional (OSHP) working with employers, but is particularly important for the insurance industry where the practice of evaluating management is common. Enormous amounts of data are compiled from OSHPs activities, and can be coupled with workers' compensation claims data for a more complete picture of employers. These data are not standardized across insurance carriers, and are often proprietary information. Many insurance carriers employ OSHPs who are tasked with using their expert opinion to assess current or prospective policyholders on risk, programs and controls, and also on a perceived management commitment, attitude or willingness to partner. This subjective opinion on "commitment" can often be taken into consideration in the same respect as the more factual and objective measures of the OSHP assessment. It would be assumed that an employer with lack of commitment is at increased risk of employee injury and increased claim severity, both from a pre-injury hazard control and a post-injury claim management standpoint, whereas an employer with good commitment is at a decreased risk.

OSHP assessments often have major ramifications for both the employers and the insurance carriers from a financial and injury prevention standpoint. An insurance carrier may decline to insure a company if it feel the company is not committed to claim prevention, or the carrier may increase premiums and costs for the employer. Alternately, an insurance carrier may give discounts in pricing to employers perceived as committed and possessing a good attitude. An insurance carrier may focus or direct OSHP efforts and resources based, in part, on the perception of an employer's commitment to safety and what is believed to be subsequent risk of employee injury.

Research about management commitment and translation to employee safety in the construction industry has illustrated that management commitment was cited as an important factor in worksite safety (Choudhry, Fang & Lingard, 2009; McDonald, Lipscomb, Bondy & Glazner, 2009; Gillen, et al., 2002). However, construction may differ from other industries due to multiple, changing worksites and unique industry culture where risky behavior may be more normalized, emphasis on safety is put secondary to task completion, or employees are punished for injury (Barksy, 1997; Breslin, Polzer, MacEachen, Morrongiello & Shannon, 2007; DeLeire & Levy, 2004; Grazier & Sloane, 2008; Gregory, 2006; Iacuone, 2005; Leigh, 1986; Lipscomb, Nolan, Patterson, Sticca & Myers, 2013; Paap, 2006; Savage, 1993; Smith, Huang, Ho & Chen, 2006; Thoms & Venkata, 2002; Veveers & Gee, 1986). Construction has a high rate of injuries and worker fatalities (BLS, 2013; NIOSH, 2009). Employment in construction has been associated with a higher probability of disability from injury (Stover, Wickizer, Zimmerman, Fulton-Kehoe & Franklin, 2007) and disproportionately higher direct and indirect cost of injury, almost double compared to other industries (Waehrer, Dong, Miller, Haile & Men, 2007).

Measuring a significant relationship between the OSHP's perception of employer commitment and risk of injury can help both OSHPs and insurance carriers focus on more effective strategies to reduce human and financial loss from a workplace injury. The detection of a reliable relationship allows for more exploration of this measure and continued use to direct business and loss prevention decisions; the lack of a relationship acknowledges that the OSHP's perception of management attitude, although perhaps accurate, does not translate into an accurate predictor of employee risk. This study aimed to explore if OSHP's perception of poor, compared to good, commitment, is related to increased risk of employee injury and severity.

Materials & Methods

Population Data & Collection

Workers' compensation claims were used to examine injuries in employees who obtain workers' compensation insurance from a self-insured workers' compensation fund that insures companies engaged in construction and construction-related businesses within the state of Minnesota. During the study period all companies in the study employed fewer than 200 employees, with the majority of companies having 50 employees or less. The study included all data from all companies insured by the fund during the time period 2004 to 2009.

Person-time at risk was established for all employees of each company through monthly payroll and analyzed as hours worked in each class code within the company. Class codes are a pricing component in workers' compensation that classify risk or workplace exposure (e.g., clerical versus carpentry). Minnesota uses the classification system that is devised and maintained by National Council on Compensation Insurance (NCCI). A class that is more likely to experience loss due to risk of work being performed has a higher insurance cost. Some class codes in this study were combined to form trade groups with similar exposures for analysis. Companies were also classified by union status and premium bands of $1-$15K; $15,001 to $75K; and greater than $75,001K. Premium is a pricing mechanism that combines class code, rate and payroll and, thus, enables an estimation of risk of operations, company size and OSHP attention; larger premiums generally receive more OSHP attention.

Claims Data, Collection & Outcomes

Claims data captured all injuries and illnesses reported by employees and submitted to the insurance fund by policyholders for compensation. All claims are classified as medical or lost-time. Minnesota state statutes define a lost-time claim as claims that involve injuries or illnesses resulting in more than three consecutive calendar days of lost work time and include payment of medical and wage loss costs. Medical-only claims involve injured or ill workers who receive care but have not missed more than 3 consecutive days of work time and incurred only medical costs.

OSH Professionals & Management Commitment Rating

The insurance fund has a comprehensive loss control (LC) division that evaluates policyholder safety practices to identify modifiable factors to reduce injuries and compensation costs. The LC division is comprised of OSHPs with advanced degrees in their field. Comprehensive policyholder evaluations were conducted, in most cases, within 60 business days of commencement of workers' compensation policy and, periodically, thereafter in 1- to 3-year intervals based upon company size. OSHPs meet with a policyholder representative and conduct a standardized evaluation interview. The evaluations ascertain the company's operations, employment practices, major hazards and loss sources, safety efforts and programs, hazard controls and injury management process. A portion of the evaluation asks the OSHPs to consider their perception of management's willingness to cooperate, to implement safety recommendations, abate hazards, accept assistance, partner with the insurance carrier to reduce risk and cost of injury, as well as the general tone and atmosphere of the meeting.

From these general guidelines, OSHPs formulate their qualitative rating of management commitment and select between the two choices of "good" or "poor" on the survey instrument. A third comparison group, "not yet rated," was created for the hours at-risk during the time before a company received the initial LC visit and evaluation and had OSHP contact. A policyholder's rating could change throughout the study period, based upon the results of additional evaluations. The hours at-risk of companies that transitioned to different rating categories over the study time period were changed at month of the switch to the new categorization. Ratings of management of commitment were categorized as: ***poor*** (n = 363 claims, n = 7,195,780 hours, 3,597 FTE) or ***not yet rated*** (n = 1,935 claims, n = 33,730,250 hours, 16,865 FTE) vs. ***good*** (n = 7,688 claims, 144,882,922 hours, 72,441 FTE). Groups were dummy coded and run against the good group as a comparison. No sampling was conducted for this study; all companies insured throughout the time of the study were included. Even so, only a small percentage of companies were rated as having "poor" commitment during the course of the study.

Analysis

The injury claims and hours at-risk data were used to determine injury rates. The effect of commitment ratings on injury were evaluated by estimating rate ratios (RR) and 95% confidence intervals (CI) as a function of injury rate. Time-dependent multivariate analysis was used to examine total, medical, and lost-time claim outcomes. A Poisson regression model was chosen due to the rate structure of the data and accounted for time-dependent factors (Haenszel, Loveland & Sirken, 1962). Robust standard errors were used for the parameter estimates to control for violation of distribution assumptions and over-dispersion and zero-inflation were taken into consideration. Generalized estimating equations (GEE) were used to account for correlated observations within companies over time (Liang & Zeger, 1986). An auto-regressive matrix was used for GEE, assuming observations closer together in time were more correlated than those further apart. The model included potentially confounding covariates of trade, union status and manual premium size, identified a priori. All analyses were done using SAS (2011).

Results

During the study period, 1,360 companies compiled 185,766,467 hours of employee time at risk, representing approximately 92,882 full-time equivalent employees (FTE) and 9,986 workers' compensation claims for an average claim rate of 10.75 per 100 FTE. Medical claims comprised 7,693 of overall claims and 2,292 were lost-time injury claims. The total incurred cost of all injury claims during this period was $90,416,073. Rates varied among trade categories. Iron and steel workers had noticeably higher rates (82.8 per 100 FTE) than the second highest trade category of HVAC and plumbing workers (26.2 per 100 FTE). Union companies and companies of larger premium size had higher injury rates (Table 1, p. 189). The ratio of lost-time to medical claims in our population revealed the poorly rated group had a much higher ratio (0.385) than the good group (0.293) and the not-yet-rated group (0.302), thus they reported fewer medical claims per lost-time claim than the other groups; companies rated as good reported the most medical claims per lost-time claim.

Analysis did not reveal any significant differences in risk of injury between those companies that were perceived as having poor management commitment to safety and those rated as having good management commitment (Table 2, p. 190). This trend was true for total injury claims RR = 0.94 (CI = 0.74-1.19), as well as when analyzed by lost-time injury classification RR = 1.15 (CI = 0.85-1.55) and medical claim classification RR = 0.88 (CI = 0.67-1.15). However, during the period of before the evaluation by the OSHP there was an increased risk of injury for total claims RR = 1.11 (CI = 1.03-1.21) and medical claims RR = 1.11 (CI = 1.11-1.22) and lost-time RR = 1.13 (CI = 0.99-1.28). No significant differences were associated for management commitment ratings and risk of injury with respect to a company's union status or manual premium size.

Analysis of risk by trade stratification revealed associations with rating of management commitment for total injury claims. Compared to a company with a good management rating, companies with a poor rating with trades of drywall RR = 1.82 (CI = 1.15-2.88), flooring installation and flatwork RR = 2.06 (CI = 1.28-3.29), and iron and steel RR = 5.75 (CI = 1.96-16.82), were at significantly increased risk of injury claims (Table 3, p. 191). However, three trades, supervisors, garbage and recycling, and equipment installation and assembly had decreased risks of injury when management was rated poorly. Significantly increased risk of injury for companies in the not-yet-rated group was present for: the trades interior carpentry; flooring and flatwork; iron and steel; and nursery and landscaping.

When examining risk lost-time injury, elevated risk was present when the management was rated poorly for drywall RR = 2.32 (CI = 1.02-5.26), flooring installation and flatwork

RR = 2.39 (CI = 1.12-5.12), electrical installation RR = 2.03 (CI = 1.04-3.95), and roadwork and equipment operators RR = 2.44 (CI = 1.23-4.84) (Table 4, p. 193). There were no trades that continued to exhibit reduced risk with a poor rating. The increased risk of injury for companies in the 'not yet rated' group was only illustrated in one trade, nursery and landscaping, when examining lost-time injuries.

Discussion

The utilization of workers' compensation data, as well as internal OSHP data, allowed for the unique ability to follow a cohort of construction companies and track injury experience and rating of management commitment. The time period of this study itself was unique in that it included both the peak of the housing boom, the time preceding the housing market crash, as well as its initial years of the recession. These widespread economic conditions may affect data in ways unknown.

Worker's compensation data may be limited when injuries are underreported and evidence exists that underreporting does occur both at a systemic and industry level (Fan, et al., 2006; Lipscomb, et al., 2013; Shannon & Lowe, 2002). Underreporting, depending on the magnitude, can hinder precise ascertainment of injury rates. It can be particularly troublesome if one group non-randomly underreports more than another group. It could be assumed that medical injuries are easier to hide and underreport than more severe lost-time claims, and our data showed a much less liberal ratio of lost-time to medical reporting in the poor group versus the other groups. Employees in

Table 1 Overall Lost-Time & Medical Claim Rates† by Trade, Union Status & Premium Size

Exposed	Overall Claims (n)	Overall Rates	Lost-Time Claims (n)	Lost-Time Rates	Medical Claims (n)	Medical Rates
Total Population	9,986	10.75	2,292	2.46	7,693	8.28
Trade						
Rough Carpentry	1,835	24.32	452	6.0	1,382	18.32
Interior Carpentry	336	20.53	77	4.79	259	15.92
Supervisors	259	5.31	60	1.24	199	4.09
Crane Operators	33	9.75	11	3.26	22	6.50
Sales and Retail	158	0.54	22	0.08	136	0.47
Shop, Yard and Deliveries	1,240	7.56	238	1.46	1,002	6.11
Drywall	601	16.71	173	4.81	428	11.90
HVAC and Plumbing	1,304	26.22	259	5.21	1,045	21.02
Auto Repair	50	13.49	11	2.97	39	10.52
Roofing	94	31.12	27	8.95	67	22.21
Manufacturing	606	19.00	85	2.67	521	16.35
Flooring Installation and Flatwork	441	24.05	123	6.72	318	17.35
Trucking	19	7.82	5	2.06	14	5.76
Electric Installation	271	14.22	48	2.52	223	11.70
Painting	437	14.61	104	3.48	333	11.14
Concrete and Masonry	1,107	14.39	334	4.38	773	10.07
Iron and Steel	274	82.79	58	17.62	216	65.34
Roadwork and Equipment Operators	310	11.22	89	3.24	221	8.01
Garbage and Recycling	155	12.42	33	2.65	122	9.79
Nursery and Landscaping	287	23.96	54	4.53	233	19.46
Equipment Installation and Assembly	169	21.11	29	3.66	140	17.56
Union Status						
Non-Union	5,920	9.83	1,272	2.13	4,647	7.73
Union	4,066	11.86	1,020	3.07	3,046	8.94
Premium Size Classification						
$0-$15K	788	7.23	198	1.83	590	5.42
$15,001-$75K	4,226	9.49	940	2.13	3,285	7.40
>$75,001	4,972	12.76	1,154	3.02	3,818	9.83

Note. † Rate per 100 FTE (200,000 hours)

Table 2 Management Commitment & Risk of Injury by Claim Type

Claim Type	Management Commitment Rating	Claims	RR†	95% CI
Total	Not Yet Rated	1,935	1.11	1.03-1.21
	Good	7,688	1.0	.
	Poor	363	0.94	0.74-1.19
Lost-Time	Not Yet Rated	449	1.13	0.99-1.28
	Good	1,742	1.0	.
	Poor	101	1.15	0.85-1.55
Medical	Not Yet Rated	1,485	1.11	1.01-1.22
	Good	5,946	1.0	.
	Poor	262	0.88	0.67-1.15

Note. †Controlling for trade, union status and manual premium size.

workplaces where they do not perceive management support or fear retaliation may be inclined to underreport (Gillen, et al., 2002; Lipscomb, et al., 2013; McDonald, et al., 2009). In a survey of union carpenters, reporting of injuries was fifty percent less prevalent when there was a negative consequence for injury and about one-third of the population said that injuries were almost never or rarely reported (Lipscomb, et al., 2013). Employers who lack insurance reporting knowledge and proper procedures, or who are willing to misrepresent their injury experience, may also underreport injuries (McDonald, et al., 2009). Either of these scenarios could reduce the effect of a poor management commitment rating if those companies underreport at greater rates than companies with good ratings. Interestingly, the total claims data showed that supervisors were at reduced risk of injury when their employer was rated as having a poor commitment; this relationship ceased for supervisors, and all trades, when examining just the more severe, lost-time claims. This was perhaps as a result of underreporting less severe medical claims versus a true reduction in risk of injury, due to effects of unsupportive management. Insurance companies and OSHP can more closely examine whether a company is not reporting the number of claims that would be expected and focus attention on management education and employee reporting.

There was limited difference on an aggregate level between companies perceived as having a good or a poor management commitment. A review of other safety culture assessment surveys found similar results, with their conclusions noting there was great likelihood for non-random measurement error (O'Conner, et al., 2011). However, when Smith et al. (2006), examined the relation between safety climate and injury rates, they found that when they adjusted for the hazard levels of different industries, it significantly altered their results. This could possibly explain the results that showed significant risk for some trades; their inherent risk may be greater than others. This also lends itself to the numerous studies on the more risk tolerant culture and workers of the construction industry (Barksy, 1997; Breslin, et al., 2007; DeLeire & Levy, 2004; Grazier & Sloane, 2008; Gregory, 2006; Iacuone, 2005; Leigh, 1986; Paap, 2006; Savage, 1993; Smith, et al., 2006; Thoms & Venkata, 2002; Veveers & Gee, 1986). Coupled with widespread job sites, this culture may make management commitment to safety harder to consistently establish and demonstrate and, thus, more difficult to accurately measure compared to other industries. Even sincere management commitment without adequate translation to work sites may make employees think safety is not important (Hofmann & Stetzer, 1996; Hofmann, et al., 1995). An OSHP may correctly assess management commitment, but the actual implementation of it in the field may be imperfect, leading to the non-difference in injury rates between good and poorly rated companies. OSHPs could focus attention and provide resources to promote more consistent displays of management commitment, such as supervisory training, site safety visits, enforcement of safety rules or emphasis on injury reporting.

A small percentage of employers were rated as poor in this study, which led to sparse data in some areas of analysis. OSHPs may have been hesitant to give a poor rating in some circumstances, especially if they were trying to form a consultative relationship with the employer. Or, an employer could have had a high baseline injury risk, yet have been open and committed to OSHP assistance and injury reduction, thus, avoiding a poor rating. A higher degree of standardization could be necessary. Other areas that were not examined in this study, but are utilized by the OSHP during assessment, such as injury history, safety training, hazard controls and written programs, when coupled with the management rating, provide a more complete picture of a company's injury risk. Similarly, Vredenburgh (2002) noted that management commitment was only predictive in reduction of injury risk when combined with other management measures, not when examined alone. Further research may be warranted into what combination(s) of company attributes, when combined with management commitment rating, can predict risk of injury.

An additional interesting outcome of the research was the result indicating that employers were at significantly increased risk in the time prior to meeting and being evaluated by the insurer's OSHP. Other research seems to support related results looking at OSHA and OSHP contact (Baggs, Silverstein & Foley, 2003). The association of OSHP activity and injury risk reduction should be further explored. Utilizing these often low-cost or free services from workers' compensation insurers could be an excellent resource and avenue for employers to reduce injuries in their workforce.

Table 3 Management Commitment & Risk of Overall Injury By Trade

Trade	Management Commitment Rating	Hours	Claims (n)	RR†	95% CI
Rough Carpentry	Not Yet Rated	3,558,937	477	1.07	0.89-1.27
	Good	11,060,553	1,322	1.00	.
	Poor	456,830	36	0.77	0.51-1.16
Interior Carpentry	Not Yet Rated	484,361	73	1.54	1.05-2.27
	Good	2,685,508	262	1.00	.
	Poor	43,067	1	0.25	0.06-1.04
Supervisors	Not Yet Rated	2,057,294	35	0.56	0.37-0.83
	Good	7,356,793	218	1.00	.
	Poor	276,048	6	0.83	0.30-2.28
‡Crane Operators	Not Yet Rated	258,309	9	.	.
	Good	417,587	24	.	.
	Poor	19	0	.	.
Sales and Retail	Not Yet Rated	10,327,160	40	1.43	0.91-2.25
	Good	45,022,025	113	1.00	.
	Poor	2,469,555	5	0.83	0.30-2.28
Shopyard and Deliveries	Not Yet Rated	6,367,580	246	1.06	0.82-1.37
	Good	25,542,973	964	1.00	.
	Poor	798,580	30	1.01	0.52-1.94
Drywall	Not Yet Rated	768,560	61	0.99	0.69-1.40
	Good	5,998,989	484	1.00	.
	Poor	423,638	56	1.82	1.15-2.88
HVAC and Plumbing	Not Yet Rated	1,808,676	238	0.98	0.76-1.28
	Good	7,332,633	985	1.00	.
	Poor	800,499	81	0.73	0.47-1.15
‡Auto Repair	Not Yet Rated	194,559	17	.	.
	Good	522,468	33	.	.
	Poor	22,809	0	.	.
‡Roofing	Not Yet Rated	47,570	6	.	.
	Good	551,597	88	.	.
	Poor	4,081	0	.	.
Manufacturing	Not Yet Rated	944,867	90	1.09	0.71-1.66
	Good	5,287,659	513	1.00	.
	Poor	123,609	3	0.28	0.08-1.03
Flooring Installation and Flatwork	Not Yet Rated	589,751	97	1.64	1.17-2.32
	Good	3,010,355	330	1.00	.
	Poor	59,439	14	2.06	1.28-3.29
‡Trucking	Not Yet Rated	49,035	1	.	.
	Good	437,361	18	.	.
	Poor	16	0	.	.
Electric Installation	Not Yet Rated	444,783	31	0.84	0.56-1.27
	Good	3,040,217	226	1.00	.
	Poor	323,109	14	0.61	0.33-1.11
Painting	Not Yet Rated	625,324	58	1.42	0.91-2.22
	Good	5,332,139	377	1.00	.
	Poor	23,193	2	1.62	0.35-7.50
Concrete and Masonry	Not Yet Rated	2,935,000	231	1.07	0.84-1.37
	Good	11,540,199	831	1.00	.
	Poor	768,975	45	0.81	0.41-1.58
Iron and Steel	Not Yet Rated	97,828	43	1.85	1.19-2.90
	Good	557,839	190	1.00	.
	Poor	2,505	41	5.74	1.96-16.82
Roadwork and Equipment Operators	Not Yet Rated	732,059	42	1.19	0.75-1.89
	Good	4,542,281	253	1.00	.
	Poor	224,101	15	1.48	0.75-2.90
Garbage and Recycling	Not Yet Rated	688,621	42	0.95	0.64-1.43
	Good	1,482,622	101	1.00	.
	Poor	315,311	12	0.59	0.40-0.86
Nursery and Landscaping	Not Yet Rated	432,110	78	1.72	1.07-2.75
	Good	1,932,086	208	1.00	.
	Poor	21,670	1	0.55	0.07-4.51
Equipment Installation and Assembly	Not Yet Rated	317,866	20	0.66	0.42-1.05
	Good	1,229,038	148	1.00	.
	Poor	38,724	1	0.17	0.10-0.28

Note. †Controlling for company premium size and union status. ‡Not enough data available for analysis.

Table 4 Management Commitment & Risk of Lost-Time Injury by Trade

Trade	Management Commitment Rating	Hours	Claims (n)	RR†	95% CI
Rough Carpentry	Not Yet Rated	3,558,937	117	1.07	0.81-1.41
	Good	11,060,553	324	1.0	.
	Poor	456,830	11	0.91	0.48-1.70
‡Interior Carpentry	Not Yet Rated	484,361	16	.	.
	Good	2,685,508	61	.	.
	Poor	43,067	0	.	.
Supervisors	Not Yet Rated	2,057,294	10	0.76	0.36-1.60
	Good	7,356,793	47	1.0	.
	Poor	276,048	3	1.92	0.48-7.62
‡Crane Operators	Not Yet Rated	258,309	3	.	.
	Good	417,587	8	.	.
	Poor	19	0	.	.
‡Sales and Retail	Not Yet Rated	10,327,160	6	.	.
	Good	45,022,025	16	.	.
	Poor	2,469,555	0	.	.
Shop, yard and Deliveries	Not Yet Rated	6,367,580	52	1.18	0.83-1.68
	Good	25,542,973	180	1.0	.
	Poor	798,580	6	1.09	0.48-2.48
Drywall	Not Yet Rated	768,560	13	0.76	0.39-1.48
	Good	5,998,989	139	1.0	.
	Poor	423,638	21	2.32	1.02-5.26
HVAC and Plumbing	Not Yet Rated	1,808,676	44	0.91	0.62-1.32
	Good	7,332,633	197	1.0	.
	Poor	800,499	18	0.85	0.51-1.42
‡Auto Repair	Not Yet Rated	194,559	7	.	.
	Good	522,468	4	.	.
	Poor	22,809	0	.	.
‡Roofing	Not Yet Rated	47,570	3	.	.
	Good	551,597	24	.	.
	Poor	4,081	0	.	.
Manufacturing	Not Yet Rated	944,867	12	1.0	0.51-1.97
	Good	5,287,659	72	1.0	.
	Poor	123,609	1	0.67	0.13-3.54
Flooring Installation and Flatwork	Not Yet Rated	589,751	23	1.21	0.72-2.04
	Good	3,010,355	96	1.0	.
	Poor	59,439	4	2.39	1.12-5.12
‡Trucking	Not Yet Rated	49,035	0	.	.
	Good	437,361	5	.	.
	Poor	16	0	.	.
Electric Installation	Not Yet Rated	444,783	6	0.98	0.43-2.25
	Good	3,040,217	35	1.0	.
	Poor	323,109	7	2.03	1.04-3.95
Painting	Not Yet Rated	625,324	11	1.01	0.54-1.89
	Good	5,332,139	92	1.0	.
	Poor	23,193	1	1.65	0.52-5.28
Concrete and Masonry	Not Yet Rated	2,935,000	77	1.34	0.92-1.96
	Good	11,540,199	246	1.0	.
	Poor	768,975	11	0.66	0.24-1.78
‡Iron and Steel	Not Yet Rated	97,828	7	.	.
	Good	557,839	42	.	.
	Poor	2,505	9	.	.
Roadwork and Equipment Operators	Not Yet Rated	732,059	11	1.11	0.54-2.25
	Good	4,542,281	71	1.0	.
	Poor	224,101	7	2.44	1.23-4.84
‡Garbage & Recycling	Not Yet Rated	688,621	9	.	.
	Good	1,482,622	24	.	.
	Poor	315,311	0	.	.
Nursery and Landscaping	Not Yet Rated	432,110	17	2.19	1.30-3.70
	Good	1,932,086	36	1.0	.
	Poor	21,670	1	3.24	0.38-27.86
Equipment Installation and Assembly	Not Yet Rated	317,866	5	0.92	0.44-1.92
	Good	1,229,038	23	1.0	.
	Poor	38,724	1	0.79	0.44-1.39

Note. †Controlling for company premium size and union status. ‡Not enough data for analysis

An outside perception of management commitment does not appear to be wholly indicative of risk of injury within a company, but may be predicative for some construction trades or potentially in combination with other measures. Continued exploration of valuable workers' compensation data sources may help refine this measure. More investigation can direct OSHPs as to how to provide resources and assist management in improving their commitment, and its visibility to employees, for injury prevention. ✪

References

Baggs, J., Silverstein, B., & Foley, M. (2003). Workplace health and safety regulations: Impact of enforcement and consultation on workers' compensation claims rates in Washington State. *American Journal of Industrial Medicine, 43*(5), 483-494.

Breslin, F.C., Polzer, J., MacEachen, E., Morrongiello, B. & Shannon, H. (2007). Workplace injury or "part of the job"?: towards a gendered understanding of injuries and complaints among young workers. *Social Science & Medicine*, *67*, 782-793.

Bureau of Labor Statistics (BLS), 2013. United States Department of Labor. Online database: nonfatal cases involving days away from work: selected characteristics (2004-2009). 2006 data available at www.bls.gov/iif/home.htm. Accessed September 12, 2013.

Choudhry, R.M., Fang, D., & Lindgard, H. (2009). Measuring safety climate of a construction company. *Journal of Construction Engineering and Management, 135*(9), 890-899.

Choudhry, R.M., Fang, D., & Mohamed, S. (2007). The nature of safety culture: A survey of the state-of-the-art. *Safety Science, 45*(10), 993-1012.

Cooper, M.D. (2000). Towards a model of safety culture. *Safety Science, 36*(2), 111-136.

Cooper, M.D. & Phillips, R.A. (2004). Exploratory analysis of safety climate and safety behavior relationship. *Journal of Safety Research*, *35*(5), 497-512.

Courtney, T.K., Matz, S. & Webster, B. S. (2002). Disabling cccupational injury in the U.S. construction industry, 1996. *Journal of Occupational & Environmental Medicine, 44*(12), 1161.

Dement, J. M., & Lipscomb, H. (1999). Workers' compensation experience of north carolina residential construction workers, 1986-1994. *Applied Occupational & Environmental Hygiene*, 14(2), 97-106.

Fan, Z.J., Bonauto, D.K., Foley, M.P. & Silverstein, B.A. (2006). Underreporting of work-related injury and illness to workers' compensation: individual and industry factors. *Journal of Occupational and Environmental Medicine*, *48*(9), 914-922.

Flin, R., Mearns, K., O'Connor, P. & Bryden, R. (2000). Measuring safety climate: identifying the common features. *Safety Science, 34*(1-3), 177-192.

Garrett, R.B., & Perry, A. J. (1996). A safer way to move patients. *Occupational Health and Safety, 65*(9), 60-64.

Gillen, M., Baltz, D., Gassel, M., Kirsch, L. & Vaccaro, D. (2002.) Perceived safety climate, job demands, and coworker support among union and nonunion injured construction workers. *Journal of Safety Research, 33*(1), 33-51.

Grazier, S. & Sloane, P.J. (2008) Accident risk, gender, family status and occupational choice in the U.K. *Labour Economist*, *15*(5), 938-957.

Gregory, C. (2006). Among the dockhands: another look at working-class male culture. *Men and Masculinities*, *9*(2), 252-260.

Griffin, M.A. & Neal, A. (2000). Perceptions of safety at work: a framework for linking safety climate to safety performance, knowledge, and motivation. *Journal of Occupational Health Psychology*, 5, 347-358.

Guldenmund, F.W. (2000). The nature of safety culture: a review of theory and research. *Safety Science, 34*(1-3), 215-257.

Haenszel, W., Loveland, D. & Sirken, M. (1962). Lung-cancer mortality as related to residence and smoking histories. *Journal of the National Cancer Institute, 28*(Appendix C):1000.

Hofmann, D.A., Jacobs, R. & Landy, F. (1995). High reliability process industries: individual micro, and macroorganizational influences on safety performance. *Journal of Safety Research, 26*(3), 131-149.

Hofmann, D.A. & Stetzer, A. (1996). A cross-level investigation of factors influencing unsafe behaviors and accidents. *Personnel Psychology,* 49, 307-339.

Huang, H.Y., Ho, M., Gordon, S.S. & Chen, P.Y. (2006). Safety Climate and self-reported injury: Assessing the mediating role of employee safety and control. *Accident Analysis & Prevention*, *38*(3), 425-433.

Iacuone, D. (2005). "Real men are tough guys": hegemonic masculinity and safety in the construction industry. *The Journal of Men's Studies*, *13*(2), 247-266.

Kletz, T.A. (1985). *An engineer's view of human error.* Warwickshire, England: Institution of Chemical Engineers.

Kletz, T.A. (1993). Organizations have no memory when it comes to safety: A thoughtful look at why plants don't learn from the past. *Hydrocarbon Processing, 6,* 88-95.

Lehtola, M.M., van der Molen, H.F., Lappalainen, J., Hoonakker, P.L. T., Hsiao, H., Haslam, R.A., et al. (2008). The effectiveness of interventions for preventing injuries in the construction industry: A systematic review. *American Journal of Preventive Medicine, 35*(1), 77-85.

Leigh, J.P. (1986). Who chooses risky jobs? *Social Science Medicine, 23*(1), 57-64.

Liang, K.-Y., & Zeger, S.L. (1986). Longitudinal data analysis using generalized linear models. *Biometrika, 73*(1), 13-22.

Lipscomb, H.J., Nolan, J., Patterson, D., Sticca, V. & Myers, D.J. (2013). Safety, incentives and the reporting of work-related injuries among union carpenters: "You're pretty much screwed if you get hurt at work." *American Journal of Industrial Medicine*, *56*(4), 389-399.

McDonald, M.A., Lipscomb, H.J., Bondy, J. & Glazner, J. (2009). "Safety is everyone's job:" The key to safety on a large university construction site. *Journal of Safety Research*, *40,* 53-61.

Mueller, L.M., DaSilva, N., Townsend, J.C. & Tetrick, L.E. (1999). An imperial investigation of competing safety climate measurement models. Paper presented to the 14th Annual Meeting of the Society for Industrial and Organizational Psychology, Dallas, TX.

National Institute of Occupational Safety and Health (NIOSH). (2009). *NIOSH Safety and Health Topic: Construction*. Retrieved from www.cdc.gov/niosh/topics/construction/

O'Conner, P., Buttrey, S.E., O'Dea, A. & Kennedy, Q. (2011). Identifying and addressing the limitations of safety climate surveys. *Journal of Safety Research*, 42, 259-265.

Paap, K. (2006). *Working construction: Why white working-class men put themselves voluntarily in harm's way.* Ithaca, NY: Cornell University Press.

SAS Institute. (2011). The SAS System Version 9.2. Cary, NC: Author.

Savage, I. (1993). Demographic influences on risk perceptions. *Risk Analysis, 13*(4), 413-420.

Shannon, H.S., Mayr, J. & Haines, T. (1997). Overview of the relationship between organizational and workplace factors and injury rates. *Safety Science, 26*(3), 201-217.

Shannon, H.S. & Lowe, G.S. (2002). How many injured workers do not file claims for workers' compensation benefits? *American Journal of Industrial Medicine*, *42*(6), 467-473.

Acknowledgments

This work was supported by a traineeship from the National Institute of Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention, through the University of Minnesota (T42OH008434) and by the CPWR—The Center for Construction Research and Training through a NIOSH cooperative agreement OH009762. The authors acknowledge The Builders Group (TBG) for access and continued use of its data. The content of this work is solely the responsibilities of the authors and does not necessarily represent the official views of NIOSH, CPWR or TBG.

Smith, G.S., Huang, Y., Ho, M. & Chen, P.Y. (2006). The relationship between safety climate and injury rates across industries: The need to adjust for injury hazards. *Accident Analysis and Prevention*, *38,* 556-562.

Stover, B., Wickizer, T.M., Zimmerman, F., Fulton-Kehoe, D. & Franklin, G. (2007). Prognostic factors of long-term disability in a workers' compensation system. *Journal of Occupational & Environmental Medicine, 49*(1), 31-40.

Thoms, P. & Venkata, R.R. (2002). Relation of managers personality to accident and injury rates. *Psychological Reports, 91,* 1007-1115.

Turner, B.A. (1991). The development of a safety culture. *Chemistry and Industry, 4,* 241-243.

Waehrer, G.M., Dong, X.S., Miller, T., Haile, E. & Men, Y. (2007). Costs of occupational injuries in construction in the United States. *Accident Analysis & Prevention, 39*(6), 1258-1266.

Wirth, O. & Sigurdsson, S.O. (2008). When workplace safety depends on behavior change: Topics for behavioral safety research. *Journal of Safety Research, 39*(6), 589-598.

Veevers, J.E. & Gee, E.M. (1986). Playing it safe: Accident mortality and gender roles. S*ocial Focus*, *19*(4), 349-360.

Vredenburgh, A.G. (2002). Organizational safety: which management practices are most effective in reducing employee injury rate? *Journal of Safety Research*, *33,* 259-276.

Zohar, D. (1980). Safety climate in industrial organizations. *Journal of Applied Psychology, 65*(1), 96-102.

Validation of a Simple Seat Satisfaction Questionnaire

Ahmed Radwan, Janelle Buell, Meredith Merchant, Michael Oeser, James Smith, Judy Spilka, Jonathan Wood and Jared Wydysh

Abstract

The 16-item simple seat satisfaction questionnaire (SSSQ) is a graphically enhanced questionnaire that assesses ergonomic quality of seats. A scoring system for the questionnaire is proposed utilizing Lkert-scale-based scoring system. Questionnaire was distributed to 220 volunteers from an educational institute. Response rate was 82%. Statistical validation of the SSSQ was conducted and the results were compared to independent ergonomic analysis of seats. The questionnaire was deemed statistically valid with overall Cronbach's alpha reliability coefficient of .85. Fifty percent of the sample had pain claimed to be related to seats, especially among females. Similarly, complaints and dissatisfaction with seats were greater among students than instructors and staff. According to the proposed scoring system, 30% of the seats needed ergonomic adjustments. The proposed SSSQ is a valid, graphically enhanced, easy-to-use questionnaire that assesses ergonomic quality of seats. Emphasizing sitting comfort will decrease the incidence of low back pain and improve productivity among workers.

Keywords
seat, ergonomics, workplace design, satisfaction

Introduction

Low back pain (LBP) among adolescents is likely to be attributable to poor sitting posture in inappropriate school furniture (O'Sullivan, et al., 2011). Similarly, LBP among working adults has been found to be associated with prolonged sitting postures at sub-optimal workstations (Van Niekerk, Louw & Hillier, 2012). Given the prevalence of LBP, it can be assumed that most chairs within workplaces and educational institutions across the U.S. are not of appropriate ergonomic design, meaning that the chair design does not enhance the performance of the task for which they were intended (Corlett, 2009).

The questionnaires that have been developed to evaluate both the extent of comfort and the quality of ergonomic design of a given seat are mostly comprised of too many questions and are often time-consuming to complete, which make them inefficient for public use. Additionally, there is lack of validated questionnaires that address the aspects of a seat, evaluate postural variables, and assess an individual's overall satisfaction with a seat in order to facilitate the completion of tasks in a given workplace or educational setting.

We propose the simple seat satisfaction questionnaire (SSSQ) as the first graphically enhanced seat satisfaction questionnaire that assess the users' overall satisfaction with, and the ergonomic value of seats. Through its proposed scoring system, this questionnaire will help identify areas in need for ergonomic intervention which will not only decrease the incidence of low back pain, but will also increase productivity among workers.

Methodology

The SSSQ is a graphically enhanced questionnaire that includes two sections comprising a total of 16 items. The first section is designed to obtain general subjective information from the participant regarding their position at the college, their gender, and the presence and location of any pain they may experience while seated at their workstation. The second section is comprised of 12 items and is designed to obtain information regarding the appropriateness of the following characteristics of the seat (seat height, seat depth, seat width, seat surface, backrest angle, seat pan angle, leg room as well as the presence and quality of backrest, lumbar support and armrests) in an attempt to evaluate the overall ergonomic quality of the seat utilizing a Likert scale.

Dr. Ahmed Radwan, PT, DPT, Ph.D., is an assistant professor in the physical therapy program at Utica College in Utica, NY. He may be reached at aradwan@utica.edu or (315) 792-3853.

Dr. Janelle Buell, PT, DPT, is currently practicing as a pediatric physical therapist at Building Blocks LLC in Clinton, NY.

Dr. Meredith Merchant, PT, DPT, is currently practicing as an acute care physical therapist at Roaonke Memorial Hospital in Roanoke, VA.

Dr. Michael Oeser, PT, DPT, is currently practicing as an outpatient physical therapist in Poughkeepsie, NY.

Dr. James Smith, PT, DPT, is currently practicing as an outpatient physical therapist in West Babylon, NY.

Dr. Judy Spilka, PT, DPT, is currently practicing as a physical therapist at Fairway Physical Therapy in Manlius, NY.

Dr. Jonathan Wood, PT, DPT, is currently practicing as an acute care therapist at Montefiore Medical Center in Bronx NY.

Dr. Jared Wydysh, PT, DPT, is currently working at the outpatient clinic and Newark-Wayne Hospital affiliate of Rochester Regional Heath Network.

The Likert scale was chosen in order to assess the strength of the participants' responses to a declarative statement on the 'ideal' characteristics of an ergonomically efficient seat. The responses were later analyzed to determine the ergonomic quality of the seats. A response of 5 (strongly agree) indicated high ergonomic quality of the seat characteristic under assessment; while a response of 1 (strongly disagree) indicated low ergonomic quality of the seat characteristic under assessment.

Survey Scoring

Scoring of the SSSQ contains cut-off scores based on the American National Standards Institute for ergonomic chair requirements and recommendations (Hedge, 2008). To score the questionnaire, the evaluator added the numbers that correlated with the participant's answers in the second section. For example, if the subject answered 4 or higher on all of the questions, a score of 48 to 60 was given, and the chair was classified as an "adequate chair." A score ranging from 36 to 47 was considered "fair" and a score of less than 36 was identified as "needs improvement."

Survey Validation

The survey was deemed content valid through expert opinion (A. Hedge, personal communication, April 2013). Additionally, the statistical analysis of the pilot study that was conducted on 20 participants (faculty, staff, students) supported this validation and reflected an overall Cronbach's alpha reliability coefficient of .89.

Survey Implementation

The SSSQ was administered in paper format to 220 participants (students, instructors, staff members) within the educational institute; 180 participants responded back for an overall response rate of 82%. Of these 180 subjects, 32% were undergraduate students, 29% were graduate students, 16% were faculty and 22% were staff members. Thirty-two percent of the individuals were males and 68% were females.

Results

Overall statistical validation and inferential statistics were performed using Statistical Package for Social Sciences (SPSSTM) v21. Descriptive analysis was performed for both subjective and objective information gathered through the questionnaire. In regards to pain, 55% of subjects experienced pain while sitting and 45% did not. Forty eight percent of subjects reported that they were satisfied with their chair while 49% reported that they were unsatisfied. Regarding objective seat design aspects, three aspects were reported mostly inappropriate by participants: presence of lumbar support, adequate seat pan tilt angle and presence of armrests (Table 1).

Upon calculating the final scores that each participant assigned to his/her specific chair, the total adequacy of chairs assessed was declared as follows: 28% of chairs needed improvement, 41% of chairs were of "fair quality," and 29% of chairs were considered of "adequate ergonomics." However, the difference between these three categories was statistically insignificant according to the chi-square test of goodness of fit ($p = .30$).

The independent ergonomic analysis for all seats that was performed by the research team was based on the appropriateness of nine seat parameters (seat height, seat depth, seat width, seat surface, backrest angle, seat pan angle, the presence and quality of backrest, lumbar support, and armrests). Chairs were deemed "adequate" if they met 8 or 9 parameters, "fair" if they met 6 or 7 parameters, and "need improvement" if they met 5 parameters or less. The results of the ergonomic analysis of seats were similar to the results obtained from the survey, where approximately 30% of seats analyzed were "adequate," 35% of seats were "fair" and about 35% of seats were found to be "needing improvement." However, the difference between the three categories was statistically insignificant ($p = .35$).

Reliability Analysis

Cronbach's alpha reliability coefficient of the full questionnaire was calculated. The internal consistency of the questionnaire was .86, which indicated that the questionnaire had

Table 1 Descriptive Analysis of All 12 Aspects of Seating as Reported From SSSQ

Seat Aspect	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Lumbar Support	18%	25%	13%	28%	16%
Seat Pan Tilt Angle	8%	30%	19%	29%	13%
Armrest	57%	11%	6%	14%	11%
Seat Height	2%	15%	7%	28%	47%
Seat Depth	5%	18%	10%	41%	26%
Seat Width	7%	17%	13%	32%	31%
Backrest	11%	26%	13%	27%	23%
Seat Pan Backrest Angle	8%	27%	16%	21%	27%
Seat Surface	21%	23%	9%	28%	18%
Vertical Leg Room	3%	8%	9%	40%	39%
Lateral Leg Room	1%	7%	8%	44%	40%
Forward Leg Room	2%	4%	8%	45%	39%

acceptable internal reliability (Tavakol & Dennick, 2011). Cronbach's alpha was also performed on the related items within the questionnaire as follows: reliability of all seat-pan-related questions was 0.73, for all back-rest-related questions 0.69, and for all leg-room-related questions was 0.74. Such high correlations confirm the internal consistency of the questionnaire.

Analysis of Relationship

Chi-square test of association was performed to analyze the associations between gender and pain, position in the educational institute and satisfaction with one's chair, position in college and total rating of one's chairs, pain and total rating of chairs, and finally how pain was related to all 12 chair aspects as reported by the SSSQ. A significant association was found between gender and the experience of pain. The results showed that females significantly experienced more pain than males. The extent of this correlation was ($x^2 = 5.60$, $p = .018$).

There was a significant association between individuals' position within the college community and the extent of satisfaction with their seat. Students (especially undergrads) were the most unsatisfied with their seats. The extent of association was ($x^2 = 11.8$, $p = .008$). Also, a significant correlation was found between position and the total rating of one's chair, where undergraduate students were found having more chairs that "needed improvement." The chi-squared test for association scores for this correlation were ($x^2 = 63.2$, $p = .001$).

When analyzing the association of pain and specific chair aspects. Significant correlations were found between pain and lumbar support ($x^2 = 29.2$, $p = .01$), seat pan – back rest angle ($x^2 = 25.6$, $p = .01$), seat pan tilt ($x^2 = 24.9$, $p = .01$), and seat surface comfort ($x^2 = 17.4$, $p = .002$). The previously mentioned aspects were found to be the highest correlations. However, pain was also found to be associated with seat depth ($x^2 = 17.0$, $p = .002$), seat height ($x^2 = 16.6$, $p = .002$), backrest support ($x^2 = 16.1$, $p = .003$), lateral leg room($x^2 = 12.0$, $p = .017$), and forward leg room ($x^2 = 10.6$, $p = .032$). There was no significant correlation found between pain and vertical legroom, presence or absence of arm rests, or seat width dimension (Table 2).

Overall, the association between total rating of chairs and pain was significant at ($x^2 = 27.2$, $p = .000$). Seats of the participants that reported having pain, were among the category of chairs scoring less than 36 in the overall questionnaire score and labeled as "need adjustment."

Table 2 Correlation Between Pain & the Different Aspects of Seating Ergonomics Using the Chi-Square Test of Association
(descending order from most significant correlation on top)

Correlation between pain and:	Chi-Square Test of Association	Comment
Lumbar Support	$x^2 = 29.2$, $p = .000$	People who had pain had inappropriate lumbar support in their chair
Backrest Seat-Pan Angle	$x^2 = 25.5$, $p = .000$	People who had pain had inappropriate backrest seat-pan angle
Seat Pan Tilt	$x^2 = 24.9$, $p = .000$	People who had pain had inappropriate seat pan tilt
Seat Surface	$x^2 = 17.4$, $p = .002$	People who had pain had inappropriate seat surface on their chair
Seat Pan Depth	$x^2 = 17.0$, $p = .002$	People who had pain had inappropriate seat pan depth
Seat Height	$x^2 = 16.6$, $p = .002$	People who had pain had inappropriate seat height
Backrest	$x^2 = 16.1$, $p = .003$	People who had pain had inappropriate backrest
Lateral Leg Room	$x^2 = 12.0$, $p = .017$	People who had pain had inappropriate lateral leg room available
Forward Leg Room	$x^2 = 10.6$, $p = .032$	People who had pain had inappropriate forward leg room available
Seat Width	$x^2 = 9.3$, $p = .053$	Correlation between having pain and seat width was insignificant
Vertical Leg Room	$x^2 = 4.3$, $p = .362$	Correlation between having pain and vertical leg room was insignificant
Armrest	$x^2 = 1.8$, $p = .771$	Correlation between having pain and inappropriate armrests was insignificant

Discussion

Response Rate

Administration of a paper-based format of the SSSQ within the current study yielded a response rate of 82%. Response rates ranging from 60% to 80% are considered excellent (Portney & Watkins, 2009). Although research shows that the administration of web-based surveys are advantageous in that they allow for respondent convenience, ease of data entry and analysis, and ease of follow-up, they also pose some potential threats that include, but are not limited to, low response rate and unclear answering instructions (Evans & Mathur, 2005). Research members attempted to emulate the strengths and address the threats previously mentioned of web-based surveys via the implementation of an appealing, color-printed and graphically enhanced paper-based format of the SSSQ.

Validity of the Questionnaire

The content validity of the SSSQ was deemed appropriate in determining the ergonomic appropriateness of a chair (A. Hedge, personal communication, April 2013). Similarly, the statistical validity of the SSSQ was proven to be acceptable (0.86 Chronbach's alpha correlation coefficient) according to Portney and Watkins (2009).

Several questionnaires in the current literature have been developed to assess user satisfaction. Currently, two valid and reliable seat satisfaction questionnaires exist, the Automotive Seating Discomfort Questionnaire (ASDQ) and the Quebec User Evaluation of Satisfaction With Assistive Technology (QUEST 2.0). However, they do not evaluate seat satisfaction pertaining to office chairs (Demers, Weiss-Lambrou & Ska, 2002; Smith, Andrew & Wawrow, 2006)

Aside from these two previously mentioned surveys, several other surveys have been developed that are more specific to the ergonomics of the chair, but have yet to be proven valid and reliable. The SSSQ, a questionnaire that has been deemed valid and reliable, enables objective measurement of the ergonomic appropriateness of a given chair and its related extent of worker's satisfaction.

Survey Results

Seating & Pain

The results of the present study found that approximately half of the subjects surveyed experienced pain while sitting in their chairs. Similar evidence was found in a study of 190 school children in North-Eastern Slovenia. Turnk, Vauhnik, and Micetic-Turk (2011) found that 43% of children from elementary schools and 44% of children from secondary schools experienced back pain which lasted more than one day. However, this pain is not necessarily related to ergonomic quality of the chairs.

Further research studies have reported that it is not only the adjustability of specific seating aspects that play a role in the reduction of pain, but also the postures assumed by the seated individual (Groenesteijn, Ellegast, Keller, Krause, Berger & Looze, 2012). Office work often involves prolonged sitting, or prolonged chair use and assumed postures. Not all tasks within these types of jobs enhance the use of proper postures. While adequate ergonomic seating helps to minimize the assumption of improper postures, it cannot eliminate them all together (Groenesteijn, et al., 2012). Therefore, the amount of time a person spends in a sitting position, adjustability of chair aspects, awareness of these adjustments, and modification of these adjustments to the task at hand are key components in minimizing pain and play an integral role in the amount and/or level of pain experienced by an individual. That being said, The pain reported in the SSSQ survey could have been due to the chair design or to the other aforementioned factors

Seating Aspects at the College

Lumbar support, seat pan tilt angle and armrests were among the seat aspects that were most often rated inappropriate by the participating subjects. Moreover, armrests were consistently rated lower than all other chair aspects by the subjects surveyed.

Evidence in the literature reiterates the importance of these chair aspects. The biomechanics of these seating aspects are well understood. Lumbar support is essential for reducing the load on spine by maintaining the natural lordotic curve of the lumbar spine (Alnaser & Wughalter, 2009). In a review of literature, Harrison, Harrison, Croft, Harrison and Troyanovaich (1999), reported that seats with good backrest inclination plus lumbar support are associated with the lowest disc pressures and the lowest electromyography recordings from spinal muscles. Harrison, et al. (1999), also reported that a seat pan forward inclination of five degrees and armrests can further reduce lumbar disc pressures. These studies echo the necessity of good lumbar support, seat pan tilt angle and armrests in a chair to reduce the pressure on the spine, thereby reducing the risk of discomfort.

Position at the College & Chair-Related Complaints

Students surveyed in both graduate and undergraduate classrooms reported significantly lower levels of satisfaction with their chairs when compared with faculty and staff. Undergraduate and graduate students also reported experiencing more pain when compared to their faculty and staff counterparts. In addition, both undergraduate and graduate students were more likely than faculty and staff counterparts to classify their chairs as "needs improvement."

To our knowledge, no studies in the current literature associate faculty, staff and student satisfaction with their chairs to the quality of their chairs, or to the pain levels associated with them. Additionally, no data were found that associate higher pay, job position or social standing with increased seat satisfaction, chair quality and lower pain related to seats. However, many studies exist that discuss the discrepancy between the anthropometric measurements of students and the corresponding parameters of their school seats that might explain the extent of pain experienced while using their chairs.

A study by Ramadan (2011) of Saudi Arabian elementary school furniture suggested that there was a high level of body mismatch in desk-chair combinations even with adjustable furniture. Brewer, et al. (2009), found an extremely high prevalence of ergonomic mismatch of students and their chairs' in a Midwestern U.S. school district. Almost all of the 139 students measured were found to not fit in their chairs. These data demonstrate a consistent discrepancy among students and their seats, which are further confirmed by the results of the present study, as both undergraduate and graduate students consistently reported their chairs to be of lower quality when compared to faculty and staff.

Gender & Pain

Significant correlations were found between the gender of the subjects and the amount of pain reported. Women were found to report a significantly higher level of pain than men. Many studies in the literature correlate gender and pain. Previous studies have concluded that women had a greater frequency of chronic musculoskeletal pain than men (45% to 31%). In a European study, which was specifically focused on reports of back pain, 24% of women not only reported a higher prevalence of back pain as compared to men (21%), but also reported a higher sensitivity to that pain through the use of the SF-36 Bodily Pain Scale (Fillingim, King, Ribeiro-Dasilva, Rahim-Williams & Riley III, 2009).

One review notes that many factors influence an individual's perception of pain, which include, but are not limited to, gender, sociocultural factors, age and the type of painful stimulus. These factors combine to produce the personal experience of pain (Bradbury, 2003). According to Bradbury (2003), it has been known for years that men and women have different pain thresholds. Such differences in pain thresholds between men and women have been found to be secondary to the differences in genetics and the neurochemical means by which pain is processed. However, this difference in pain does not appear to manifest until a certain age.

Another study determined the differences in mechanical pain thresholds between young boys and girls with a mean age of 11.4 by applying pressure to five aspects of the body (elbow, wrist, knee, ankle and paraspinals) (Hogeweg, Kuis, Oostendrop & Helders, 1996). This study determined that gender did not influence the amount of mechanical pain threshold reported in these young individuals. The significance of these studies suggests that differences in pain thresholds cannot necessarily be assumed until post-pubescent age occurs (Fillingim, et al., 2009). These findings are consistent with our study, as all subjects whom took the survey were older than the age of 18, and significant differences were found between gender and the amount of pain reported.

Association Between Chair Ergonomic Aspects & Pain

The quality of chair used by the individual being surveyed was found to influence the pain experienced. In many of the studies reviewed, the term discomfort is used in lieu of pain. Because these terms are similar, they will be used interchangeably for the purposes of this study.

The quality of the chair being used can play a major role in the pain that an individual experiences. The most common cause of pain experienced by an individual using an inadequate chair is the lack of an adjustable seat, backrest height and armrests (Niekerk, Louw & Hillier, 2012). Niekerk, et al. (2012), report that the addition of these adjustable features allows for decreased activity of the neck, shoulders and back muscles, with additional relief in intervertebral pressure. Therefore, adjustability of the chair remains a high priority as it has been proven to minimize one's experience of pain (Niekerk, et al., 2012).

The results of the present study found that several different aspects of the chairs were correlated with pain reported by the surveyed subjects. From highest to lowest correlation, the chair aspects were lumbar support, seat pan to backrest angle, seat pan tilt, and seat surface comfort. Other significant findings include seat depth, seat height, backrest support, lateral leg room and forward leg room. This explains the relatively high dissatisfaction level among participants with their own chairs and might trigger establishing a priority list of modifications/ergonomic adjustments that should be implemented by the management of the institute.

To our knowledge, no other studies have correlated this variety of chair design characteristics with pain. With that said, there are certain aspects of chair design that have been extensively studied. For example, lumbar support is a popular subject in the literature. The biomechanics of lumbar support are well known. Makhsous, et al. (2009), reported that enhanced lumbar support has been found to significantly redistribute the spinal load, and reduce lumbar paraspinal muscle activity in both asymptomatic and in patients with back pain. This analysis is consistent with the findings of the present study, as absence of lumbar support was the chair aspect that was found to be the most correlated to pain.

The degree and direction of seat pan tilt has been associated with decreased incidence of low back pain. O'Sullivan, McCarthy, White, O'Sullivan and Dankaerts (2012) suggested that a forward inclination of the seat pan increased lumbar lordosis, reduced lumbar paraspinal muscle activity, and thus reduced the incidence of low back pain. Furthermore, Rasmussen, Torholm and De Zee (2009) suggested that a forward seat pan inclination of up to approximately 10 degrees was beneficial in minimizing spinal loading if accompanied by an appropriate friction coefficient. In concordance, the results of our study demonstrated a strong correlation between inappropriate seat pan tilt and pain.

In addition to seat pan tilt, studies have also shown that an adequate seat pan to backrest angle contributed to higher comfort (Hedge, 2011; HFES, 2007; Vos, Congleton, Moore, Amendola & Ringer, 2006). Groenesteijn, et al. (2009), found that proper seat pan to backrest angle that reached 124 degrees increased comfort of users during non-visual display unit (VDU) tasks such as reading and phone use. Similarly, the results of our study confirmed a strong correlation between inappropriate seat pan to backrest angle and presence of pain. Additionally, it is worth noting that the students who took the SSSQ (n = 99) were non-VDU users.

Conclusions

In conclusion, it has been determined that one-third of the tested chair sample within the college community needed adjustment. Approximately half of the study's subjects were unsatisfied with their current chairs and experienced pain secondary to poor ergonomic design of their chairs. Furthermore, this complaint was consistently higher in women. The SSSQ is a valid and reliable tool that can be used to assess the overall ergonomic quality of a chair. It is a graphically enhanced questionnaire that incorporates ergonomic education of the proper seating aspects while measuring seat satisfaction. The questionnaire is user friendly and can be conveniently completed in as little as five minutes. Future studies should be directed toward establishing reliability of the instrument's use outside of the educational setting. ○

References

Alnaser, M., & Wughalter, E. (2009). Effect of chair design on ratings of discomfort. *Work, 34*(2), 223-234. doi:10.3233/WOR-2009-0919

Bradbury, J. (2003). Why do men and women feel and react to pain differently? *The Lancet, 361*(9374), 2052-2053.

Brewer, J., Davis, K., Dunning, K. & Succop, P. (2009). Does ergonomic mismatch at school impact pain in school children? *Work, 34*(4), 455-464. doi:10.3233/WOR-2009-0946

Corlett, E.N. (2009). Ergonomics and sitting at work. *Work, 34*(2), 235-238.

Demers, L., Weiss Lambrou, R. & Ska, B. (2002). The quebec user evaluation of satisfaction with assistive technology (QUEST 2.0): An overview and recent progress. *Technology and Disability, 14*(3), 101-105.

Evans, J.R. & Mathur, A. (2005). The value of online surveys. *Internet research, 15*(2), 195-219.

Fillingim, R.B., King, C.D., Ribeiro-Dasilva, M.C., Rahim-Williams, B. & Riley, J.L. III (2009). Sex, gender, and pain: A review of recent clinical and experimental findings. *The Journal of Pain, 10*(5), 447-485.

Groenesteijn, L., Ellegast, R.P., Keller, K., Krause, F., Berger, H. & Looze, M.P. (2012). Office tasks effects on comfort and body dynamics in five dynamic office chairs. *Applied Ergonomics, 43*(2), 320-328.

Groenesteijn, L., Vink, P., de Looze, M. & Krause, F. (2009). Effects of differences in office chair controls, seat and backrest angle design in relation to tasks. *Applied Ergonomics, 40*(3), 362-370. doi:10.1016/j.apergo.2008.11.011

Harrison, D.D., Harrison, S.O., Croft, A.C., Harrison, D.E. & Troyanovaich, S.J. (1999). Sitting biomechanics Part I: Review of the literature. *Journal of Manipulative and Physiological Therapeutics, 22*(9), 594-609.

Hedge, A. (2008). Chair checklist (ANSI/HFES 100-2007).

Hedge, A. (2011). Ergonomic seating. Ithaca, NY: Cornell University, Department of Ergonomics. Retrieved from http://ergo.human.cornell.edu/DEA3250allnotes.html

Human Factors and Ergonomics Society. (2007). : Human factors engineering of computer workstations (ANSI/HFES 100-2007). Santa Monica, CA: Author.

Hogeweg, J.A., Kuis, W., Oostendrop, R. . & Helders, P.J. (1996). The influence of site of stimulation, age, and gender on pain threshold in healthy children. *Physical Therapy, 76(12),* 1331-1339.

Makhsous, M., Lin, F., Bankard, J., Hendrix, R.W., Hepler, M. & Press, J. (2009). Biomechanical effects of sitting with adjustable ischial and lumbar support on occupational low back pain: evaluation of sitting load and back muscle activity. *BMC Musculoskeletal Disorders, 10*(17), 1-11.

Niekerk, S., Louw, Q.A. & Hillier, S. (2012). The effectiveness of a chair intervention in the workplace to reduce musculoskeletal symptoms. A systems review. *BMC Musculoskeletal Disorders, 13*(145), 1-7.

O'Sullivan, K., McCarthy, R., White, A., O'Sullivan, L. & Dankaerts, W. (2012). Can we reduce the effort of maintaining a neutral sitting posture? A pilot study. *Manual Therapy, 17,* 566-571.

O'Sullivan, P.B., Smith, A.J., Beales, D.J., & Straker, L.M. (2011). Association of biopsychosocial factors with degree of slump in sitting posture and self-report of back pain in adolescents: A cross-sectional study. *Physical Therapy, 91*(4), 470-483.

Portney, L.G. & Watkins, M.P. (2009). *Foundations of clinical research: Applications to practice* (3rd ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Ramadan, M. (2011). Does Saudi school furniture meet ergonomics requirements? *Work, 38*(2), 93-101. doi:10.3233/WOR-2011-1111

Rasmussen, J., Torholm, S. & De Zee, M. (2009). Computational analysis of the influence of seat pan inclination and friction on muscle activity and spinal joint forces. *International Journal of Industrial Ergonomics, 39*, 52-57.

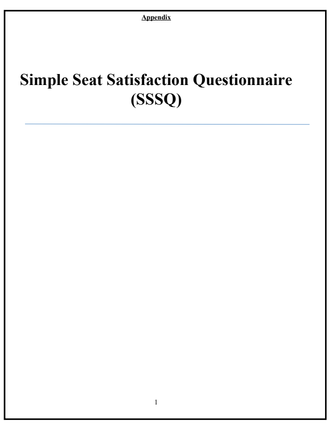
Smith, D.R., Andrews, D.M. & Wawrow, P.T. (2006). Development and evaluation of the automotive seating discomfort questionnaire. *International Journal of Industrial Ergonomics, 36*(2), 141-149.

Tavakol, M. & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education, 2*, 53-55. doi:10.5116/ijme.4dfb.8dfd

Turnk, Z., Vauhnik, R., & Micetic-Turk, D. (2011). Prevalence of nonspecific low back pain in schoolchildren in north. *Collegium Antropologicum, 35*(4), 1031-1035

Van Niekerk. S.M., Louw, Q.A. & Hillier, S. (2012). The effectiveness of a chair intervention in the workplace to reduce musculoskeletal symptoms. A systematic review. *BMC Musculoskeletal Disorders, 13*,145.

Vos, G.A., Congleton, J.J., Moore, S.J, Amendola, A.A. & Ringer, L. (2006). Postural versus chair design impacts upon interface pressure. *Applied Ergonomics, 37*(5), 619-628.


Appendix

Simple Seat Satisfaction Questionnaire (SSSQ)

1

Click here to view Appendix: Simple Seat Satisfaction Questionnaire

Evaluation of Fuzzy Linguistic Modeling Performance to Predict Health Effects of Occupational Vibration Exposure

Farman A. Moayed and Yuan-Hsin Cheng

Abstract

The occupational safety field requires great amount of human reasoning involving the use of variables which are usually estimated subjectively. Researchers have traditionally used categorical data analysis methods in their research. Such methods allow variables to have a certain values based on their category and it is not possible to assign any values between categories. However, same variables can be defined as fuzzy variables with fuzzy set values by which multiple values can be assigned to one variable. Fuzzy linguistic models use subjective variables to estimate the values of outcome variables. The main objective of this study was to compare the performance of logistic regression models and fuzzy linguistic models at predicting possible health effects of occupational vibration exposure among stone cutting workers. A secondary data analysis was conducted on a dataset about occupational vibration exposure and its possible health effects among stone cutting workers in Taiwan. Two sets of models were constructed; logistic regression (LR) models and fuzzy linguistic (FL) models, and the models were used to predict the most probable values of outcome variables. Then the performance of both models was compared with one another using Root-Mean-Square-Error (RMSE). A paired t-test was conducted on RMSE values of LR and FL models with a significance level of five percent and 31 degree of freedom. The p-value was less than 0.001, which indicated that the FL models performed better than LR models in predicting the most likely values of the outcome variables. Fuzzy linguistic models may be a better and more reliable method for hazard analysis by incorporating the experts' opinion and patterns of historic data. Experts can customize models to predict the severity of health effects of a given exposure or hazard.

Keywords
Fuzzy linguistic models, logistic regression, model performance, predictions, occupational vibration

Occupational Application
One significant application of this research is that safety professionals can take advantage of subjective and/or historic data, using their expert opinion to construct FL models and predict the most probable health effects of exposure to certain sets of factors (e.g., short- and long-term exposure to vibration). The construction of FL models can be less time consuming, requires less statistical/mathematical skills and does not need sensitivity analysis.

Another potential application could be in developing administrative control methods to reduce employees' risk through work scheduling and job rotation even without dose-response data. Safety managers can gain a better understanding about the patterns of short- and long-term exposure to certain agents (e.g., vibration) and their health effects on workers just by following the trends in historic data. Such insight can help safety managers develop more effective work schedules and job rotation plans to minimize the health effects of hazard exposure.

Introduction

The traditional methods of data analysis in occupational safety are not suitable for dealing with systems in which the relationship between variables cannot be represented in terms of exact values and equations. Other fields such as biology, sociology, economics, and more generally, any field with humanistic aspect in nature rather than mechanistic are facing similar problems with methods of data analysis (Zadeh, 1994). One common approach to deal with uncertainty or inaccuracy in problem solving and modeling when using numerical methods is probabilistic methods or sensitivity analysis, where researchers try to determine the range of values that a certain variable can take and still be able to make the same conclusion without changing the model significantly.

The occupational safety field requires a great amount of human reasoning which involves the use of variables whose values are fuzzy sets. This observation is the center for the concept of a linguistic variable, that is, a variable whose values are words rather than numbers. The concept of a linguistic variable has played a significant role in application of fuzzy set theory and fuzzy logic (Zadeh, 1994).

Traditional methods of data analysis in

Farman A. Moayed, Ph.D. P.E., is an assistant professor in the occupational safety management program in the College of Technology at Indiana State University, Terre Haute, IN. He can be reached at (812) 237-3461 or farman.moayed@indstate.edu.

Yuan-Hsin Cheng is a doctoral student in Department of Agricultural and Biological Engineering in Purdue University. She can be reached at (765) 494-1162.

these fields are oriented towards the use of statistical techniques such as categorical data analysis and logistic regression analysis. Most of the time it is difficult, if not impossible, to accurately and objectively measure the correlation between some of the elements that are under study due to their nature by using crisp and exact quantitative methods. For example, the correlation between the heaviness of a load and severity of lower back pain can only be measured subjectively by using categorical data analysis methods. This opens the field to applications of fuzzy sets and fuzzy logic analysis, and fuzzy linguistic controls in particular. To be more specific, in the linguistic approach the focus shifts from difference and differential equations to fuzzy if-then rules in the form of *if X is A then Y is B,* where *X* and *Y* are fuzzy variables and *A* and *B* are their linguistic values (Zadeh, 1994). Rules similar to that are used to characterize the imprecise correlation among variables, and have been used in different studies and projects as a modeling tool.

Some researchers believe that the limitations of traditional models for risk assessment and data analysis in occupational safety and health are based on uncertainty, imprecision and incompleteness of data. These limitations draw criticism to the results and their practical implementation (Karwowski & Mital, 1986; Pinto, Nunes & Ribeiro, 2011). Some researchers try to add sensitivity analysis after modeling and conducting data analysis, in which the researcher tries to study if the output of a model can remain the same when the value of one or more uncertain variable(s) change within a given range (Chatterjee & Hadi, 1988; Haimes, 2009). Despite the benefits of this approach, the actual model is constructed based on the initial dataset that might be incomplete, inaccurate, usually subjective, and imprecise. Logistic regression models are mathematical methods with the goal of finding the best fitting and most parsimonious models to describe the relationship between variables. The difference between logistic regression and linear regression models is that in the logistic regression the outcome variable is binary. However, special forms of logistic regression models have been developed to deal with categorical variables (Hosmer & Lemeshow, 2000).

A large portion of real-world problems that arise in the analysis, control and decision making are far from simple. Fuzzy sets and fuzzy linguistic modeling are not intended to replace the existing methods, rather to provide additional tools to solve problems. The Mamdani model was the first fuzzy rule-based model developed to implement linguistic variables (in form of if-then rules) in a control system and later on its application spread to other areas such as decision making in business and outcome prediction in epidemiology (Mamdani & Assilian, 1999; Massad, Ortega, de Barros & Struchiner, 2008). Nowadays, the applications of fuzzy logic and fuzzy linguistic (FL) modeling mimic human cognition imitate human judgment in common sense reasoning to describe the relationship between variables. FL models are able to resolve detail and store information in order to enhance the tolerance for imprecision and uncertainty to achieve controllability, robustness, low solution cost and better prediction of the most probable outcome (Chen & Pham, 2001; Mukaidono, 2001; Zadeh, 2002).

The applications of fuzzy logic and FL models have expanded to a variety of fields and areas over the years, but they have not been established as another data analysis tools among occupational safety experts and practitioners. The purpose of this article is to study and compare the performance of FL models against logistic regression models (LR) that are sometimes used by safety researchers.

Objective

The main objective of this study was to compare the performance of LR models and FL models by constructing two sets of models, one set for each, and predicting possible health effects of occupational vibration exposure among stone cutting workers in Taiwan. The root-mean-square-error (RMSE) was used to assess the accuracy of each model in terms of number of correct predictions. In other words, the null hypothesis of this study was:

$$H_0\text{: } (RMSE)_{\text{FL Model}} - (RMSE)_{\text{LR Model}} = 0$$

It is important to emphasize the intent of this study was not to conduct a data analysis on occupational vibration exposure and its health effects, but rather to compare the performance of two different sets of models in predicting the health effects of vibration exposure accurately.

The significance of this study is that in a field such as occupational safety most of the judgments about outcomes rely on experts' opinions and historic data associated with each case, particularly when the number of factors that can affect the outcome is high and usually different from one case to another. Furthermore, researchers do not always include all of them in their studies. Therefore, FL models can be an alternative method for predicting potential outcomes particularly when the dataset is not large enough for conducting statistical data analysis.

To achieve this goal, first a review of previous studies is provided in next section. Then similarities and differences of these studies are briefly reviewed and discussed. Next, a dataset containing information about whole-body and hand-arm-induced vibration exposure and severity of musculoskeletal disorders among stone cutting workers was used to develop two sets of models: LR and FL models. In this study, the FL models were selected over regular fuzzy logic models for two main reasons: 1) the FL models do not need fuzzification and defuzzification to process; and 2) FL models function by simulating human cognitive and reasoning. The models were used to estimate the severity of musculoskeletal disorders based on self-reported exposure levels and the estimates were compared to the actual severity of disorders reported by subjects. The performance of models was determined based on the errors in prediction. The model with fewer and smaller error was considered to have better performance.

Literature Review

A literature search was conducted during the fall 2012 on electronic resources related to this topic (occupational safety and health and fuzzy logic models) and accessible to the authors. The search resulted in six different articles that were reviewed (Table 1). As shown in this table, there were differences among articles in regard to their source of data, methodology, utilized/developed fuzzy models, and input and output variables, which make the comparison difficult.

All selected articles can be divided into two groups, the studies that utilized simple FL models and the studies that developed hybrid fuzzy linguistic models for data analysis. The latter groups mixed FL models with another method of modeling in order to enhance the quality or customize the model for their research.

McCauley-Bell and Crumpton (1997), Gürcanli and Müngen (2009), and Padma and Balasubramanie (2011b) were the articles in the first group. Besides using simple FL models, they all used risk of a certain kind of occupational injury or accident as their outcome variable. Each article utilized different number of input/exposure variables for their models and only McCauley-Bell and Crumpton (1997) and Padma and Balasubramanie (2011b) compared the performance of their FL models with other modeling method.

McCauley-Bell and Crumpton (1997) was one of the early publications that applied FL modeling to predict the risk of carpal tunnel syndrome (CTS) among 17 subjects with different occupations, such as reservationist, technician, data entry operator, and cook. Eighteen exposure variables were identified and categorized in three groups (i.e., task-related risk factors, personal risk factors and organizational risk factors. The overall risk was defined as a linear function of all risk factors with assigned weights. Comparing this technique with the

Table 1 Summary of Literature Review

Author(s) & Year	Subjects	Exposure / Input Variable(s)	Outcome / Output Variable(s)	Method & Goal	Results
McCauley-Bell & Crumpton 1997	- 17 subjects	- Total of 18 variables categorized in three groups: task, personal and organizational	- One variable as risk of developing CTS	- Fuzzy linguistic modeling to predict the risk of CTS - One fuzzy variable was defined as a linear function of exposure variables with different weights	- The model out-performed other test procedures to predict the risk of CTS - It can help identify employees at high risk for intervention
Gürcanli & Müngen 2009	- 4347 cases of construction accidents	- Accident likelihood - Consequent severity - Current safety level	- Level of risk	- Fuzzy linguistic modeling to assess the risk level for different construction sites	- The model produced general risk assessment results for different sites - It can help identify departments with high level of risk for intervention
Grassi *et al.* 2009	- Different jobs in food industry	- Injury magnitude - Occurrence probability - Undetectability - Sensitivity to maintenance non-execution - Sensitivity to PPE non-utilization	- Risk index	- Modified fuzzy linguistic modeling (fuzzy TOPSIS) to assess the risk index	- New model was able to provide more detailed information for management compared to traditional method
Ciarapica & Giacchetta 2009	- Dataset about 190,116 cases of work-related injuries	- Sex - Status of employment - Age - Type of work - Type of lesion - Physical activity - Material agent	- Frequency of injury - Severity of injury	- Neuro-Fuzzy modeling to classify and predict the frequency and severity of injuries	- The model's performance was acceptable in predicting injuries compared to other models
Padma & Balasubramanie 2011a	- Three different jobs (*i.e.,* office workers, sewing machine operators, ambulance crews)	- Total of 13 different variables categorized in 3 different groups	- Level of risk for developing shoulder-neck pain	- Fuzzy analytic hierarchy processing modeling to assess the risk level for shoulder-neck pain in different jobs	- The model output ranked jobs with respect to the level of risk for shoulder-neck pain
Padma & Balasubramanie 2011b	- Sample of 131 people, 93 had shoulder-neck pain and 38 had no pain	- Total of 13 different variables categorized in 3 different groups	- Level of risk for developing shoulder-neck pain	- Fuzzy linguistic modeling to predict the risk of shoulder-neck pain	- The fuzzy linguistic model was accurate and valid compared to the AHP (Analytic Hierarchy Process) in predicting the development of shoulder-neck pain and its severity

physicians' findings, 82.4% of results obtained using the carpal compression technique were correct. Also, 14.7% of these results were false negatives. Phalen's test yielded 82.4% correct results, 8.8% false negatives and 8.8% false positive results. Meanwhile, vibrometry results were 70% correct in diagnosing CTS among subjects with 16.7% false negatives and 13.3% false positives diagnosis. The electroneurometer testing results appeared least accurate with 48.3% correct diagnosis, 41.4% false negatives and 10.3% false positives.

In another study, Gürcanli and Müngen (2009) assessed the risk level of accidents at different construction sites. They used different input variables that were accident likelihood, consequent severity and current safety level. The input parameters of the fuzzy system were derived from the judgment of experts, and raw data of construction incidents between 1969 and 1999 in Turkey. Variables such as accident likelihood, consequence severity and current safety level were used as input variables in an FL model using Mamdani-type inference system to assess the risk level of each construction site. The authors claimed that this method was only focused on daily, routine safety measures rather than safety management principles. In conclusion, this method could provide a preliminary assessment of general risk level for different construction sites, which can be used for intervention by management.

In Padma and Balasubramanie (2011b), the authors considered 13 different possible factors as input variables and categorized them in three groups which were psychosocial-related risk factors, physical-related risk factors; and mechanical-related risk factors. They created an FL model to predict the risk of developing musculoskeletal disorders in shoulder and neck areas by using a sample of 131 subjects, among which 38 had no pain and 93 had shoulder-neck pain with different levels of severity. By applying the predictive value theory, their FL model validated the results and its efficiency. This showed that percentage of efficiency of the results (in terms of sensitivity and specificity) for different linguistic risk levels from "little to no risk" to "very strong" varied from 78.3% to 83.6%, which showed that the results were more reliable and almost equivalent to the domain experts knowledge-based results.

The second group of articles that used hybrid FL models consists of Grassi, et al. (2009), Ciarapica and Giacchetta (2009), and Padma and Balasubramanie (2011a). The latter article was the only study in this group that did not compare the results and performance of their model with other methods of data analysis or modeling, while the other two articles concluded that their customized hybrid-FL models performed better than other methods.

Grassi, Gamberini, Mora and Rimini (2009) developed a fuzzy multi-attribute model for risk assessment for different jobs in food industry, which was a modified FL model referred to as fuzzy TOPSIS. The input variables in this model were 1) injury magnitude; 2) occurrence probability; 3) sensitivity to maintenance non-execution; and 4) sensitivity to PPE non-utilization. The output of this model was a variable called risk index that was mathematically formulated to provide a value between zero and one as a measure for risk level of an occupational accident for a given job. Considering the fact that multi-attribute solution methodology based on fuzzy logic can raise the level of complexity, the authors claimed it also can guarantee coherence in evaluation even when a large number of activities were taken into account. This study showed that the outcome of this approach could provide more tangible results which were easily interpreted for management to identify hazardous jobs and understand the correlation between poor execution of maintenance and lack of use of PPE in workplace.

The model used by Ciarapica and Giacchetta (2009) for predicting and classifying injuries by frequency and severity was a neuro-fuzzy model. This type of artificial neural network (ANN) uses a neural network model to learn from patterns that represent correlations between exposure variables and outcome variables by training. In this study, seven different factors were considered as input/exposure variables and a dataset of about 190,116 cases of work-related injuries from the period of 2002 to 2006 were used to develop and train the neuro-fuzzy model. The "number of injuries" was used as measurement for frequency and "days lost" for severity of injuries.

The results produced by such model were compared with moving average, linear regression, Holt-Winters and ANN modeling methods, and it was concluded that the neuro-fuzzy model was able to perform better by generating fewer errors. The percentage of errors produced by the neuro-fuzzy model was 7.9 for frequency of injuries compared to moving average, linear regression, Holt-Winter and ANN methods errors, which were 14.7%, 14.0%, 10.3% and 11.2%, respectively. Similarly, the percentage of errors produced by neuro-fuzzy model for severity of injuries was 7.8 compared to moving average, linear regression, Holt-Winter and ANN methods errors , which were 28.5%, 11.3%, 11.1% and 8.1%, respectively.

In an article by Padma and Balasubramanie (2011a), a fuzzy analytic hierarchy processing model was developed as a decision support system to assess the risk level for shoulder-neck pain (output variable) for three different jobs (i.e., office workers, sewing machine operators, ambulance crews). Thirteen different possible factors were considered as input variables and categorized in three groups (i.e., psychosocial-related risk factors, physical-related risk factors, mechanical-related risk factors). The result showed that the fuzzy analytic hierarchy processing model was able to rank the three jobs based on their level of risk for shoulder-neck pain and, in conclusion, this research was able to formulate an occupational disorder (i.e., shoulder-neck pain) as a multi-criteria decision-making problem but the performance of the model was not compared to other methods.

By looking at articles listed in Table 1, some significant differences stand out among the studies such as the type of the fuzzy models used for risk assessment, sample size or the type of jobs and industry sector, and all of them were able to show that their models can be successfully used for risk assessment or outcome prediction. However, among the seven articles included in the literature review, McCauley-Bell and Crumpton (1997) and Ciarapica and Giacchetta (2009) were the only studies that quantitatively compared the performance of their fuzzy model to other commonly used models in their fields and

Table 2 List of Dependent & Independent Variables

Independent/Exposure Variables	Dependent/Outcome Variables
- long term exposure to vibration - daily exposure to vibration - perceived level of exposure to Hand-Arm Vibration (HAV), - presence of Whole Body Vibration (WBV) - presence of Hand-Arm Vibration (HAV)	- frequency and severity of pain in major body joints/parts, *i.e.* back, shoulders, neck, wrists, elbows, knees and head - tingling sensation in hands/fingers - numbness in hands/fingers

were able to demonstrate how reliable and valid the results of fuzzy models were.

The significant difference between the articles cited and the current study was that none of the reviewed articles had purely ordinal or categorical data in their datasets and they did not compare their FL model to LR modeling, which is a common data analysis tool among occupational safety and health researchers when dealing with such variables. The approach in this study was to develop simple FL models to estimate the risk of developing musculoskeletal disorders potentially caused by occupational vibration exposure and compare the results to their corresponding logistic regression models.

Methodology

The dataset used in this study was initially collected and studied in another research project (Moayed & Cheng, 2012) during summer 2010, with the goal of assessing the level of occupational vibration exposure and its health effects among stone cutting workers in Taiwan and China. Since data analysis and risk assessment were not included in the objectives of this study, readers are referred to Moayed and Cheng (2012) for more detailed information about questionnaire development, sample selection, Institutional Review Board approval, statistical data analysis and its results.

Due to the characteristics of the dataset, number of variables, and complexity of the model, a subset of the initial dataset was selected for this study that included the Taiwanese portion of dataset. The decision to exclude the Chinese portion of dataset was made mainly because their responses seemed too perfect to be true. The sample subjects used in this study consisted of 33 male Taiwanese stone cutting workers with average of 37.7 years of age ($SD = 8.53$) and average weight and height of 74.4 kg ($SD = 10.9$) and 171.8 cm ($SD = 6.8$), respectively. The subjects were using various vibrating power tools and equipment such as hammers, grinders, polishers, drills, overhead cranes, trucks, sand blasters and saws to break and cut larger stones into smaller pieces and polish them to their final shape and size.

A survey questionnaire comprised of about 58 questions was distributed among subjects. The questions were answered subjectively and no direct observation or measurement was made during this study. Among all the variables collected in the initial research (Moayed & Cheng, 2012), a subset of variables was included in this study (Table 2).

Thirty-two separate LR models were constructed during this project. In 16 models, the severity and frequency of pain in back, shoulders, neck, wrists, elbows, knees and head, as well as tingling and numbness in fingers were considered as outcome variables with levels of long term and daily vibration as exposure variables. Another 16 models were constructed with similar dependent (outcome) variables and three different independent (exposure) variables (i.e., perceived level of exposure to HAV, presence of WBV, HAV). In all 32 LR models the effects of variable interactions were considered minimal and were not included and the general guideline explained by Hosmer and Lemeshow (2000) was followed in development of LR models during this project with limited discretionary modifications. The SAS System 9.0 for Windows was used to estimate the variable parameters for all LR models.

Overall, 32 FL models were developed during this project; that is one FL model with similar exposure and outcome variables corresponding to every LR model. For every FL model a different set of linguistic rules were developed based on experts' opinion and consensus, and incorporating the observed patterns in the existing dataset.

The performance comparison was conducted by estimating the RMSE for all models by measuring the difference between the actual value of a given outcome variable with the predicted value in each model. Then a paired *t*-test was conducted to compare the performance of FL models versus LR models. The result of paired *t*-test was able to show if there was a significant difference between the performance of FL models and LR models in predicting the outcome accurately.

In situations in which both exposure and outcome variables are ordinal (similar to this study), a typical LR model predicts the probability of occurrence for each level of outcome variable because in LR models with ordinal variables, it is assumed that the outcome variables behave linearly with respect to the exposure variable and the only difference is in y-intercepts. (Harrel, 2001; Hosmer & Lemeshow, 2000; Moayed & Shell, 2011a, 2011b). For the purpose of this study, the value with the highest probability of occurrence was selected as the predicted value for the given outcome variable in LR models.

In summary, the following algorithm was followed in this study:

1) Break the original dataset into 32 subsets.

2) Construct a logistic regression model for each subset by using SAS system.

3) Construct a fuzzy linguistic model for each subset using expert opinion.

Table 3 Acceptable Ordinal Values for Outcome & Exposure Variables

back pain severity (*Y*)	long term exposure to vibration (X_1)	daily exposures to vibration (X_2)
1- Negligible	1- Less than one year	1- Less than one hour
2- Moderate	2- One to two years	2- One to two hours
3- Somewhat Severe	3- Two to five years	3- Two to four hours
4- Severe	4- Five to ten years	4- Four to six hours
5- Very Severe	5- More than ten years	5- More than six hours

4) Predict the value of the outcome variable in each model separately using logistic regression and fuzzy linguistic models.

5) Compare the predicted values and the actual values of the outcome variables for each model.

6) Compare the performance of each logistic regression model with its corresponding fuzzy linguistic model in terms of the number of correct predictions and RMSE.

7) Include all 32 pairs of estimated RMSEs in a set and conduct a paired *t*-test to investigate if significant difference exists.

Due to the large number of models constructed in this research, the construction of only one LR model and its corresponding FL model is explained here and their performances are compared in order to help the readers have a better understanding about the methodology used in this study.

In one of the LR models, back pain severity was the outcome variable (*Y*) and long term and daily exposures to vibration were exposure variables (X_1 and X_2). All three variables were categorical and the acceptable values are presented in Table 3.

In this example, just like any LR model, it can be denoted that:

$$\pi_Y = \int(X_1, X_2)$$

In which π_Y represents the probability of the occurrence of any possible value for variable *Y*. By using the Proc Probit procedure in the SAS system, the parameters for exposure variables and y-intercepts for different levels of outcome variable were estimated (Table 4). Obviously the number of y-intercepts is one less than the number of levels for the outcome variable and the difference between the y-intercepts represents the difference in the likelihood of occurrence for each level of outcome variable.

The numbers in Table 4 were used to predict the probability of different levels of back pain severity and the one with the highest probability was chosen as the prediction of the potential outcome. For instance, if one subject answered that his/her long term exposure to vibration was two to five years ($X_1 = 3$) and daily exposure to vibration was four to six hours ($X_2 = 4$) it was estimated that the probability of having negligible, moderate, somewhat severe, severe or very severe back pain was 0.05, 0.48, 0.27, 0.13 and 0.06, respectively, and as a result moderate back pain was selected to predict the outcome because it had the highest likelihood of occurrence ($\pi_{Y=2}$) = 0.48).

The corresponding FL model was developed based on expert opinion by considering the patterns in the existing dataset which was specific to this industry and sites. Figure 1 (p. 207) shows the expert rules that were used to predict the potential outcome (*Y*) based on the values of exposure variables (X_1 and X_2). It should be noted that half of the 32 models had three exposure variables and their rules were different with the one presented in Figure 1 as an example.

Table 4 Estimated Values for Parameters & y-intercepts in the SAS System

Intercept 1	2.5674
Intercept 2	1.6897
Intercept 3	4.0175
Intercept 4	6.7579
X_1	-2.0823
X_2	0.0895

After using both the LR and FL models to predict the outcome (back pain severity) for all 33 subjects in the dataset and comparing the results, it showed that both models were able to predict the exact value of the outcome correctly for 10 subjects and there were errors in the remaining 23 predictions. The RMSE for the FL model was estimated at 1.03. It was less than RMSE for the LR model which was estimated at 1.50. This reduction of RMSE indicates that although the FL model was not able to predict the exact value of outcome variable but the predicted values were closer to the actual values of the outcome variable (i.e., smaller errors in estimates).

Results

After completing the first six of seven steps listed in the algorithm, the list of all LR and FL models developed in this study along with the name of outcome and exposure variables in every model are presented in Table 5 (p. 208). In this table, the number of correct prediction of outcome values and estimated RMSEs are listed for each model where paired models can be compared side-by-side.

As presented in Table 5, the results of the number of correct prediction of outcome variables were mixed. In some subsets, logistic regression models were able to correctly predict the outcome variable more frequently and in some cases fuzzy linguistic models were able to do so. However, by looking at the

RMSEs, it is obvious that in general the FL models predictions were closer to the actual values than LR models.

The estimated average of RMSEs were 1.38 and 1.14 for LR models and FL models, respectively, and the variance of RMSEs were 0.13 for LR models and 0.05 for FL models. A paired *t*-test was conducted (H_0: D = 0,where D = $(RMSE)_{LR}$-$(RMSE)_{FL}$) with 5% level of significance and 31 degrees of freedom and as the result the null hypothesis was rejected ($p < 0.001$). This indicated that the Fuzzy Linguistic Models developed in this study were able to perform better than Logistic Regression Models to estimate the potential outcome. In other words, the FL models were able to better match the (self-reported) exposure factors with the (self-reported) symptoms of MSDs.

Discussion

Conventional statistical/mathematical modeling methods such as linear regression and logistic regression are based on a few assumptions which are not applicable to categorical data analysis. For example, in LR analysis, it is assumed that the exposure variables are intervals or ratio and the residuals have normal distribution (Neter, Kutner, Nachtsheim & Wasserman, 1996); or in LR analysis it is assumed that in a model made of all categorical variables, all possible values of outcome variable have the same linear correlation with exposure variables except the value of y-intercept. This assumption is made regardless of the possibility that the correlation might not be linear (Hosmer & Lemeshow, 2000), which can reduce the accuracy of the linear regression and logistic regression models in estimating possible outcomes, given a certain values for each exposure variable.

A typical occupational illness or disorder usually develops gradually and in the field of occupational safety and health, it is not practical to use a binary method to identify somebody as either “healthy” or “injured” (McCauley-Bell & Badiru, 1996). Similarly, there is no evidence that the gradual development of an occupational illness or disorder occurs linearly with constant pace (equal slope). Therefore, an LR model would not be a perfect model for predicting potential outcomes. On the contrary, the linguistic logic features of fuzzy models allow researchers to represent different stages of an occupational injury or disorder, which most often occur gradually over long time.

Sensitivity analysis is one method to deal with the uncertainty of predicted outcomes in mathematical or statistical models, which can be done in different ways. One approach is to add or drop one or more exposure variable(s) in or out of the model to see whether the predicted value of the outcome variable changes and, if it does, by how much (Hosmer & Lemeshow, 2000). Another common approach is to add in or drop out one or more specific point(s) of data from dataset and rebuild the model to see whether there is any change in the predicted value of the outcome variable (Chatterjee & Hadi, 1988). Either way, sensitivity analysis could be a time-consuming and complicated process as the size and complexity of the model grow. In this study, it was shown that using an FL model can provide a better solution to a situation in which the

Figure 1 Expert Rules for Predicting Back Pain Severity as Outcome of Long-Term & Daily Exposure to Vibration

$Rule\ 1$: $if\ X_1 = 1 \wedge (X_2 = 1 \vee X_2 = 2)\ then\ Y = 1$

$Rule\ 2$: $if\ X_1 = 1 \wedge X_2 = 3\ then\ Y = 2$

$Rule\ 3$: $if\ X_1 = 1 \wedge X_2 = 4\ then\ Y = 3$

$Rule\ 4$: $if\ X_1 = 1 \wedge X_2 = 5\ then\ Y = 4$

$Rule\ 5$: $if\ X_1 = 2 \wedge X_2 = 1\ then\ Y = 1$

$Rule\ 6$: $if\ X_1 = 2 \wedge X_2 = 2\ then\ Y = 2$

$Rule\ 7$: $if\ X_1 = 2 \wedge X_2 = 3\ then\ Y = 3$

$Rule\ 8$: $if\ X_1 = 2 \wedge (X_2 = 4 \vee X_2 = 5)\ then\ Y = 4$

$Rule\ 9$: $if\ X_1 = 3 \wedge (X_2 = 1 \vee X_2 = 2)\ then\ Y = 2$

$Rule\ 10$: $if\ X_1 = 3 \wedge X_2 = 3\ then\ Y = 3$

$Rule\ 11$: $if\ X_1 = 3 \wedge X_2 = 4\ then\ Y = 4$

$Rule\ 12$: $if\ X_1 = 3 \wedge X_2 = 5\ then\ Y = 5$

$Rule\ 13$: $if\ X_1 = 4 \wedge X_2 = 1\ then\ Y = 2$

$Rule\ 14$: $if\ X_1 = 4 \wedge X_2 = 2\ then\ Y = 3$

$Rule\ 15$: $if\ X_1 = 4 \wedge X_2 = 3\ then\ Y = 4$

$Rule\ 16$: $if\ (X_1 = 4 \vee X_1 = 5) \wedge (X_2 = 4 \vee X_2 = 5)\ then\ Y = 5$

$Rule\ 17$: $if\ X_1 = 5 \wedge (X_2 = 1 \vee X_2 = 2)\ then\ Y = 3$

$Rule\ 18$: $if\ X_1 = 5 \wedge X_2 = 3\ then\ Y = 4$

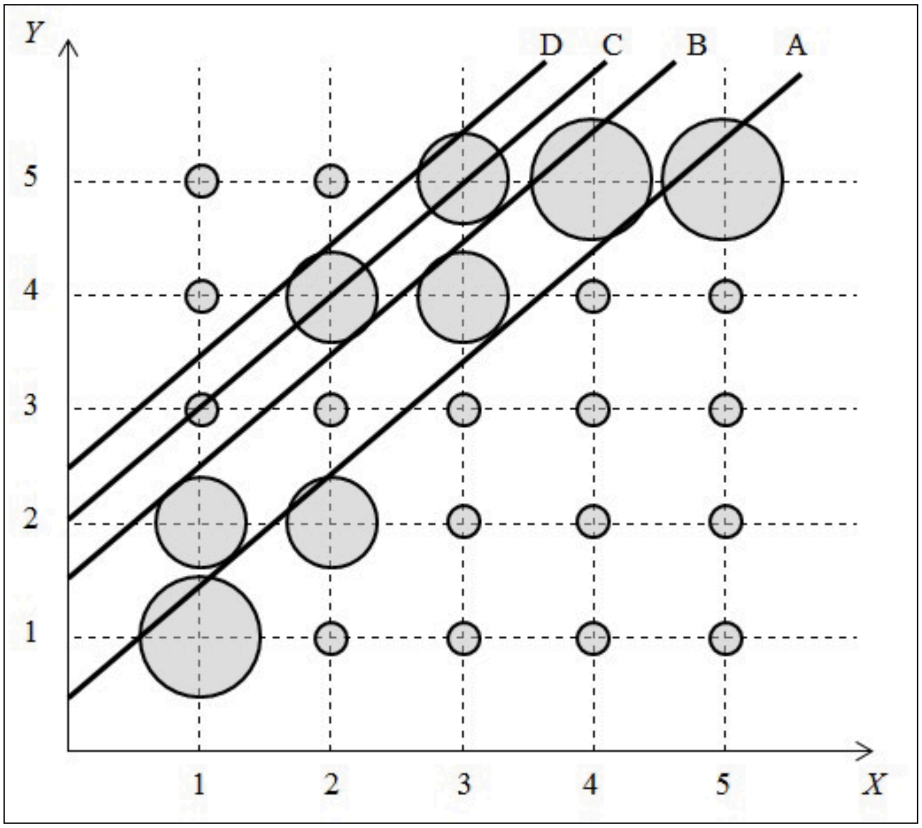
data are subjective and categorical with higher level of uncertainty without performing any sensitivity analysis.

One possible explanation of why an FL model had better performance compared to LR model is provided in Figure 2 (p. 209). Figure 2 represents a hypothetical distribution of two categorical variables, with *X* as exposure variable and *Y* as outcome variable. Each of them has five different values from one to five. The size of the circles represent the frequency of occurrences for the given pair of (*X, Y*) values. For example, according to Figure 2, the frequency of (*X, Y*) = (5, 5) was larger than (*X, Y*) = (5, 3) in a hypothetical dataset. As is obvious from Figure 2, the hypothetical distribution of *X* and *Y* is

Table 5 Side-By-Side Comparison of LR & FL Models in Terms of Number of Correct Prediction & RMSE

		No. of Correct Prediction		Root-Mean-Square Error	
Outcome Variable	**Exposure Variables**	**LR Model**	**FL Model**	**LR Model**	**FL Model**
Back pain severity	Long term & daily exposure	10	10	1.50	1.03
Back pain frequency	Long term & daily exposure	14	11	1.11	0.97
Shoulder pain severity	Long term & daily exposure	6	10	1.73	1.31
Shoulder pain frequency	Long term & daily exposure	12	15	1.18	1.00
Neck pain severity	Long term & daily exposure	9	17	1.46	1.26
Neck pain frequency	Long term & daily exposure	15	16	1.03	1.06
Wrists pain severity	Long term & daily exposure	7	9	1.68	1.34
Wrists pain frequency	Long term & daily exposure	13	14	1.06	1.09
Elbows pain severity	Long term & daily exposure	10	9	2.01	1.61
Elbows pain frequency	Long term & daily exposure	12	11	1.11	1.31
Knees pain severity	Long term & daily exposure	16	7	1.71	1.49
Knees pain frequency	Long term & daily exposure	14	13	1.04	1.22
Head pain severity	Long term & daily exposure	18	17	1.52	0.92
Head pain frequency	Long term & daily exposure	19	13	1.14	0.94
Numbness in hands/fingers	Long term & daily exposure	13	8	1.92	1.53
Tingling in hands/fingers	Long term & daily exposure	14	14	2.26	1.35
Back pain severity	Perceived level of exposure, WBV & HAV	4	7	1.60	1.18
Back pain frequency	Perceived level of exposure, WBV & HAV	10	12	1.02	0.76
Shoulder pain severity	Perceived level of exposure, WBV & HAV	4	10	1.68	1.15
Shoulder pain frequency	Perceived level of exposure, WBV & HAV	10	8	1.25	0.95
Neck pain severity	Perceived level of exposure, WBV & HAV	6	8	1.41	1.20
Neck pain frequency	Perceived level of exposure, WBV & HAV	10	10	0.90	0.82
Wrists pain severity	Perceived level of exposure, WBV & HAV	9	4	1.56	1.23
Wrists pain frequency	Perceived level of exposure, WBV & HAV	9	10	0.85	0.82
Elbows pain severity	Perceived level of exposure, WBV & HAV	7	1	1.73	1.29
Elbows pain frequency	Perceived level of exposure, WBV & HAV	9	10	1.05	1.05
Knees pain severity	Perceived level of exposure, WBV & HAV	12	9	1.25	1.05
Knees pain frequency	Perceived level of exposure, WBV & HAV	12	8	1.13	1.07
Head pain severity	Perceived level of exposure, WBV & HAV	12	6	1.35	1.13
Head pain frequency	Perceived level of exposure, WBV & HAV	15	12	0.82	0.90
Numbness in hands/fingers	Perceived level of exposure, WBV & HAV	8	3	1.70	1.53
Tingling in hands/fingers	Perceived level of exposure, WBV & HAV	12	9	1.48	1.05

Figure 2 Hypothetical Logistic Regression Model



not normal, they are not interval variables and the correlation between these two variables and their probabilities are not linear. However, an LR model will assume the correlation between the values of exposure variable (*X*) and the probability of different values for outcome variable (*Y*) is linear with equal slope for each level, but different values of y-intercepts. That means the distance between y-intercepts of lines A, B, C and D represents the differences of probability for outcome values, while in reality the actual correlation can be non-linear (Moayed & Shell, 2011a, 2011b).

Such assumptions in modeling process can lead to lower accuracy (or higher uncertainty) in predicting the potential outcome value. On the other hand, in Figure 3, an FL model was developed to fit the same hypothetical dataset. In this method, the model behaves like a step-wise function based on expert knowledge and existing data. In this approach, the model does not assume the same linear correlation between different values and provides a model that fits better into the dataset which can predict the outcome value with the highest likelihood of occurrence. Obviously, if more variables are included in the model, it increases the dimensions of the model and lines become planes and hyper-planes. This means the model gets more complex and its accuracy might decline.

Conclusion

In this study, it was shown that FL models have better performance in estimating the values of outcome variables compared to logistic regression models. It means that the likelihood of predicting a correct value for outcome variable by FL models can be higher than LR models. One major shortcoming of this study is that no reliability and validity test has been done on models, and that was due to the dataset's limiting attributes such as its small size, and self-reported nature of responses.

One significant application of this research is that safety professionals can take advantage of subjective and/or historic data, using their expert opinion to construct an FL model and predict the most probable health effects of exposure to certain set of factors (e.g., short-term and long-term exposure to vibration). The construction of FL model can be less time consuming, requires less statistical and mathematical skills, and does not need sensitivity analysis.

The FL models could provide a better and more efficient method for hazard analysis. However, such FL models are valid only for the given conditions under which the data was collected and if any aspect of conditions changes (such as new facility, different group of subjects, different type of jobs, or even adding one more year of historic data to the dataset) then a new set of if-then rules would be needed.

Another potential application of FL models could be in administrative control methods to reduce employees' exposure to vibration through work scheduling and job rotation even without knowledge of exact exposure dose to vibration. Safety managers can gain a better understanding about the patterns of short-term and long-term exposure to certain agents such as vibration and their health effects on workers just by following the trends in their historic data. Such insight can help safety managers to develop more effective work schedules and job rotation plan to minimize the risk of health effects.

It is necessary to emphasize that further studies are needed to evaluate performance of FL models if the dimension of model increases. It can happen when more variables (such as age or pre-existing medical conditions) are added to the model which increases the complexity of the model. An FL model can become even more complex when some of the exposure variables are correlated to one another as well as the outcome variable also as complexity increase, it would be harder to determine the fuzzy rules. ⭘

References

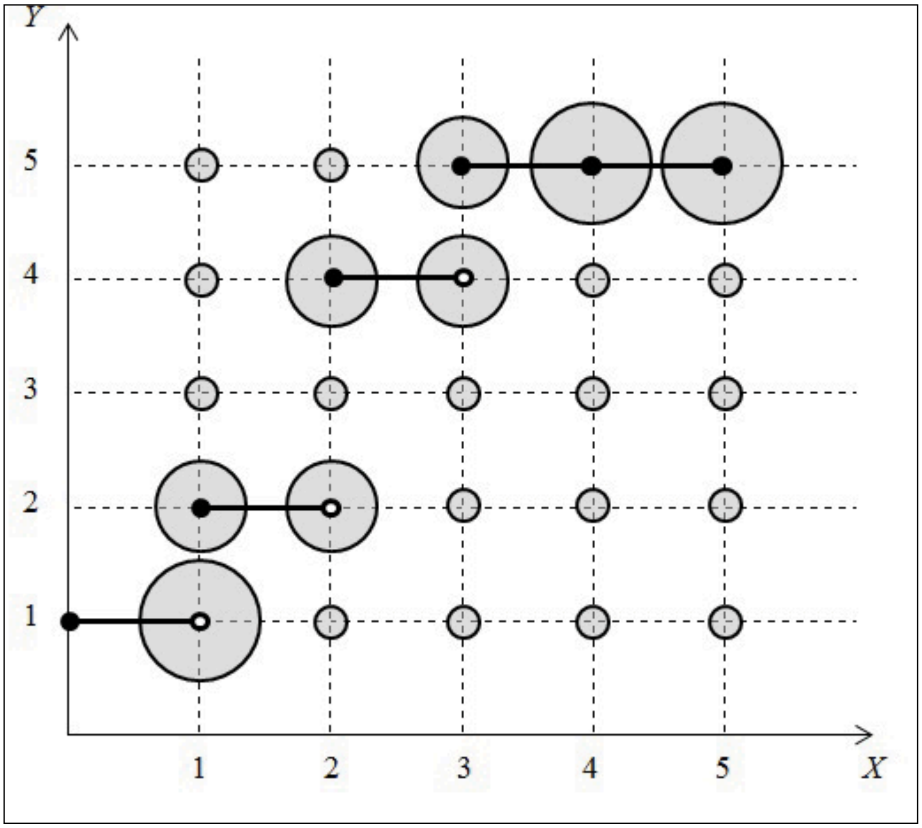
Chatterjee, S. & Hadi, Al. S. (1988). *Sensitivity analysis in linear regression.* New York, NY: John Wiley & Sons.

Chen, G. & Pham, T.T. (2001). I*ntroduction to fuzzy sets, fuzzy logic and fuzzy control systems.* Boca Raton, FL: CRC Press.

Ciarapica, F.E. & Giacchetta, G. (2009). Classification and prediction of occupational injury risk using soft computing techniques: An Italian Study. *Safety Science, 47*(1), 36-49.

Grassi, A., Gamberini, R., Mora, C. & Rimini, B. (2009). A fuzzy

Figure 3 Hypothetical Fuzzy Linguistic Model



multi-attribute model for risk evaluation in workplaces. *Safety Science, 47*(5), 707-716.

Gürcanli, G.E. & Müngen, U. (2009). Ac occupational safety risk analysis method at construction sites using fuzzy sets. *International Journal of Industrial Ergonomics, 39*(2), 371-387.

Haimes, Y.Y. (2009). *Risk modeling, assessment and management* (3rd ed.). Hoboken, NJ: John Wiley & Sons.

Hosmer, D.W. & Lemeshow, S. (2000). *Applied logistic regression.* (2nd ed.). New York, NY: John Wiley & Sons.

Karwowski, W. & Mital, A. (1986). Potential application of fuzzy sets in industrial safety engineering. *Fuzzy Sets and Systems, 19*(2), 105-120.

Mamdani, E.H. & Assilian, S. (1999). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Human-Computer Studies, 51*(2), 135-147.

Massad, E., Ortega, N.R.S., de Barros, L.C. & Struchiner, C.J. (2008). *Fuzzy logic in action: Application in epidemiology and beyond.* Berlin, Germany: Springer.

McCauley-Bell, P. & Crumpton, L. (1977). A fuzzy linguistic model for the prediction of carpal tunnel syndrome risks in an occupational environment. *Ergonomics, 40*(8), 790-799.

McCauley-Bell, P. & Badiru, A.B. (1996). Fuzzy modeling and analytic hierarchy processing to quantify risk levels associated with occupational injuries—Part I: The development of fuzzy-linguistic risk levels. *IEEE Transactions on Fuzzy Systems, 4*(2), 124-131.

Moayed, F.A. & Cheng, Y.H. (2012). Occupational vibration exposure assessment among stone workers in Taiwan and China. IIE Annual Conference and Expo, Orlando, FL.

Moayed, F.A. & Shell, R. L. (2011a). Application of artificial neural network models in occupational safety and health utilizing ordinal variables. *Annals of Occupational Hygiene, 55*(2), 132-142.

Moayed, F.A. & Shell, R.L. (2011b). Constructing the function of "magnitude-of-effect" (MoF) and its application in artificial neural network models. *Annals of Occupational Hygiene, 55*(2), 143-151.

Mukaidono, M. (2001). *Fuzzy logic for beginners.* River Edge, NJ: World Scientific.

Neter, J., Kutner, M.H., Nachtsheim, C.J. & Wasserman, W. (1996). *Applied linear regression models* (4th ed.), New York, NY: WCB/McGraw-Hill.

Padma, T. & Balasubramanie, P. (2011a). A fuzzy analytic hierarchy processing decision support system to analyze occupational menace forecasting the spawning of shoulder and neck pain. *Expert Systems with Applications, 38*(12), 15303-15309.

Padma, T. & Balasubramanie, P. (2011b). Domain experts' knowledge-based intelligent decision support system in occupational shoulder and neck pain therapy. A*pplied Soft Computing, 11*(2), 1762-1769.

Pinto, A., Nunes, I.L. & Ribeiro, R.A. (2011). Occupational risk assessment in construction industry: Overview and reflection. *Safety Science, 49*(5), 616-626.

Zadeh, L.A. (1994). Foreword. In E. Cox (ed.), *The fuzzy systems handbook: A practitioner's guide to building, using and maintaining fuzzy systems* (pp. XXIX-XXX). Boston, MA: AP Professional.

Zadeh, L.A. (2002). Foreword. In S. Barro and Marín, R. (eds.), *Fuzzy logic in medicine* (pp. V-VII). New York, NY: Physica-Verlag.

A Literature Review of the Ambient Air Asbestos Concentrations

Kim E. Anderson, Kimberly A. Hoppe Parr and Cynthia A. Boyd

Abstract

Various ambient air asbestos concentrations are presented in the scientific literature. As defined by the U.S. Environmental Protection Agency (EPA, 2011), and for the purposes of this manuscript, ambient air is defined as "that portion of the atmosphere, external to buildings, to which the general public has access." The objective of this manuscript is to conduct a comprehensive literature review focusing on publications that have evaluated the ambient air asbestos concentrations, provide a summary of the results and, when available, discuss the analytical methodology used. A comprehensive review of the scientific literature, including the U.S. Department of Health Services, Public Health Service, Agency for Toxic Substances and Disease Registry (ATSDR) Toxicological Profile for Asbestos [Toxicological Profile (ATSDR, 2001)] was conducted. During this review, publications presenting original data and using transmission electron microscopy (TEM) as the analytical method for evaluating the asbestos concentration were most important due to the analytical capabilities of TEM at identifying the fiber type present. In conclusion, few publications actually conducted sampling for the ambient air asbestos concentrations with a limited number of the publications utilizing TEM analysis. These publications reported the ambient air concentrations ranged from 2.0×10^{-5} f/mL to 1×10^{-2} f/cc, demonstrating that airborne asbestos has and continues to be present in the ambient air in the U.S. and other locations.

Keywords
ambient asbestos, environmental health, asbestiform fibers

Introduction

Various ambient air asbestos concentrations are presented in the scientific literature. As defined by the EPA (2011), and for the purposes of this article, ambient air is defined as "that portion of the atmosphere, external to buildings, to which the general public has access. Ambient airborne asbestos fibers can originate from naturally occurring sources or from degradation, manipulation and handling of manufactured asbestos-containing materials (ACMs) (ATSDR, 2001). Most often, low ambient asbestos concentrations have been identified and are based on sampling and analysis methodologies that are not consistent with those methods utilized by OSHA as specified in 29 CFR 1910.93a and 1910.1001 (Asbestos). The literature often compares potential workplace exposures from working with or near asbestos-containing products with ambient air asbestos concentrations. Workplace exposures are most generally not applicable to the general public and a compilation of ambient air asbestos concentrations is not available in the scientific literature; therefore, a comprehensive literature review of the published ambient air asbestos concentrations was performed. The objective of this article is to provide a summary of the scientific literature that has evaluated ambient air asbestos concentrations and, when available, discuss the analytical methodology that was used.

Several publications discussing the ambient air asbestos concentrations cite selected references, many of which did not perform original sampling. A frequently cited publication, the U.S. Department of Health Services, Public Health Service, Agency for Toxic Substances and Disease Registry (ATSDR) Toxicological Profile for Asbestos (Toxicological Profile) did not perform original sampling, but reviewed and described the airborne asbestos concentrations specified in numerous publications. A thorough analysis of the Toxicological Profile and of the primary publications, whether or not the references were included in the Toxicological Profile, that conducted the sampling of the ambient air to evaluate the asbestos concentration is necessary to provide proper assessment of the potential exposure to the public. Therefore, a review of the scientific literature, beginning with the publications referenced in the Toxicological Profile and other publications that provide ambient air asbestos concentrations, is paramount and was performed in this literature review.

Following is an overview of the ambient air asbestos concentrations included in the Toxicological Profile, as well as numer-

Dr. Kim E. Anderson is a senior principal and director of toxicology, environmental health and safety at GZA GeoEnvironmental Inc. Anderson has his doctorate from the University of Oklahoma in Toxicology. His practice focuses on human toxicology and he provides consultation services to a wide array of industrial clients for permitting, regulatory compliance and on acquisitions and divestitures. He may be contacted at kim.anderson@gza.com.

Dr. Kimberly A. Hoppe Parr is an environmental scientist and toxicologist at GZA GeoEnvironmental Inc. Parr has her doctorate from the University of Iowa in Occupational and Environmental Health and she specializes in environmental health, toxicology, indoor air quality and exposure assessments.

Cynthia A. Boyd is an assistant project manager at GZA GeoEnvironmental Inc. Boyd has a master's degree from the University of Wisconsin in Toxicology and her project work at GZA includes occupational exposure reconstruction, data analysis and interpretation of scientific literature research for GZA's occupational health and litigation support practices.

ous other publications in the scientific literature (ATSDR, 2001). The Toxicological Profile provides a comprehensive discussion of asbestos while referencing approximately 1,876 scientific publications and selected unpublished materials. In particular, it referenced several large summary reports pertinent to ambient air asbestos concentrations including: Chesson, Hatfield, Schultz, Dutrow and Blake (1990); Committee on Nonoccupational Health Risks of Asbestiform Fibers, Board on Toxicology and Environmental Health Hazards, Commission on Life Sciences, Division on Earth and Life Studies, National Research Council (NRC) (1984); Health Effects Institute-Asbestos Research (HEI-AR) (1991); EPA, Office of Research and Development, Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office (1986); and World Health Organization (WHO), International Agency for Research on Cancer (WHO-IARC) (1977).

Chapter 7 of the Toxicological Profile discussed the various analytical methods used to quantify asbestos concentrations. Airborne asbestos concentrations are reported in a "variety of units, including ng/m^3 [nanogram of particulate matter per cubic meter of air] (measured by midget impinger counting analysis), TEM f/mL [fibers measured by transmission electron microscopy (TEM)], and PCM f/mL [fibers measured by phase contrast microscopy (PCM)]" (ATSDR, 2001). It should be noted that one mL is equal to one cubic centimeter (cc); therefore, 1 f/mL is equivalent to 1 f/cc.

For the purpose of quantifying asbestos fibers, a fiber is defined by OSHA as having a length greater than or equal to 5 micrometers (µm) and a length to width ratio, termed aspect ratio, of at least 3:1 (ATSDR, 2001; OSHA, 1992). For settings (locations) where there is a defined presence of asbestos and minimal extraneous particulate, PCM analysis, which to reiterate is used by OSHA, has been used historically. However, in environmental settings where numerous inorganic and non-soluble particles may be present, the use of PCM analysis may prove challenging due to the potential for overloading of non-asbestos fibers which can lead to an overestimation of the airborne asbestos concentration and the inability of the PCM analytical method to specifically identify asbestos fibers (ATSDR, 2001). Due to the superior method of quantification of fibers and the identification of the fibers, the use of TEM is often valuable (ATSDR, 2001). Therefore, for the purposes of this literature review, studies that performed original sampling and subjected the ambient air samples to TEM analysis were most important, while studies that utilized other analytical methodologies are also presented.

Methods

A review of the previously listed publications, as well as additional references not cited in the Toxicological Profile but identified using PubMed, is included in this review of ambient air asbestos concentrations included in the published literature. As noted, this literature review examined studies that

Table 1 (Part A) Ambient Air Asbestos Concentrations From the Toxicological Profile & Additional References

Setting	Measured Concentration Reported	Correction Factor Applied (f/cc)	Reference	Sampling Conducted
Remote/ Rural	0.001 to 0.1 ng/m3 (remote from any source)	3.3 x 10^{-8} to 3.3 x 10^{-6} f/cc	Toxicological Profile (NRC, 1984*)	No
	1x10^{-5} TEM f/mL or 2 x 10^{-7} PCM f/cc		Toxicological Profile (HEI-AR, 1991*)	No
	0.01 to 0.1 ng/m^3	3.3 x 10^{-7} to 3.3 x 10^{-6} f/cc	Suta & Levine, 1979	No
	0.01 to 0.1 ng/m^3	3.3 x 10^{-7} to 3.3 x 10^{-6} PCM f/cc	Thompson & Morgan, 1971	Yes
	40 to 100 f/m^3 or 4 x 10^{-5} to 1 x 10^{-4} f/cc		Murchio et al., 1973	Yes
	0.0005 f/cc		Corn, 1994	Yes
	0 to 6.5 x 10^{-4} f/cc		Murbach et al., 2008	No
Urban	0.1 to 10 ng/m^3	3 x 10^{-6} to 3.3 x 10^{-4} PCM f/cc	Toxicological Profile*	No
	2.3 ng/m^3 (1.6 ng/m^3 to 13.7 ng/m^3)	7.6 x 10^{-5} PCM f/cc	NRC, 1984* (median [ ] in US Cities)	No
	0.09 to 70 ng/m^3	3 x 10^{-6} to 2.3 x 10^{-3} f/cc	Suta & Levine, 1979	No
	1.6 to 13.7 ng/m^3	5.3 x 10^{-5} to 4.5 x 10^{-4} f/cc	Nicholson et al., 1971	Yes
	6.7 ng/m^3	2.2 x 10^{-4} f/cc	Nicholson et al., 1975	Yes
	2.3 ng/m^3	7.6 x 10^{-5} f/cc	USEPA, 1974	Yes
	0.9 ng/m^3	3 x 10^{-5} f/cc	Constant et al., 1983	Yes
	3.3 ng/m^3 to 16 ng/m^3	1.1 x 10^{-4} to 5.3 x 10^{-4} f/cc	Nicholson et al., 1983 (also published as USEPA, 1986)	No

Notes:
* Indicates the publication was included in the ATSDR Toxicological Profile for Asbestos
+ Reported as, f/L concentration using TEM and all lengths with an aspect ratio >3:1.
++ Reported as, optical equivalent (f/ml) = fibers at least 5 µm long with a diameter of at least 0.25 µm
1. ng/m^3 = nanograms of particulate per cubic meter of air (not exclusively asbestos).
2. PCM f/mL or f/cc = Phase Contrast Microscopy (PCM) fibers per milliliter of air or per cubic centimeter of air (all fibers ≥ 5 micrometers [µm] and 3:1 aspect ratio).
3. s/L = structures per liter of air
4. s/cc = structures per cubic centimeter of air
5. A correction factor of 0.000033 is multiplied by the mass of particulate (in ng/m^3) to produce an estimated concentration in f/cc.

performed original ambient air sampling and the analytical methods utilized. An evaluation of the analytical methods that were utilized in the analysis of the samples was evaluated due to the significant differences in the capabilities and limitations of each method.

The literature review began with the Toxicological Profile due to the fact that it is frequently and generally most often referenced in publications. Chapter 6 of the Toxicological Profile, "Potential for Human Exposure," included a discussion of ambient air asbestos concentrations (ATSDR, 2001). Airborne asbestos concentrations measured or those that were estimated were discussed in Chapter 6, Section 4.1.

The Toxicological Profile referenced various publications that did not include the collection of asbestos samples, but rather provided a review of previously published results; therefore, it was necessary to evaluate the primary publications that were cited that included the collection of asbestos samples. Additional literature was reviewed, specifically publications published following the publication of the Toxicological Profile in 2001, that investigated ambient air asbestos concentrations from non-point source locations and away from areas where apparent elevated ambient concentrations of naturally occurring asbestos (NOA) have been found. Some of the literature reviewed presented ambient air concentrations sampled near local sources and NOA. Ambient air concentrations near known asbestos sources were not the focus of this manuscript; however, the published results were provided in the presented data, but are not included in the evaluation of the background ambient air asbestos concentrations.

Table 1 (Part B) Ambient Air Asbestos Concentrations From the Toxicological Profile & Additional References

Setting	Measured Concentration Reported	Correction Factor Applied (f/cc)	Reference	Sampling Conducted
Urban (continued)	1 to 10 x 10^{-3} ng/m^3 or up to 0.002 f/cc		Corn, 1994*	No
	2 s/L or 2 x 10^{-3} s/cc		Corn et al., 1991	Yes
	0.00006 f/mL (0.00004 f/ml to 0.0065 f/ml)		RJ Lee Group	Yes
	0.1 to 50 ng/m^3	3.3 x 10^{-6} to 1.65 x 10^{-3} f/cc	Nicholson & Pundsack, 1973*	Yes
	typically less than 1 ng/m^3 and rarely exceed 5 ng/m^3	typically less than 3.3 x 10^{-5} f/cc and rarely exceed 1.65 x 10^{-4} f/cc	USEPA, 1991*	No
	0.9 ng/m^3 (0.0 to 4.3 ng/m^3)	2.97 x 10^{-5} f/cc	Nicholson, 1989	Yes
	< 1 ng/m^3	< 3.3 x 10^{-5} f/cc	Sebastien et al., 1980	Yes
	10.3 f/L (0.0 to 27 f/L) or 1 x 10^{-2} f/cc^{+}		Perkins, 1987	Yes
	3.9 x 10^{-4} s/cc		Hatfield et al. (USEPA), 1988	Yes
	11 to 60 ng/m^3 (in NYC)	3.6 x 10^{-4} to 2.0 x 10^{-3} PCM f/cc	Selikoff et al., 1972*	Yes
	10 ng/ m^3 to 100 ng/m^3 (in PA and NJ)	3.3 x 10^{-4} to 3.3 x 10^{-3} f/cc	Selikoff et al., 1972*	Yes

In addition to a review of the Toxicological Profile, an extensive database search was performed by GZA GeoEnvironmental Inc. (GZA) that utilized PubMed, governmental online libraries and an onsite database of thousands of references pertaining to asbestos, including reports prepared by federal and local governments to identify literature sources that identified ambient air asbestos concentrations. The comprehensive literature review searched publications to locate published literature encompassing "ambient air," "outdoor air," "environmental asbestos" and "asbestos concentrations or levels."

The published documents that were identified were systematically reviewed focusing on whether original sampling was performed and, if so, the analytical methodologies utilized, the location the samples were collected and the concentrations reported. Results of this comprehensive literature review are displayed in Table 1. For publications that did not perform original sampling, the references were cross-referenced and the referenced publications were reviewed. As discussed above and in the Toxicological Profile, precedence was provided to studies utilizing TEM analysis.

It is important to note that the sampling and analysis methodology used to measure the mass of particulate per cubic meter of air does not measure fibers and, therefore, the fiber concentration using the OSHA definition of a fiber (length greater than or equal to 5 µm and an aspect ratio of 3:1) was not possible. Rather, the Toxicological Profile provided a conversion factor to compare the results across several publications. Specifically, the Toxicological Profile stated, "When data on airborne levels are available only in terms of mass/volume (e.g., mg/m^3) [or ng/m^3], it is not possible to accurately convert these to units of PCM fibers/mL, because the ratio between mass and fiber number depends on fiber type and size distribution and because of the measuring technique employed. For the purposes of making rough calculations when a more accurate conversion factor is not available, it has been assumed that a concentration of 1 mg/m^3 in air is equal to 33 PCM f/mL" (ATSDR, 2001). Likewise, a correction factor of 0.000033 is multiplied by the mass of particulate (in ng/m^3) to produce an estimated concentration in fibers per cubic centimeter (f/cc). Therefore, for the purposes of this review, the correction factor utilized in the Toxicological Profile, and applied in several studies, was utilized.

Results & Discussion

Table 1 provides the ambient air asbestos concentrations presented in the Toxicological Profile and concentrations from other publications including the corresponding citation for the publication in which the concentrations were provided. The publications projected on Table 1 that include an asterisk (*) were cited in the Toxicological Profile. Asbestos ambient air concentrations, included in Table 1, were categorized by the setting (rural/remote, urban, various sites, near industrial operations involving asbestos and local sources, and near NOA). For comparative purposes, ambient air concentrations collected near local sources and NOA that were discussed in the reviewed literature were included in Table 1; however, these concentrations were not included in the evaluation of the ambient air asbestos concentrations as they would likely results in the results reflecting higher airborne concentrations.

Settings were classified as "various sites" when the sampling location(s) was/were not identified. This categorization of the setting was selected, as ambient air asbestos concentrations can vary greatly depending on the location where the sampling was conducted. After compiling the reviewed literature in Table 1, the publications were further classified and presented in Table 2 and Figures 2 and 3 (pp. 215-219) displaying the studies that conducted original sampling. Of these studies that conducted original sampling presented in Table 2, those that utilized TEM for the analysis of the asbestos concentrations are presented in Table 3. It should be noted that many of the ambient airborne asbestos concentrations presented in Table 1 did not actually measure the asbestos concentrations, but rather were a measure of the mass of particulate matter per cubic meter of air (ng/m^3), with the correction factor utilized in the Toxicological Profile applied and denoted in column 3 of Table 1.

Ambient air asbestos concentrations presented in the Toxicological Profile ranged from 0.001 ng/m^3 in areas "remote from any special sources" to 5,000 ng/m^3 "[n]ear industrial operations" (or 3.3×10^{-8} f/cc to 0.165 f/cc when the correction factor was used) (ATSDR, 2001). In this overview, when bracketed concentrations ( ) are shown, it is the estimated values based on the application of

Table 1 (Part C) Ambient Air Asbestos Concentrations From the Toxicological Profile & Additional References

Setting	Measured Concentration Reported	Correction Factor Applied (f/cc)	Reference	Sampling Conducted
Urban (continued)	0.0001 to 0.01 f/mL		WHO, 1998*	No
	0.0003 f/mL (not detected - 0.008 f/mL)		Chesson et al., 1985	Yes
	5×10^{-5} f/mL		Tuckfield et al., 1988	Yes
	0.1 to 100 ng/m^3	3.3×10^{-6} to 3.3×10^{-3} PCM f/cc	WHO-IARC, 1977*	No
	3.9×10^{-4} to 2×10^{-2} f/cc		Murbach et al., 2008	No
	0.00039 f/cc		Crump & Farrar, 1989	Yes
	0.01 to 0.02 f/cc		Mangold, 1983	Yes
	1×10^{-5} to 4×10^{-4} f/cc		SRC, Inc., 2013	No
	2×10^{-4} s/cc		Van Orden et al., 1995	Yes
	0.0001 TEM f/mL or 2×10^{-6} PCM f/mL		HEI-AR, 1991	No
Various Sites	0.00109 s/mL; 0.00074 s>5um/mL; 0.79 ng/m^3		Lee & Van Orden, 2008	Yes
	2.0×10^{-5} f/mL^{++}		Lee et al., 1992	Yes
Near Industrial Operations involving Asbestos and local sources	up to 5,000 ng/m^3 (industrial)	0.165 f/cc	Toxicological Profile*	No
	up to 100 ng/m^3 (local sources)	3.3×10^{-3} f/cc	Toxicological Profile*	No
	100 to 1,000 ng/m^3	3.3×10^{-3} to 3.3×10^{-2} f/cc	USEPA, 1991	No
	10 to 5,000 ng/m^3	3.3×10^{-4} to 0.165 PCM f/cc	WHO-IARC, 1977	No
Near Naturally Occurring Asbestos	0.0004 f/cc		ATSDR, 2011 (in El Dorado Hills, CA)	Yes
	0.003 f/cc		ATSDR, 2011	No

the correction factor. Again, since several publications were being compared in this article where various sampling and analysis techniques were employed, correction factors were used to convert the mass measurements to fiber concentrations to project the results of the reviewed literature in Table 1.

Table 2 (Part A)
Ambient Air Asbestos Concentrations From Original Data

Setting	Measured Concentration Reported	Correction Factor Applied (f/cc)	Reference	Analysis Used
Rural/ Remote	0.01 to 0.1 ng/m^3	3.3×10^{-7} to 3.3×10^{-6} PCM f/cc	Thompson & Morgan, 1971	mass concentration
	40 to 100 f/m^3 or 4×10^{-5} to 1×10^{-4} f/cc		Murchio et al., 1973	electron microscopy
	0.0005 f/cc		Corn, 1994	PCM
Urban	1.6 ng/m^3 to 13.7 ng/m^3	5.3×10^{-5} to 4.5×10^{-4} f/cc	Nicholson et al., 1971	mass concentration
	6.7 ng/m^3	2.2×10^{-4} f/cc	Nicholson et al., 1975	TEM as a mass concentration
	2.3 ng/m^3	7.6×10^{-5} f/cc	USEPA, 1974	mass concentration
	0.9 ng/m^3	3×10^{-5} f/cc	Constant et al., 1983	mass concentration
	2 s/L or 2×10^{-3} s/cc		Corn et al., 1991	TEM
	0.1 to 50 ng/m^3	3.3×10^{-6} to 1.65×10^{-3} f/cc	Nicholson & Pundsack, 1973*	mass concentration
	0.00006 f/mL (0.00004 f/ml to 0.0065 f/ml)		RJ Lee Group	PCM
	0.9 ng/m^3 (0.0 to 4.3 ng/m^3	2.97×10^{-5} f/cc	Nicholson, 1989	TEM as mass concentration
	< 1 ng/m^3	< 3.3×10^{-5} f/cc	Sebastien et al., 1980	TEM as mass concentration
	10.3 f/L (0.0 to 27 f/L) or 1×10^{-2} f/cc$^+$		Perkins, 1987	TEM
	3.9×10^{-4} s/cc		Hatfield et al. (USEPA), 1988	TEM

Notes:
* Indicates the publication was included in the ATSDR Toxicological Profile for Asbestos
$^+$ Reported as, f/L concentration using TEM and all lengths with an aspect ratio >3:1.
$^+$ Reported as, optical equivalent (f/ml) = fibers at least 5 µm long with a diameter of at least 0.25 µm
1. ng/m^3 = nanograms of particulate per cubic meter of air (not exclusively asbestos).
2. PCM f/mL or f/cc = Phase Contrast Microscopy (PCM) fibers per milliliter of air or per cubic centimeter of air (all fibers ≥ 5 micrometers [µm] and 3:1 aspect ratio).
3. s/L = structures per liter of air
4. s/cc = structures per cubic centimeter of air
5. A correction factor of 0.000033 is multiplied by the mass of particulate (in ng/m^3) to produce an estimated concentration in f/cc.

A review of the ambient air asbestos concentrations presented in the Toxicological Profile, the associated referenced literature, and additional literature not presented in the Toxicological Profile was conducted. The results of this review are presented in the following sections of this article. Several of the citations in the Toxicological Profile are review articles and contained no original sampling and results. In the following sections, the referenced publication is identified, as is the source of the original data that were presented in the publication. The ambient air asbestos concentrations are further classified by the location at which the sampling was conducted: remote/rural, urban and various locations. As noted, ambient air asbestos concentrations measured near local sources and NOA are included in the data presentation, but were not included in the evaluation of ambient air asbestos provided in this review article.

Remote/Rural Ambient Air Asbestos Concentrations Discussed in the Toxicological Profile

The Toxicological Profile referenced two publications, NRC (1984) and HEI-AR (1991), which measured the ambient air asbestos concentrations in remote/rural locations. These publications are described below.

The first publication that described rural outdoor (ambient) air asbestos concentrations is a 1984 report by NRC. The NRC report did not present sampling results from its performance of ambient air asbestos sampling, but rather reported results from other studies. The Toxicological Profile cited the NRC report when it stated "ambient outdoor air, remote from any special sources, is generally found to contain 0.001-0.1 ng/m^3 of asbestos (3×10^{-8}-3×10^{-6} PCM f/mL)" (ATSDR, 2001; NRC, 1984). The NRC report referenced a study published by Suta and Levine which "estimated that the rural U.S. population (60 million people) might be exposed Co [sic] concentrations ranging from 0.01 to 0.1 ng/m^3" (or 3.3×10^{-7} to 3.3×10^{-6} PCM f/cc) (NRC, 1984; Suta & Levine, 1979). Suta and Levine (1979) attributed these airborne asbestos concentrations to a publication by Thompson and Morgan (1971). Additionally, Suta and Levine cited Murchio, Cooper and De Leon (1973), as reporting airborne asbestos concentrations from a remote area of California "of 40-100 electron-microscope-visible fibres/m^3."

The second publication referenced in the Toxicological Profile that reported rural ambient air asbestos concentrations in the Toxicological Profile was a 1991 report by the HEI-AR group

(HEI-AR, 1991). The HEI-AR report was not a research study, but rather cited results from several other publications. The publications referenced in the HEI-AR report are displayed in Table 4-8 of its report and referenced approximately 26 international publications on ambient asbestos concentrations from various environmental settings.

As stated in the Toxicological Profile, the HEI-AR report identified a rural ambient air asbestos concentration of “1 x 10^{-5} TEM f/mL (2 x 10^{-7} PCM f/mL)” (ATSDR, 2001; HEI-AR, 1991). The HEI-AR report presented a summary of ambient air background concentrations of asbestos in tabular form, with the ambient airborne asbestos concentrations identified in various units, including structures per liter (s/L), PCM f/mL and mass per volume of air (ng/m^3). The international airborne asbestos concentrations presented in Table 4-8 of the HEI-AR report (1991) for rural areas ranged from 0 to 47 s/L, and a mass concentration of 0 to 5 ng/m^3 [or 0 to less than 1.65 x 10^{-4} PCME (PCM equivalent0 f/ml].

The HEI-AR report (1991) also stated that individual samples collected in rural or remote locations were found to rarely exceed 1 ng/m^3 (3.3 x 10^{-5} PCM f/cc), while median concentrations were found to be 1 to 2 orders of magnitude lower. The HEI-AR report (1991) noted that TEM analysis is the only definitive method that can be utilized to measure outdoor ambient airborne asbestos concentrations and that “wide variations and limitations in the analytical techniques and analytical sensitivities employed” existed between the different studies reviewed in its report.

Urban Ambient Asbestos Concentrations & Cited Publications in the Toxicological Profile

The Toxicological Profile referenced seven publications measuring the ambient air asbestos concentrations in urban locations. These publications are described below. Concentrations of asbestos in urban ambient air samples ranged from 0.1 to 10 ng/m^3 (3.3 x 10^{-6} to 3.3 x 10^{-4} PCM f/cc), with sampling occurring around local sources, such as quarries, resulting in concentrations up to 100 ng/m^3 (3.3 x 10^{-3} PCM f/cc) (ATSDR, 2001). The publications cited for these airborne concentrations included: NRC (1984); Corn (1994); Nicholson and Pundsack (1973); EPA, Office of Research and Development, Office of Health and Environment Assessment, Environmental Criteria and Assessment Office (1991); Selikoff, Nicholson and Langer (1972); WHO (1998); and WHO-IARC (1977) .

Table 2 (Part B)
Ambient Air Asbestos Concentrations From Original Data

Setting	Measured Concentration Reported	Correction Factor Applied (f/cc)	Reference	Analysis Used
Urban (continued)	11 ng/ m^3 to 60 ng/m^3	3.6 x 10^{-4} PCM f/cc to 2.0 x 10^{-3} PCM f/cc	Selikoff et al., 1972*	electron microscopy
	10 ng/ m^3 to 100 ng/m^3 (in PA and NJ)	3.3 x 10^{-4} to 3.3 x 10^{-3} f/cc	Selikoff et al., 1972*	electron microscopy
	0.0003 f/mL (not detected - 0.008 f/mL)		Chesson et al., 1985	PCOM
	5 x 10^{-5} f/mL		Tuckfield et al., 1988	PCOM
	0.00039 f/cc		Crump & Farrar, 1989	PCM
	0.01 to 0.02 f/cc		Mangold, 1983	PCM
	2 x 10^{-4} s/cc		Van Orden et al., 1995	TEM
Various Sites	0.00109 s/mL; 0.00074 s>5um/mL; 0.79 ng/m^3		Lee & Van Orden, 2008	TEM
	2.0 x 10^{-5} f/mL++		Lee et al., 1992	TEM
Near Naturally Occurring Asbestos	0.0004 f/cc		ATSDR, 2011 (in El Dorado Hills, CA)	TEM

As noted, the Toxicological Profile referenced the 1984 NRC report, which did not include the collection of samples, but rather described the sampling results from other studies. The NRC report (1984) included an estimated median airborne asbestos concentration in the U.S. of 2.3 ng/m^3 (7.59 x 10^{-5} PCM f/mL) (ATSDR, 2001). In addition, the NRC report stated that the median airborne asbestos concentrations measured in the United States' cities (urban areas) ranged from 1.6 ng/m^3 (5.3 x 10^{-5} PCM f/cc) to a high of 13.7 ng/m^3 (4.6 x 10^{-4} PCM f/cc) as measured in New York City (NRC, 1984). The NRC report (1984) referenced the publication by Suta and Levine (1979), which listed atmospheric asbestos concentration data for urban areas in Table 5.2 of Suta and Levine that ranged from 0.09 ng/m^3 to 70 ng/m^3 (3 x 10^{-6} PCM f/cc to 2.3 x 10^{-3} PCM f/cc). Suta and Levine (1979) referenced several publications in their analysis of ambient asbestos including Heffelfinger, Melton and Kiefer (1972); Murchio, et al. (1973); Nicholson and Pundsack (1973); Nicholson, Rohl and Weisman (1975); and Selikoff, et al. (1972).

On page 220 of the NRC report (1984), Table 7-6 is presented, which was adopted from a draft by Nicholson (1983), which was published as a final report by the EPA (1986). Table 7-6 projects several U.S. and international publications that measured outdoor (ambient) environmental airborne asbestos concentrations (EPA, 1986). Table 7-6 displayed the outdoor (ambient air) asbestos concentrations at both urban and at undisclosed settings in the U.S., which were originally published in: Constant, et al. (1983); Nicholson, et al. (1975); Nicholson, Rohl and Ferrand (1971); and EPA (1974). The Nicholson 1983 publication (EPA, 1986) cited in the NRC report, stated that the mean ambient air asbestos concentrations across the United States ranged from 3.3 ng/m^3 to 16 ng/m^3 (1.1 x 10^{-4} PCM f/cc to 5.3 x 10^{-4} PCM f/cc) (EPA, 1986). These samples were collected at various locations across the U.S., including outside of schools (unclassified setting) and in cities (urban areas). Furthermore, the NRC report (1984) stated that during 1969 to 1970, the "average airborne asbestos mass concentrations ranged from 0.6 to 95.0 ng/m^3" (1.98 x 10^{-5} to 3.135 x 10^{-3} f/cc) in industrial cities in the continental U.S.

Corn (1994), cited in the Toxicological Profile, was not a research study, but rather cited previous original sampling as the source of the ambient asbestos concentrations discussed [Corn, Crump, Farrar, Lee and McFee (1991) and Corn (1994) stated that additional data were provided by R.J. Lee Group]. Corn (1994) stated that "[a]irborne asbestos mass concentrations in remote locations are less than 1 ng/m^3 [3.3 x 10^{-5} PCM f/cc], as are concentrations in rural locations. These concentrations are generally equivalent to fibre concentrations less than 0.0005 f/cc. . . . In urban areas total fibre concentrations of 1-10 ng/m^3 or up to 0.002 f cm^3 greater than 5 μm length." R.J. Lee Group sampled airborne asbestos concentrations outside of several locations and specifically found ambient air asbestos concentrations at "school and university" of 0.00004 f/mL; "public and commercial" of 0.00012 f/mL, "residence" of 0.00006 f/mL and "total" 0.00006 f/mL.

Nicholson and Pundsack (1973) analyzed 187 ambient air samples collected from 49 cities in the U.S. from 1969 to 1970. They analyzed the samples using an electron microscope for the chrysotile content in the ambient air samples and found that the ambient airborne concentrations of asbestos ranged from 0.1 to 50 ng/m^3 with the majority of samples (163 out of 187) less than 4.9 ng/m^3 (Nicholson & Pundsack, 1973). These results are also described in Nicholson, et al. (1971).

The Toxicological Profile referenced an EPA (1991) document entitled "Indoor Air: Assessment, Indoor Concentrations of Environmental Carcinogens." The EPA assessment reported that the "[a]verage concentrations of asbestos in urban ambient air are typically less than 1 ng/m^3 and rarely exceed 5 ng/m^3" and that ambient concentrations of asbestos outside of buildings with known "asbestos-containing materials seldom show increased concentrations of airborne asbestos over ambient levels" (EPA, 1991; 1974). Asbestos ambient air concentrations "near specific asbestos emissions sources" ranged from 100 ng/m^3 to 1,000 ng/m^3 (EPA, 1991). The EPA assessment did not conduct original sampling, but rather reviewed previous publications, including Constant, et al. (1983); Burdett and Jaffrey (1986); Dupré, Mustard and Uffen (1984); Nicholson (1978, 1989); Nicholson, et al. (1975); Perkins (1987); and Sebastien, Billion-Galland, Dufour and Bignon (1980) for outdoor ambient sampling results measured by TEM [provided in EPA (1991), Table 4] (EPA, 1991).

Additional publications by EPA were included in the reference section of the Toxicological Profile, but were not described in sufficient detail in the text to provide for an evaluation in this article. A publication referred to as the Public Buildings Study by EPA is referenced several times in different publications by the same authors (Chesson & Hatfield, 1990; Chesson, et al., 1990; Hatfield, et al., 1988; and others). The Toxicological Profile referenced, but did not specifically describe the 1988 EPA report by Hatfield, et al. (1988), which presented outdoor (ambient) airborne concentrations of asbestos. Specifically, in 1988, EPA funded a study to collect air samples from within and outside of 49 buildings owned by the General Services Administration (GSA). From the 49 GSA buildings, a total of 48 outdoor sites were sampled for airborne asbestos using TEM analysis and found a mean concentration of 3.9 x 10^{-4} s/cc and a median asbestos concentration of <0.00001 s/cc (Hatfield, et al., 1988).

Selikoff, et al. (1972) evaluated the airborne asbestos concentration in New York City and other locations utilizing high-volume samplers (up to 40 ft^3/min) and personal monitoring samplers [up to 2 liters per minute (l/min)]. The airborne asbestos concentrations obtained in New York City ranged from 11 ng/m^3 (3.63 x 10^{-4} PCM f/cc) in Staten Island to 60 ng/m^3 (1.98 x 10^{-3} PCM f/cc) in Manhattan (Selikoff, et al., 1972). As a comparison, air samples were also collected in Pennsylvania and New Jersey and the airborne asbestos concentrations collected in these two states ranged from 10 to 100 ng/m^3 (Selikoff, et al., 1972).

In 1998, WHO released a report titled, "Environmental Health Criteria 203, Chrysotile Asbestos" that reviewed previous publications that sampled

Table 3 Ambient Air Asbestos Concentrations From Original Data Using TEM

Setting	Measured Concentration Reported	Reference	Analysis Used
Urban	2 x 10^{-3} s/cc	Corn et al., 1991	TEM
	1 x 10^{-2} f/cc^{+}	Perkins, 1987	TEM
	3.9 x 10^{-4} s/cc	Hatfield et al. (USEPA), 1988	TEM
	2 x 10^{-4} s/cc	Van Orden et al., 1995	TEM
Various Sites	1.1 x 10^{-3} s/mL; 7.4 x 10^{-4} s>5um/mL	Lee and Van Orden, 2008	TEM
	2.0 x 10^{-5} f/mL^{++}	Lee et al., 1992	TEM

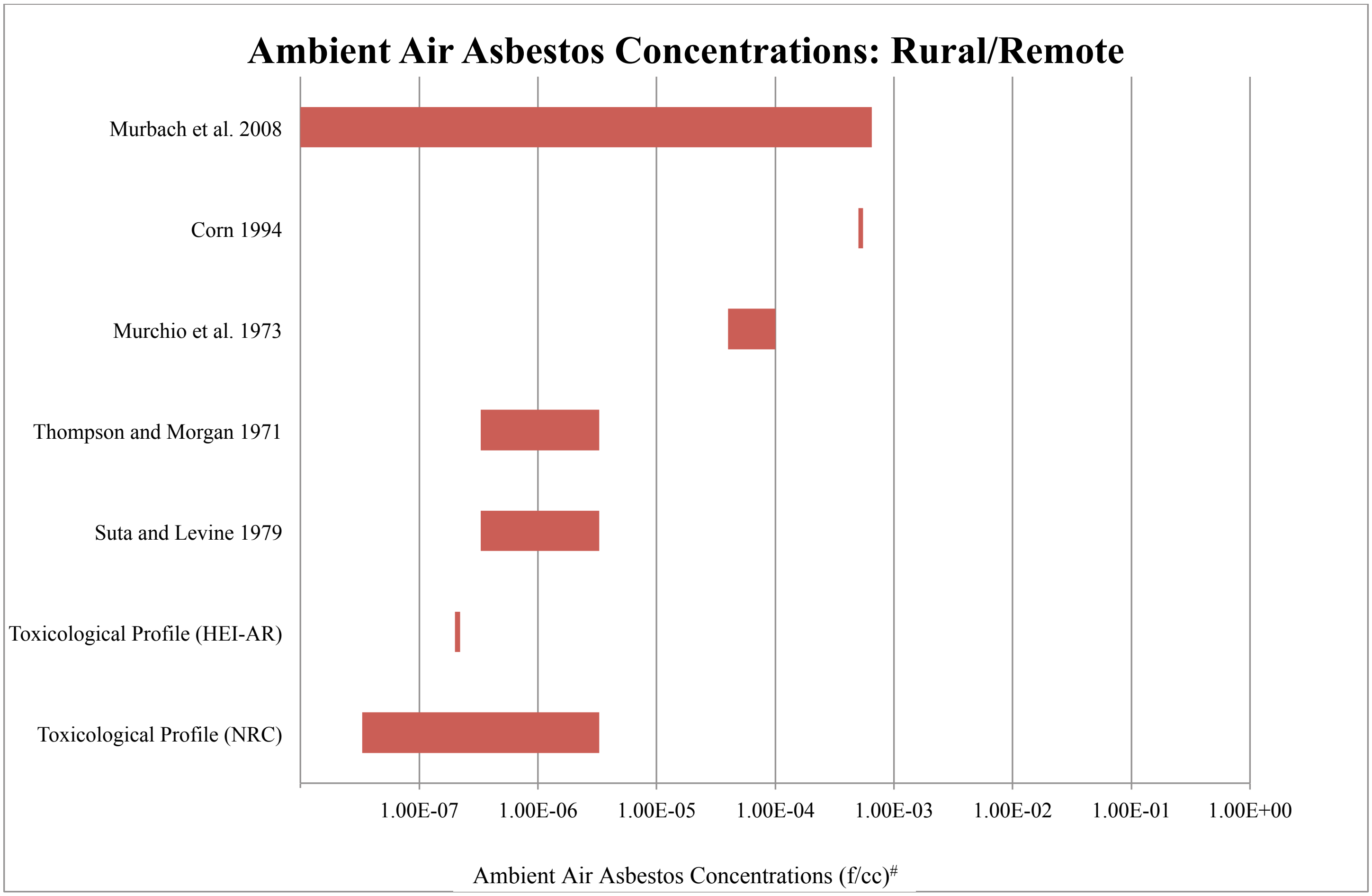
Notes:

$^{+}$ Reported as f/L concentration using TEM and all lengths with an aspect ratio >3:1.

$^{++}$ Reported as optical equivalent (f/ml) = fibers at least 5 μm long with a diameter of at least 0.25 μm

1. s/L = structures per liter of air
2. s/cc = structures per cubic centimeter of air

Figure 1 Ambient Air Asbestos Concentrations: Rural/Remote



When necessary, asbestos concentrations converted to f/cc
Results displayed as a range or as a single value (median or average) of ambient air asbestos concentrations reported

the ambient air for asbestos. The WHO (1998) report stated that "[b]ased on surveys conducted before 1986, fibre concentrations (fibres > 5 µm in length) in outdoor air, measured in Austria, Canada, Germany, South Africa and U.S., ranged between 0.0001 and about 0.01 f/ml, levels in most samples being less than 0.001 f/mL." The WHO (1998) report referenced two publications that measured "[(a)sbestos fibre concentration in outdoor air (f/ml PCOM [Phase Contrast Optical Microscopy] equivalent fibres—TEM)]" in urban air in the U.S. by Chesson, et al. (1985) and Tuckfield, et al. (1988). Chesson, et al. (1985), reported a median asbestos concentration in outdoor air of 0.0003 f/mL (range of not detected to 0.008 f/mL) using PCOM and Tuckfield, et al. (1988) reported a median of 0.00005 f/mL reporting the total structures > 5 µm in length. The WHO report also referenced Corn (1994) and HEI-AR (1991), which were previously discussed in this article.

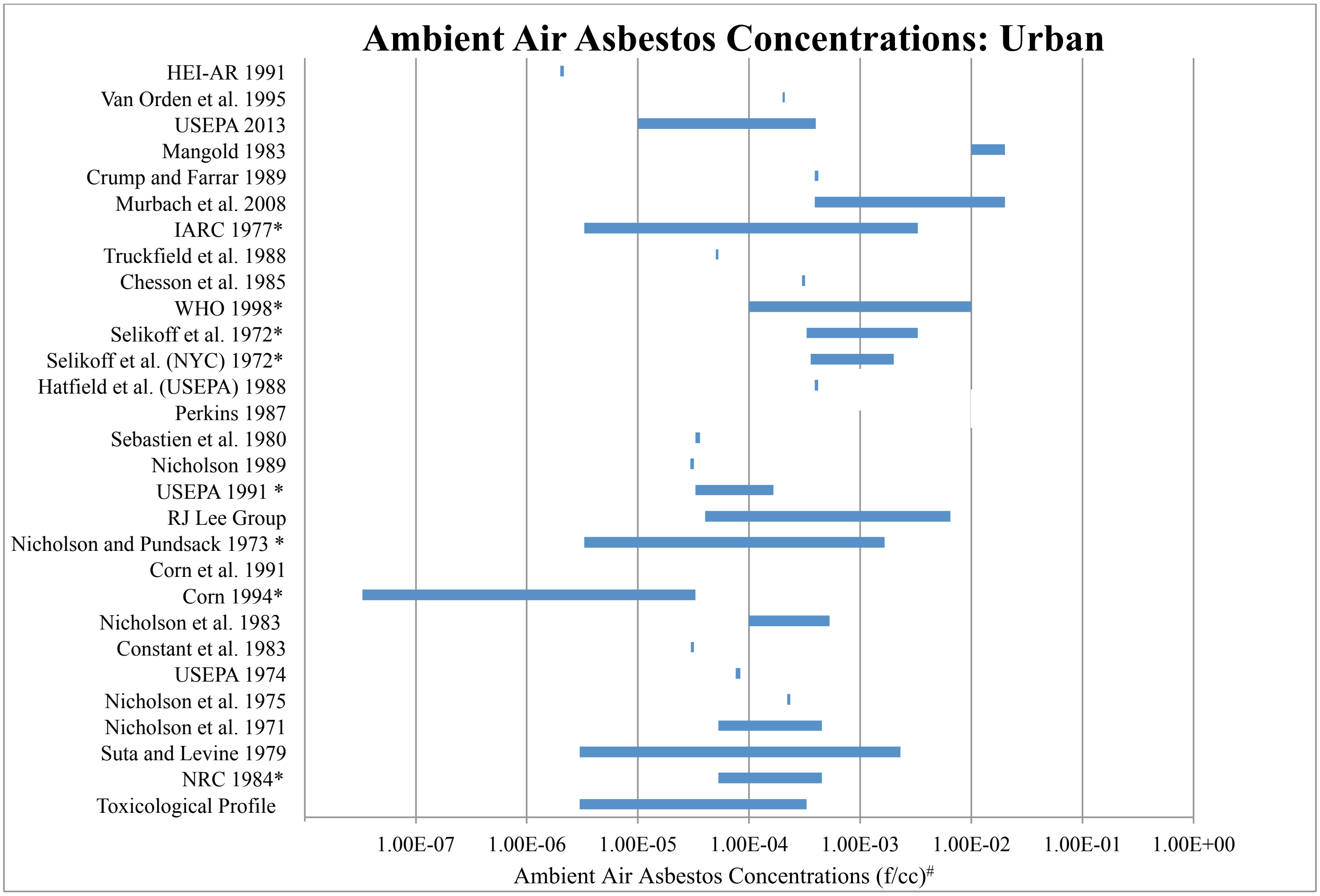
The 1977 IARC monograph was not a research study, but rather reviewed previous original sampling results from other studies that were reported as the total particulate mass and not as asbestos fiber concentrations (WHO-IARC, 1977). The IARC monograph stated that concentrations of asbestos in the general urban atmosphere were usually less than 10 ng/m^3 and did not exceed 100 ng/m^3 (3.3 x 10^{-4} to 3.3 x 10^{-3} PCM f/cc, respectively), citing publications by Holt and Young (1973); Nicholson and Pundsack (1973); Sebastien and Bignon (1974); Sebastien, Bignon, Gaudichet, Dufour and Bonnaud (1976); and Selikoff, et al. (1972) (WHO-IARC, 1977). The IARC monograph also noted that the ambient airborne concentrations of asbestos fibers, reported near some factories which used asbestos, ranged from 10 to 5,000 ng/m^3 (3.3 x 10^{-4} to 0.165 PCM f/cc) citing publications by Nicholson, et al. (1975) and Rickards (1973); (WHO-IARC, 1977). Table 10 of the IARC monograph listed the asbestos concentration in urban ambient air in the U.S. as ranging from 0.1 to 100 ng/m^3 (3.3 x 10^{-6} to 3.3 x 10^{-3} PCM f/cc) referencing the Nicholson, et al. (1975) publication of asbestos concentrations in public buildings in New York City, Chicago, San Francisco-Berkeley and Boston (WHO-IARC, 1977).

Ambient Asbestos Publications Not Included in the Toxicological Profile

The Toxicological Profile did not include several publications that either collected samples or reviewed other studies that presented the ambient air asbestos concentrations in the United States. These publications included the following five references: Lee and Van Orden (2008); Murbach, et al. (2008); WHO-IARC (2012); ATSDR (2011); and SRC Inc. (2013).

Lee and Van Orden (2008) sampled over a 10-year period and collected a total of 1,678 outdoor samples across the U.S.,

Figure 3 Ambient Air Asbestos Concentrations: Urban



When necessary, asbestos concentrations converted to f/cc

** Asbestos Concentrations from original sampling using TEM.

Results displayed as a range or as a single value (median or average) of ambient air asbestos concentrations reported

half of which were reported in Lee, Van Orden, Corn and Crump (1992). Samples were analyzed with TEM using an energy dispersive X-ray detector and selected area electron diffraction (SAED) to identify and classify the fibers. The average outdoor asbestos concentration was 0.00109 s/ml or 0.00074 s/ml using the AHERA regulations that classify an asbestos fiber as possessing "a length of at least 0.5 µm and at least five times the width" and a mass concentration for all structures of 0.79 ng/m^3 (Lee & Van Orden, 2008). Lee and Van Orden (2008) further reported that the average airborne asbestos concentration for asbestos fibers longer than 5 µm was 0.00003 f/mL.

Murbach, et al. (2008) compiled and analyzed historical airborne asbestos concentrations collected from 1978 to 1992, aboard maritime shipping vessels. This publication did not sample for airborne asbestos, but rather, the authors compared the maritime sample results to ambient and occupational airborne asbestos concentrations reported in the scientific literature. In Table 4 of Murbach, et al. (2008), the results published by Corn (1994), Crump and Farrar (1989), Mangold (1983) and NRC (1984) are presented. In Murbach, et al. (2008), the mean outdoor ambient airborne asbestos concentrations for rural areas ranged from 0 (below the analytical detection limit) to 6.5 x 10^{-4} f/cc, while the mean values for urban ambient airborne asbestos ranged from 3.9 x 10^{-4} to 2 x 10^{-2} f/cc. The lowest urban ambient airborne asbestos concentrations are attributed to Crump and Farrar (1989) and presented the mean ambient outdoor airborne asbestos concentrations estimated for five regions in the U.S. [Washington, DC, Kansas City, New York City, Denver and California (Los Angeles and San Francisco)] as 0.00039 f/cc (Murbach, et al., 2008).

In 2012, the IARC released an update to its 1977 Asbestos monograph (WHO-IARC, 2012). The 2012 IARC monograph included results published in the Toxicological Profile (ATSDR, 2001). The IARC monograph stated, "Low levels of asbestos have been measured in outdoor air in rural locations (typical concentration, 10 fibres/m^3 [f/m^3]). Typical concentrations are about 10-fold higher in urban locations and about 1,000 times higher in close proximity to industrial sources" (WHO-IARC, 2012).

The ATSDR published a Health Consultation in August 2011, entitled "Evaluation of Community-Wide Asbestos Exposures." The ATSDR Health Consultation evaluated community exposures to naturally occurring asbestos in El Dorado

Hills, CA. The ATSDR report presented background asbestos concentrations in El Dorado Hills, CA, of 0.0004 f/cc when no active disturbances were present and cited other references that measured an ambient asbestos concentration near NOA sources as 0.003 f/cc (ATSDR, 2011).

A report by SRC Inc. (2013) provided a "Summary of Published Measurements of Asbestos Levels in Ambient Air" prepared for EPA Region 8. SRC Inc.'s (2013) summary, which did not include sampling for airborne asbestos but rather reviewed other publications, excluded studies where sampling was performed in occupational settings, during asbestos remediation or removal, during building renovation, maintenance or demolition, and in locations with high NOA. SRC Inc.'s (2013) summary reported an average outdoor asbestos concentration in urban areas that ranged from 1 x 10^{-5} to 4 x 10^{-4} f/cc and referenced Van Orden, Lee, Bishop, Kahane and Morse (1995). Van Orden, et al. (1995) conducted sampling in the outdoor air in San Francisco and found asbestos concentrations to be 2 x 10^{-4} s/cc. EPA also referenced the publications discussed above by Hatfield, et al. (EPA) (1988), HEI-AR (1991) and Lee and Van Orden (2008). The HEI-AR report provided an urban air asbestos concentration of "0.0001 TEM f/mL (2 x 10^{-6} PCM f/mL)" (ATSDR, 2001; HEI-AR, 1991).

Summary

Clearly, the methods utilized to measure the ambient air concentrations of asbestos vary widely and the validity of the sample results is dependent on a number of factors. These factors include, but are not limited to, location of the sampling, season of the sampling, wind direction during the sampling, the number of samples collected and the method of sample collection and analysis. In addition, sampling results provide data from a single event, which may not be an accurate representation of the actual airborne asbestos concentrations over time; however, by converting and contrasting several studies which collected and analyzed samples in several similar areas, the airborne concentrations can be approximated if not defined. Many of the samples from earlier studies were collected as total mass or respirable mass (ng/m^3) and not as f/cc or s/cc.

It should be noted that samples reporting the mass of particulate per volume of air are subject to bias, as it provides no information regarding the size distribution of the particles or the identification of the particulate including fibers, if any. Analysis by PCM is limited in that it cannot definitively identify fibers as asbestos or other types of materials (wool, cotton, fiberglass, etc.). The PCM method counts all fibers greater than or equal to 5 µm, with a 3:1 aspect ratio and diameter of 2.5 µm. TEM, which provides an accurate definition of a fiber's morphology, should be used to identify the type of fiber present and the concentration. Correction factors have been applied to historic publications that presented the ambient air asbestos concentration as mass/m^3 to provide for asbestos concentration in f/cc.

In evaluating the literature for ambient air asbestos concentrations, publications presenting original data and using TEM to analyze the asbestos concentration are most important. This literature review identified a limited number of publications that conducted original sampling, Table 2 displays these publications that conducted ambient air asbestos sampling and the analytical method that was utilized. As can be seen in Table 2, only 24 publications were found in our review that conducted original sampling.

Of these studies conducting original sampling, only a few publications utilized the TEM analytical method, which is able to distinguish asbestos fibers from other fiber types. The use of TEM is paramount for evaluating environmental samples where several fiber types may be present. Table 3 projects the publications that conducted original sampling while subjecting the samples to TEM analysis, including Corn et al. (1991); Hatfield, et al.; EPA, 1988; Lee and Van Orden (2008); and Lee et al. (1992); Perkins (1987); and Van Orden, et al. (1995). Additionally, studies that performed sampling near local sources or NOA were not included in Table 3 as evaluating the ambient air asbestos concentration present near known asbestos sources was not the objective of this review. The ambient air asbestos concentrations from these publications that conducted original sampling and performed TEM methodologies reported ambient air asbestos concentrations that ranged from 2.0 x 10^{-5} f/mL to 1 x 10^{-2} f/cc (Table 3).

Conclusions

The studies evaluated in the article of the sampling of airborne asbestos fibers consistently show that airborne asbestos concentrations have and continue to be present in the ambient air in the U.S. and other locations. The ubiquitous nature of airborne asbestos has served in at least part as the basis for public health policy, including regulations involving asbestos concentrations. Public health officials and future studies should utilize this concentration range in identifying and analyzing potential exposures that the general public may encounter. Additionally, future studies analyzing the ambient air asbestos concentrations should utilize TEM methodologies to exclusively ensure that asbestos fibers are being evaluated. ○

References

Burdett, G.J. & Jaffrey, S.A. (1986). Airborne asbestos concentrations in buildings. *The Annals of Occupational Hygiene, 30*(2), 185-199.

Chesson, J. & Hatfield, J. (1990, March). Comparison of airborne asbestos levels determined by transmission electron microscopy (TEM) using direct and indirect transfer techniques (EPA 560/5-89/004). Washington, DC: EPA, Office of Pesticides and Toxic Substances, Exposure Evaluation Division.

Chesson, J., Hatfield, J., Schultz, B., Dutrow, E. & Blake, J. (1990, Feb.). Airborne asbestos in public buildings. *Environmental Research, 51*(1), 100-107.

Chesson, J., Margeson, D.P., Ogden, J., Reichenbach, N.G., Bauer, K., Constant, P.C., Bergman, F.J., Rose, D.P., Atkinson, G.R. & Lentzen, D.E. (1985, Oct.). Evaluation of asbestos abatement techniques. Phase 1: removal (EPA 560/5-85-019). Washington, DC: EPA, Office of Pesticides and Toxic Substances, Exposure Evaluation Division.

Constant, P.C. Jr., Bergman, F.J., Atkinson, G.R., Rose, D.R., Watts, D.L., Price, B.P. & Ogden, J.S. (1983, June). Airborne asbestos levels in schools (EPA 560/5-83-003). Washington, DC: EPA, Office of Pesticides and Toxic Substances, Office of Toxic Substances, Exposure Evaluation Division.

Corn, M. (1994). Airborne concentrations of asbestos in non-occupational environments. *The Annals of Occupational Hygiene, 38*(4), 495-502, 410.
Corn, M., Crump, K., Farrar, D.B., Lee, R.J. & McFee, D.R. (1991). Airborne concentrations of asbestos in 71 school buildings. *Regulatory Toxicology and Pharmacology, 13*(1), 99-114.
Crump, K.S. & Farrar, D.B. (1989). Statistical analysis of data on airborne asbestos levels collected in an EPA survey of public buildings. *Regulatory Toxicology and Pharmacology, 10*(1), 51-62.
Dupré, J.S., Mustard, J.F. & Uffen, R.J. (Eds.). (1984). Report of the royal commission on matters of health and safety arising from the use of asbestos in Ontario. Toronto, Ontario: Ontario Ministry of the Attorney General.
EPA. (1974). A preliminary report of asbestos in the Duluth, MN, area. Washington, DC: Author, Office of Technical Analysis.
EPA). (2011, July 1). 40 CFR 50.1(e). Retrieved from http://www.gpo.gov/fdsys/pkg/CFR-2011-title40-vol2/pdf/CFR-2011-title40-vol2-sec50-2.pdf
EPA. (1986, June). Airborne asbestos health assessment update (EPA/600/8-84/003F). Research Triangle Park, NC: Author.
EPA. (1991, Jan.). Indoor air - assessment. Indoor concentrations of environmental carcinogens (EPA/600/8-90/042). Research Triangle Park, NC: Author.
Hatfield, J., Stockrahm, J., Todt, F., Ogden, J., Leczynski, B., Price, B., Russell, J., Chesson, J., Ford, P., Fitzgerald, J., Thomas, J., Roat, R., Lee, R., Dunmyre, G., Van Orden, D., Constant, P. & McHugh, J. (1988, May). Assessing asbestos exposure in public buildings (EPA 560/5-88-002). Washington, DC: USEPA, Office of Pesticides and Toxic Substances, Exposure Evaluation Division.
Health Effects Institute-Asbestos Research (HEI-AR). (1991, Jan. 1). Asbestos in public and commercial buildings: A literature review and synthesis of current knowledge. Cambridge, MA: HEI-AR.
Heffelfinger, R.E., Melton, C.W. & Kiefer, D.L. (1972, Feb. 29). Development of a rapid survey method of sampling and analysis for asbestos in ambient air. Covering the period June 1969 through July 1971 (Contract No. CPA 22-69-110). Columbus, OH: Battelle Columbus Laboratories.
Holt, P.F. & Young, D.K. (1973, May). Asbestos fibres in the air of towns. *Atmospheric Environment, 7*(5), 481-483.
Lee, R.J. & Van Orden, D.R. (2008, Mar.). Airborne asbestos in buildings. *Regulatory Toxicology and Pharmacology, 50*(2), 218-225.
Lee, R.J., Van Orden, D.R., Corn, M. & Crump, K.S. (1992, Aug.). Exposure to airborne asbestos in buildings. *Regulatory Toxicology and Pharmacology, 16*(1), 93-107.
Mangold, C.A. (1983, March). Asbestos fibers in the ambient air in the greater San Francisco area (Unpublished Report).
Murbach, D.M., Madl, A.K., Unice, K.M., Knutsen, J.S., Chapman, P.S., Brown, J.L. & Paustenbach, D.J. (2008, June). Airborne concentrations of asbestos onboard maritime shipping vessels (1978-1992). *The Annals of Occupational Hygiene, 52*(4), 267-279. doi: 10.1093/annhyg/men015.
Murchio, J.C., Cooper, W.C. & De Leon A. (1973, March 1). Asbestos fibers in ambient air of California: final report to the California Air Resources Board and Project Clean Air, University of California, Riverside. Retrieved from http://www.asb.ca.gov/research/apr/past/4-054-1.pdf
National Research Council (NRC). (1984). *Asbestiform fibers: nonoccupational health risks.* Washington, DC: National Academy Press.
Nicholson, W.J. (1978). Control of sprayed asbestos surfaces in school building: A feasibility study. (Final Report; Contract I-ES-2113). Research Triangle Park, NC: National Institute of Environmental Health Sciences.
Nicholson, W.J. (1989). Airborne mineral fibre levels in the non-occupational environment. *IARC Scientific Publications, 90,* 239-261.
Nicholson, W.J. & Pundsack, F.L. (1973). Asbestos in the environment. Biological effects of asbestos. *IARC Scientific Publications, 8,* 126-132.
Nicholson, W.J., Rohl, A.N. & Ferrand, E.F. (1971). Asbestos air pollution in New York City. In H.M. England & W.T. Barry (Eds.), *Proceedings of the second international Clean Air Congress* (pp. 136-139). New York, NY: Academic Press.
Nicholson, W.J., Rohl, A.N. & Weisman, I. (1975, Oct.). Asbestos contamination of the air in public buildings (EPA-450/3-76-004). Retrieved from http://www.epa.gov/airtoxics/asbes/pdfs/epa450-3-76-004_October1975PublicBuildings.pdf
OSHA. (1992). OSHA. 57:7877-7878, 24310-24331, 49657-49661.
Perkins, R.L. (1987). Asbestos in residential environments: preliminary draft report (Contract No. CR812281-01-0). Research Triangle Park, NC: Research Triangle Institute.
Rickards, A.L. (1973). Estimation of submicrogram quantities of chrysotile asbestos by electron microscopy. *Analytical Chemistry, 45*(4), 809-811.
Sebastien, P. & Bignon, J. (1974). Contribution à letude de la pollution particulaire de l'air ambiant de la Ville de Paris par les microfibrilles d'amiante, rapprt final (Contract No. 206). Paris, France: Ministère de la Qualité de la Vie.
Sebastien, P., Bignon, J., Gaudichet, A., Dufour, G. & Bonnaud, G. (1976). Les pollutions atmosphériques urbaines pa l'asbeste. Rev. franç. MaL. Resp, 4(Suppl 2), 51-62.
Sebastien, P., Billion-Galland, M.A., Dufour, G. & Bignon, J. (1980, Aug.). Measurement of asbestos air pollution inside building sprayed with asbestos (EPA-560/13-80-026). Washington, DC: EPA, Office of Pesticides and Toxic Substances.
Selikoff, I.J., Nicholson, W.J. & Langer, A.M. (1972, July). Asbestos air pollution. *Archives of Environmental Health, 25*(1), 1-13.
SRC, Inc. (2013, May 20). Summary of published measurements of asbestos levels in ambient air. Retrieved from http://www2.epa.gov/sites/production/files/2013-08/documents/libbyasbestos_ambientairlitsearch5-20-2013.pdf
Suta, B.E. & Levine, R.J. (1979, Apr.). Nonoccupational asbestos emissions and exposures. In S.S. Chissick & L. Michaels (Eds.), *Asbestos. Properties, applications and hazards* (Vol. 1, pp. 171-205). New York, NY: John Wiley & Sons Ltd.
Thompson, R.J. & Morgan, G.B. (1971). Determination of asbestos in ambient air. Presented at Identification and Measurement of Environmental Pollutants Symposium, Ottawa, Ontario, Canada.
Tuckfield, R.C., Tsay, Y., Margeson, D.P., Ogden, J., Chesson, J., Bauer, K., Constant, P.C., Bergman, F.J. & Rose, D.P. (1988). Final report for tasks 1-6: Evaluation of asbestos abatement techniques phase 3: Removals (EPA-68-02-4294). Washington DC: EPA.
U.S. Department of Health Services (DHHS). (2001). Toxicological profile for asbestos. Washington, DC: Author, Public Health Service, Agency for Toxicological Substances and Disease Registry (ATSDR).
U.S. DHHS. (2011). Health consultation. Evaluation of community-wide asbestos exposures. El Dorado Hills naturally occurring asbestos site, El Dorado Hills Boulevard, El Dorado Hills, CA (EPA facility ID: CAN000906083). Retrieved from http://www.atsdr.dcd.gov/hac/PHA/ElDoradoHills/ElDoradoHillsFinalHC08162011.pdf
Van Orden, D.R., Lee, R.J., Bishop, K.M., Kahane, D. & Morse, R. (1995, Feb.). Evaluation of ambient asbestos concentrations in building following the Loma Prieta earthquake. *Regulatory Toxicology and Pharmacology, 21*(1), 117-122.
World Health Organization (WHO). (1998). Environmental health criteria 203: chrysotile asbestos.
WHO & International Agency for Research on Cancer (IARC). (1977). Asbestos. In IARC monographs on the evaluation of carcinogenic risks to humans. Retrieved from http://monographs.iarc.fr/ENG/Monographs/vol1-42/mono14.pdf
WHO & IARC. (2012). Asbestos (chrysotile, amosite, crocidolite, tremolite, actinolite and anthophyllite). Retrieved from http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-11.pdf

Conflict of Interest/Disclosure
Author Anderson has served as an expert witness for defendants in toxic tort cases involving asbestos. Authors Parr and Boyd have written expert reports in support of toxic tort litigation involving asbestos.

Safety Performance Assessment of a Construction Site Using Construction Safety Index: Evidence From Indian Construction Industry

Devendra Kumar Pathak and K.N. Jha

Abstract

Construction safety is an important issue and it is prudent to measure the safety performance of a construction site. The hierarchical framework developed by an earlier research has been utilized for computing construction safety index (CSI) score, which is useful for safety performance evaluation (SPE) of construction sites. The relative weights of the first level factors and second level attributes of the CSI framework have been computed based on the responses to a questionnaire survey conducted among Indian construction professionals using analytic hierarchy process (AHP), while the relative weights of third-level attributes have been computed using the mean ranking and mean score method. Further data collected from 30 construction sites have revealed statistically significant association between CSI and safety indicators (lost-time injury frequency rate and lost-time injury incident rate). The devised SPE sheet may serve as a new safety management tool for construction safety professionals and CSI scores, calculated through it, can be used for safety assessment and depending on its value further corrective measures can be taken for better safety practices at construction site.

Keywords
construction safety index, safety performance assessment, safety management systems, analytic hierarchy process

Introduction

In India, the construction industry is the second largest industry after agriculture and it accounts for 11% of India's GDP. The construction industry employs about 33 million people throughout India with its total market size estimated as 2,48,000 crores (35,640 million USD) (Jha, 2011). According to the 12th Five-Year Plan (2012-17), total infrastructure expenditure has increased to USD 1,025 billion from USD 514 billion in the 11th Five-Year Plan (2007-2012).

The construction industry is considered to be one of the most significant industries in terms of its contribution to GDP and also in terms of its impact on the safety and health of the working population in both the developed and developing part of the world (Farooqui, Arif & Rafeeqi, 2008). The industry is both economically and socially important. However, at the same time, the industry is also recognized as being the most hazardous.

According to 11th Five-Year Plan (2007-12), the Indian construction industry, employing the largest labor force, has accounted for about 11% of all occupational injuries and 20% of deaths resulting from occupational incidents. Therefore, due to the increasing number of reported accidents and injuries on construction projects, safety is becoming an important issue in today's construction environment. The safety standards and occupational hazard management at a construction site can inevitably be improved by continuous monitoring, review and assessment of a site's safety performance.

The specific objectives of the present study are to evaluate the priorities of the potential attributes affecting construction site safety and to develop an index to measure and evaluate the safety performance of a construction site. The priority represents the rank that will be given on the basis of calculated weight-age. Higher the weight-age, the higher will be the priority. It may be difficult to implement all the key attributes during the implementation of a safety management system (SMS). The results of first part of this project would help to know the priorities of all the key attributes that will ensure that construction firms utilize their resources in an effective manner for proper SMS implementation. Through the second part of objective, an index would be developed. Scoring using the developed index will also help construction personnel to identify potential risks at an early stage so that corresponding preventive measures can be taken to avoid unnecessary financial losses due to disruptions at construction sites, delay in project completion, damage to equipment and harm to the firm's reputation. The term factor represents the main attributes that affect the safety of a construction site.

Literature Review

The significance of construction industry to the economic and social life of India is noteworthy. The construction industry is large, complex and different from other industries. An important factor is the change of site personnel themselves. All of these factors along with the inherent nature of construction jobs make this industry one with high incident risks. Therefore, safety management is must in a construction industry.

Devendra K. Pathak is an assistant professor in the Department of Mechanical Engineering at ITM University Gurgaon (Haryana), India. He can be reached at pathakdev15@gmail.com.

Dr. K.N. Jha is an associate professor in the Department of Civil Engineering, Indian Institute of Technology, Delhi, India. He has published more than 50 papers in international and national journals and conference proceedings. His book, *Construction Project Management,* was published by Pearson Education, and *Formwork for Concrete Structures,* published by Tata McGraw Hill, is widely accepted as a textbook in different universities.

Rowlinson (2003) found that the safety legislation and policies are the most promising factors to affect the safety level of a construction project. Legislation forms a framework in which safety and health is regulated and controlled. Hinze (2002) emphasized that incentives should be well structured to reduce workplace injuries at construction sites and reported that for successful implementation of incentive programs, firms should use safety incentives of low value in the form of frequent awards to crews. Chan, Kwan and Duffy (2004) prioritized 14 key safety processes under five decision criteria among three different kinds of construction enterprises: joint venture (JV), well-established (W-E), and small and medium-sized enterprises (SMEs). The results indicated that the highest priorities were given to emergency preparedness, evaluation of sub-contractors and job hazard analysis for SMEs, and to emergency preparedness, safety committees and incident investigation for JVs. Safety training received low priority and, thus, was a problem area in the three types of construction enterprises.

Teo, Ling and Chong (2005) identified potential factors that significantly affect construction safety and proposed a policy, process, personnel and incentive (3P + I) framework that may help project managers to manage construction site safety and thereby to reduce the frequency of incidents. The main finding of this study was that site safety is affected by four main factors: company safety policy, construction process, personnel management with regard to safety and incentives. The policy factor was considered to present the importance of safety legislation and policies, occupational health and safety management system, and permit-to-work system. The process factor was considered to represent the process of carrying out work by construction personnel in a safe manner that will require effective communication and information transfer between management and employees.

For managing process factor in an effective way, there should be control over the large number of subcontractors; different construction methods should meet safety standards; and there should be proper understanding and implementation of safety procedures. Personnel factors present issues related to different human aspects involved in construction work, such as management and workers' safety behavior and attitude at construction site. Aksorn and Hadikusumo (2008) evaluated 16 critical success factors (CSFs) of safety program implementation based on their degree of influence. The 16 CSFs were grouped under four dimensions: worker involvement, safety prevention and control system, safety arrangement and management commitment. The results revealed that management support was the most influential factor for safety program implementation.

Ng, et al. (2005), used a set of factors and subfactors to develop a safety performance evaluation (SPE) framework for evaluating the safety performance of construction contractors at the organizational and project level. Chang and Liang (2009) developed a plan, do, control, act (PDCA) cycle based model to measure the performance of a process safety management system at paint manufacturing facilities in terms of safety index (SI) by using a three-level multi-attribute value model (MAVT) approach.

In India, traditionally construction safety performance is assessed by evaluating the physical safety conditions on the construction site as well as reviewing the lost-time injury records, while there is no provision to consider the SMS factors that affect a site's safety. The lost-time-injury-related safety indicators evaluated on the basis of post-accident data analysis can at best be considered as reactive and, thus, are of limited use. For effective assessment of safety performance, there is a need to move toward a proactive approach such as safety audits or assessment of SMS rather than just depending on the reactive data. Hinze, et al. (2013), explained leading indicators of safety performance as the measures for safety process as they are applied to construction activities; on the other hand, safety-results-oriented factors, such as injury incident rates, are lagging indicators. The results of their study presented the use of leading indicators for improving safety performances.

Through the proactive approach, essential feedback on performance may be available before an incident occurs. Thus, to effectively oversee the SMS, a composite performance evaluation system that encompasses all of the potential factors affecting a construction site's safety is of essential. One major issue regarding improvement of safety performance at construction sites is the lack of comparable data or index to indicate how well or bad, in terms of safety, a construction site is performing.

Through the SPE sheet presented in this study, the performance of a construction site can be computed in terms of construction safety index (CSI), a means to objectively measure the effectiveness of SMS at different construction sites, which can provide real-time feedback on safety performance. Teo and Ling (2006) developed a model for the measurement of the effectiveness of safety management system based on a 3P + I (policy, process, personnel and incentive factors) framework and a three-level MAVT.The relative weights for the first-level factors along with second- and third-level attributes were not reported by the authors. Besides, the framework required assessment of more than 500 lower-level attributes that would make it cumbersome for practitioners. The authors also did not develop an SPE sheet for quick assessment of a construction site, and did not report the correlation of CSI (a measure for proactive approach) with lost-time-injury-based safety indicators (measures for reactive approach). The authors performed their study in the context of Singapore, and the importance weights and attributes were strongly influenced by the local environment and culture.

Nevertheless, the present study takes its lead from this MAVT approach and develops an SPE sheet forassessment of safety performance and represents correlation between safety performance indicators and CSI. Hereby, the developed SPE sheet can be used by the practitioners easily. The proposed framework with some local adjustment can be applicable to any country.

Research Method

The research method adopted to achieve the stated objectives is explained briefly in the following discussion.

Step 1: Framework Selection

The first step is to select a framework that could measure construction safety performance in an efficient manner. As noted, a few models exist for measuring safety performance. The framework known as 3P + I (policy, process, personnel and incentive) developed by Teo, et al. (2005) has been used here. In their study, authors had performed *t*-test and factor analysis using Statistical Package for Social Sciences (SPSS) software package. Basically, they had identified all the third-level attributes under each first-level factor, then with that result they have assigned all third-level attributes to second-level attributes. This framework is suitable for the current application as it encompasses almost all the key potential attributes that affect a construction site's safety, as specified in literature review section, and all the third-level attributes can easily be rated by safety professionals at sites to calculate CSI for a construction site.

The first-level factors are policy, process, personnel and incentive. These first-level factors have been classified into 14 second-level attributes, then each second-level attribute is further classified into several third (lower)-level attributes. All of these second- and third-level attributes have been taken from the selected 3P + I framework.

Step 2: Preparation of Hierarchy

In the second step, the hierarchy has been prepared corresponding to the selected framework. The hierarchy consists of four first-level factors (policy, process, personnel and incentives), 14 secondlevel attributes (as mentioned in Appendix 1), and several measurable third-level attributes (as mentioned in Table 5). For the present study, we have considered a three-level hierarchy and its first level is for representing first-level factors, the second level of this hierarchy is for representing second-level attributes and third level is for representing lower-level attributes. The main motive of the hierarchy preparation is first to calculate the local weights of first-level factors as well as of second-level attributes, then to compute the global weights for each second-level attribute.

Step 3: Questionnaire Development

A two-section questionnaire was designed to survey construction sites' personnel. The questions (Figure 1) in the first section were primarily designed to determine the relative weights of the first-level factors (policy, process, personnel, incentives), then to prioritize the second-level attributes that come under their corresponding first-level factors (the questions are prepared likewise for the first-level factors as shown in Figure 1), pertinent to safety performance, while the second section aims to determine the relative importance of all third-level attributes. Through the questions (Figure 2), respondents' opinion were sought to determine the relative weights of lower-level attributes. The respondents' views were sought on a five-point Likert scale in which 1 represented "strongly disagree" and 5 represented "strongly agree." The intermediate values of 2, 3 and 4 represented "disagree," "undecided" and "agree," respectively.

Figure 1 Sample Question for the First-Level Factors

Q. 1:How would you give comparatively preference (from 1 to 9) to following first level factors affecting construction site safety?

Please tick (✓) the factor which is more important				Please indicate level of importance for the 'more important' factor								
Policy		Process		1	2	3	4	5	6	7	8	9
Policy		Personnel		1	2	3	4	5	6	7	8	9
Policy		Incentives		1	2	3	4	5	6	7	8	9
Process		Personnel		1	2	3	4	5	6	7	8	9
Process		Incentives		1	2	3	4	5	6	7	8	9
Personnel		Incentives		1	2	3	4	5	6	7	8	9

Legend:**1: Equally important, 3: Moderately important, 5: Strongly important, 7: Very strongly important, 9: Extremely important, (2,4,6 and 8 are intermediate values)**

Figure 2 Sample Question for the Third-Level Attributes

Q. To what extent the following attributes contribute in the effectiveness of safety management systemfor construction sites? Please provide your degree of agreement on a five-point scale as mentioned in the legend.

SI. no.	Third level attributes	1	2	3	4	5
1	Understanding of Factories Act					
2	Understanding of SMS					
3	………………..					

Legend:**1: Strongly disagree, 2: Disagree, 3: Undecided, 4: Agree, 5: Strongly agree**

Step 4: Conducting Questionnaire Survey & Collection of Responses

From the 124 questionnaires sent, 72 responses were received (response rate of 58%). Data from these 72 questionnaires were checked, recorded and analyzed.

Respondents belonged to manager level (35%), engineer level (48%) and supervisor level (17%). Of the total respondents, 39% were safety personnel. Safety personnel consisted of health, safety and environment (HSE) managers, HSE engineers and safety supervisors. As 44.4% of the total respondents have worked for more than 9 years in the construction industry, it is expected that the data collected from them are reliable. Respondents are mainly contractors from public sector, government, multinational and private sector companies operating in India.

Step 5: Computations of Relative Weights Using AHP, MR & MS Method

The relative weights of the first-level factors and second-level attributes were determined using analytic hierachy process (AHP). Due to involvement of large number of third-level attributes AHP could not be applied and, thus, mean ranking (MR) and mean score (MS) technique explained by Assaf, Al-Khalil and Al-Hazmi (cited in Ng, et al., 2005) was used to determine the relative importance.

Step 6: Development of SPE Sheet

The SPE sheet is developed using the computed weights of first-level factors and second-level attributes and third-level attributes. The rating for third-level attributes is captured using 0/1 rating option (where 0 stands for "no" and 1 for "yes") explained in Teo and Ling (2006). The objective of SPE sheet is to calculate the safety performance of a construction industry in terms of CSI.

The relative importance of each third-level attribute and the global weights of its corresponding second-level attribute can be combined with the rating score to calculate the CSI as shown in Equation 1.

$$CSI_{ij} = W_j \times RI_{ij} \times r_i \quad (1)$$

$$Overall\ weight = W_j \times RI_{ij} \quad (2)$$

The overall weight of the third-level attributes can be calculated using Equation 2.

Where CSI_{ij} is the construction safety index of i^{th} third-level attribute under the second-level attribute, W_j is the global weight of j^{th} second-level attribute, RI_{ij} is the relative importance of i^{th} third-level attribute under j^{th} second-level attribute and r_i is the auditor's assessment (rating) on i^{th} third-level attribute of a specific construction site. Further details about CSI and overall weight are discussed later.

Step 7: Validation of Model

The second stage questionnaire survey is conducted for 30 construction sites by using the SPE sheet, devised from the first questionnaire survey results, to calculate CSI. During this survey, accident data were also recorded from these 30 construction sites. The motive for conducting the second stage questionnaire is to validate the devised model via site surveys and to test whether the questions framed in the form of 0/1 ratings are easily understandable by safety professionals at these sites and, thereby, to check the objectivity of devised sheet. Furthermore, the SPE sheet was also improved to ensure its usability and comprehensibility.

The safety indicators were calculated from the accident statistics recorded at the involved sites. The correlation and regression analysis were used with .05 statistical significance level in order to determine whether there is a statistically significant association between CSI and the safety indicators and, if so, to what extent. Based on the results, conclusions were made (see p. 229).

Data Analysis Tools

As noted, the computation of weights at different level of hierarchy has been carried out using AHP, mean score (MS) and mean ranking (MR). These are explained briefly in this section.

Analytic Hierarchy Process

The AHP has been used to find out the weights for first-level factors and second-level attributes. The method allows the use of qualitative as well as quantitative criteria in evaluation (Saaty, 1980) and is one of the most widely used methods in which the decision-making problem is divided in hierarchical levels.

The AHP consists of following four phases:

1) Development of a hierarchy of decision criteria and defining the alternative courses of actions.

2) Data collection through pair-wise comparisons and measurement.

3) Calculation of normalized priority weights of individual factors.

4) Analyzing the priority weights, checking consistency and deriving solutions to the problem.

Mean Ranking & Mean Score

The MR and MS method explained by Assaf, Al-Khalil and Al-Hazmi (cited in Ng, et al., 2005) has been used to find out the relative importance of each third-level attribute. The mean score is computed by:

$$MS = \frac{\sum f \times S}{N} \quad (3)$$

Where f is the frequency of responses to each rating for each third-level attribute, S is the score given to each third-level attribute by the respondents and N is the total number of responses obtained for the given attribute.

The relative importance (RI) of each third-level attribute is calculated using the following expression:

$$RI_{ij} = \frac{MS_{ij}}{\sum_{i=1}^{n} MS_{ij}} \quad (4)$$

Where RI_{ij} is the relative importance of i^{th} third-level attribute under j^{th} second-level attribute, and MS_{ij} the mean score of ith third-level attribute under j^{th} second-level attribute.

Priority of First- & Second-Level Elements

The computation of relative weights of first- and second-level elements in the hierarchy has been performed using AHP. The detailed computation method for one element in the first-level hierarchy using the four steps mentioned earlier has been explained in this section.

Establishment of Pair-Wise Comparison Matrix

In establishing the priorities, AHP requires respondents to state how important each criterion is relative to each other criterion. The comparison is done in a pair-wise manner. Thus, there are $n(n-1)/2$ judgments required to be formulated for a pair-wise matrix. Where n is the number of factors/attributes to be compared in a pair wise matrix. As noted, there are four factors in first-level hierarchy, thus respondents were required to provide 4 × (4-1)/2 = 6 pair-wise responses of their preferences on a nine-point scale (Saaty, 1980).

Calculation of Priority

Using the pair-wise comparison matrix, the priority of each factor in terms of its contribution to the overall goal can be calculated. For this, the values in each column of the pair-wise comparison matrix are summed up first, and each element in the pair-wise comparison matrix is divided by its column total. The resulting matrix is referred to as the normalized pair-wise comparison matrix. The average of the elements in each row of the normalized pair-wise comparison matrix is now calculated, which reflects the relative priorities, importance or weights for the factors.

Calculation of the Maximum Eigen Value (λ_{max})

The pair-wise comparison matrix is multiplied with the acquired priority vector to produce a $n \times 1$ matrix. The resulting matrix is divided by the priority vector to acquire unit vectors. The average of the unit vectors is calculated sequentially to get the maximum eigenvalue λ_{max}.

Examination of Consistency

If A is preferred three times as much as B, and B is preferred twice as much as C, then A must be preferred six times as much as C to be consistent. Therefore, there is a need to check the consistency of the pair-wise comparison matrix. AHP provides a measure of the consistency for the pair-wise comparison by computing a consistency ratio. The consistency index (CI) is found by the following expression:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (5)$$

Then the consistency ratio (CR) can be calculated:

$$CR = \frac{CI}{RandomnessIndex(RI)} \quad (6)$$

The RI values as suggested by Saaty and Kearns (1985) have been considered in the study. The RI for n equal to one and two are 0. For n equal to 3 to 10, RI values are 0.58, 0.90, 1.12, 1.24, 1.32, 1.42, 1.45 and 1.49, respectively.

According to Saaty (1980), comparison matrix is consistent when, CR < 0.1; otherwise, the comparison matrix should be updated as this is an indication of inconsistent responses. In other words, the responses of experts should be sought again and again until the desired consistency is achieved. In practice, this is difficult and time consuming. To deal with inconsistencies in the responses, the literature suggests the use of the geometric mean of all the responses in multiple response scenarios (Chen, 2006). Geometric mean of the responses is used for determining the relative weights of first-level factors and second-level attributes.

As group decision making is used for the study, individual judgment resulted from the second phase were combined to produce the group judgment results, Geometric means of all individual judgments were then computed with the following formula to produce the group judgment:

$$X = \sqrt[N]{x_1 \times x_2 \times x_3 \times \ldots \ldots \ldots x_N} \quad (7)$$

Where X is geometric mean, N is the number of respondents and $x_1, x_2, x_3 \ldots x_N$ are the responses for the same factor/attribute by different respondents. The pair-wise comparison matrix formed on the basis of geometric mean of responses for the first-level factors is shown in Table 1. The normalized pair-wise comparison matrix for first-level factors are shown in Table 2.

Table 1 Pair-Wise Comparison Matrix for First-Level Factors

	Policy	Process	Personnel	Incentives
Policy	1.000	3.527	3.480	4.070
Process	0.284	1.000	3.250	3.040
Personnel	0.287	0.307	1.000	1.910
Incentives	0.246	0.329	0.524	1.000
Sum of column value	1.817	5.163	8.254	10.020

Table 2 Normalized Pair-Wise Comparison Matrix for First-Level Factors

	Policy	Process	Personnel	Incentives	Priority (Row Average)
Policy	0.550	0.683	0.422	0.406	0.515
Process	0.156	0.194	0.394	0.303	0.262
Personnel	0.158	0.059	0.121	0.191	0.132
Incentives	0.135	0.064	0.063	0.099	0.091

The maximum eigen value λ_{max} is computed next.

$$n_1 = \frac{(1\times0.515) + (3.527\times0.262) + (3.48\times0.132) + (4.07\times0.091)}{0.515} = 4.4003$$

$$n_2 = \frac{(0.284\times0.515) + (1\times0.262) + (3.25\times0.132) + (3.04\times0.091)}{0.262} = 4.2539$$

$$n_3 = \frac{(0.287\times0.515) + (0.307\times0.262) + (1\times0.132) + (1.91\times0.091)}{0.132} = 4.0332$$

$$n_4 = \frac{(0.246\times0.515) + (0.329\times0.262) + (0.524\times0.132) + (1\times0.091)}{0.091} = 4.1146$$

$$\lambda_{max} = \frac{(n_1)+(n_2)+(n_3)+(n_4)}{4} = \mathbf{4.2005}$$

CI and CR are computed next.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} = 0.0668$$

$$CR = \frac{CI}{Randomness\ Index\ (RI)} = \frac{0.0668}{0.9} = 0.0742$$

Table 3 Summary of Priorities of First-Level Factors

Factors	Weight-age	Rank	λ_{max}	CI	CR
Policy (PO)	0.515	1	4.20	0.066	0.074
Process (PR)	0.262	2			
Personnel (PE)	0.132	3			
Incentives (IN)	0.091	4			

Table 4 Summary of Global Weights of Second-Level Attributes

First-level factors	Second-level attributes	Global Weights (W)	Relative ranking
Policy (PO)	PO.1	0.288	1
	PO.2	0.155	2
	PO.3	0.072	5
Process (PR)	PR.1	0.112	3
	PR.2	0.059	6
	PR.3	0.052	7
	PR.4	0.020	11
	PR.5	0.019	12
Personnel (PE)	PE.1	0.076	4
	PE.2	0.041	9
	PE.3	0.016	13
Incentives (IN)	IN.1	0.049	8
	IN.2	0.029	10
	IN.3	0.012	14

Table 3 shows the priorities of the four first-level factors computed based on the results of the respondents. The results are considered to be consistent, since the CI and CR are less than 0.1. From the results it is clear that policy is the most important factor with 0.515 weight. Safety policy also has been identified as one of the most crucial factors that affects SMS by Rowlinson (2003); Chan, et al. (2004); Law, et al. (2006); Teo, et al. (2005); and Teo and Ling (2006). Process, personnel and incentives factors are at second, third and fourth rank, respectively, with 0.262, 0.132, 0.091 weights. In comparison to policy, process and personnel factors, incentives have received relatively less priority. Therefore, for proper implementation of SMS, more emphasis should be given to the policy factor due to its higher weight.

A similar procedure was used to compute the priorities (local weights) of second-level attributes. The global priority was determined by multiplying the local weight of second-level attribute with the corresponding local weight of first-level factor under which it appears. Global weights and relative ranking of second-level attributes is shown in Table 4. The most important second-level attributes emerged to be "understanding and implementation of safety management system" (PO.1), "understanding and participation in occupational health and safety management system" (PO.2) and "quality of subcontractors" (PR.1). Their global priorities are 0.288, 0.155 and 0.112, respectively. "Management's attitude toward safety" (PE.1) ranks fourth, which has been considered as one of the most important attributes by Abudayyeh, et al. (2006); Aksorn and Hadikusumo (2008); Ng, et al. (2005); Sambasivan and Fei (2007); and Teo, et al. (2005). The safety professionals in India have accorded the least priority to the "contextual characteristics of workers" (IN.2) and "disciplinary action" (IN.3). The disciplinary action against employees received the 14th rank.

Relative Importance of Third-Level Attributes

The mean score and relative importance of all the third-level attributes were computed using Equations (3) and (4) and are presented in Table 5. "Proper implementation of SMS" (PO.1.3) has received the highest rank with a mean score of 1.43 followed by "understanding of SMS" (PO.1.2), and "identification of hazardous and dangerous activities" (PR.2.1) both having same mean score of 1.388. "Degree, level and type of punishments in terms of suspension from work" (IN.3.3) has received the lowest rank among all third-level attributes with a mean score of 0.277.

The relative importance is computed using Equation (4). For example, the relative importance of the attribute PO.1.1 is 1.222/[(1.222+1.388+1.430+1.333)] = 0.227). The overall weight of a third-level attribute was computed by multiplying its relative importance to the global weight of the second-level attribute that contains the third-level attribute [as shown in Equation (2)]. It is observed from Table 5 that the relative importance of the attribute PO.1.1, which is part of PO.1 group, is 0.227 and the global weight of PO.1 is 0.288. Thus, the overall

Second-level attributes (global weights)	Third-level attributes	Mean score	Relative importance
PO.1 (W= 0.288)	Understanding of Factories Act	1.222	0.227
	Understand of safety management system (SMS)	1.388	0.257
	Proper implementation of SMS	1.430	0.266
	Understanding of in-house rules and regulations	1.333	0.248
PO.2 (W= 0.154)	Understanding of OHSMS	1.222	0.367
	Company's participation in OHSMS	1.125	0.337
	Understanding of insurance policies	0.986	0.296
PO.3 (W= 0.072)	Proper implementation of in-house rules and regulations	1.222	0.335
	Understanding of permit- to-work system	1.333	0.365
	Proper implementation of permit-to-work system	1.097	0.300
PR.1 (W= 0.112)	Selection of subcontractors	1.291	0.348
	Co-ordination, control and management of subcontractors	1.250	0.337
	Technically competency subcontractors	1.166	0.314
PR.2 (W= 0.059)	Identification of hazardous and dangerous activities	1.388	0.344
	Understanding of safety procedures	1.305	0.323
	Proper implementation of safety procedures	1.347	0.333
PR.3 (W= 0.052)	Identification of unsafe practices on site	1.208	0.190
	Proper implementation of safe practices on site	1.361	0.214
	Good house-keeping	1.291	0.203
	Proper handling of tools, equipment and plants	1.305	0.205
	Tight control of hazardous activities at site	1.180	0.186
PR.4 (W= 0.02)	Total number of subcontractors	1.000	0.216
	Familiarity with type and method of construction by safety officers/supervisors	1.125	0.243
	Communication and information flow	1.236	0.267
	Maintenance regime of tools, equipment and plants	1.263	0.273
PR.5 (W=0.019)	Type and method of construction	1.138	1.000
PE.1 (W= 0.076)	Safety committee's roles and responsibilities	1.361	0.289
	Understanding of safety committee's aims and objectives by employees	1.069	0.227
	Management role and responsibilities towards safety and health promotion	1.180	0.250
	Management's safety culture	1.097	0.233
PE.2 (W= 0.041)	Safety and health training	1.236	0.231
	Attitude of workers and supervisors towards safe work practices	0.930	0.174
	Adoption of safe work behavior by workers and supervisors	1.013	0.190
	Work experience of workers and supervisors	1.111	0.210
	Influence of managers and supervisors over worker	1.069	0.200
PE.3 (W= 0.016)	Workers' cultural backgrounds	0.986	0.349
	Workers' adaptation to working environment	0.819	0.291
	Workers' language and communication barriers	1.013	0.360
IN.1 (W= 0.05)	Introduction of incentives	1.055	0.517
	Level and type of incentives in terms of bonus (Monetary)	0.986	0.483
IN.2 (W= 0.03)	Level and type of incentives in terms of certificate of recognition	0.972	0.511
	Level and type of incentives in terms of employee of the month award	0.930	0.489
IN.3 (W= 0.012)	Introduction of penalties and punishments	0.944	0.535
	Degree, level and type of punishments in terms of fines (Monetary)	0.541	0.307
	Degree, level and type of punishments in terms of suspension from work	0.277	0.158

Table 5 Summary of Relative Importance of Third-Level Attributes

weight of the attribute PO.1.1 is 0.227 x 0.288 = 0.065. The overall weights for all the lower-level attributes were computed in a similar manner and are shown in Appendix 1.

Development of a Safety Performance Evaluation Sheet

Safety performance and its improvement at construction sites have received a great deal of attention since the implementation of the Occupational Safety and Health Act. In India, several statutes under occupational safety and health legislation are being followed, including The Factory Act 1987; Building and Other Construction Workers (Regulation of Employment and Conditions of Service) Central Rules, 1998; Building & Other Construction Workers (Regulation of Employment and Conditions of Service) Act, 1996; Explosives Rules, 1983; and National Building Code of India.

An effective assessment of safety performance is of utmost importance for proper safety management on construction sites. The CSI calculated using Equation (1) represents the score that can be assigned to each third-level attribute according to the actual safety performance at a particular site. Teo and Ling (2006) have suggested the following four ways in which each of the third-level attribute can be rated:

- 0/1: 0 or 1(no or yes);
- 0-1: fraction between 0 and 1;
- 0/1/NA: 0 or 1 or not applicable;
- 0-1/NA: fraction between 0 and 1 or not applicable.

In the present study, the 0/1 rating method is used for the simplicity it offers to an auditor. For example, the safety index corresponding to a third-level attribute would be either 0 corresponding to a 0 rating or it would be equal to the overall weight of the attribute as explained earlier corresponding to 1 rating. For an illustration, suppose there is a 0 rating corresponding to the attribute "implementation of Factories Act" (PO.1.1)at a construction site; the corresponding score against this attribute would be 0. On the other hand, if the site implements the Factories Act (PO.1.1), the corresponding score would be 0.065 as shown in the Appendix 1 for a given site.

A similar procedure is used to convert 0/1 rating against all third-level attributes into a safety score. This is achieved in a systematic manner by adopting an SPE sheet. Adding up all the scores against the third-level attributes provides the CSI for a construction site.

Validation of CSI

To assess the validity of the CSI and to explore the possible correlation with various site safety indicators, accident statistics of 30 construction sites were collected as part of second stage questionnaire. The statistical test for the significance of a correlation coefficient is conducted using a t-statistic. The following hypotheses were framed:

Null hypothesis H_0 = There is no association between CSI and a safety indicator (r = 0).

Alternate Hypothesis H_1 = There is statistically significant association between CSI and a safety indicator (r ≠ 0).

Test statistic is derived as follows:

$$t_{n-2} = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{8}$$

Where, r = correlation coefficient between the variables
n - 2 = Degree of freedom

Using the devised SPE sheet, CSI scores of 30 construction sites were computed. For Site No. 19 in Table 6, the safety manager rated the framed questions for third-level attributes having code no. PR.3.5, PR.4.1, PR.5.1, PE.2.4, IN.1.1, IN.1.2, IN.2.1, IN.2.2, IN.3.1, IN.3.2 and IN.3.3 as 0 and the rest of the attributes were rated as "1" (Appendix 1). Thus, the CSI for this site is 0.8656. Similar calculations were made for all the remaining sites and are presented in column 2 of Table 6. With the help of accident data collected from the second stage questionnaire survey for 30 construction sites, the various safety performance indicators such as lost-time injury frequency rate (LTIFR), lost-time injury severity rate (LTISR), and lost-time injury incident rate (LTIIR) were computed using the following expressions (Source: IS : 3788 – 1983).

The sample calculations of these indicators are explained

$$LTIFR = \frac{Number\ of\ lost\ time\ injuries}{Man\ hours\ worked} \times 1{,}000{,}000 \tag{9}$$

$$LTISR = \frac{Man\ days\ lost\ due\ to\ lost\ time\ injuries}{Man\ hours\ worked} \times 1{,}000{,}000 \tag{10}$$

$$LTIIR = \frac{Number\ of\ lost\ time\ injuries}{Number\ of\ persons\ employed} \times 1{,}000 \tag{11}$$

for Site No. 19 in Table 6. At the time of data collection, the project had inducted a total of 2,431 worker who had worked 3,289,789 manhours collectively. The record showed a total of seven lost-time injuries, six near-miss incidents and seven dangerous occurrences. The project team had organized 2,417 toolbox meetings, 94 safety task assessments and 73 training/awareness programs at the construction site. Until the time of data collection, four safety audits had been conducted. The project had achieved 3,289,349 safe manhours without lost-time injuries. Based on the data collected, the site's LTIFR, LTISR and LTIIR using the above expressions are computed to be 2.127, 13.374 and 2.879, respectively. Similar computations were performed for all the remaining sites and the results are shown in Table 6.

Correlation analysis was used to examine the association between CSI and safety indicators. The analysis finds out the degree to which two variables fluctuate with reference to each other. Correlation analysis results show negative correlation between CSI and LTIFR, LTISR and LTIIR. The correlation coefficients between CSI and LTIFR, CSI and LTISR, and CSI and LTIIR are -0.878, -0.171 and -0.745, respectively. The negative sign indicates movement of the variables in opposite directions (i.e., when CSI increases, LTIFR, LTISR and LTIIR decrease).

Now for a 0.05 level of significance, if calculated *t* by using Equation (8) is greater than *t*-critical probability distribution value with n - 2 degree of freedom, the null hypotheses of no association between CSI and a safety indicator is rejected. The *t* calculated value between CSI and LTIFR as well as between CSI and LTIIR is more than the *t*-critical value (Table 7), therefore for these the null hypotheses will be rejected. While the *t*-calculated value between CSI and LTISR is less than the *t*-critical value (Table 7), its null hypotheses will be valid. If the value of correlation coefficient is greater than 0.5, there is strong correlation between the variables (Apte, 2009). As the value is closer to -1, there is a high degree of correlation between CSI and LTIFR. It is clear that there is also a high degree of negative association between CSI and LTIIR with a correlation coefficient of -0.745. There is no statistically significant association, however, between CSI and LTISR as the significance *F* value (Table 7) is greater than the 0.05 (level of significance).

The correlation analysis results presented indicate the association of CSI with safety indicators and, thus, it can be concluded that the attributes used in the development of the CSI are adequate. A construction site having a low CSI is more prone to fatalities and steps can be taken to improve safety on that site before fatalities occur. Thus, by having better CSI, the chances of injuries can be reduced. CSI is a leading or proactive safety indicator, as it is being calculated by considering the effectiveness of an SMS at a construction site, while LTIFR and LTIIR are lagging safety indicators. Thus, by having a higher CSI score (i.e., higher proactive safety indicator), the proneness to large lagging indicators can be decreased and with the help of CSI, the substandard areas of the SMS can be identified and appropriate remedial actions can be planned to decrease the chance of incidents at construction sites.

From Table 6 it is clear that the top 10 construction sites have a CSI score of more than 0.95 and can be used for benchmarking purposes. The other sites should endeavor to first reach a 0.95 CSI score for improving their site performance, then efforts should be made to sustain this achieved performance.

Regression analysis was also performed to provide a measure of the relationship and also to facilitate predicting a particular safety indicator for a given value of CSI. The regression analysis results are shown in Table 7.

The results presented in Table 7 can be used to predict LTIFR and LTISR values based on the CSI scores. For example, the equations for predicting the LTIFR and LTIIR based on CSI are:

$$LTIFR = -8.673 \times CSI + 9.688 \quad (12)$$

$$LTIIR = -10.51 \times CSI + 11.827 \quad (13)$$

As in the present study, three-level hierarchy is used. For improving predictability from the provided equations, third-level attributes can be further divided rationally into fourth- level attributes in order to have a four-level hierarchy. However, as far as the correlation is consid-

Table 6 Summary of CSI & Safety Indicators for 30 Sites

S. No.	CSI	LTIFR	LTISR	LTIIR
1	0.9981	1.162	6.686	1.841
2	0.9867	0.000	0.000	0.000
3	0.9813	1.135	7.062	1.854
4	0.9801	1.272	44.510	0.750
5	0.9723	1.308	10.683	2.194
6	0.9720	1.344	18.146	1.912
7	0.9709	1.392	8.353	1.030
8	0.9697	1.403	9.222	2.345
9	0.9573	1.507	10.625	2.219
10	0.9503	1.508	13.070	2.072
11	0.9497	1.511	10.120	3.310
12	0.9407	1.596	18.624	2.051
13	0.9314	1.623	37.823	1.412
14	0.9239	1.598	10.963	2.36
15	0.8968	1.768	8.840	1.425
16	0.8930	1.762	11.578	2.854
17	0.8884	1.9	10.150	1.618
18	0.8726	1.933	12.478	2.349
19	0.8656	2.127	13.374	2.879
20	0.8625	2.242	15.376	2.974
21	0.8616	2.43	15.974	3.161
22	0.8548	2.653	15.587	1.880
23	0.8468	2.503	19.028	2.639
24	0.8390	2.381	19.728	4.024
25	0.8316	3.793	21.92	2.590
26	0.8231	2.503	28.257	3.514
27	0.7911	2.666	20.262	1.981
28	0.7699	2.540	13.549	4.237
29	0.7499	2.886	15.671	4.144
30	0.7196	3.299	14.571	4.977

Table 7 Summary of Regression Analysis

Regression statistics	Between CSI and LTIFR	Between CSI and LTISR	Between CSI and LTIIR
Multiple R	0.878	0.171	0.745
R Square	0.771	0.029	0.555
Adjusted R Square	0.762	-0.005	0.539
Standard Error	0.368	8.934	0.732
Observations	30	30	30
y-axis intercept	9.688	33.254	11.827
x variable coefficient	-8.673	-19.94	-10.51
Significance F	1.87E-10	0.366	2.34E-06
t (Calculated) [By using Equation (8)]	9.701	0.9182	5.909
t (Critical) [from t distribution table with 28 degree of freedom and 5% level of significance]	2.048	2.048	2.048

ered, statistically significant association exists except between CSI and LTISR.

Based on the CSI score calculated (Appendix 1) for Site No. 19 in Table 6, it is clear that the site does not have any provision for monetary incentives, non-monetary incentives and disciplinary action as all the third-level attributes under these second-level attributes are rated as 0. Therefore, by introducing the provision of incentives for this site, the CSI score can be enhanced and the chances of an incident can be further reduced.

Summary & Conclusions

An existing framework for the safety performance evaluation has been utilized and necessary modifications have been made to make it pertinent for construction safety professionals. The weights of different attributes at different levels of hierarchy have been evaluated based on the responses to a questionnaire survey conducted among Indian construction professionals. The analysis tools primarily included analytic hierarchy process, mean score and mean ranking. In terms of weight, the most important first-level factors are found to be policy and process while the most important second-level attributes are found to be understanding and implementation of SMS and understanding and participation in OHSMS.

The weights so obtained and the lower-level attributes have been utilized to develop an SPE sheet. The auditor or assessor has to simply rate the lower-level attributes on a 0/1 scale and then a site's CSI can be calculated.

The CSIs can provide an objective tool to measure the effectiveness of SMS that management can use for appraisal purposes and, hence, it can help safety managers to make decisions to improve safety performance. The evaluation of CSI for an industry with the help of an SPE sheet can be done by safety personnel under the guidance of the project manager in order to assess the safety performance at any stage of the construction process—from design, to preconstruction and finishing. This evaluation may be performed quarterly, half-yearly or yearly depending on the structure and size of an organization.

The strong association with safety indicators such as LTIFR and LTIIR suggests that the safety performance of a construction site can efficiently be reflected in terms of CSI scores. Besides, the knowledge of association can be utilized to forecast the LTIFR and LTIIR for a given CSI. Depending on management commitment, the LTIFR and LTIIR can be improved by concentrating on factors for which the current rating is 0. The framework uses a systematic method and is simple to apply.

The safety performance assessment method suggested here can be easily applied on Indian construction projects. The proposed framework with some local adjustment can be made applicable to any country. The framework utilizes 0/1 rating systems and, thus, it is not able to rate effectively the partially implemented system in place at a construction site. However, the 0/1 rating was chosen primarily for ease in implementation and other ratings system can be employed and its implications can be studied. Also, the number of lower-level attributes to be included for rating can also be debated and can be taken up for future study. ○

References

Abudayyeh, O., Fredericks, T.K., Butt, S.E. & Shaar, A. (2006). An investigation of management's commitment to construction safety. *International Journal of Project Management, 24,* 167-174.

Aksorn, T. & Hadikusumo, B.H.W. (2008). Critical success factors influencing safety program performance in Thai construction projects. *Safety Science, 46,* 709-727.

Apte, D.P. (2009). *Statistical tools for managers: Using MS Excel.* New Delhi, ND: Excel Books.

Chan, A.H.S., Kwan, W.Y. & Duffy, V.G. (2004). Using AHP for determining priority in a safety management system. *Industrial Management & Data Systems, 104*(5), 430-445.

Chang, J.I. & Liang, C.-L. (2009). Performance evaluation of process safety management systems of paint manufacturing facilities. *Journal of Loss Prevention in the Process Industries, 22,* 398-402.

Chen, C.F. (2006). Applying the analytical hierarchy process (AHP) approach to convention site selection. *Journal of Travel Res., 45*(11), 167-174.

Farooqui, R.U., Arif, F. & Rafeeqi, S.F.A. (2008, August). Safety performance in construction industry of Pakistan. First International Conference on Construction in Developing Countries, Karachi, Pakistan.

Hinze, J. (2002). Safety Incentives: Do they reduce injuries? *Practice Periodical on Structural Design and Construction, 7*(2), 81-84.

Hinze, J., Thurman, S. & Wehle, A. (2013). Leading indicators of construction safety performance. *Safety Science, 51*(1), 23-28.

Jha, K.N. (2011). *Construction project management: Theory and practice.* India, IN: Pearson.

Law, W.K., Chan, A.H.S. & Pun, K.F. (2006). Prioritising the safety management elements: A hierarchical analysis for manufacturing Enterprises. *Industrial Management & Data Systems, 106*(6), 778-792.

Ng, S.T., Cheng, K.P. & Skitmore, R.M. (2005). A framework for evaluating the safety performance of construction contractors. *Building and Environment, 40,* 1347-1355.

Rowlinson, S. (2003). *Hong Kong construction: Safety management and law* (2nd ed.). Hong Kong: Sweet and Maxwell Asia.

Saaty, T.L. (1980). *The analytic hierarchy process.* New York, NY: McGraw-Hill.

Saaty T.L. & Kearns, K.P. (1985). *Analytical planning: The organization of systems.* Oxford, U.K.: Oxford Pergamon Press.

Sambasivan, M. & Fei, N.Y. (2008). Evaluation of critical success factors of implementation of ISO 14001 using analytic hierarchy process (AHP): A case study from Malaysia. *Journal of Cleaner Production, 16,* 1424-1433.

Teo, E.A.L. & Ling, F.Y.Y. (2006). Developing a model to measure the effectiveness of safety management systems of construction sites. *Building and Environment, 41,* 1584-1592.

Teo, E.A.L., Ling, F.Y.Y. & Chong, A.F.W. (2005). Framework for project managers to manage construction safety. *International Journal of Project Management, 23,* 329-341.

Additional Resources

Details about Indian construction industry

For *t*-critical probability distribution value

For details about construction industry in India compared to other countries

Click here to view Appendix: Safety Performance Evaluation Sheet for Construction Site (Site No.19 in Table 6)