Critical Success Factors for Construction Safety: Review and Meta-Analysis of Safety Leading Indicators

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Abstract: Safety leading indicators are measures of the safety management system that correlate with injury rates. The literature on the topic is dispersed and equivocal in the definition, categorization, and measurement of candidate indicators, which makes validation and replication difficult. This study includes a comprehensive review of safety leading indicator research, offers a distinction between leading indicators and other methods of safety prediction, and defines a clear method for distinguishing between active and passive indicators. By applying these definitions and leveraging empirical data, a statistical meta-analysis was performed to compute the relative effect sizes and significance for all salient indicators. Although active leading indicator research is rare and relatively recent, the meta-analysis indicates that inspections and pretask safety meetings correlate strongly with near-term project safety performance. Passive leading indicator research is relatively common and has been conducted for several decades. The results of the meta-analysis indicate that implementing safety recordkeeping, safety resource, staffing for safety, owner involvement, safety training/orientation, personal protective equipment, safety incentives program, and safety inspections and observation each improves long-term safety performance. The findings validate suspected leading indicators and serve as a first step toward standardization. Practitioners may use the findings to justify and target resource expenditures using pervasive scientific evidence. **DOI: 10.1061/(ASCE)CO.1943-7862.0001626.** *© 2019 American Society of Civil Engineers.*

Author keywords: Construction safety; Active safety leading indicator; Passive safety leading indicator; Safety performance measure; Safety climate; Safety risk analysis; Meta-analysis.

Introduction

In recent years, there has been growing awareness that lagging safety indicators (e.g., recordable injury rates) have limited use in the prevention of future injuries (Hinze et al. 2013b). Although important for tracking performance and benchmarking, there is no direct evidence that prior safety performance predicts future performance (Hinze et al. 2013b). Furthermore, there is no evidence that lagging indicators reflect the strength of an organization's safety system (Hopkins 2009). Alternatively, recent research has shown that some safety leading indicators are predictive (Salas and Hallowell 2016), provide early warnings of potential hazards (Guo and Yiu 2015), and can be used as levers to improve future performance (Lingard et al. 2017). Not surprisingly, there is a growing body of literature that supports a professional transition from lagging to leading indicators.

Construction safety leading indicators is a relatively new research domain. The National Institute of Occupational Safety and Health (2016) has promoted it as an industry best practice. Early studies have documented industry programs and tested the efficacy of candidate indicators by measuring and analyzing their relationships to safety outcomes (e.g., Rajendran 2012; Hinze et al. 2013b; Hallowell et al. 2013). Invariably, these studies have aimed to identify the best predictors or controls of future performance. However, the literature is dispersed, and there is no consensus on the relative efficacy of individual indicators. In fact, even the definition and use of the term *safety leading indicator* is equivocal. This study aims to formalize this research domain by performing a comprehensive literature review and statistical meta-analysis of all empirical studies. Such analysis will reveal patterns and divergence of findings across studies and enable future researcher to build upon a solid and congruent foundation of knowledge. Additionally, a set of operational definitions are offered, which can enable consistency and enhanced internal validity of future inquiries.

At present, safety leading indicator programs are established in an ad hoc fashion based on intuition and judgment (Hinze et al. 2013b). Formalization and aggregation of the research findings will enable practitioners to strategically select indicators, especially when initiating a program and when resources are constrained. Additionally, a single resource that statistically aggregates previous scientific study will make the body of research feasible for consumers.

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Note. This manuscript was submitted on March 26, 2018; approved on September 6, 2018; published online on January 11, 2019. Discussion period open until June 11, 2019; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

Background: Indicating Future Safety Performance

There are a variety of methods that can be used to indicate aspects of future safety performance. These include safety climate (Patel and Jha 2016; Panuwatwanich et al. 2016; Lingard et al. 2012), safety risk analysis (Hallowell and Gambatese 2009), and safety leading indicators (Rajendran 2012; Salas and Hallowell 2016). Safety leading indicators are expressly described as predictive measures of the safety system (Hinze et al. 2013b). These three safety measurement constructs are often implied to indicate future performance. However, these three safety measurement constructs are described, compared, and contrasted to show the position of safety leading indicators in a broader context. Furthermore, this review reveals the wide array of safety leading indicators and significant overlap with other measures of safety system strength. Thus, some previous work that was not published with explicit reference to safety leading indicators (e.g., Jaselskis et al. 1996; Hinze and Gambatese 2003) may be highly relevant in a statistical meta-analysis.

Safety Climate

One of the most prolific research areas in safety is safety climate. In the context of prediction, the measure of safety climate might be considered as an indirect measure of the strength of the safety system that indicates future performance (Clarke 2006). Several authors also claim that safety climate can be an indicator of safety culture (Choudhry et al. 2007; Flin et al. 2000), which is thought by many to be the nebulous underlying driver of high-performance safety. According to Neal and Griffin (2006), safety climate encompasses "individual perceptions of policies, procedures, and practices relating to safety in the workplace." In other words, safety climate reflects individuals' opinions of their organization's safety management efforts (Schwatka et al. 2016). Surveys are often used to measure safety climate and include a variety of climate dimensions, such as management commitment to safety, safety rules and procedure, safety training, worker involvement, and risk-taking behavior (Alruqi et al. 2018). Together, survey scores of each dimension comprise the overall safety climate score of an organization, and these composite scores often indicate performance.

The association between safety climate and safety performance was observed in past studies (Goldenhar et al. 2003; Lingard et al. 2012; Panuwatwanich et al. 2016). Researchers found that a positive safety climate is associated with fewer accidents and injuries. For example, McCabe et al. (2016) conducted a longitudinal safety climate study and concluded that safety climate accounted of 20% of the variance in injury rate. Furthermore, Lingard et al. (2012) found that supervisors' perceptions mediated the relationship between organizational safety climate and injury rate. In general, much of the literature supports the role of safety climate in improving the safety performance in the construction industry (Chen et al. 2013; Goldenhar et al. 2003; Lingard et al. 2012; Panuwatwanich et al. 2016).

Safety Risk Analysis

Risk analysis is a method used in many fields, where past data are used to indicate future liabilities. Specifically, data are used to make probabilistic estimates for a specific time or exposure that are based on past trends. The same general methodology is applied to construction safety risk analysis, where past injury records are used to indicate the likelihood and severity of injury for a specific work period (Hallowell and Gambatese 2009), work package (Tixier et al. 2017), or project (Zhang et al. 2014). At present, most safety risk analyses are focused on the dangers that are defined primarily on the basis of the attributes of the work (e.g., means and methods of construction, environmental conditions, and task) (Tixier et al. 2017). Regardless of methodology, all safety risk analysis studies operate under the assumption that previous trends will remain relatively stable in the short term such that the magnitude of previous risks reflect the magnitude of near-term risks. For example, if lubricating materials is noted as a key risk for formwork construction in the past two years, this task may be anticipated as a key risk for the next year (Hallowell and Gambatese 2009).

Safety Leading Indicators

Unlike safety climate and risk analysis, leading indicators directly and empirically measure the strength of the safety management system and how it improves future performance (Hallowell et al. 2013). Typically, the proposition made by a researcher is that the leading indicator measure taken now predict general safety performance (e.g., recordable injury rates for a project). Hinze et al. (2013b) described leading indicators as a group of selected measures that can provide insight safety process effectiveness. In addition, leading indicators are described as supporting proactive responses because actions can be taken to control the system before an injury propagates (Hallowell et al. 2013).

One may distinguish safety climate and safety leading indicators with one major criterion. Although both measure the strength of the safety system, climate is based on perceptions of generalities (e.g., management commitment to safety), and leading indicators are empirical measures of specific safety activities (e.g., frequency of prejob safety meetings). Despite the similarities between climate and leading indicators, the literature on the two constructs has been almost completely isolated. In fact, there is no research that explores covariance, interaction, or composite predictions of these two areas. However, Lingard et al. (2011) implicitly treated safety climate scores as a leading indicator when diagnosing health and safety performance. The study found that aggregating these safety measures captures the dynamics of safety performance on the site.

On the other hand, risk analysis is typically purported to be *anything* that is formally analyzed to predict the likelihood and magnitude of future injuries (Hallowell and Gambatese 2009; Baradan and Usmen 2006). That is, if measures of safety climate or safety leading indicators are analyzed for the purposes of indirectly indicating the likelihood and severity of future injuries, the method could be considered as a risk analysis. However, since climate and leading indicators are typically used to reflect the strength of the safety system rather than the danger associated with specific work attributes, these metrics are rarely explained as risk factors. Nevertheless, there are blurry delineations among safety risk analysis, safety climate, and leading indicators, and the true differences are merely theoretical and ideological.

Although safety leading indicators and risk factors could theoretically be used interchangeably depending on the epistemological positioning, patterns in the current literature offer little confusion. All safety risk analysis studies involve quantification for specific work or project characteristics. For example, Fung et al. (2010) quantified safety risk for construction trades (e.g., welding), Hallowell and Gambatese (2009) quantified safety risk for construction tasks and environments (e.g., ascending and descending a ladder), and Tixier et al. (2017) defined safety risk on the basis of fundamental attributes (e.g., uneven work surface). Other researchers such Mitropoulos and Namboodiri (2010), and Rosa et al. (2015) quantified risk on the basis of project activities (e.g., roofing activity).

The sum of the dangers associated with a work package is referred to by Hallowell and Gambatese (2010) as *demand*. Alternatively, all safety leading indicator studies discuss the quantity or quality of safety management activities implemented to prevent injuries. Hallowell and Gambatese (2010) refer to the sum total of preventative efforts as *capacity*. According to this theory, one could differentiate safety leading indicators as measuring capacity only and not concerning the physical characteristics that make work dangerous.

However, leading indicators can be measured at different periods. For example, an organization could measure daily

Table 1. Examples, descriptions, and sources of construction safety leading indicators

Leading indicator	Description	Example item	Selected references
Upper-management involvement	The degree of upper-management commitment to safety aspects of worker safety and health	Safety support includes safety funding, training, and engagement in safety meeting	Hallowell and Gambatese (2009), Choudhry et al. (2008), and Salas and Hallowell (2016)
Training/orientation	The degree of providing training and orientation of jobsite hazards for skilled and unskilled workers	Jobsite orientation sessions; in-house safety training	Hallowell and Gambatese (2009) and Hinze and Wilson (2000)
Pretask safety meeting	The frequency of pretask safety planning conducted by both supervisors and workers as daily tasks to ensure that day-to-day activities are performed safely	Safety pretask plan; formal safety meetings with project supervisor	Hallowell et al. (2013), Rajendran (2012), and Jaselskis et al. (1996)
Safety inspections/observation	The frequency of safety inspection/observation to identify hazards or safety violation to ensure worker safety and health	Safety officer makes specific jobsite safety walk-through; safety auditing	Hallowell and Gambatese (2009), Hinze and Raboud (1988), and Salas and Hallowell (2016)
Hazard and accident analysis	The frequency of safety hazard and accidents analysis reported and reviewed for construction process	Near-miss reporting; project risk assessment; accident investigation	Cheng et al. (2015), Hinze et al. (2013a), and Salas and Hallowell (2016)
Owner involvement	The degree of owner involvement in safety aspects	Owner safety walk-throughs; review safety plans; attend safety meeting	Salas and Hallowell (2016), Hinze et al. (2013), and Hinze and Raboud (1988)
Safety record	The degree of reporting and maintaining accident records and safety performance records	Accident reporting; first-aid log is maintained	Hinze et al. (2013a) and Cheng et al. (2015)
Worker involvement	The degree of worker involvement in safety aspects, such as safety decisions and feedback to top management	Workers involved in safety policy, perception surveys, and safety feedback	Hinze et al. (2013a)
Safety resource	The effort of the safety committee (e.g., supervisory, owner safety representative, and project leaders) in providing required safety resources	Providing medical facilities in worksite	Hinze et al. (2013a)
Staffing for safety	The number of certified safety representatives in the worksite	The percentage of workers to safety professionals	Jaselskis et al. (1996) and Hinze et al. (2013a)
Written safety plan	A complete and comprehensive safety plan that guides project safety	Written safety plan includes safety goals; objectives, and procedures	Hallowell and Gambatese (2009)
Personal protective equipment (PPE)	The provision of the required PPE for all workers	PPE program; providing worker with safety clothes and shoes	Aksorn and Hadikusumo (2008), Choudhry et al. (2008), and Sawacha et al. (1999)
Substance abuse	The frequency of random drug and alcohol tests to prevent substance abuse among workers	Drug and alcohol testing	Lingard et al. (2017) and Hinze and Gambatese (2003)
Incentives	The safety promotions and praise for workers with positive and safe work behavior	Safety incentive programs; assessment of craft worker penalties	Hallowell et al. (2013), Hinze and Gambatese (2003), and Jaselskis et al. (1996)

management activities, weekly safety meeting frequency, or monthly safety audit scores (Hallowell et al. 2013). These proactive metrics should be valid and reliable measures that cover all relevant safety aspects, have positive effects in reducing injury, quantitatively measure and monitor data, and have less impact on both time and cost of a construction project (Biggs et al. 2010; Guo and Yiu 2015; Hale 2009; Hallowell et al. 2013; Leveson 2015).

Recent studies have addressed various aspects of leading indicators in the construction industry; for example, identifying proactive safety metrics (Guo and Yiu 2015; Hallowell et al. 2013), measuring and controlling these indicators (Hallowell et al. 2013), investigating their relationship to worksite injury (Rajendran 2012; Salas and Hallowell 2016), and measuring how they relate and cycle over time (Lingard et al. 2017).

As shown in Table 1, there are a plethora of possible indicators identified in early research on the topic. For example, through expert panel and case studies, Hallowell et al. (2013) identified 13 proactive safety indicators that improve safety performance. These indicators include near-miss reporting, safety observation, auditing program, pretask safety meeting, housekeeping program, and worker involvement. Later, in a study of 261 contractors, Salas and Hallowell (2016) found evidence that empirically supported the following as predictive: near-miss reporting, stop-work authority, upper-management engagement in safety activities, worker involvement, owner involvement, safety auditing and observation, and safety risk assessment. To provide practical recommendations for the formation of a leading indicator program, Guo and Yiu (2015) presented a model for developing leading indicators based on four major steps: define the system and analysis level (conceptualization), include only measurable constructs (operationalization), develop leading indicators (indicator generation), and validate selected leading indicators (validation and revision). This process was then applied to a hypothetical construction project, and 32 leading indicators were generated. These included the number of sites visited by an owner or safety representative, written safety plan, supervisory support, stop-work authority, and frequency of pretask safety meeting. Clearly, both the process to create leading indicators and the leading indicators themselves vary widely. Thus, aggregation and standardization of this body of literature is needed.

Most importantly, the definition and categorization of safety leading indicators is equivocal and nebulous. This has led to serious confusion in the literature in what is a leading indicator and what is not, active versus passive indicators, and the role of near-misses. The following section provides clarity in the epistemological positioning of safety leading indicators to standardize the definitions using logical and empirical evidence.

Distinguishing between Passive and Active Safety Leading Indicators

Leading indicators are classified as active and passive indicators, and both have been used to predict safety performance (Hinze et al. 2013b). The following section highlights the differences between active and passive leading indicators and reviews 27 studies published between 1986 and 2016.

Differences between Active and Passive Leading Indicators

Passive leading indicators are typically implemented before work begins and remain relatively static once a project has begun (Hinze et al. 2013b). Measures of these indicators are also generally dichotomous in that the organization implements them or does not. Examples of passive leading indicators include a steel-toed boots policy, a design for safety review in the design phase, and contract provisions that require subcontractor compliance with a site-specific safety policy or program (Hinze et al. 2013a, b). These activities are not likely to change once a project begins and can be noted as implemented or not implemented before construction. The common data entry for these indicators is a binary yes/no response.

In contrast, active leading indicators can be readily changed during the construction phase (Hallowell et al. 2013; Hinze et al. 2013b). These indicators are generally continuous in that they occur at a frequency or are measures of quality of implementation. Examples of active leading indicators include the frequency of jobsite safety meetings, quality of prejob safety meetings, rate of involvement of upper management in safety walk-throughs, and safety audit scores (Hallowell et al. 2013). Each of these indicators can be modified during construction if goals are not met (Hallowell et al. 2013). For example, the organization can increase the frequency or quality of safety meetings, increase the involvement of upper management, and seek to improve safety audit scores.

The use of these terms is inconsistent in the literature. Often, authors describe active indicators as passive, and vice versa. Typically, inconsistencies exist in the ways that the indicators are discussed. For example, authors may consider safety meetings as an active indicator. However, the distinction between active and passive for safety meetings depends on how the indicator is measured (Hallowell et al. 2013; Hinze et al. 2013b). For example, if the researchers asked whether the organization implemented prejob safety meetings, the indicator would be passive (i.e., the data were collected as dichotomous). Alternatively, if the frequency or quality of safety meetings was monitored and controlled over time, this indicator would be active (Hallowell et al. 2013). That is, many indicators could be both active and passive, and the true distinction between active and passive depends on the way that the data are collected (i.e., the data form).

Fig. 1 provides a flowchart to assist researchers with correctly distinguishing indicators. This figure was developed on the basis of the review of the theory of safety leading indicators research and was applied in the present study to make consistent, operationalized definitions and distinctions in the meta-analysis. This was critical for consistency in an area of literature where the distinction is often erroneous or unclear.

Examples of Passive Leading Indicators

Per the definition in Fig. 1, 22 of the 27 extant studies investigated passive indicators. Interestingly, there is a significant body of knowledge that examined how safety strategies affect safety performance. Although not explicitly labeled as leading indicator research, these studies include data and perspectives that are completely aligned with the definitions in this paper (Hinze and Gambatese 2003; Hinze et al. 2013a; Jaselskis et al. 1996). Thus, they are included in this review.

Among the indicators studied, the most common are safety training and orientation, incentives, and safety inspections. Examples of how some passive safety leading indicators are assessed and the extent that they predict performance were reviewed. The most prominent passive safety leading indicator is safety training, appearing in the majority of studies on the topic (Jaselskis et al. 1996; Hinze and Gambatese 2003; Aksorn and Hadikusumo 2008; Lai et al. 2011; Cheng et al. 2012; Hinze et al. 2013a; Goh and Chua 2013; Alarcón et al. 2016). The proposition is that having

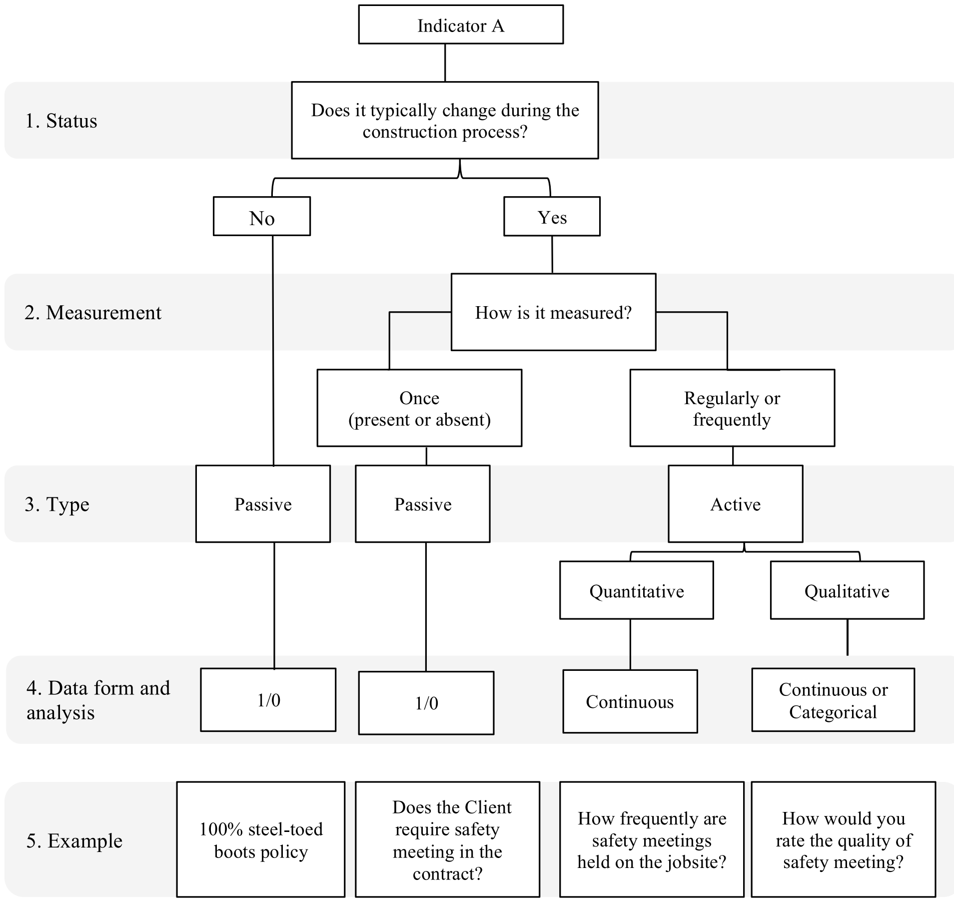

Fig. 1. Procedure to distinguish between active and passive safety leading indicators.

a safety training program on a project reduces the frequency of injuries (Hallowell and Gambatese 2009). Research unequivocally connected enhancements in training with improvements in performance. Safety training was typically assessed by questions such as, "Is health and safety training provided to the employees of subcontractors?" (Choudhry and Zahoor 2016).

Similarly, the relationship between safety incentives programs and injury rate was included in nearly 80% of studies (Hinze and Gambatese 2003; Idoro 2008; Alarcón et al. 2016; Choudhry and Zahoor 2016). However, the connection to performance was less conclusive (Jaselskis et al. 1996; Hinze and Gambatese 2003; Idoro 2008; Alarcón et al. 2016). In fact, the existence of safety incentive programs in some specialty contractors had no effect on company safety performance (Hinze and Gambatese 2003), and others found that safety incentive programs *increase* injury rates (Hinze et al. 2013a). An example of a question assessing this indicator is, "Do workers receive an incentive or reward for not being injured?" (Hallowell et al. 2013).

As a final example, safety inspection/observation appeared in 11 studies (50%) (Hinze and Raboud 1988; Jaselskis et al. 1996; Hinze and Gambatese 2003; Idoro 2008; Goh and Chua 2013; Cheng et al. 2015; Alarcón et al. 2016). This indicator includes site safety auditing, formal safety inspection, and worker behavior observation. Studies showed moderately strong evidence of a reduction in injury rates (Hinze and Gambatese 2003; Hinze and Raboud 1988; Jaselskis et al. 1996). This indicator is typically assessed with questions like, "Does the job supervisor or safety officer make specific jobsite safety tours?" (Hinze and Raboud 1988).

Active Leading Indicators

The measurement of active leading indicators is comparatively rare, which is likely because these studies require significant resources and access to a large volume of sensitive company data. An interesting difference between active and passive indicators is the way that they are measured. Rather than yes/no questions measured once to indicate overall project performance, active indicators are measured at a regular frequency (e.g., monthly) to indicate future performance on the same project (e.g., with a 3-month delay).

Of the 27 studies identified, only five measured active leading indicators as they are defined here (Rajendran 2012; Hallowell et al. 2013; Guo et al. 2016; Salas and Hallowell 2016; Lingard et al. 2017). Hazard reporting and accident analysis, safety inspection and observation, and pretask safety meeting were the most common. The strongest predictors of future performance were safety inspection and observation and pretask safety meetings (Rajendran 2012; Salas and Hallowell 2016). For example, Salas and Hallowell (2016) measured the frequency of contractor internal safety audits using data reported in the client's standardized safety management system software. The results predicted recordable injury rates 3 months later for the same project. This is a representative example of the data collection and analysis process.

Meta-Analysis for Empirical Research

Meta-analysis uses a statistical approach to combine quantitative research findings from multiple empirical studies. This approach combines effect sizes from different studies to increase power

Table 2. Characteristics of empirical studies included in the meta-analysis

			Indicator category								
Reference	N	Indicator type	Safety inspection/ observation	Pre-task safety meeting	Training/ orientation	Incentive	Safety resources	Staffing for safety	Safety record	PPE	Owner involvement
Salas and Hallowell (2016)	191	Active	x	x							
Alarcón et al. (2016)	1,180	Passive			x	x					
Hinze et al. (2013a)	28	Passive			x		x	x	x	x	x
Rajendran (2012)[a]	684; 1,417	Active	x	x							
Idoro (2008)	43	Passive	x			x	x			x	
Hinze and Gambatese (2003)	46	Passive	x		x	x					
Jaselskis et al. (1996)	69	Passive	x	x		x		x			
Hinze and Raboud (1988)	14	Passive	x	x				x	x		x

[a]Reported two different sample sizes for each leading indicator.

and capture the true effect (Card 2011; Hunter and Schmidt 2014). Lipsey and Wilson (2001) explained that meta-analysis can be used to summarize empirical research studies that reported quantitative results. Interest in meta-analysis has increased sharply in recent years, and this approach has been used in different scientific fields such as medicine, psychology, and marketing (Hunter and Schmidt 2014).

Research Approach

A meta-analysis method used to assess the predictive validity of both active and passive construction safety leading indicators. The method of meta-analysis used in this research is based on the explanation of Card (2011) and Hunter and Schmidt (2014). This process of conducting a meta-analysis consisted of reviewing literature, coding studies, standardizing effect sizes, and calculating the combined effect size. These steps are discussed with practical examples in the following sections.

Comprehensive Literature Search

The overall goal of the comprehensive literature search was to locate all published studies on the topic and to compute and aggregate effect size for each salient variable (Card 2011). The authors searched for studies using search engines offered by ASCE, Web of Science, Scopus, Engineering Village, and Google Scholar. Additionally, a variety of individual and combined keywords were used, such as *safety management system*, *safety program*, *construction safety practices*, *safety performance*, *safety strategies*, *safety leading indicators*, and *proactive indicators*. The scientific database research located a total of 114 studies. Studies were included in the meta-analysis procedure if they (1) investigated the relationship between either active or passive safety leading indicators (e.g., construction safety practices) and accidents or injury; (2) reported the effect size (e.g., correlation values) or enough information to calculate the effect size; (3) sampled data from the construction industry; and (4) were peer reviewed. If more information on a study was needed, the primary author was contacted via email. Six authors were contacted to provide missing data (e.g., sample size and correlation values between indicators and safety outcome). Three authors responded with the required information, and these studies were included in the meta-analysis.

Coding Study Characteristics and Effect Sizes

Studies that met the inclusion criteria were coded into a database using the following categories: author, publication date, measurement characteristics (i.e., active or passive safety leading indicators), and outcome characteristics (e.g., recordable injury rate). Table 2 shows the coding and characterization of eight studies that were included in the meta-analysis procedure.

The second step of the coding process was extracting the effect size from individual studies (e.g., correlation values) or statistics information (e.g., z-value) to compute the effect size. When a study reported a correlation value between individual leading indicators and injury rate, the correlation value was used directly as the index of effect size (Card 2011). Leading indicators identified from different studies were assigned to specific categories, as shown in Table 1. Distinctions between active and passive leading indicators were based on distinctions presented in Fig. 1. When more than one leading indicator from a study was assigned to a category, the overall correlation value was calculated by using the composite score correlation formula given by Hunter and Schmidt (2014, pp. 430–439), as shown in Eq. (1)

$$r_{xY} = \frac{\sum r_{xyi}}{\sqrt{n + n(n-1)\bar{r}_{yiyj}}} \tag{1}$$

where r_{xyi} = sum of correlations; n = sample size (i.e., number of correlations); and $\bar{r}_{yiyj}$ = average correlation among these indicators. For example, Salas and Hallowell (2016) provided the correlation of the following five leading indicators with injury rates (e.g., grouped into safety inspection and observation category): safety observation ($r = 0.32$); client audits ($r = 0.15$); contractor safety audits ($r = 0.22$); subcontractor safety audits ($r = 0.12$); and corrective action items ($r = 0.26$). The sum of these correlations is 1.09, and the average correlation among these indicators ($\bar{r}_{yiyi}$) is 0.129. Thus, the composite score correlation was then calculated as follows: $1.09/\sqrt{5 + 5(5-1) \times 0.129} = 0.4$.

Table 3 shows a practical example of applying the following equations and procedures for the relationship between pretask safety meeting and injury rates. The correlation values were transformed (Z_r) to avoid the assumption of skewness linked to the distribution of sample r (Card 2011) by using Fisher transformation of r equation, as shown in Eq. (2)

Table 3. Effect size calculation results for the relationship between pre-task safety meeting and injury

Reference	N	r	Z_r	SE_{zr}
Salas and Hallowell (2016)	191	0.38	0.40	0.07
Rajendran (2012)	684	0.51	0.56	0.04

Note: N = sample size; r = correlation value reported in each study; Z_r = Fisher transformation of r; and SE_{zr} = standard error of the Fisher test.

Table 4. Fixed- and random-effect calculation procedure and results for the relationship between pretask safety meeting and injury

Reference	Fixed-effect model				Random-effect model			
	w_i	w_i (%)	$w_i \times Z_r$	$(w_i \times Z_r^2)$	w_i^2	w_r	w_r (%)	$w_i Es_i (w_r \times Z_r)$
Salas and Hallowell (2016)	188	21.63	74.77	29.74	35,344	67.21	42.57	26.73
Rajendran (2012)	681	78.37	380.46	212.56	463,761	90.67	57.4	50.66
Total	869	100	455.23	242.29	499,105	157.8	100	77.38

Note: w_i = study weight (fixed-effect model); and w_r = study weight (random-effect model).

$$Z_r = 1/2 \ln\left(\frac{1+r}{1-r}\right) \tag{2}$$

where Z_r = Fisher transformation of r; and r = correlation coefficient. The standard error of the Fisher test was then calculated by using Eq. (3)

$$SE_{Zr} = \left(\frac{1}{\sqrt{N-3}}\right) \tag{3}$$

where SE_{Zr} = standard error of Z_r, and N = sample size for the individual study.

Hunter and Schmidt (2014) identified 11 artifacts that the meta-analyst can use to correct the collected effect sizes, including correcting errors of measurement in individual studies, range variation, and dichotomization of a continuous variable. To make these corrections, more information was required for each primary study, such as reliability coefficients to correct the measurement error artifacts. When the artifact information was reported in some of the included studies, Hunter and Schmidt (2014) suggested the distributions of artifacts method of using available information from these studies. However, the studies included in this meta-analysis lacked the required statistical information to correct the effect sizes, so no correction was applied.

In the forthcoming analysis, the details of the analytical procedure are described in detail, and two examples are provided from Salas and Hallowell (2016) and Rajendran (2012). These data are provided so that researchers can replicate and validate the method and so that the safety community has a clear guide on the use of meta-analysis.

Standardization

Many studies reported different statistics to represent the effect size. In cases where the statistic varied among studies, the data were standardized to one comparable statistic. For example, when a study reported the result of z statistical significance test, Eq. (4) was used to compute the effect size r

$$r = \sqrt{\frac{Z^2}{N}} \tag{4}$$

where r = effect size; $z = z$-score; and N = sample size.

In addition, when a study reported only the statistical significance of t-tests or chi-square tests (e.g., Jaselskis et al. 1996), this method was used to transfer those reported statistical significance values to effect size r (Card 2011, pp. 101–102). Once the corresponding z-score of that statistical significance is found, Eq. (4) was used to transfer that z-score to effect size r.

Computation of Overall Effect Size

The effect sizes from individual studies were aggregated to obtain the overall effect size for both active and passive leading indicators using a random-effect model. The main assumption is that the effect sizes from each primary study vary across studies (Borenstein et al. 2009). Table 4 illustrates the calculation procedures of the overall effect size. Each study was weighted by the inverse of the standard error of the effect size to ensure that the more accurate individual study effect sizes have a greater impact on the overall effect size than the less accurate (Card 2011). Eq. (5) shows the formula to calculate the weighted values for each study

$$w_i = \left(\frac{1}{SE_i^2}\right) \tag{5}$$

where w_i = weight for study i; and SE_i = standard error of the effect size estimate for study i calculated using Eq. (3).

Once each study was weighted, the result was used to estimate the weighted mean effect size. Eq. (6) illustrates the generic equation to calculate the weighted mean effect size referred to by Card (2011)

$$\overline{ES} = \frac{\sum(w_i Es_i)}{\sum(w_i)} \tag{6}$$

where $\overline{ES}$ = weighted average effect size; Es_i = effect size; and w_i = weight for each individual study calculated by using Eq. (5).

The next step was to evaluate heterogeneity among studies. The heterogeneity test can help determine whether all included studies in the meta-analysis were measuring the same effect (Higgins et al. 2003). Eq. (7) illustrates how to calculate the heterogeneity among included studies by using the Q test (Card 2011)

$$Q = \sum(w_i ES_i^2) - \frac{(\sum(w_i ES_i))^2}{\sum w_i} \tag{7}$$

where Q = heterogeneity statistic; w_i = weight of study i; and ES_i = effect size estimate for such a study.

By applying this equation to the example illustrated in Table 4, a value of 3.81 was obtained. The result obtained from the Q test can be used to evaluate the random variance associated with true differences among different studies by using Eq. (8)

$$\tau^2 = \frac{Q-(k-1)}{(\sum w_i) - \frac{(\sum w_i^2)}{(\sum w_i)}} \tag{8}$$

where τ^2 = random variance; Q = heterogeneity statistic; $k-1$ = degrees of freedom, where k = number of included studies; and W_i = weight for each individual study.

Because this study used a random-effect model, a new weighted calculation was needed. Eq. (9) was used to calculate the weighted values for individual studies in the random-effect model by using the results from Eqs. (3) and (8)

$$w_i = \left(\frac{1}{\tau^2 + SE_i^2}\right) \tag{9}$$

where w_i = weight for study i; τ^2 = random variance of heterogeneity; and SE_i = standard error of the effect size estimate for study i.

By calculating the overall effect size (Z_r) for the example in Table 4 by using Eq. (6), a value of 0.49 was obtained. However, Card (2011) suggested transforming this value back to r because the Z_r is less frequently used and may increase the difficulty of interpreting results. Eq. (10) shows the mathematical process to transform Z_r back to r

$$r = \left(\frac{e^{2z_r} - 1}{e^{2z_r} + 1}\right) \tag{10}$$

By applying the Eq. (10) to the value we obtained from the previous step ($Z_r = 0.49$), we found $r = 0.45$. The confidence intervals then were calculated for each weighted mean effect size by using the following equation:

$$r \pm (1.96 \times SE) \tag{11}$$

where r = mean effect size across studies; and SE = standard error of the mean effect size.

This procedure was used to conduct two distinct meta-analyses, one for active and another for passive safety leading indicators. The data were not aggregated across groups because of the differences in the constructs being measured, data form, and implications as indicated in Fig. 1.

Meta-Analysis Results

The results of this meta-analysis revealed that the effect sizes of the relationship between leading indicators and injury varied widely, as shown in Tables 5 and 6. Nine construction safety leading indicators were included in this analysis. As shown in Table 5, the effect sizes of the relationships between safety inspection and observation and injury ($r = 0.51$; 95%CI = 0.30–0.67) and between pretask safety meeting and injury were very large ($r = 0.45$; 95%CI = 0.32–0.57).

For the nine passive leading indicators, eight were significant ($p < 0.05$) as shown in Table 6. Specifically, the relationship between injury rate and safety record ($r = 0.56$; 95%CI = 0.20–0.79) and safety resources ($r = 0.48$; 95% CI = 0.28 to 0.65) had large effect sizes. Staffing for safety ($r = 0.44$; 95%CI = 0.12–0.68), owner involvement ($r = 0.45$; 95%CI = 0.16–0.67), training and orientation ($r = 0.42$; 95%CI = 0.10–0.66), personal protective equipment ($r = 0.40$; 95%CI = 0.17–0.58), and incentives programs ($r = 0.30$; 95%CI = 0.15–0.43) were all moderate. Finally, the effect size of safety inspections and observation was low ($r = 0.27$; 95%CI = 0.12–0.41), and that of pretask meetings was not significant ($p = 0.103$).

An interesting finding was that pretask safety meetings was shown to be a significant predictor of future performance when measured regularly and treated as an active leading indicator. However, considering pretask safety meetings as a passive indicator (i.e., does the organization have meetings or not?) is not predictive. This underscored the need to understand the most effective use of each indicator and the importance of a formal distinction and meta-analysis offered in this paper.

Conclusion and Discussions

This paper offers three primary contributions: (1) a clear definition and distinction of safety leading indicators from other predictive safety techniques; (2) a practical method for distinguishing active and passive indicators; and (3) the first meta-analysis of safety leading indicators. The objective of the meta-analysis was to determine a set of common indicators and measure the extent to which they predict injury rates across multiple studies and samples. This addresses a current gap in the literature in which the epistemological positions are highly variable and findings remained preliminary and have yet to be validated. This study identified nine common leading indicators that are significantly correlated with worksite injuries: safety record, safety resource, staffing for safety, owner involvement, safety training/orientation, personal protective equipment, safety incentives program, safety inspections and observation, and pretask safety meeting. The source studies included diverse types of construction projects (e.g., rail, highway, oil and gas, and buildings), geographies (e.g., United States, Australia, and Canada) (e.g., Lingard et al. 2017; Salas and Hallowell 2016; Alarcón et al. 2016; Idoro 2008), and companies. Thus, for the first time, this

Table 5. Correlation of active construction safety leading indicators and injury rate

Active indicators	K	N	r	95% CI Lower	95% CI Upper	P-value
Safety inspections and observation	2	1,608	0.51	0.30	0.67	0.000
Pretask safety meeting	2	875	0.45	0.32	0.57	0.000

Note: K = number of studies; N = sample size; r = effect size; and 95% CI = confidence interval around r.

Table 6. Correlation of passive construction safety leading indicators and injury rate

Passive indicators	K	N	r	95% CI Lower	95% CI Upper	P-value
Safety record	2	42	0.56	0.20	0.79	0.005
Safety resource	2	71	0.48	0.28	0.65	0.000
Owner involvement	2	42	0.45	0.16	0.67	0.003
Staffing for safety	3	111	0.44	0.12	0.68	0.013
Training/orientation	2	1,254	0.42	0.10	0.66	0.016
Personal protective equipment	2	71	0.40	0.17	0.58	0.001
Incentives	3	1,338	0.30	0.15	0.43	0.000
Safety inspections and observation	4	168	0.27	0.12	0.41	0.001
Pretask safety meeting	2	83	0.40	−0.07	0.72	0.103

Note: K = number of studies; N = sample size; r = effect size; and 95% CI = confidence interval around r.

study revealed that these indicators are valid and generalizable across geographies, industry sectors, company types, and safety cultures.

Regarding active safety leading indicators, safety inspection and observation had a large effect size ($r = 0.51$). This finding is explained qualitatively by Toole (2002), who found that proper inspection and worker observation target unsafe behaviors, poor skills and safety knowledge, and errors that are the root cause of many injuries. In practice, Hallowell et al. (2013) suggested that an average number of safety observations conducted by a trained observer per 200,000 work hours should be considered as the standard method of measuring this indicator.

Additionally, this study found a large effect size for the relationship between pretask safety meeting and injury ($r = 0.45$). A wide variety of studies propose that safety meetings and their corresponding job hazard analyses are the foundation of an effective safety program (Hinze and Wilson 2000). Hallowell et al. (2013) suggested that the frequency of pretask plans conducted at the jobsite should be used to measure this indicator. Interestingly, in a later study, Albert et al. (2013) developed and tested a new method of assessing, tracking, and improving the quality of these meetings. Although the present study includes only quantitative approaches to indicator measurement, this new research suggests that qualitative indicators may also be effective.

Regarding passive safety leading indicators, this meta-analysis revealed that eight passive safety leading indicators predict safety performance, ranging from strong to weak predictive power: (1) safety record; (2) safety resource; (3) staffing for safety; (4) owner involvement; (5) safety training/orientation; (6) personal protective equipment; (7) safety incentives program; and (8) safety inspections and observation. These include safety management activities such as record keeping that many consider to be standard practice. In this way, some of the passive indicators may be used to distinguish standard practice from divergent organizations. Active indicators, on the other hand, can be used to distinguish even among high-performance organizations because frequency and quality of implementation can vary widely.

Nevertheless, not all passive indicators would measure divergence. For example, safety resources (e.g., the availability of medical facilities in the jobsite) was shown to have the second-strongest correlation with performance ($r = 0.48$) and is not necessarily standard practice. Organizations may use these findings to justify additional resource expenditure. More important, the pretask safety meeting indicator was found to be not significant when it is measured as a passive leading indicator.

The practices that are moderately predictive (Table 6) are considered by most previous researchers to be harmonious and interactive in the creation of a comprehensive safety program (Hallowell and Calhoun 2011). The commitment and involvement of clients in safety activities, for example, can effectively reduce injuries and ensure effective implementation of personal protective equipment, staffing, training, and incentives (Huang and Hinze 2006; Hallowell and Calhoun 2011).

The findings of this study are important for both researchers and practitioners to create and validate common leading indicators of safety performance for the construction industry, and serve as a first step toward standardizing leading indicators for the construction industry. Researchers and practitioners are encouraged to contribute to the debate and suggest other epistemological positions or to apply the rules for distinguishing leading indicators from other predictive safety methods and for distinguishing between the two primary types of safety indicators. Consistency among perspectives and methodologies would enable scientific discourse that is presently lacking.

Study Limitations

A meta-analysis generally requires at least two or more studies to be conducted. However, a small number of studies might produce many challenges, including heterogeneity in the included study (IntHout et al. 2015). Even though heterogeneity tests might not perform well with the small number of included studies (Higgins et al. 2003; von Hippel 2015), high heterogeneity exists in this study, especially in the calculation of active leading indicators. However, empirical studies on construction safety leading indicators are rare, and access to a large volume of empirical data was one of the major limitations of this meta-analysis. Specifically, studies reporting active leading indicators were very rare. Only six in the current literature reported active leading indicators, and only two qualified for inclusion in this meta-analysis. Of the 13 common leading indicators identified in this study (Table 1), only nine were included in this meta-analysis due to insufficient sample sizes. Researchers may see this as an opportunity to expand upon this work as the field matures. More empirical investigation of the relationship of active safety leading indicators should be considered. Thus, a meta-analysis should be replicated in the future with a large sample size (i.e., number of studies).

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

Acknowledgments

The authors of this paper would like to thank the numerous authors who provided information about their studies postpublication upon request. This work would not have been possible without the contribution of those authors who volunteered their time and effort to provide detailed data.

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