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Utilizing construction safety leading and lagging indicators to measure project safety performance: A case study

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ABSTRACT

Background & objectives: Due to the dangers of the construction industry, leading and lagging safety indicators have been developed to measure safety performance and prevent injury. It is important to examine the effect of leading indicators on a project level to better understand how leading indicator data can be used by company management. This study examines the relationship between safety leading and lagging indicators when measured on a company level using company administrative data.
Methods: This case study collected safety indicators from 47 construction projects. Four zero-inflated Poisson models were run to determine whether an increased number of leading indicators, site inspections or toolbox talks, led to a lower frequency of lagging indicators, injuries or first aid injuries.
Results: There were few injuries in the dataset across all projects. Findings from univariate models showed the expected relationship between higher site inspections and toolbox talks and lower injuries and first aid injuries, although these findings were only significant with first aid outcomes. The estimated effect sizes of these models were very small.
Conclusion: Although these results parallel some past studies, the limited number of injuries common to most single employers prevents adequate data for statistical analysis. Population level studies with multiple employers will more likely have adequate power to show associations in safety metrics. Single employers may use their data as a benchmark and show trends over time. However, employers should closely examine the quality of their data, and collect relevant variables to track the progress of their safety metrics.

1. Introduction

Construction is one of Canada's most dangerous occupations. The Association of Workers' Compensation Boards in Canada found that in 2016 the construction industry experienced the highest number of fatalities and the fourth highest number of lost time injuries of the 19 surveyed Canadian industries (Association of Workers' Compensation Boards of Canada, 2017). Specifically, in Ontario, construction accounts for 11% of all lost-time injuries, 26% of all falls from heights (Ministry of Labour, 2016), and 22% of all workplace fatalities (Association of Workers' Compensation Boards of Canada, 2015). These are very high percentages considering that construction workers only account for 7% of Ontario's workforce (Statistics Canada, 2017a). These high levels of injuries and fatalities increased the importance of construction safety for lawmakers, employers, and researchers. As a result, there has been a growing interest in developing safety indicators to determine how accident prevention impacts safety outcomes (Manual, 2009). Much research has been completed on safety indicators in construction, yet, as shown by the later scoping review, few studies have examined the relationship between leading and lagging indicators across projects. Most studies have tested the performance of indicators between companies or in a single project. Company decision makers generally base their safety decisions on data from their project management program (Cha and Kim, 2011; Rajendran, 2013). For example, if a company determines their safety efforts on a project increased worker safety performance, the results may support the implementation of additional safety efforts across the company (Lingard et al., 2011; Hinze et al., 2013). Businesses are always evaluating and re-evaluating their decisions in order to stay successful. Similarly, safety should be measurable and interpretable within a company. This study used safety administrative data routinely collected on construction company projects to test the relationship between safety leading and lagging indicators. The

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hypothesis examined whether construction projects with higher levels of positive leading indicators (i.e. better safety performance) are associated with fewer lagging indicators (e.g., accidents) than projects from the same company with lower levels of positive leading indicators.

2. Literature review

To help select the best safety indicators from administrative data sources, a scoping review was completed to determine the safety indicators that have been used in previous research studies in construction. Administrative data is data that is routinely collected for reasons other than research, such as the regular business practice (Hashimoto et al., 2014; Statistics Canada, 2017b). Information on the performance of many safety indicators is recorded by construction companies in Ontario to meet reporting requirements outlined in the Ontario Health and Safety Act (1990) and the Workplace Safety and Insurance Act (1997). These reporting requirements, including site inspection logs, hazard reports, first aid logs, injury reports, and many other reports, create data that may be used for research with permission from the company. This scoping review aims to provide a comprehensive list of safety indicators that can be used for the purpose of this research and to summarize the relationship between leading and lagging indicators from past studies.

2.1. Literature review research methodology

Relevant studies were selected using the electronic database PubMed and Scopus. These databases provide comprehensive coverage of the research available in both the medical and engineering fields pertaining to construction safety. Search terms were used to search the title and abstract of the available articles. The articles needed to contain "Construction" and "Indicator(s)" and "Safety" and "Leading or Lagging." References were excluded if they were books, duplicates, not in English, or unavailable in full-text by the researcher. There were no date range exclusion criteria. The scoping review process was completed using DistillerSR (DistillerSR, Ottawa, ON). A two-step screening process was completed on the articles selected through the databases and this process is further explained below.

In phase one, 81 articles were selected using the search strategy explained above. After duplicates were removed, 79 articles were reviewed for inclusion based on the following criteria: (1) be related to construction, (2) include safety indicators, (3) identify leading and lagging indicators and (4) be an academic journal article. Phase one review excluded 46 articles, leaving 33 articles for the next round. In Phase two, the 33 articles were reviewed for the presence of measured safety indicators at a construction project level. A total of 21 articles were excluded. The remaining 12 articles were eligible for full-text review. In Phase 3, two articles were removed as the full text was not available, leaving 10 articles remaining for full text review and data extraction. Data extraction was completed using an excel spreadsheet to track the author, date, journal, safety indicators used and relationships between safety indicators used. Overall, the studies used small sample sizes. Additionally, the articles contained many recurring authors, showing that few researchers are involved in this area of study. Tables 1 and 2 provide the title, author(s), year and brief summary of each study's research goal, methodology and results.

As is evident in Tables 1 and 2, the research questions of the final 10 articles varied. For leading indicators to be used on construction projects, the indicators first need to be developed, and second, must be tested for validity in a construction project setting (Rajendran, 2013). Many of the articles from the scoping review focused on the first step – development of indicators, such as defining (Hinze et al., 2013; Schwatka et al., 2016), developing (Guo and Yiu, 2015; Lingard et al., 2011; Niu et al., 2017), or measuring indicators (Ng et al., 2010; Ng et al., 2012). Few studies focused on the second step, conducting validation testing of the leading and lagging indicators on construction projects (Lingard et al., 2017; Rajendran, 2013).

The present study identified and categorized the safety indicators from the scoping review articles as either leading or lagging indicators. There were 15 leading and 4 lagging indicators identified. The indicators with similar names were grouped together. The most common indicators that were categorized as "leading" were safety attitudes and safety climate, site inspections/audits, training and safety talks, and worker safety behaviours. The most common indicators that were categorized as "lagging" were first aid injuries and lost time injuries (Table 3).

2.2. Interaction of leading and lagging indicators

Only two articles addressed the relationship between leading and lagging indicators on construction projects.

The study by Lingard et al. (2017) completed a temporal analysis of leading indicators to examine whether leading indicators are actually leading (that is, occur before a lagging indicator), and the time needed between the implementation of leading indicators and the improvement in lagging indicators. Lingard studied 11 leading indicators which included safety talks, hazards reported, and safety inspections. Data came from subcontractors and contractors on a large, 5-year construction project in Australia. The frequency data was adjusted for man-hours prior to analysis. Their study showed that the frequency of leading indicators is dynamic over the course of a project. Leading indicators were not associated with the key lagging indicator, the total recordable injury rate, in the expected, predictable way. Lingard et al. (2017) recognized that understanding safety leading indicators is complex and suggests that there is a bidirectional relationship between leading and lagging indicators. For example, toolbox talks led to a decrease in injuries for the first four months, then injuries led to an increase in the number of toolbox talks for the next two months. In this way, both indicators, injuries and toolbox talks, caused a change in the other indicator, so indicators may be viewed as bidirectional. While this study enhanced the research on leading and lagging indicators, the findings provide little guidance for construction companies and management. The terminology on leading versus lagging indicators cause confusion for construction companies even though there is considerable uptake in using indicators to measure safety performance in the industry.

In a second study, Rajendran (2013) collected both leading and lagging indicators on one construction project to determine if there was correlation between the leading and lagging indicators. Three leading indicators, pretask plan review, worker safe behaviour observation score, and site safety audit score, were compared to four lagging indicators: first aid, near miss incidents, OSHA recordable incidents, and all project incidents. The indicators were collected for 37 weeks by safety professionals. Results showed modest correlations between pretask plan review and total incidents ($r = -0.507$), pretask plan review and first aid ($r = -0.573$), worker safe behaviour observations and total incidents ($r = -0.588$), and worker safe behaviour observations and first aid ($r = -0.635$). Although the results of these two studies are promising, both studies were conducted with data from a single construction project. These case studies provide insight into the real-life relationships of these indicators, but more studies are needed to confirm their findings.

3. Methods and materials

3.1. Study sample

Melloul Blamey Construction (MB) is a general contractor in Ontario, provided the project data used in this case study. MB specializes in several types of construction including industrial, commercial and institutional sectors as well as multi-residential buildings, such as student apartment buildings. Between 2012 and 2016, the time period of this study, MB completed 78 projects ranging with a cost from

Table 1
Primary articles on construction project leading and lagging indicators.

Article Year, Title	Author(s)	Sample	Methods	Measures	Results
2010, An experiment with Leading Indicators for Safety	Ng, Laurlund, Howell, & Lancos	• One $14,000 construction project, consisting of two medical buildings • 11 month project • Approximately 75,000 man-hours	• Leading indicators from administrative data were categorized into ten general safety categories were observed prior, during and after the implementation of the 5S program • Categories include railings and covers, ladders and stairs, housekeeping, fall protection, and personal protective equipment • Not all categories and statistical analysis (i.e. p values) were provided. • The 5S program is based on lean principles and consists of 5 stages: Sort, Set in order, Shine, Standardize, Sustain	• Rates of each safety category measured per 200 man-hours	• Implementation of 5S program led to an overall increase in project safety performance • Fewer leading indicators were observed as the project progressed. • First four months = 9.75 • Final four months = 3.5 leading indicators
2011, The development and testing of a hierarchical measure of project OHS performance	Lingard, Wakefield, & Cashin	• One large civil construction project, $17,000,000 and approximately 2 years to complete • Approximately 460,000 man-hours	• Monthly safety index and quarterly safety climate measures were conducted to determine OHS performance • Safety Index indicators include: members of public injured, medically treatable injuries, first aid incidents, lost time injury, incident/near miss incidents reported, safety walks, safety walk observations, site safety inspections conducted, site safety inspection problems noted, safety assessment, safety assessments problems identified • Safety climate measures were management commitment to safety, safety communication, supervisor leadership to safety and coworker support to safety	• Safety climate and monthly weighted safety index	• Both measures were shown to diagnose specific problems with the health and safety system during the project. • Ex. when the safety climate score was broken into components, the supervisor leadership scores fell (mean = 6.2) from the first to second quarter (mean = 5.2). • Ex 2. The safety index scores remained high over the course of the project (no lower than 82.7%). This can be attributed to the most weighted indicators, lost time injuries and injuries to members of the public, never occurring.
2012, Lean safety: Using leading indicators of safety incidents to improve construction safety	Ng, Laurlund, Howell, & Lancos	• One construction project, renovation of an existing facility • Approximately $14,000,000	• 10 leading indicators from administrative data were observed prior, during and after the implementation of a 5S program • The 5S program is based on lean principles and consists of 5 stages: Sort, Set in order, Shine, Standardize, Sustain	• Rates of each leading indicator during different periods over time	• There were difficulties with implementing the 5S program on this complex project. The easiest tools to implement were those that were direct, easy to read and comprehend. • Fewer leading indicators were observed as the project progressed. • First quarter = 1.29 per 200 man-hours • Second and third quarter = 0.22 per 200 man-hours
2013, Enhancing construction worker safety performance using leading indicators	Rajendran	• One large manufacturing construction project • 37 weeks of data collection • No more details provided	• Three leading indicators were evaluatied against four lagging indicators for their ability to provide useful information to construction contractors. • Leading Indicators: pretask plan review (PTP), worker safe behaviour (WSBO), site safety audits (SSA) • Lagging Indicators: Near miss incidents (NMR), first aid injuries (FA), total recordable injury rate (TRIR), total injuries (TI)	• Pearson correlations were run between each leading indicator and each lagging indicator	• Pretask plan review had strong negative correlations with TI ($r = -0.507$) and FA ($r = -0.537$) • Worker Safety Behaviour Observations had strong negative correlations with FA ($r = -0.635$) and TI ($r = -0.538$) • Site Safety Audit Scores found weak correlations with FA ($r = -0.107$), NMR ($r = -0.4$), TRIR ($r = -0.101$), and TI ($r = -0.081$)
2015, Development of a safety communication and recognition program for construction	Sparer, Herrick, & Dennerlein	• Preliminary: two months of a construction project. • After redesign: 6 months on the same construction project.	• 3 step process: initial program design, implementation feasibility testing • The three step process was repeated once	• Site inspection score, interview and focus groups.	• The safety performance of the site exceeded the recognition threshold 50% of the time • Workers and managers indicated that safety communication led to an increase in site 'camaraderie' • The competition seemed to increase communication with trades that did not typically communicate

(*continued on next page*)

Table 1 (*continued*)

Article Year, Title	Author(s)	Sample	Methods	Measures	Results
					● Yet, the program is reliant on reliable inspection data
2017, Leading or lagging? Temporal analysis of safety indicators on a large infrastructure construction project.	Lingard, Hallowell, Salas, & Pirzadeh	● 1 infrastructure construction project over 5 years ● Multibillion dollar project with up to 645,640 man-hours	● Recordable injury rate (TRIFR) and 14 leading indicators were collected through administrative data and the relationship between each leading indicator and the recordable injury rate was measured over time. ● Leading indicators: toolbox meetings, pre-brief meetings, safety observations, site surveillance inspection carried out, penalties, occupational health and safety audits, non-compliance, hazards reported, hazards closed out, statutory authority inspections carried out, alcohol tests, drug tests, safe-work method statements, site inspections	● Fifteen safety indicators and time using cross correlational, VAR modeling and Granger causality Wald tests.	● Toolbox led TRIFR four months prior lagged for the next 2 months. ● Pre-brief led TRIFR 2 months prior. ● TRIFR led Safety Observations by one month, for the next 4 months. ● Site Surveillance lagged TRIFR at month 2. ● Audits led TRIFR at month 2 prior, then lagged months 2 after. ● Non-compliance led TRIFR one month prior, then lagged for the next two months. ● TRIFR led Alcohol Test, Drug Tests, SWMS and Site Induction by one month, then lagged for the next month.
2017, Developing safety climate indicators in a construction working environment	Niu, Leicht, & Rowlinson	● 2 focus groups of 17 safety experts	● A literature review was completed to identify construction specific indicators related to safety climate. Focus groups then worked to identify and validate the indicators and their relationship to safety climate.	● Focus groups worked to identify indicators and organize them based on importance.	● Safety indicators were classified based on the dynamic features of the working environment and process-control elements.

$100,000′s to multi millions. MB is certified under the Ontario Government's Certificate of Recognition Program (COR) which requires a health and safety management system that meets national standards endorsed by the Canadian Federation of Construction Safety Associations (IHSA, n.d.).

MB was chosen as the study sample for several reasons. First, being a mid-sized general contractor, they have many projects underway at one time, so data from a large number of projects may be available within a four-year period. Second, MB has tried to improve their interproject safety reporting reliability, which may provide more usable data for research purposes. And finally, using data from a single company provides insight into how well routinely collected administrative data across projects may be used to evaluate safety performance. Theoretically, data collected within a single company may have higher reliability of measurement of the selected indicators.

This project was reviewed and approved by the Human Research Ethics Committee at the University of Waterloo.

3.1.1. The projects

Data from construction projects completed from 2012 through the end of 2016 were used for this study. In 2012, MB changed management of their administrative data to storing project information on electronic databases. This made the data readily available for research purposes. Through MB's electronic database, 78 projects were identified and evaluated for research eligibility. Reasons for excluding projects can be seen in Fig. 1 below. The inclusion criteria of projects developed by two authors (KV and PB) were applied systematically to all the projects. Project inclusion used the following criteria:

1. The construction contract was either fixed bid, design build or construction management. The inclusion of the three main Canadian Construction Documents Committee (CCDC) contracts ensured the different projects had similar administrative techniques used between them and were therefore comparable. MB has two divisions, their construction division and the small contracts division which does small renovation and quality assurance jobs. Complex contracts and projects managed by more than one project-management group within MB were excluded. The inclusion of the CCDC contract as part of the criteria ensured that the projects were being completed by the construction division, and therefore, was a 'typical' project.
   - 1.1. Fixed Bid: "standard prime contract between Owner and prime Contractor that establishes a single, pre-determined fixed price, or lump sum, regardless of the Contractor's actual costs." (CCDC, 2019)
   - 1.2. Design-Build: "standard prime contract between the Owner and the Design-Builder where the Design-Builder provides the Design Services and performs the Work under one agreement, for a single, pre-determined stipulated or fixed price." (CCDC, 2019)
   - 1.3. Construction Management: "standard contract between Owner and Construction Manager to provide advisory services during the pre-construction phase and perform the required Work during the construction phase." (CCDC, 2019)
2. The project was completed with no additional collection of administrative data.
3. The project was recorded consistently across MB departments.

As shown in Fig. 1, 18 projects were excluded since the projects did not record data consistently across departments within MB. This occurred because the project was managed by multiple project management groups within MB. Ten additional projects were excluded because they did not use one of the required construction contracts. Three projects were not completed by the start of the research. In total, there were 47 eligible projects available.

Table 2
Secondary articles on construction project leading and lagging indicators.

Article Year, Title	Author(s)	Style	Purpose	Findings
2013, Leading indicators of construction safety performance	Hinze, Therman, & Wehle	Review (not systematic)	● To define leading and lagging indicators and identify where they can be used to measure project safety performance.	● Steps into using leading indicators for construction safety measures were noted including training, current issues and implementation.
2015, Developing leading indicators to monitor the safety conditions of construction projects	Guo & Yiu	Theoretical	● To present a framework for developing leading indicators for the construction industry.	● For leading indicators to be developed there are four steps. Conceptualization, Operationalization, Indicator Generation and Validation / Revision.
2016, Defining and measuring safety climate: a review of the construction industry literature	Schwatka, Hecker, & Goldenhar	Scoping Review	● To complete a review on research available on safety climate within the construction industry	● Frequent definitions, measures and associations related to safety climate were listed.

3.2. *The indicators*

For each of the 47 projects, 8 safety indicators were consistently logged by MB. The indicators were logged using reports previously collected by the company and stored by the safety department.

3.2.1. *Safety indicator selection*

Through MB, eight safety indicators were evaluated for inclusion in this research. Additional indicators were considered as part of the literature review but they were not accessible at the time of research. Although many of the indicators are required to be reported by the government, there are many reasons why they may not be consistent over time. Examples include: government reporting procedures changing over time, differences in reporting for different project types, whether the indicator is reported to the government or just stored in-house for due-diligence, or errors in reporting (Jablonowski, 2011). Available indicators were evaluated for inclusion based on three criteria: (1) whether or not the data was available, (2) whether or not they are indicators commonly used in research, (3) and whether the indicators were collected with reasonable consistency across the projects. Criteria 3 was used as a measure of data quality. As this study was completed retrospectively, researchers did not have control over the data as it was being produced. Criteria 3 was assessed through observations and interviews with the safety professionals at MB, as they were collecting and using the data for the four years of the study sample.

3.2.1.1. Leading Indicators. Three leading indicators were considered for inclusion in this study: number of toolbox talks, number of site inspections, and number of near misses. While there were more leading indicators available, they were used less commonly, often as their reporting was not mandatory, and changed reporting style over the course of the four years. Examples of these indicators would be supervisor safety review scores, daily hazard assessments, and pre-construction safety meetings. While they would have provided more options for leading indicators, the changes in legislation and reporting made them too variable to be included. Descriptions of the three leading indicators are below:

The number of toolbox talks and number of site inspections are common safety activities on construction projects. A toolbox talk is a short onsite training session that occurs on a regular basis to educate the workers on site specific hazards as well as refresh workers safety training (Lingard et al., 2011). Site inspections are walkarounds completed by the superintendent or site safety representative that involves looking for safety hazards using a standardized checklist (Rajendran, 2013). The frequency that each of these safety activities is performed may produce a safer project, and therefore are considered leading indicators. In this study, both of these leading indicators were measured by the frequency of occurrence. Count data is highly reliable, but counts do not provide information about the quality of the activity. Thus, the reason a toolbox talk was selected, the number of hazards noted, or the preventative measures taken as a result of safety violations cannot be determined using counts of these indicators. During 2012–2016, according to a safety practitioner at MB, records or logs of toolbox talks and site inspections were reported consistently across sites, but the context and quality of the activities within the documentation were not consistent across sites. The count data was deemed more reliable, rather than using the more detailed data for analysis (D. Henhoeffer, personal communication, May 23, 2018). Despite the limitations, toolbox talks and site inspections met the criteria, as they were available, commonly used in past research studies, and consistently collected.

The third leading indicator, near misses, are unplanned incidents that do not result in injury or loss of property (Lingard et al., 2011). A near miss is an indicator of potential risk on a construction site and relies on individual judgement and reporting. For example, if a worker nearly fell from the second floor of a construction site when he lost his

Table 3
Summary of safety indicators.

Author(s), Year	Safety Indicator Type Leading									
	Alcohol / Dug Testing	Attitutes and Safety Climate	Fall Protection	Housekeeping	Ladders and Stairs	Near Miss	Pre-Task Safety Plans	PPE	Railings and Covers	Safety Corrections
Ng et al. (2010)			X	X	X			X	X	X
Lingard et al. (2011)		X								X
Ng et al. (2012).			X	X	X			X	X	X
Hinze et al. (2013)		X				X				
Rajendran (2013)						X	X			
Guo and Yiu (2015)		X		X			X			
Sparer et al. (2015)										
Schwatka et al. (2016)		X								
Lingard et al. (2017)	X						X			
Niu et al. (2017)		X								
Total	1	5	2	3	2	2	3	2	2	3

Author(s), Year	Safety Indicator Type Leading					Lagging			
	Safety Positive Reinforceme-nts	Site Inspections / Audits	Subcontractor Safety	Training / Job Safety Talks	Worker Safety Behaviour	First Aid Injuries	Lost Time Injuries	Members of the Public Injured	Reported Incidents
Ng et al. (2010)									
Lingard et al. (2011)		X		X	X	X	X	X	
Ng et al. (2012).									
Hinze et al. (2013)	X	X	X	X					
Rajendran (2013)		X			X	X	X		X
Guo and Yiu (2015)			X	X	X				
Sparer et al. (2015)		X	X	X					
Schwatka et al. (2016)					X				
Lingard et al. (2017)		X		X			X		
Niu et al. (2017)				X	X				
Total	1	5	3	6	5	2	3	1	1

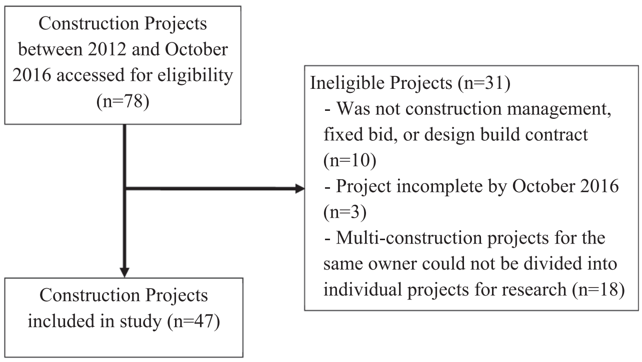

Fig. 1. Construction project removals.

balance would be considered a near miss. At MB, near misses are largely underreported. The safety practitioner suggests the MB project personnel do not lack safety knowledge or foresight, but do not want to be burdened by extra paperwork and may have feelings of blame and embarrassment associated with reporting a near miss (D. Henhoeffer, personal communication, May 23, 2018). As a result, near misses were excluded as a leading indicator for this research, failing to meet the third criteria, consistency.

After evaluation of the leading indicators, toolbox talks and site inspections were included in the data analysis.

3.2.1.2. Lagging Indicators. The lagging indicators considered for inclusion in this study were: number of lost time injuries, number of medical injuries, number of first aid injuries, number of subcontractor offenses, and number of Ministry of Labour offenses. First, lost time injuries are workplace injuries that require a person to miss at least the next day of work after an injury, or injuries that lead to permanent injury or death (Workplace Safety and Insurance Act, 1997). However, there were no lost time injuries on MB projects between 2012 and 2016. MB provides good medical management for onsite medical injuries and if necessary, a successful Return to Work program where modified work may be accommodated at the worksite for up to seven days (D. Henhoeffer, personal communication, May 23, 2018). In Ontario, using modified work is promoted, as long as the worker does not need modified work for longer than 7 days and earns their regular wage (Workplace Safety and Insurance Act, 1997).

Second, the number of medical injuries and first aid injuries were also evaluated for inclusion. An injury is a workplace injury that requires medical intervention, while a first aid injury is a workplace injury that can be treated on site using first aid. Number of medical injuries and number of first aid injuries are more reliably recorded since they are defined events with an outcome in contrast to less defined events such as near misses. Furthermore, the workers are more likely to report them if they affect their work (D. Henhoeffer, personal communication, May 23, 2018), such as a first injury that impedes their ability to complete their task on time. Workers know that they are supposed to report all injuries, and they seem to report the more severe injuries reasonably consistently. The most common injuries underreported are for very minor first aid injuries, such as small cuts. Some people may have reported these injuries, while some may have not. For example, an injured worker may prefer to treat their first aid injury by themselves and not report it. Yet, this underreporting of first aid injuries is likely consistent across projects (D. Henhoeffer, personal communication, May 23, 2018). Injury data, both medical injuries and first aid injuries was available for all 47 projects and met the study inclusion criteria.

Third, subcontractor notices of offenses are issued to subcontractors as written warnings for safety violations. These warnings may include fines. For example, MB has a policy that requires immediate removal of a subtrade from the job site if they fail to use fall protection (D. Henhoeffer, personal communication, May 23, 2018). Unfortunately, many superintendents prefer to only issue these notices in cases of severe violations, as they would prefer to issue verbal warnings (D. Henhoeffer, personal communication, May 23, 2018). As a result, subcontractor notice of offenses was excluded from the study due to a lack of consistency and too few notices.

Finally, information based on Ministry of Labour (MOL) citations was also available, but it was not used for the study as MOL inspections did not occur on every site. Additionally, often MOL inspections occur with a certain purpose in mind, based on the goals of the MOL at the time. For example, the MOL may choose to do a series of investigations focused on fall protection, called a blitz (Government of Ontario, 2018). With the purpose of the inspections changing over time, it makes this measure across time lack consistency.

Following evaluation of the lagging indicators, the number of medical injuries and the number of first aid injuries were included for data analysis, while lost time injuries, subcontractor offenses and MOL citations were excluded.

3.3. Data analysis

The goal of this research was to examine whether the relationships between safety leading and lagging indicators can be measured and understood when comparing different projects within a construction company. By furthering the research of leading and lagging indicators in a construction company, these indicators can be more effectively used as part of an injury prevention program through ongoing evaluation of injury prevention success.

For the purpose of statistical analysis, four safety indicators were used: number of toolbox talks, number of site inspections, number of medical injuries and number of first aid injuries (Table 4). Additionally, a fifth indicator, project length, defined as the time between the project start date and the completion date, was used to account for the duration of the project. We had no data that directly accounted for worker time at risk such as work hours but used project length to show difference by time as an indication of size of projects.

The five indicators were collected as counts and divided into predictor variables, outcome variables, and an offset variable. The two predictor variables were the leading indicators, site inspections and toolbox talks. The two outcome variables were the lagging indicators, number of medical injuries and number of first aid injuries. Finally, project length was used to normalize the projects, proportionate to the length of project time. The use of project length as the offset shows the difference between small and large projects.

In order to determine what statistical model would best fit the data, descriptive statistics and frequency graphs were explored. For each indicator, the mean, standard deviation, minimum and maximum values as well as frequencies of occurrence were obtained. The frequency graphs for the outcome variables showed that the lagging indicators had excess zeros. Based on these distributions, the hypothesis was that projects with higher values for the predictor variables, and therefore more site prevention, would have more zeros in the outcome variable as a result (Carrivick et al., 2003; Smith and DeJoy, 2014). In order to model this hypothesis, zero-inflated Poisson models were selected as the form of data analysis.

A zero-inflated Poisson model is a form of regression analysis which is used to analyze data with excess zero counts. The models consist of two parts: a Poisson count model and a logit model for predicting extra zeros. A zero inflated Poisson model is given by the three equations below:

$$\log\left(\frac{\lambda_i}{n_i}\right) = \boldsymbol{x}_i^{'}\boldsymbol{\beta} \tag{1}$$

$$\text{logit}(\omega_i) = \boldsymbol{z}_i^{'}\boldsymbol{\gamma} \tag{2}$$

$$\Pr(Y_i = y_i) = \begin{cases} \omega + (1-\omega)e^{-\lambda} & \text{for } y = 0 \\ (1-\omega)\frac{\lambda^{y}e^{-\lambda}}{y!} & \text{for } y = 1, 2, \cdots \end{cases} \quad (3)$$

λ_i is the rate of observed counts y_i are observed for subject i,
ω_i is the proportion of zeros in the counts of y_i observed for subject i,
n_i is the offset variable that accounts for the length of exposure under which the counts of y_i are observed.

In our application,

λ_i is the rate of observed counts of NI or NFA are observed for project i,
ω_i is the proportion of zeros in the NI or NFA are observed for project i,
n_i is the project length

To assess the association between the hypothesized variables (SI and TT) and the outcome variables (NI and NFA), a series of zero-inflated Poisson models were developed as shown in Table 5.

Additional models were also run when the predictor variables were not run independently of each other. Models were run with both a zero-inflated Poisson and a Poisson distribution with NI and NFA as the outcome variables. Early analysis found that the zero-inflated models better fit the observed frequencies. Additionally, models were run with SI and TT jointly as well as independently. Only models with SI and TT run independently led to statistically significant results. Models with SI and TT run jointly but did not lead to significant results. As a result of the early analysis, zero-inflated Poisson models were developed with SI and TT run independently of each other. All models were run using the statistical software package SAS Studio version 3.5 with a significance cut off of $p < 0.05$.

4. Results

4.1. Descriptive Statistics

Descriptive statistics for the variables of interest are given in Table 6. PL ranged from 2 months to 24 months with a mean of 10.94. The four variables SI, TT, NI, and NFA are summarized in Table 6. For the predictor variables, SI had a mean and standard deviation of 51.02 and 31.23, while TT had a mean and standard deviation of 45.15 and 30.40.

For the outcome variables, NI ranged from 0 to 8 with many of these frequencies being low reflected in a low overall mean of 1.49. These low frequencies can be seen in Fig. 2, with 42% of the values were 0 occurrences, and 21% were 1 occurrence in projects. Similarly, NFA had a mean of 3.19 also due to the high frequency of low counts. Fig. 3 shows that 27% of the projects experienced no first aid injuries, and 21% only experienced one first aid injury.

4.2. Impact of leading indicators on number of medical injuries

Model 1 tested for a negative association between NI and TT, for which the results are given in Table 7 which suggests that TT was not significantly associated with the larger number of zero counts from medical injuries in projects. Hence, this model implies that a unit increase in TT (or one additional toolbox talk) was not significantly associated with a decrease in log-odds of NI.

Similarly, Model 2 tested for a negative association between NI and SI, for which results are shown in Table 8 which suggests that SI was not significantly associated with excess zero counts for medical injuries in projects. This model shows that a unit increase in SI was not significantly associated with a decrease in log-odds of NI.

In order to test each model goodness of fit, the predicated counts under the zero-inflated Poisson model were compared to the observed counts. The chi square for goodness of fit was not significant for Model 1 ($p > 0.99$) and Model 2 ($p > 0.99$) suggesting that the lack of significant results in the zero-inflated Poisson was not due to the model fit. Thus, this analysis found that increasing the leading indicators, resulted in a small (effect size of -0.03), but not statistically significantly increase in the number of zeros in the lagging indicators, the desired outcome. An additional model was run with SI and TT jointly did not give significant results.

4.3. Impact of leading indicators on number of first aid injuries

Model 3 and 4 were run to determine the association of leading indicators (TT and SI) and NFA. Model 3 tested for a negative association between NFA and TT; results are shown in Table 9.

Model 3 shows that TT was significantly associated with higher numbers of NFA zero counts, however, the effect was very small; specifically, a unit increase in toolbox talks was associated with log-odds of NFA reducing by -0.08 (CI = -0.15, -0.01; p = 0.03). In other words, a unit increase in TT was associated with the odds of NFA reducing by a multiplicative factor of 0.92 (CI: [0.86, 0.99]; p = 0.03), or reduced first aid injuries by eight percent points.

Model 4 (Table 10) shows that SI was significantly associated with NFA zero counts, however, this effect was very small. A unit increase in SI was associated with log-odds of NFA reducing by 0.08 (CI: [-0.13, -0.02]; p = 0.01). In other words, a unit increase in SI was associated with the odds of NFA reducing by a multiplicative factor of 0.92 (CI: [0.88, 0.98]; p = 0.01), or reduced first aid injuries by eight percent points. The goodness of fit test was not significant for Model 3 ($p > 0.99$) and Model 4 ($p > 0.99$) providing evidence for good model fits. An additional model was run with SI and TT jointly but did not give significant results.

5. Discussion

The goal of this research was to examine the relationship between leading and lagging indicators using project-level, company administrative data. This study found that there was no relationship between Number of Medical Injuries and either Safety Talks or Site Inspections. There was a significant relationship between Number of First Aid Injuries and both Toolbox Talks and Site Inspections, but the size of the relationships was small (for every extra toolbox talk or site inspection the models predicted an eight percent reduction in first aid injuries). As

Table 4
Model Variables.

Indicator	Acronym	Variable Type
Number of Toolbox Talks[a]	TT	Predictor
Number of Site Inspections[a]	SI	Predictor
Number of Injuries requiring Medical Attention[a,b]	NI	Outcome
Number of First Aid Injuries[a,b]	NFA	Outcome
Project Length[a]	PL	Offset

[a] All safety indicators were measured as a count.

Table 5
Statistical Models.

Model Number	Predictor Variable	Outcome Variable
1	TT	NI
2	SI	NI
3	TT	NFA
4	SI	NFA

Note: all models were run with PL as an offset variable.

Table 6
Descriptive Statistics for Model Variables.

Variable	N	Mean	Std Dev	Min	Max
PL (month)	47	10.94	5.98	2	24
SI (count)	47	51.02	31.23	3	120
TT (count)	47	45.15	30.40	2	115
NI (count)	47	1.49	1.94	0	8
NFA (count)	47	3.19	3.65	0	15

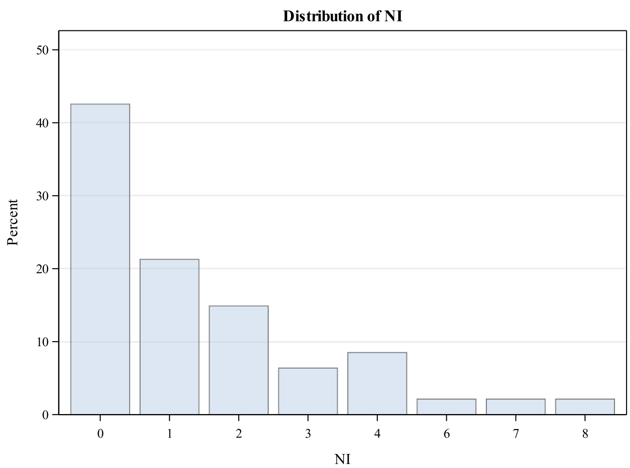

Fig. 2. Frequency histogram for NI.

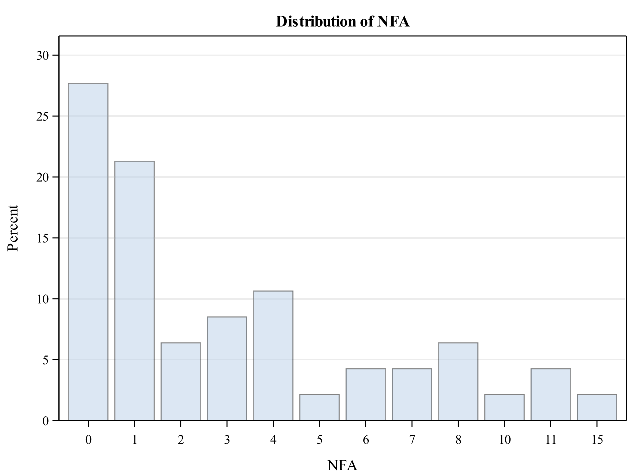

Fig. 3. Frequency histogram for NFA.

the nature of leading and lagging indicators suggests that as leading indicators increase, lagging indicators decrease, we expected to have found significant relationships, with negative estimates, for all four analysis models. Yet, as shown in the earlier literature review, the lack of expected outcome is not uncommon among leading and lagging indicator studies at a project level (Lingard et al., 2017; Rajendran, 2013).

Lingard et al (2017) studied leading indicators and found that leading and lagging indicators did not match the predicted behaviors of what would be expected based on their definitions. The Lingard study used vector autoregression to test the time-performance relationship of safety indicators. Their analysis found that leading indicators did not necessarily lead, and that, at times, lagging indicators took on a leading role. For example, when safety talk frequency increased in their studied project, the increase in safety talks was followed by a short term decrease in total recordable injury rates. However, over the entire project, the decrease in total recordable injury rates was associated with a decreased number in safety talks. These authors determined that the relationship between leading and lagging indicators was much more complex, and time-dependent, meaning the terms "leading" and "lagging" indicators may be misleading (Lingard et al., 2017).

A second study, by Rajendran (2013) found similar complexity in the results. Specifically, 12 Pearson correlations were analyzed, but only 4 of the 12 tested correlations between leading and lagging indicators led to significant results. Based on the definition of leading and lagging indicators, all twelve of the correlations tested in this study should have led to high variance explained, a negative t value, and significant predictive ability of the leading indicator on the lagging indicator.

The findings of our research study in terms of the distributions of counts for the lagging indicator variables is also noteworthy. We evaluated data from the total project periods, rather than examine it in sub-increments of time within the projects. Graphical analyses of the numbers of first aid injuries and medical injuries showed excess numbers of zeros for both variables. Poisson regression analyses, which is a common analysis for count data, produced models indicating that the data were overdispersed. Poisson overdispersion was likely caused by the excess numbers of zeros and the zero-inflated poisson better fit the data. Variance-to-mean ratios for both the models for number of first aid injuries and number of medical injuries were close to 1, indicating good model fits. Future research examining the relationships between leading and lagging indicators should examine frequency distributions prior to modeling count data.

The findings of our investigation and others focusing on project-level data suggest that the causality between leading and lagging indicators is not as simple as once suggested. Traditionally, lagging indicators were used to measure safety performance. For example, injury rates and experience rating have been extensively studied (Lengagne, 2015; Nelson et al., 1997). Leading indicators were developed to promote preventative safety or create a positive safety response to prevent injury from occurring (Hallowell et al., 2013). The thought being that the preventative safety indicators, or leading indicators, would be correlated with reduced injury rates, and these leading indicators would be targets of programs intended to improve safety performance. While the concept is logical, many researchers are now recognizing the

Table 7
Model 1 parameter estimates from zero-model regressing NI on TT with offset PL.

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Pr > ChiSq
Intercept	1	0.31	0.94	−1.53	2.15	0.74
TT	1	−0.03	0.02	−0.07	0.01	0.08

Table 8
Model 2 parameter estimates from zero-model regressing NI on SI with offset PL.

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Pr > ChiSq
Intercept	1	0.15	1.24	−2.27	2.58	0.90
SI	1	−0.03	0.02	−0.07	0.01	0.16

Table 9
Model 3 parameter estimates from zero-model regressing NFA on TT with offset PL.

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Pr > ChiSq
Intercept	1	1.10	1.00	−0.86	3.07	0.27
TT	1	−0.08	0.04	−0.15	−0.01	0.03

Table 10
Model 4 parameter estimates from zero-model regressing NFA on SI with offset PL.

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Pr > ChiSq
Intercept	1	1.65	1.05	−0.41	3.71	0.12
SI	1	−0.08	0.03	−0.13	−0.02	0.01

causal link between leading and lagging indicators is at best understudied, or at worst, incorrect (Dyreborg, 2009; Wreathall, 2009). As a result, research into leading and lagging indicators have focused on further defining what a leading and lagging indicator is (Kjellén, 2009), and measuring the causality of leading and lagging indicators (Salas, and Hallowell, 2016).

Previously, indicators were developed under the definition that if the safety action was proactive or preventive, it was a leading indicator, and if the measure indicated harm or injury, it was a lagging indicator. Many of these indicators were developed based on the descriptive nature of the indicator, rather than proven causality (Kjellén, 2009). Now, many researchers are calling for leading and lagging indicators to be labelled based on evidence of causality, rather than description. In order for leading indicators to be effective as a measurement technique, they need to be developed in a way that is consistent with accident causation models and provide measurable processes (Toellner, 2001). For example, if management commitment to safety is used as a leading indicator to prevent injuries, there needs to be an understanding of where management commitment fits in the accident causation model, and what other factors are in play in order to appropriately measure the effect. As many factors are involved in injury causation, the further upstream a leading indicator is in the causal pathway to injury the more difficult it becomes to detect its relationship with the lagging indicator. In addition, the time and sequence of leading and lagging indicators may show different results than examining project level data (Lingard et al., 2017). These may be some of the reasons why many studies are finding little to no relationship between leading and lagging indicators (Kjellén, 2009). Adding to the challenges in observing statistically significant relationships is the fact that injury rates have been declining for a number of years in many jurisdictions (Mustard et al., 2003) which increases the sample size requirements for studies. This is especially problematic when studying indicators at the project-level and within individual companies.

Finally, researchers and companies may not be choosing effective leading indicators for leading and lagging indicator analysis. For example, Lingard et al (2017), Rajendran, (2013) and this study, all used site inspection counts as a leading indicator. Yet, none of the studies provided overwhelming evidence that site inspections are a good leading indicator. Both this study and Rajendran (2013), found significant relationships but with very small effect sizes or correlations. Similarly, in Lingard et al (2017) site inspections actually behaved more like a lagging indicator than a leading. Although count data have advantages in terms of ease of collection and reliability, as measures of safety performance they are limited in terms of their validity. Counts of the numbers of inspections and safety talks provide some indication of the effort a company makes in improving safety but are relatively coarse measures that are often quite far removed from injury events on the causal pathway. Given our findings and those of Lingard et al (2017) and Rajendran (2013), it may be that counts of site inspection shouldn't be used as a leading indicator, and more robust indicators such as safety climate and indicators on the quality of the hazard response processes should be considered. Construction companies need to be proactive in preventing injuries and should work to incorporate the measurement of valid and reliable leading indicators within their project management systems. More sophisticated approaches for collecting, analyzing, and disseminating safety performance data have been developed (Xu et al., 2019) and may advance the abilities of researchers and companies to develop and test leading indicators.

6. Limitations

Limitations of this study include the use of administrative data and the study sample size. First, although there is much administrative data available to researchers of construction. Yet, although there is much available, there is still the question as to whether the data available is adequate quality to be used for research. The accuracy of administrative data can vary based on the data's original purpose and how it was collected. The administrative data collected in this study consisted of archived safety reports and project reports, previously collected to complete the project or meet legislative requirements. For example, it has been well established that injury reports are often underreported, even up to 60% (Kjellén, 2009; Probst and Estrada, 2010). Despite the fact that many governments require all injuries, except minor first aid injuries, be reported to the government, many workers only report if they absolutely have to (Toellner, 2001). By using previously reported data, it prevents researchers from completing real-time interventions and training to increase consistency and understanding among the reporting personnel. This lack of training can lead to issues related to self-reporting. Second, this research is limited by its sample size. This study had a sample size of 47 projects which can lead to low statistical power. A larger sample size could have led indicators such as NI to have a higher rate of occurrence allowing for appropriate statistical analyses. Unfortunately, for project-level studies and studies within single companies, a low sample size is expected with the use of indicators that are required to be collected by government agencies. Researchers and safety practitioners need to explore the use of more valid and reliable leading indicators to ensure companies can effectively measure the impacts of their safety initiatives. Studies have shown that the smaller a company is the longer sampling time period must be to make meaningful results. For example, Kjellén found that a company with 50 employees would need 33 months of lost time injury data, while a company with 500 employees would only need three months (2009). Therefore, if a company wanted to find statistically significant changes in injury rates over time, they would need to collect data for a long period of time, possibly years. In addition, we used project length to adjust for the duration of project, differentiating smaller from larger projects. Ideally, we would have included a variable to account for the total worker time at risk in each project, but we did not have total man-hours data available. We used project length as a crude measure to show some difference in size of project. We also selected projects that had specific types of contracts (fixed bid, design build, contractor management) so the work schedules and likelihood of unexpected delays were more similar. Large, complex, multi-construction contracts were excluded from this study. We also selected projects with complete data for all indicators to capture the typical trades that worked on MB projects.

7. Recommendations for future testing of leading indicators

This research began by asking whether construction projects with higher values for leading indicators experience fewer adverse events and lower values of lagging indicators because of the projects' preventative measures. The belief was that if the relationship between leading and lagging indicators could be seen in this case study, it would support current research and safety promotion. This study found that the relationship between leading and lagging indicators, when studied through a single company's administrative data, had a minimal to no prevention effect when examined within the entire project period rather than segments of time within the project. While the findings from our study are limited in terms of generalizability, this research does show the difficulties of investigating safety prevention from a company perspective.

One major struggle for safety professionals has been to get companies to take part in safety prevention. Companies will often say that they do not have time, it costs too much, it will not work, or they are not interested. This study shows that part of the difficulty of safety promotion may lie in the fact that companies cannot see the positive effect of injury prevention in their workplace. This may be because the metrics that we use to evaluate safety prevention are not effectively showing the strengths of safety prevention when measured within a company or the methods to examine the effects are too complex for a construction contractor. If companies could easily see the benefits of their safety prevention based on their administrative data, it would be much easier to promote safety prevention. Future research should work to improve the indicators that form the basis of safety promotion so that safety can become more relevant to the companies that the promotion is designed for.

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