Safety and environmental variables: effect on steel erection task durations

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ABSTRACT: In 2002, the construction industry had the undesirable distinction of having two of the most dangerous occupations in the United States, with fatalities among structural steel workers at 58.2 fatalities per 100,000 workers (4th highest rate) and construction laborers experiencing fatalities at the rate of 27.7 fatalities per 100,000 workers (9th highest rate). In addition to the costs associated with construction accidents such as increased insurance premiums and medical expenses, loss of productivity is a cause for concern to the industry.

This paper presents the results from the analysis of observations at steel erection projects in the state of Indiana, USA and statistical analysis of task durations in steel erection collected over a six month period. The results of the analysis showed safety and environmental factors can influence worker productivity and demonstrate the need for research in order to find the causes of these impacts.

1 INRODUCTION

Of all workplace fatalities in 2002, one thousand one hundred and twenty one (1121), approximately 20%, occurred in construction related accidents (Bureau of Labor Statistics (BLS) 2002). Structural steel workers ranked fourth and construction laborers ranked ninth with 58.2 and 27.7 fatalities per 100,000 workers, respectively (BLS 2002). About 33% of all fatalities in the construction industry are related to falls (BLS 2002). In steel erection, 63% of the fatalities are the result of falls. When fatalities or injuries occur, the productivity of the construction worker is affected. A decrease in productivity of 33% can be observed within the first 48 hours following the occurrence of an injury (Coble et al. 2000). Workers in the vicinity of the accident are also affected since the accident diverts their attention away from their work.

1.1 *Safety and productivity*

Sometimes contractors overlook the use of safety devices since they believe, without evidence, that the use of safety devices increases the time taken by the workers to perform their tasks, which in turn "impedes their productivity." It is important to determine if there are benefits to the performance of the worker when using protective equipment and to communicate those benefits so that workers will make more extensive use of the established safety requirements.

The American Institute of Steel Construction (AISC) has identified productivity as important issue affecting the steel construction industry. According to the AISC, a 25% reduction in the time required to erect a steel structure is needed to maintain competitiveness (Lytle et al. 2002). Reducing fabrication and erection time, and increasing the safety of the workers are issues that must be addressed for the industry to remain competitive.

1.2 *Characteristics of steel erection work*

Steel erection work involves three main activities: raising, fitting, and fastening. This paper focuses on safety issues related to the first two activities (raising and fitting) which can be considered as the initial stage of the steel erection process. The decking of the structure is an activity that occurs after fastening and in concert with the raising and fitting activities.

In the raising activity, the structural steel elements are lifted to the installation point and then positioned in preparation for the initial connections. The fitting activity entails the initial connection of structural steel members. In this stage not all the bolts required at the connection points are installed and the ones installed are tightened with a hand wrench. During the fastening activity the final connections are made. The remaining bolts required at all connection points are installed, and together with the bolts previously installed, tightened as per specifications using an impact wrench.

The tasks involved in the *raising* and *fitting* activities of the steel erection process are described in Table 1. The *Position*, *Connect*, and *Unhook* tasks were selected for the analysis due to the high exposure to the hazard of falls from elevations that workers encounter while performing these tasks. A study by Slaughter & Eraso (1997) evaluated the impact of innovations on construction processes considering the level of danger posed by the tasks. Based on the standard causes of construction injuries, they developed a danger index for selected steel erection tasks. The index was weighted by the number of structural steel members installed and the time the workers were exposed to different hazards. An important component of the danger index is falls, since falls constitute one of the three main causes of injuries when performing the tasks of *Position*, *Connect* and *Unhook*. Being struck by objects or equipment, and getting caught in or between materials or equipment are some of the other causes of injuries and fatalities in steel erection.

Table 1. Steel erection tasks

Task	Description
Position	The connector grabs the load to be installed and guides it to the final position where it will be attached to the structure.
Connect	Either one of the two connectors inserts the reamer or spud bar into a bolt hole and then installs the connection bolts. The worker is considered a "connector" only when working with "hoisting equipment". This includes placing components as they are received from hoisting equipment, and then connecting those components while hoisting equipment is overhead.
Un-hook	One of the two connectors instructs the crane operator to lower the hoisting cable to allow the worker to un-hook it, the load is released and the crane returns for the next piece to be installed.

This paper identifies hazards present in steel erection using the characteristics of: (1) the tools used, (2) the materials used, (3) the design of the structures, and (4) the process used. In addition, the influence of safety and environmental factors on task durations is evaluated.

2 FIELD OBSERVATION OF THE STEEL ERECTION PROCESS

Field observation of phenomena in their natural state is a valuable tool for understanding the effects of variables inherent to construction processes. The direct observation method was used in this study, allowing the researcher to "be part of the group without being observed or obtrusive" (Trochim 2001). Benefits of the direct observation method include: minimization of the influence of the observer on the behavior of the subjects, and observations are usually flexible (not required to be structured around a hypothesis). Findings from observational research are considered strong in validity because the researcher is able to collect substantial information about different aspects of the behavior of interest (Trochim 2001). Information that can be collected using the observational method include: environmental factors that might influence subject behavior, and actions specific to the subjects being observed such as motion and interactions with tools and materials. Drawbacks of this method include the inability of the researcher to control the variables being observed, problems with reliability (the extent to replicate observations), generalizability or external validity (the extent to which the findings would be extended to other groups), and the subjective interpretation of the observer.

2.1 *Safety and worker performance data collection at steel erection sites*

Site visits were conducted at seven (7) steel erection projects in Indiana, USA between the months of January 2003 and February 2004 to collect data related to safety aspects of the steel erection process and data related to worker performance. Table 2 shows the projects visited and the data collected at each. Various hazards associated with the different tasks were identified in terms of the materials used in the process (structural elements, bolts, tools, etc.), the tools used by the workers (hand tools, Personal Protective Equipment (PPE), machinery, etc.), the design of the structures (shape of structural members, configuration of members when installed, etc.), and the process of erecting the structure (interactions between workers and equipment, movements required, etc.).

One hundred and eighty six (186) observations related to worker performance (task duration) were collected at three projects. The data were collected on different days at various periods during typical 8-hour workdays between the months of April and October 2003. The characteristics of each project were important because they provided a representative sample of possible working conditions such as different elevations, inclined surfaces, and different installation configurations of steel members. The performance time of each task was measured using a stopwatch. In addition, video cameras and still photography recorded safety conditions during the data collection period. The environmental conditions at the job site, the crew size information and location of the workers during the process, were also recorded. The types of projects used in the data collection are shown in Table 3.

Table 2. Data collected at steel erection sites

Project	Dates of Data Collection	Type of data collected
Valparaiso University Library	January 2003	Hazard assessment
Entrepreneurship Center Building at Purdue University	March 2003	Hazard assessment
Chemical Engineering Building Expansion at Purdue University	April - May 2003	Task duration data Environmental conditions Safety related conditions
Stadium Avenue Dining Hall at Purdue University	May - July 2003	Task duration data Environmental conditions Safety related conditions
West Lafayette Public Library	August 2003	Hazard assessment
Birck Nanotechnology Research Center at Purdue University	September - October 2003	Task duration data Environmental conditions Safety related conditions
Presbyterian Church Building in West Lafayette, Indiana	February 2004	Hazard assessment

Table 3. Projects used for analysis

Project Description	Dates of Data Collection	No. of Observations
Project 1 - 8919 square meters (96,000 square feet), five story addition to existing academic building	April - May 2003	62
Project 2 - Two story dining hall	May - July 2003	71
Project 3 - 17373 square meters (187,000 square feet), three story research facility	September - October 2003	53
Total		186

2.2 *Limitations of the data collection process*

One limitation of the data collection process was that observations could not be made for all the variables studied. In observational studies the researcher has no control over the process being investigated. This limitation is of significance in studies of safety issues since the researcher cannot control the safety behavior of the workers, for example, by asking them not to follow safety regulations. The behavior of construction workers regarding safety may be influenced by what they perceive as safe or unsafe. Based on this perception they make decisions on when to follow or not follow the required safety precautions. Huang & Hinze (2003) found that the level of appropriate use of PPE is not satisfactory. Enforcement of safety regulations by supervisors and the safety culture in the company are factors that motivate workers to use safety equipment more effectively. If the company promotes safety as part of their core values of work ethic, it can be expected that the workers will be more motivated to make use of the safety equipment available.

Delays in material delivery and equipment breakdowns were another limitation during the data collection process. These events resulted in a limited number of observations to be collected on several days during the data collection period. Weather was another factor that affected the number of observations obtained. Extremely low temperatures (below 20 degrees Fahrenheit) caused suspension of the work. On days after it had rained, the work was also suspended for safety concerns with wet surfaces.

3 ANALYSIS OF THE DATA COLLECTED AT STEEL ERECTION SITES

The data collected at the steel erection sites were analyzed to identify hazards in steel erection tasks and to determine the effect of several factors (environment and safety related) on the performance of the ironworkers (task duration). The measure of performance used was the duration of the tasks that the ironworkers performed. Analysis of Variance (ANOVA) was used to analyze the task duration data collected. The results of the analysis of the data are presented in the subsequent sections.

3.1 *Identified hazards associated with steel erection tasks*

Hsiao & Simeonov (2001) described three factors – environmental, task related and personal factors - that affect balance during roofing work, another activity that is performed at different elevations. Similarities between roofing work and steel erection, for instance: working at heights, handling heavy loads and tools, and walking on irregular surfaces, deems the use of these factors appropriate for the analysis of the steel erection process. Environmental factors concern the information available from visual and physical interactions. In steel erection, the elevation of the work area and the surfaces on which the ironworkers move are factors that can affect their balance and thus their performance. Task related factors include load handling, physical exertion and fatigue, and complexity of the tasks. The arduous nature of steel erection work makes task related factors important to the analysis of worker performance. Personal factors include individual differences, work experience, and interaction with personal protective equipment (PPE). The use of PPE is an important issue in steel erection since is the first line of defense for ironworkers, protecting them from the hazard of falls. The factors discusses can be used to identify possible health and safety issues and hazards in the performance of steel erection tasks. Visual information about the tasks performed by steel erection workers (videos and still photographs) and the applicable safety standards were used during the identification of hazards present in the process.

An example of the health and safety issues affecting ironworkers is the weight of the tools the worker must carry. A typical ironworker usually carries one or more wrenches, a crowbar or reamer, a bag of bolts and a safety harness. The combined weight of these items is approximately 22.7 kilograms (50 pounds). Figure 1 shows some of the hazards identified according to the selected criteria.

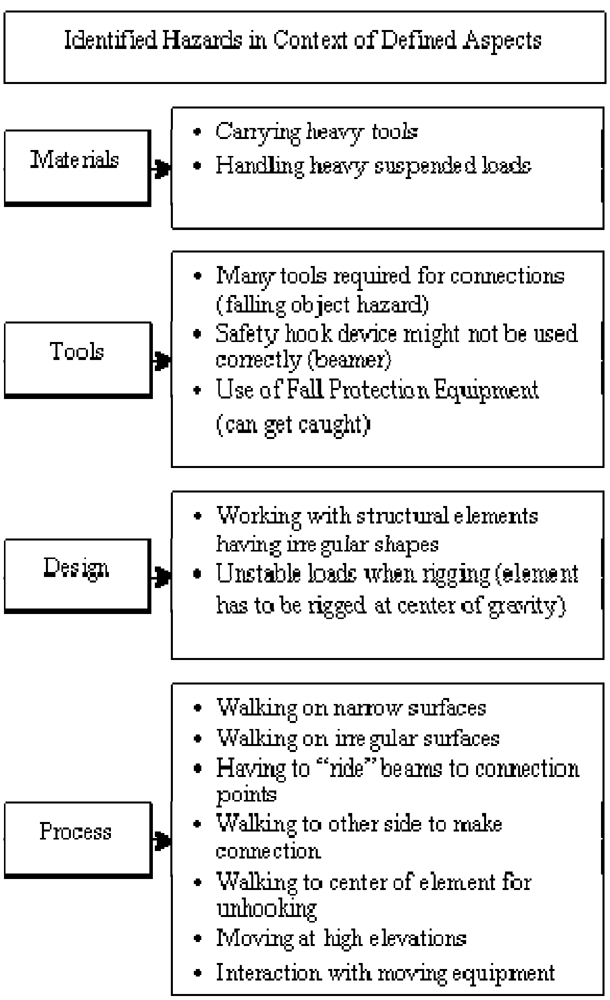

Figure 1. Identified hazards in the steel erection process

Many of the hazards observed at the job sites can be directly related to falls from elevations. The conditions related to this hazard must be considered to understand their impact on the performance of ironworkers. Using the OSHA steel erection standard (OSHA Code Subpart R - Steel Erection, Section 1926.760) three important conditions related to the hazard of falls from elevations were identified (see Table 4). The first (use of fall protection is required) and third (presence of decking on the level below the work level) conditions are important because their combination may dictate what safety precautions are required during the steel erection process. Some steel erection contractors may use this combination when planning the erection sequence to reduce the exposure of the worker to the risk of falling to lower levels. Other contractors may use the combination to prevent the loss of productivity that may be incurred when safety devices such as personal protective equipment (PPE) are used.

Table 4. Conditions related to safety in the steel erection process

Factor	Safety Related Conditions	Definition
1	Use of Fall Protection Required	Were the workers required to use personal protective equipment (PPE) as fall protection? This depends on the elevation while working (according to OSHA Code Subpart R –Steel Erection, Section 1926.760 (a)(1), (b)(1) and (b)(3))
2	Fall Protection Used	Was PPE actually used by the workers?
3	Presence of Decking on Level Below	Was there decking in place on the level below where the workers were located? This requirement is related to Section 1926.754 (b)(3) of OSHA Code Subpart R-Steel Erection. For this rule to apply the difference in elevation between the working location and the level below should be less than the 4.57m (15ft) to 9.14m (30ft) restriction set forth by Section 1926.754 (b)(3).

3.2 *Analysis of tasks duration*

Modeling the influence of environmental and safety conditions on performance involved using ANOVA to determine if there were significant differences between the average duration of the three steel erection tasks (namely, *positioning*, *connecting* and *unhooking*) under the different safety and environmental conditions studied. The duration of the three selected steel erection tasks were designated as the response variables. The environmental conditions observed and the safety related conditions were designated as the explanatory variables (sometimes referred to as factors or treatments). A description of the variables used in the analysis of the variation of task durations in steel erection is included in Table 5. The analysis of the data was performed using the general linear model (GLM) procedure in the SAS software (SAS Institute Inc., Cary, NC).

Table 5 Variables used in the development of the models

Variable	Description
Position	Response variable measured as the duration of the Positions task (seconds).
Connect	Response variable measured as the duration of the Connect task (seconds).
Unhook	Response variable measured as the duration of the Unhook task (seconds).
Temperature (temp)	Explanatory variable. Temperature recorded at the job site during data collection. The unit of measure is ºF. This is considered a quantitative variable.
Humidity (hum)	Explanatory variable. The % relative humidity recorded at the job site during the data collection. This is considered a quantitative variable.
Elevation (elev)	Explanatory variable. Elevation in feet taken from ground level to the point of installation of the steel member. This is considered a quantitative variable.
Time of Day (tod)	Explanatory variable or factor. Time of day when observations where made. The factor has two levels and the values are: (1) if the data was collected in the morning hours (8:00am to 12:00noon) and (0) if the data was collected in the afternoon hours (1:00pm to 4:00pm). This is a qualitative variable.
Use of fall protection equipment (protused)	Explanatory variable or factor. This factor has two levels. If the workers used fall protection equipment the value was one (1) and if the workers were not using the equipment the value was zero (0). This is considered a qualitative variable.
Presence of decking below (deck)	Explanatory variable or factor. This factor has two levels. If the level below the workers had metal deck already installed, the factor had a value of one (1) and a value of zero (0) if the deck was not installed. This is considered a qualitative variable.
Compliance (comp)	Explanatory variable or factor. Based of the combination of the "protused" and "deck" variables this variable determines if there was a case of compliance or non compliance with the OSHA steel erection standard. If the observation was a case of compliance the factor had a value of (1) and if there was non compliance a value of (0).
Project (proj)	Explanatory variable or factor. Used to distinguish the project from which the data was obtained. The purpose of this variable was to detect possible effects of variables that can not be easily measured like type of project, safety management practices and others. This factor has three levels, one for each project. Values of (1), (2), and (3) where assigned to the levels.

When the underlying assumptions of ANOVA were examined it was observed that the normality and the constant variance of the residuals assumptions were violated. In cases where the ANOVA assumptions are violated, transformations of the response variable can be used to stabilize the error variances and usually bring the distribution of the error terms closer to a normal distribution. Three of the most common transformations that can be used to address the violation of ANOVA assumptions are the logarithmic, square root, and reciprocal transformations (Neter et.al 1996). The logarithmic transformation provided the best results correcting the non constant variance problem and bringing the residuals closer to a normal distribution. Several outlying observations were identified and after evaluating the studentized residuals it was determined that very few observations had to be removed (one (1) for the *Position* Task, none for the *Connect* Task, and two (2) for the *Unhook* Task). These observations corresponded to unusual situations observed during the steel erection process. For example, workers talking to each other, workers smoking, and installation of steel members that did not fit correctly and required additional installation time. The significance of the factors and their interactions were evaluated for each of the tasks and final models were selected. Due to the nature of the study, which involved observing construction workers in an uncontrolled environment, the coefficient of multiple determination (R^2) for the models can be expected to be small (in this case, R^2 was 0.26 for the *Position* task, 0.10 for the *Connect* task, and 0.27 for the *Unhook* task). The following sections discuss the results obtained for each of the models (*Position, Connect,* and *Unhook*) and include interpretation of the variables and their implications for the safety and the performance of workers in the steel erection process.

3.2.1 *Effect of variables on the Position task*

The analysis of the data of the *Position* task showed that there are four significant main effects: *Project*, $p < 0.0001$, *Time of Day*, $p = 0.0009$, *Protection Used*, $p = 0.0012$, and *Deck Present*, $p = 0.0009$ (see Table 9). A main effect indicates to what extent the factor level means deviates from the overall mean (Neter et.al 1996). A significant main effect suggests that the mean of the response variable is significantly different from its overall mean at the different values of the factor being analyzed. For example, a significant main effect for the factor *Protection Used* indicates that the mean duration of the Position task is significantly different when fall protection equipment is used or not used. The variable *Elevation* was close to being significant at the $\alpha=0.05$ level, $p = 0.0544$. Since *Elevation* is considered to be an important variable related to the safety of the ironworker it was decided to include it in the model. The factor *Compliance* and the variables *Tempera-*

ture and *Humidity* were not significant. There were no significant interactions among the factors analyzed in the model.

The Tukey-Kramer multiple comparison procedure was used to determine if there were significant differences between the levels of the factors analyzed. The analysis showed that the average duration of the *Position* task was significantly higher in the morning hours, significantly higher when fall protection equipment was used, and significantly higher when decking was present under the floor being erected. It can be observed that the average task duration on Project 1 is significantly lower than on Project 3 (p=0.0002), but not significantly different from Project 2 (p=0.5521). The average task duration on Project 2 is significantly lower that on Project 3 (p=0.0008). It can be inferred that characteristics related to safety management and project and company size could have an effect on task durations on projects similar to Project 3, where task duration can be expected to be higher than on projects similar to Projects 1 and 2. The main differences between Projects 1, 2, and 3 are the presence of a full time safety coordinator or manager on site and the size of the companies (steel erector and general contractor).

Equation 1 shows the final model for the *Position* task. The purpose of the models is to describe the effect of the safety related variables and the environmental variables on the duration of the tasks. Since a logarithmic transformation was used in the modeling process, it is necessary to transform the model to obtain correct units of the response variable. The resulting transformation is shown in Equation 2.

$$\mathrm{Log}(\mathrm{T}_{\mathrm{Position}}) = \mu + \beta_i + \gamma_j + \delta \times \mathrm{elev.} + \phi_k + \nu_l + \varepsilon_{ijkl} \qquad (1)$$

$$\mathrm{T}_{\mathrm{Position}} = e^{(\mu + \beta_i + \gamma_j + \delta \times \mathrm{elev.} + \phi_k + \nu_l + \varepsilon_{ijkl})} \qquad (2)$$

The resulting model represented by Equation 2 is considered a multiplicative model. The average task duration (e^{μ}) is multiplied by each of the terms corresponding to the factors and variables in the model. Table 6 shows the parameter estimates and multiplicative terms corresponding to the levels of the factors and variables included in the model. As shown by the values of the multiplicative terms of the *Project* factor, the duration of the *Position* task is reduced relative to the mean on projects with the characteristics similar to those of Projects 1 and 2 by 3.8% and 13.3% respectively. On projects with characteristics similar to those of Project 3 the duration of the *Position* task is increased by almost 20%. This can be attributed to the strict enforcement of safety regulations on Project 3. For example, when workers make use of fall protection equipment the duration of the task would tend to increase by approximately 34%. If decking is present in the floor below the workers performing the *Position* task, the duration would be increased by approximately 21%. Elevation of the work area decreases task duration by a factor of 0.9971 raised to the elevation in feet.

Table 6. Parameter Estimates and Multiplicative Terms: *Position* Task Model

Factors / Variables	Level Value	Parameter Estimates	Multiplicative Terms
Task Mean (μ)		1.71	5.53 seconds
Project (β)	i = 1	-0.0390	0.9617
Project (β)	i = 2	-0.1431	0.8666
Project (β)	i = 3	0.1822	1.1998
Time of Day (γ)	j = 0	0	1
Time of Day (γ)	j =1	0.1521	1.1643
Elevation (δ)		-0.0028	0.9971*
Protection Used (φ)	l = 0	0	1
Protection Used (φ)	l = 1	0.2936	1.3412
Deck Present (υ)	m = 0	0	1
Deck Present (υ)	m = 1	0.1885	1.2074

*To apply factor multiply by $e^{-0.0028 \mathrm{xelev}} = (0.9971)^{\mathrm{elev}}$

For example, a project with characteristics similar to Project 3, on which the Position tasks is being performed in the morning hours at an elevation of 9.14 meters (30ft), and where fall protection is being used having decking below the work area, the task duration would increase by 1.82 seconds.

3.2.2 *Effect of variables on the Connect task*

The factors that were found to have a significant effect on the duration of the *Connect* task were *Time of Day*, p = 0.0010, and *Elevation*, p = 0.0266. The factors *Compliance*, *Project*, *Protection Used*, *Deck Present*, and the variables *Temperature* and *Humidity* were not significant in this model. No significant interactions where observed among the factors analyzed.

The results of the Tukey-Kramer multiple comparison procedure showed that the mean duration of the *Connect* task was significantly higher in the morning hours. Equation 3 shows the final model for the *Connect* task. The application of the logarithmic transformation of the data requires that the model be transformed to obtain the correct units of time. Equation 4 shows the transformed model. The resulting model is also a multiplicative model. Table 7 shows the parameter estimates and the multiplicative terms for the factors in the model. Similarly to the *Position* task, the duration of *Connect* task is higher in the morning hours by approximately 18% (see Table 7). The results also showed that the duration of the *Connect* tasks increases with increasing elevation by a factor of 1.0028 raised to the elevation in feet (see Table 7).

$$\mathrm{Log}(\mathrm{T}_{\mathrm{Connect}}) = \mu + \gamma_i + \delta \times \mathrm{elev.} + \varepsilon_i \qquad (3)$$

$$\mathrm{T}_{\mathrm{Connect}} = e^{(\mu + \gamma_i + \delta \times \mathrm{elev.} + \varepsilon_i)} \qquad (4)$$

Table 7 Parameter Estimates and Multiplicative Terms: *Connect* Task Model

Factors / Variables	Level Value	Parameter Estimates	Multiplicative Terms
Task Mean (μ)		1.9569	7.08 seconds
Time of Day (γ)	i = 0	0	1
Time of Day (γ)	i = 1	0.1638	1.1779
Elevation (δ)		0.0028	1.0028

*To apply factor multiply by $e^{0.0028 x elev} = (1.0028)^{elev}$

3.2.3 *Effect of variables on the Unhook task*

The factors *Compliance* and *Project* were not included in the model since there were empty cells on some of the combinations of these factors. This caused some parameter estimates to be inestimable. To solve this, a new factor, *PCL*, was created which is a combination of the *Project* and *Compliance* factors. Table 8 shows the levels of the *PCL* factor. When this factor was included in the model it was found to be significant (α=0.05). There were two significant factors on the *Unhook* task model, the *PCL* factor, $p = 0.0007$, and the *Protection Used* factor, $p < 0.0001$. The factor *Deck Present* and the variables *Temperature* and *Humidity* were not significant in this model. The only interaction observed during the model development process was between the variables *Temperature* and *Humidity*. This interaction was found to be significant but not important. It was a mild interaction that was eliminated since it did not benefit the performance of the model in explaining the effects of the other factors and variables on the duration of the *Unhook* task. However, it was included as a covariate to help explain variability in the data but was not successful. For this reason the final model did not include the *Temperature* and *Humidity* variables.

Table 8. The *PCL* Factor

Factors		
Project	*Compliance*	*PCL (levels)*
Project 1	0=No	1
Project 1	1=Yes	2
Project 2	0=No	3
Project 2	1=Yes	4
Project 3	0=No	5
Project 3	1=Yes	Empty Cell

As with the previous two models, the application of the logarithmic transformation of the data requires a transformation of the model in order to obtain the correct units of time. Equation 6 shows the transformed model. The *Unhook* model is also a multiplicative model. The parameter estimates and the multiplicative terms for the factors in the *Unhook* model are shown in Table 9.

$$\mathrm{Log}(\mathrm{T}_{\mathrm{Unhook}}) = \mu + \rho_i + \varphi_j + \varepsilon_{ij} \quad (5)$$

$$\mathrm{T}_{\mathrm{Unhook}} = e^{(\mu + \rho_i + \varphi_j + \varepsilon_{ij})} \quad (6)$$

Table 9. Parameter Estimates and Multiplicative Terms: *Unhook* Task Model

Factors / Variables	Level Value	Parameter Estimates	Multiplicative Terms
Task Mean (μ)		1.1287	3.09 seconds
PCL (ρ)	i = 1	-0.0001	0.9999
PCL (ρ)	i = 2	-0.0864	0.9172
PCL (ρ)	i = 3	-0.1774	0.8374
PCL (ρ)	i = 4	-0.0028	0.9972
PCL (ρ)	i = 5	0.2668	1.3058
Protection Used (φ)	j = 0	0	1
Protection Used (φ)	j = 1	0.3756	1.4558

The results of the Tukey-Kramer multiple comparison procedure showed that the mean duration of the *Unhook* task was significantly higher (approximately 31%) for projects with characteristics similar to those of Project 3 with no non-compliance of safety standards related to fall protection (*PCL* when i=5) than for projects with characteristics described by *PCL* on all other levels. There was no significant difference between the other levels of the *PCL* factor. The p-values of the Tukey-Kramer comparison procedure for the *PCL* factor are included in Table 10. The results for the *Protection Used* factor show that the duration of the *Unhook* task is approximately 46% higher when fall protection equipment is used ($p<0.0001$).

Table 10. Tukey-Kramer multiple comparison results for *PCL* factor

i/j	1	2	3	4	5
1		0.5905	0.2443	1.0000	0.0405
2	0.5905		0.8481	0.6561	0.0034
3	0.2443	0.8481		0.0610	0.0016
4	1.0000	0.6561	0.0610		0.0426
5	0.0405	0.0034	0.0016	0.0426	

It is important to understand the practical significance of the results obtained from the models developed. Since the tasks studied are of short duration (between 3 and 7 seconds on average), the effect of the factors and variables analyzed should not be interpreted as a reason for not using fall protection equipment based on the observed increase in task duration. On the contrary, the results show that safety related factors, such as the enforcement of safety regulations, have a relatively small effect in performance time. Therefore, compliance with safety regulations, such as use of required fall protection equipment is strongly encouraged.

4 DISCUSSION AND CONCLUSSIONS

Safety has traditionally not been included as a primary factor in prior studies on labor productivity. The objectives of this paper was to evaluate how factors related to safety in steel erection and the job site environment affect the performance time of ironworkers (task durations). The methods used to accomplish the objectives included site observations at seven steel erection projects and ANOVA modeling using one hundred and eighty six observations of task durations in steel erection. The results presented in this paper show that it is possible to quantify the impact of safety and environmental factors on ironworkers' performance by analyzing task duration data. By quantifying the effect that safety practices have on worker performance, modifications to improve performance of constructions processes could be evaluated considering the effects on the safety of the workers. More extensive evaluation of safety equipment could be undertaken to develop equipment that assists workers instead of hindering their performance.

Workers were observed while performing steel erection tasks and several hazards were identified. The conditions related to the hazard of falls from elevations were used to investigate the effect that these conditions have on the performance of workers in 3 key tasks namely, *Position, Connect* and *Unhook*. Five factors (*Project*, *Time of Day*, *Protection Used*, and *Deck Present*) significantly affected the duration of the *Position* task while two factors (*Time of Day*, and *Elevation*) affected the *Connect* task and two factors (*PCL* and *Protection Used*) affected the *Unhook* task. It appears that tasks, such as *Position*, which require more movement from the worker, are influenced by more factors. The combination of environmental factors, task-related factors, and personal factors can have a combined effect on the balance of ironworkers while moving, thus increasing task duration. For example, the use of fall protection significantly affected the duration of the *Position* and *Unhook* tasks. This can be expected since the workers performing these tasks move more and fall protection equipment appears to affect their movement. The environmental variables of time of day and elevation significantly affected only the *Position* and *Connect* tasks. This effect can be attributed to the actions the workers have to perform during these tasks. In the *Position* task workers are required to handle heavy loads while guiding the structural members into the installation point and in the *Connect* tasks they are required to use heavy tools to connect the structural members. The resulting physical exertion and fatigue can affect the performance of the worker by increasing the time required to perform the tasks.

The possible increase in task duration resulting from the use of safety equipment could be offset by: (1) improved quality, (2) reduction in the occurrence of accidents which results in cost savings from reduced insurance premiums and (3) increased competitiveness by having a lower experience modifier rate (EMR).

The observed impact must not be interpreted as a reason to forgo the use of safety equipment, but rather as an opportunity for further improvement in existing equipment and work procedures. Workers would benefit from lighter tools, improved installation procedures, and personal protective equipment that does not hinder worker movement, especially when working at heights.

A restriction of this study was the limited number of observations for each of the variables analyzed. This is typical in observational studies where there is no control over the process being investigated. This limitation could be addressed in future research by designing controlled experiments in simulated environments allowing a larger sample of observations to be collected.

Possible avenues for additional research include the development of improved PPE, and exploring innovative means and methods of construction that improve productivity without negatively impacting the safety of the worker.

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