Effects of the Occupational Safety and Health Administration's control of hazardous energy (lockout/tagout) standard on rates of machinery-related fatal occupational injury

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ORIGINAL ARTICLE

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Objective: To evaluate the impact of the United States' federal Occupational Safety and Health Administration's control of hazardous energy (lockout/tagout) standard on rates of machinery-related fatal occupational injury. The standard, which took effect in 1990, requires employers in certain industries to establish an energy control program and sets minimum criteria for energy control procedures, training, inspections, and hardware.

Design: An interrupted time-series design was used to determine the standard's effect on fatality rates. Machinery-related fatalities, obtained from the National Traumatic Occupational Fatalities surveillance system for 1980 through 2001, were used as a proxy for lockout/tagout-related fatalities. Linear regression was used to control for changes in demographic and economic factors.

Results: The average annual crude rate of machinery-related fatalities in manufacturing changed little from 1980 to 1989, but declined by 4.59% per year from 1990 to 2001. However, when controlling for demographic and economic factors, the regression model estimate of the standard's effect is a small, non-significant increase of 0.05 deaths per 100 000 production worker full-time equivalents (95% CI −0.14 to 0.25). When fatality rates in comparison groups that should not have been affected by the standard are incorporated into the analysis, there is still no significant change in the rate of machinery-related fatalities in manufacturing.

Conclusions: There is no evidence that the lockout/tagout standard decreased fatality rates relative to other trends in occupational safety over the study period. A possible explanation is voluntary use of lockout/tagout by some employers before introduction of the standard and low compliance by other employers after.

Traumatic occupational injuries are estimated to cause about 350 000 fatalities worldwide each year.[1 2] Many are machinery-related. In the USA, machinery-related injuries accounted for 13.2% of all occupational injury deaths in 1980–1995.[3] In developing countries, the number of machinery-related fatalities is likely to climb with increasing industrialization.[2]

Because potentially hazardous energy cannot be eliminated from many industrial processes, its unexpected release must be prevented to protect workers. Production processes can be designed so that workers are separated from hazardous energy during normal operation by machine guarding and by establishing safety procedures, including rules prohibiting workers from entering dangerous zones near equipment. However, during installation, maintenance, or repair, workers often must enter dangerous zones to perform job tasks.

"Lockout/tagout" is the practice of shutting down and disconnecting power from machinery or equipment and placing locks and warning tags on energy-isolating devices to prevent activation of the machine or equipment during maintenance or servicing.[4 5] In 1989, the US federal Occupational Safety and Health Administration (OSHA) enacted The Control of Hazardous Energy (Lockout/Tagout) Standard (29 CFR 1910.147).[6] The standard, which took effect in January 1990, requires all employers in certain industries to establish an energy control program for locking out equipment and blocking or dissipating stored energy, criteria for employee training, and periodic inspections.[7]

OSHA estimated that the lockout/tagout standard would prevent more than 100 fatalities and thousands of non-fatal injuries every year,[8] but the effects of the standard have not been rigorously evaluated. OSHA conducted a "lookback review" of the lockout/tagout standard in the late 1990s.[9] On the basis of comments and testimony from industry representatives, OSHA concluded that the standard should be continued without change. Two analyses described in the lookback review provide some evidence of a decline in lockout-related fatalities among unionized employees in the auto and steel industries after 1990. However, the auto industry study reported only post-standard fatalities, and the steel industry study reported lockout-related fatalities only as proportions of all fatalities, substantially limiting causal inferences.

It is important to determine whether occupational safety and health policies have reduced fatality rates so that appropriate future policy actions can be taken. However, relatively few OSHA standards have been carefully evaluated. This study estimates the impact of the lockout/tagout standard on rates of fatal machinery-related occupational injuries.

METHODS

Study design

To estimate the effect of the lockout/tagout standard, we used an interrupted time-series design with multiple comparison groups. Any impact of the standard should be concentrated in the manufacturing industry, where 74–82% of all lockout/tagout-related incidents occur,[8] and should be specific to fatalities involving machinery. Therefore, changes in machinery-related fatalities in manufacturing after the adoption of the

Abbreviations: GDP, gross domestic product; ICD, International Classification of Diseases; OSHA, Occupational Safety and Health Administration standard were assessed relative to changes in two comparison measures: (1) fatal injuries from all other causes (non-machinery-related) in the manufacturing industry, and (2) machinery-related fatalities in the construction industry. These comparison measures should reflect changes in other relevant occupational safety conditions, but theoretically should not have been affected by the standard. Construction was selected as a comparison industry because it was excluded from the standard and because rates of machinery-related fatalities in construction are more similar to those in manufacturing than are the rates in other excluded industries such as mining.[10] Before the standard (1980–1989), annual machinery-related fatality rates in manufacturing were more highly correlated with those in construction (r = 0.52) than with those in mining (r = −0.10).

Outcome measures

The primary outcome of interest in this study is the rate of machinery-related fatalities in the manufacturing industry. It is impossible to directly identify lockout/tagout-related fatalities using standardized cause-of-death codes. There is no code to indicate that an incident involved the unexpected release of hazardous energy during maintenance or servicing and could be considered a ''lockout/tagout'' case. It was therefore necessary to use a proxy that is coded in a standardized way. Machinery-related fatalities is the best proxy for lockout/tagout-related fatalities because prior research indicates that 43–76% of machinery-related fatalities result from failure to control hazardous energy.[11]

Machinery-related fatalities in the manufacturing industry will be referred to as the ''machine-manufacturing'' industry-cause group or the ''experimental'' group. Rates of non-machinery-related fatalities in the manufacturing industry and machinery-related fatalities in the construction industry will be referred to as the ''comparison groups'' or, specifically, the ''non-machine-manufacturing'' and ''machine-construction'' industry-cause groups, respectively.

The number of fatal occupational injuries in each of the years from 1980 through 2001 was obtained from the National Traumatic Occupational Fatalities surveillance system which is maintained by the National Institute for Occupational Safety and Health. Employment data, including the number of production workers and the average weekly hours of production workers for each industry and year, were obtained from the Bureau of Labor Statistics Current Employment Statistics Survey.[12] Industry-specific fatality rates were calculated as the number of fatalities occurring in an industry divided by the number of production worker full time equivalents in that industry. The outcome measure was restricted to fatalities because, although non-fatal injury data generally provide more cases than fatality data, lockout/tagout-related incidents account for only 2% of non-fatal injuries, compared with 7% of fatalities.[8]

Covariates

Because changes in economic conditions and workforce demographics can affect injury rates, multiple regression techniques were used to control for changes in these factors. Covariates were identified on the basis of the strength of the association with the outcome measure, as established in the literature,[13–19] the variability of the predictor, and, in some cases, the observed correlation with the outcome measure. Candidate predictors included the percentage of workers in each industry who are males aged 16–24, the percentage of workers without a high school diploma, real gross domestic product (GDP) by industry, the 1-year lag of GDP, the average weekly overtime of production workers (available for manufacturing only), real earnings by industry, and the percentage of firms in each industry with fewer than 20 employees. The final set of predictors was selected on the basis of model fit.

Statistical analysis

To determine the best form of the regression models, the distributions of the number of deaths and death rates in each industry-cause group were examined for normality using histograms, quantile-normal plots, kernel density estimate plots, the Shapiro–Wilk test, and the Skewness/Kurtosis test for normal data. Although Poisson and negative-binomial regression are commonly used for modeling count data, all tests indicated that the outcome data are approximately normally distributed in every industry-cause group. Therefore, linear regression modeling was chosen.

Separate linear regression models were constructed for each industry-cause group. In each model the outcome measure was the annual fatality rate. Each model included an intervention term set equal to zero for 1980 through 1989 and set equal to one for 1990 through 2001. Because fatality rates declined throughout the study period in all industry-cause groups, and

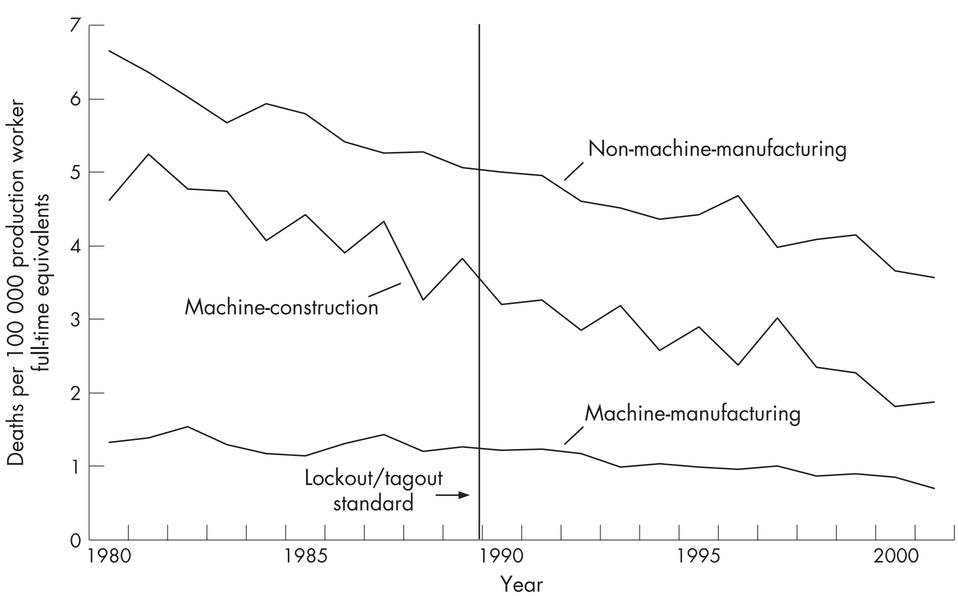

Figure 1 Crude fatality rates by industry-cause group, USA, 1980–2001.

Table 1 Coefficient estimates from regression models of fatality rates by industry-cause group

Predictor	Machine-manufacturing ($R^2=0.87$, $R^2_{adj}=0.81$) β (SE)	95% CI	Non-machine-manufacturing ($R^2=0.97$, $R^2_{adj}=0.96$) β (SE)	95% CI	Machine-construction ($R^2=0.93$, $R^2_{adj}=0.91$) β (SE)	95% CI
Intervention	0.05 (0.090)	−0.14 to 0.25	0.18 (0.167)	−0.18 to 0.53	−0.72 (0.438)	−1.65 to 0.21
Time	−0.06 (0.031)	−0.12 to 0.01	−0.17 (0.057)	−0.29 to −0.05	−0.003 (0.099)	−0.21 to 0.21
% young male	−0.13 (0.058)	−0.25 to −0.01	0.13 (0.108)	−0.10 to 0.36	−0.08 (0.112)	−0.32 to 0.16
Real GDP*	0.63 (0.901)	−1.29 to 2.55	1.93 (1.67)	−1.64 to 5.49	−4.32 (4.32)	−10.0 to 4.83
Overtime†	0.01 (0.132)	−0.27 to 0.29	−0.16 (0.246)	−0.69 to 0.36	N/A	N/A
Less education‡	0.04 (0.064)	−0.10 to 0.18	−0.07 (0.119)	−0.32 to 0.19	0.17 (0.127)	−0.10 to 0.44
Intercept	1.44 (0.829)	−0.33 to 3.20	4.87 (1.539)	1.59 to 8.15	3.95 (1.598)	0.57 to 7.34

GDP, gross domestic product; N/A, not available.
*Trillions of dollars.
†Average weekly hours.
‡Percentage of workers without a high school diploma.

broad changes in occupational safety may not be fully explained by the predictors in the model, a linear trend term (where 1980 = 0, 1981 = 1,…2001 = 21) was included in each model to account for this downward trend. The interaction between the intervention term and the linear trend term was also tested to determine whether the intervention is best modeled as a change in the rate of decline of fatality rates rather than a change in the mean level of fatality rates. The percentage of workers who are young males and real GDP were included as predictors in all of the models. The other candidate predictors were tested by comparing model fit with and without each predictor.

Model fit was assessed using the R^2 and partial-R^2 statistics, plots of predicted versus observed values, plots of model errors, and the Breusch–Pagan/Cook–Weisberg test for heteroskedasticity. Autocorrelation coefficients for the model residuals, along with their corresponding Q statistics and correlograms, were examined for evidence of significant autocorrelation. The Durbin–Watson statistic was also used to test for first-order autocorrelation.

Sensitivity analyses were performed to determine the degree to which the results of the analysis depend on the form of the model or the specification of certain parameters. All statistical analyses were performed using the Stata statistical software package (Stata Corp, V.9.0, 1984–2005).

Ethical approval

This study was approved by the Johns Hopkins Bloomberg School of Public Health Committee on Human Research.

Table 2 Intervention coefficient estimates from the alternative machine-manufacturing models

Alternative model	β	SE	95% CI Lower	95% CI Upper
Comparison groups as covariates	0.02	0.089	−0.17	0.21
Gradual effect 1	0.06	0.109	−0.17	0.30
Gradual effect 2	0.07	0.161	−0.28	0.41
Early effect 1	0.07	0.125	−0.20	0.34
Early effect 2	0.05	0.113	−0.19	0.29
Series without 1999–2001	−0.04	0.115	−0.29	0.21

Gradual effect 1: standard has a gradual effect beginning in 1990, full effect by 1991; gradual effect 2: standard has a gradual effect beginning in 1990, full effect by 1993; early effect 1: standard has a gradual effect beginning in 1989, full effect by 1992; early effect 2: standard has a gradual effect beginning in 1988, full effect by 1991; series without 1999–2001: immediate effect in 1990, but excluding data for 1999−2001.

RESULTS

Annual fatalities and fatality rates

There were a total of 124 023 traumatic occupational fatalities in the USA from 1980 to 2001. Of these, 3323 (2.7%) were machinery-related in manufacturing, 14 564 (11.7%) were non-machinery-related in manufacturing, and 2946 (2.4%) were machinery-related in construction.

Figure 1 shows crude fatality rates over the study period by industry-cause group. From 1980 to 1989, the rate of machinery-related fatalities in manufacturing changed little, with an average annual increase of 0.15% per year. However, from 1990 to 2001, the rate in this group declined by an average of 4.59% per year. Similarly, the rate of machinery-related fatalities in construction declined by an average of 1.08% per year from 1980 to 1989, and then by 4.53% per year from 1990 to 2001. The average annual decline in the rate of non-machinery-related fatalities in manufacturing was much more consistent before and after introduction of the standard, at 2.93% per year from 1980 to 1989 and 2.71% per year from 1990 to 2001.

Regression model estimates

Table 1 presents regression model estimates of the effect of the lockout/tagout standard by industry-cause group. The intervention effect is not statistically significantly different from zero in any of the models. For the machine-manufacturing group, the intervention term is close to zero at β = 0.05 (95% CI −0.14 to 0.25), which translates into a very small increase of just seven deaths per year, and, with a partial-R^2 of 0.003, explains less than half of 1% of the variability in fatality rates.

The best-fitting model includes the percentage of workers who are young males, real GDP, overtime hours worked, and the education level of workers as predictors. However, none of the candidate models yield qualitatively different results. The intervention effect estimates are similar for models without the education variable, models with the firm size variable, models including the intervention-by-time interaction, and models without the linear time trend variable.

Although few of the covariates in the final model are independently statistically significant, probably because of a certain degree of collinearity among them, the adjusted-R^2 values are close to the R^2 values, indicating that each covariate does explain some additional portion of the variance. Although collinearity among predictors can be problematic in regression analyses that aim to identify the most important predictors of an outcome, it is less of a problem in regression analyses, such as this one, that aim only to evaluate one predictor of interest (the intervention term), as long as the covariates are not also highly collinear with the predictor of interest.[20]

The autocorrelation functions of the residuals from the machine-manufacturing and non-machine-manufacturing models show no evidence of significant serial correlation. The autocorrelation function of the residuals from the machine-construction model indicates negative serial correlation for lag 1 (AC = −0.58, Q = 8.55, p = 0.004), and the Durbin–Watson statistic for this model is inconclusive (d(6,22) = 3.12, 4-d = 0.88).[21] Inclusion of the 1-year lag of the fatality rate eliminates the serial correlation in the machine-construction model, but does not substantially alter the intervention effect in any of the industry-cause groups.

Sensitivity analyses

Results of several sensitivity analyses are similar to the results of the primary analysis.

The intervention effect estimates for machine-manufacturing from these alternative models are all close to zero and not statistically significant (table 2).

Comparison groups as covariates

One sensitivity analysis includes the fatality rates of the comparison groups as covariates in the machine-manufacturing model. Because the lockout/tagout standard does not apply to the non-machine-manufacturing and machine-construction groups, they can act as controls for general changes in occupational safety over time (not related to the standard) that are difficult to measure. The combined model explicitly controls for trends in the comparison groups, making the magnitude and significance of the intervention term for the experimental group easier to interpret.

Alternative intervention transfer functions

The primary models assume an immediate, full effect of the standard, but it is possible that the standard was not implemented fully at the beginning of 1990. Alternative transfer functions were therefore modeled. One gradual-effect model assumes that the standard takes 1 year to implement, beginning in 1990. A second gradual-effect model assumes that the standard's implementation is spread evenly over 4 years, beginning in 1990. Because employers had advance notice of the standard, it is also possible that they began implementing lockout/tagout before 1990. One early-effect model assumes a 4-year gradual effect beginning in 1989, the year that the standard was promulgated (but before it took effect). A second early-effect model assumes a 4-year gradual effect beginning in 1988, the year that the proposed standard was published.

Series without 1999–2001

A final sensitivity analysis was performed to determine whether the results are different if the fatality data from 1999 to 2001 are removed from the analysis. In the National Traumatic Occupational Fatalities surveillance system, fatalities are classified according to the International Classification of Diseases (ICD). Coding from 1980 to 1998 followed the ICD Ninth Revision (ICD-9), but coding from 1999 to 2001 followed the ICD Tenth Revision (ICD-10). For this study, the numbers of fatalities for each of the years 1999 to 2001 were adjusted using the ICD-10/ICD-9 comparability ratio,[22] so some error may be associated with these data points.

Power analysis

Statistical power was calculated to determine whether this analysis had sufficient power to detect a significant change in fatality rates had one occurred. OSHA estimated that the standard would prevent 85% of fatalities from exposure to hazardous energy.[8] Assuming that 43–76% of machinery-related fatalities are lockout/tagout-related, and given an annual average of 175 machinery-related fatalities in manufacturing during the pre-standard period, we would have expected 64–113 fewer machinery-related manufacturing fatalities annually during the post-standard period. Although we cannot know precisely what the partial-R^2 would have been for such an effect, we estimated that 64 deaths per year would have a partial-R^2 of approximately 0.03, and 113 deaths per year would have a partial-R^2 of approximately 0.05, based on the results of our primary regression model.

Using the power calculation method proposed by Murphy and Myors,[23] we determined that with $\alpha = 0.05$, there would have been a power of 0.50 to detect an intervention effect with a partial-R^2 of 0.03, and a power of 0.80 to detect an intervention effect with a partial-R^2 of 0.05. With an estimated power between 0.50 and 0.80, this study would have been more likely than not to detect a change in fatality rates of the magnitude expected by OSHA.

DISCUSSION

There is no evidence that the lockout/tagout standard decreased machinery-related fatality rates in manufacturing relative to other trends in occupational safety over the study period. The average annual rate of machinery-related fatalities in manufacturing changed very little before the lockout/tagout standard took effect, but declined by 4.59% per year after the standard. However, when changes in workforce demographics, economic conditions, and unmeasured occupational safety conditions are controlled for, this pre–post difference in fatality rates disappears. The finding of no statistically significant effect of the standard is consistent across different forms of the regression models and different specifications of key parameters. When comparison groups are included as covariates in the machine-manufacturing model, there is still no evidence of an intervention effect. Taken together, these results provide no evidence that the lockout/tagout standard has significantly decreased rates of machinery-related fatalities in manufacturing.

The lack of a decline in the rate of machinery-related fatalities in manufacturing after 1990 may be due to a low level of compliance with the standard. The lockout/tagout standard was one of the standards most often cited by OSHA for violations during the early and mid-1990s and continues to be one of the top five most often cited standards in every manufacturing division today.[9 24]

Key findings

- There is no evidence that the lockout/tagout standard decreased machinery-related fatality rates in manufacturing relative to other trends in occupational safety over the study period.
- The finding of no statistically significant beneficial effect of the standard is consistent across different forms of the regression models and different specifications of key parameters.
- Failure to find a beneficial effect of the lockout/tagout standard does not indicate that the practice of lockout/tagout is ineffective.
- The lack of a decline in the rate of machinery-related fatalities in manufacturing after the standard took effect may be due to a low level of compliance with the standard.

These results may also reflect the voluntary use of lockout/tagout by some employers during OSHA's long rule-making process. Voluntary guidelines for locking out hazardous energy had been available since the early 1970s.[4] Some employers were already using lockout/tagout before 1990, even if they did not have comprehensive energy control programs.[4] However, sensitivity analyses that included assumptions that the standard's impact began as early as 1988 still yielded no statistically significant beneficial effect of the standard.

Limitations of the study

Identifying lockout/tagout cases

The need to use machinery-related injury as a proxy for lockout/tagout-related injury is a limitation of this study. Most lockout/tagout incidents are machinery-related, but not all machinery-related fatalities involve failure to control hazardous energy during maintenance and servicing. It is therefore possible that the lockout/tagout standard did actually decrease rates of lockout/tagout-related fatalities, but not enough for the corresponding change in the rate of all machinery-related fatalities to be statistically significant. It is also possible that a decrease in the rate of lockout/tagout-related fatalities was masked by an increase in the rate of other types of machinery-related fatalities, leading to an underestimate of the impact of the standard.

This concern was addressed, to the extent possible, through statistical modeling that explained a large proportion of the variability in rates of machinery-related fatalities in manufacturing (87% for the primary model). In addition, there is no evidence from the literature that the rate of other types of machinery-related fatalities changed substantially during the study period.

Measuring covariates

In the statistical models, it was not possible to explicitly control for every factor that could have affected occupational injury fatality rates over the study period. Including a time trend in the regression model and using the comparison groups as covariates in the model of machine-manufacturing fatality rates were two different ways that such unmeasured factors were controlled for in this study.

Implications for prevention

Given evidence that the *practice* of lockout/tagout is effective in reducing machinery-related injuries,[9] but no evidence for the effectiveness of the lockout/tagout *standard*, the question becomes how to ensure that employers and workers comply with the standard. If the types of situations in which workers are not likely to follow appropriate lockout procedures can be identified, prevention efforts can be targeted at workers who are often in these situations, or work routines can be altered so that these situations can be avoided altogether. In addition, enhanced OSHA enforcement of lockout/tagout standard violations might improve the standard's effectiveness.

The lockout/tagout standard sets minimum criteria for energy control programs, but employers have discretion in designing specific aspects of their programs. Many employers may be implementing only the bare minimum required by law. Incentives to exceed the minimum requirements might also enhance the effectiveness of the lockout/tagout standard.

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