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Effectiveness of temporary traffic control measures in highway work zones

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A B S T R A C T

In the United States, hundreds of people lose their lives each year and many more are injured due to vehicle crashes in the work zones. Over the years, temporary traffic control (TCC) measures have been developed and deployed in work zones. To continuously improve the safety, there is a need to identify the traffic control deficiencies in work zones by evaluating the effectiveness of existing TTC measures based on the real crash cases. In this study, researchers evaluated the effectiveness of several commonly used TTC methods using logistic regression techniques and various significance test methods including likelihood ratio test, score test, and Wald test. These TTC methods included flagger/officer, stop sign/signal, flasher, no passing zone control, and pavement center/edge lines. A total of 655 severe crashes in Kansas highway work zones between January 2003 and December 2004 were used for the evaluation, which included 29 fatal crashes and 626 injury crashes. Results indicated that flagger, flasher, and pavement center/edge lines were effective in reducing the probability of causing fatalities when severe crashes occurred. In addition, using these devices could prevent some common human errors, such as "disregarded traffic control," "inattentive driving," "followed too closely," and "exceeded speed limit or too fast for condition," from causing severe crashes.

1. Introduction

Highway work zones constitute a major safety concern for government agencies, the legislature, the highway industry, and the traveling public. The number of people killed in motor vehicle crashes in work zones rose from 872 in 1999 to 1028 in 2003 in the United States. In addition, approximately 40,000 people are injured each year as a result of motor vehicle crashes in these areas. Today, the majority of highway funds are being allocated to road and bridge preservation and enhancement, which means the traveling public is encountering more and more highway work zones.

Over the years, many temporary traffic control (TTC) measures have been developed and deployed in highway work zones. The primary function of these TTC measures in work zones is to provide highway users reasonably safe and efficient movement through work zones while protecting construction workers and equipment. Traffic engineers expect TTC measures to improve safety in work zones when they are designed, installed, and maintained properly. However, it is not clear the extent to which safety has been improved by using these measures. To determine the effectiveness of the safety countermeasures in work zones, there is a need to quantify the effectiveness of existing TTC measures.

2. Research objectives and methodology

Among all possible work zone crashes, crashes involving injuries and/or fatalities are the most severe and calamitous. Reducing these crashes will yield the most benefit to society. The objective of this research project was to quantify the effectiveness of several popular TTC measures, including flagger/officer, stop sign/signal, flasher, no passing zone, and pavement center/edge lines, in reducing fatalities when a severe crash occurs and in preventing common human errors from causing work zone severe crashes.

The project was conducted through three major steps. First, fatal and injury crash data were extracted from the Kansas Department of Transportation (KDOT) accident database. A total of 655 severe crashes, including 29 fatal crashes and 626 injury crashes, in Kansas highway work zones between January 2003 and December 2004 were collected for the evaluation. Then, logistic regression analysis was used to evaluate the effectiveness of the safety measures in these work zones. Finally, conclusions and recommendations for future research were formulated based on the results of data analyses.

3. Literature review

A highway work zone refers to a road section undergoing a construction or maintenance project. When the normal function of the highway is interrupted around a work zone, a TTC plan must be

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developed to provide continuity of movement for motor vehicles. As included in the Manual of Uniform Traffic Control Devices (MUTCD), some TTC methods that are commonly used in work zones include flaggers, traffic signs, arrow panels and portable changeable message signs, channelizing devices, pavement markings, lighting devices, and temporary traffic control signals (FHWA 2003). This section presents a brief review of these traffic control methods and previous evaluations.

Flagger control. Flaggers are qualified personnel with high-visibility safety apparel who are equipped with handheld devices such as STOP/SLOW paddles, lights, and red flags to control road users through work zones. Richards and Dudek (1986) suggested that flaggers have been most efficient on two-lane, two-way rural highways and urban arterials, where they had the least competition for drivers' attention; flaggers were also well suited for short-duration applications (less than one day) and for intermittent use at long-duration work zones. Garber and Woo (1990) concluded that the most effective combination of traffic control devices for work zones on multilane highways was cones, flashing arrows, and flaggers, and the effective combinations of traffic control devices for work zones on urban two-lane highways were both cones and flaggers as well as static signs and flaggers. However, a study by Benekohal et al. (1995) indicated that there was a need for improving flagging for heavy truck traffic. Their survey results showed that one-third of the truck drivers indicated that flaggers were hard to see, and half considered the directions of flaggers to be confusing.

Traffic signs. As listed in the MUTCD, traffic signs in work zones include regulatory signs, warning signs, and guide signs. Traffic signs in work zones are important for informing travelers about interrupted traffic conditions. Benekohal et al. (1995) indicated that half of the surveyed truck drivers wanted to see warning signs 3–5 miles in advance. Garber and Woo (1990) found that static traffic signs could effectively reduce crashes in work zones on urban two-lane highways when used together with flaggers.

Arrow panels and *portable changeable message signs.* Arrow panels and portable changeable message signs usually contain luminous panels with high visibility, which makes them an ideal traffic control supplement in both daytime and nighttime. Garber and Patel (1994) and Garber and Srinivasan (1998) conducted a two-phase research project to evaluate the effectiveness of changeable message signs for controlling speeds in work zones in Virginia. The changeable message signs could automatically display a real-time warning message to speeding drivers. The study concluded that changeable message signs were a more effective means than traditional work zone traffic control devices in reducing the number of speeding vehicles in work zones. Richards and Dudek (1986) commented that changeable message signs could result in only modest speed reductions (less than 10 mph) when used alone and would lose their effectiveness when operated continuously for long periods with the same messages. Huebschman et al. (2003) argued that changeable message signs were actually no more effective than traditional message panels.

Channelizing devices. Channelizing devices are used to warn road users of changed traffic conditions in work zones and to guide travelers to drive safely and smoothly through work zones. Channelizing devices include cones, tubular markers, vertical panels, drums, barricades, and temporary raised islands. The results of a previous study (Pain et al., 1983) showed that most of the channelizing devices were effective in alerting and guiding drivers, but the devices only obtained their maximum effectiveness when properly deployed as a system or array of devices. Garber and Woo (1990), however, found that the use of barricades in any combination of traffic control devices on urban multilane highways seemed to reduce the effectiveness of other traffic control devices.

Temporary pavement markings. Temporary pavement markings are used along paved highways in long- and intermediate-term stationary work zones to outline the travel paths. Pavement markings can be used to control speeds. For instance, a traffic control strategy using modified optical speed bars to meet the conditions of highway work zones has been applied to control speeds in work zones. Optical speed bars are an innovative speed control technique that uses transverse stripes spaced at gradually decreasing distances on pavement to affect the driver's perception of speed. Meyer (2004) conducted a study to evaluate the effectiveness of this strategy in reducing work zone speed in Kansas. The study showed that the speed bars had both a warning effect and a perceptual effect and were effective in controlling speeds and reducing speed variations.

Lighting devices. Lighting devices are used based on engineering judgment to supplement retroreflectorized signs, barriers, and channelizing devices. Some lighting devices commonly used in work zones include floodlights, flashing warning beacons, warning lights, and steady burn electric lamps. These devices raise drivers' attention, warn drivers of complicated travel conditions, and/or illuminate work zones at night. Some studies (Huebschman et al., 2003; Arnold, 2003) found that flashing warning lights, especially police vehicles with flashing lights, were one of the most effective approaches for reducing speeds in work zones.

Temporary traffic control signals. Temporary traffic control signals are typically used for conditions such as temporary one-way operations in work zones with one lane open and work zones involving intersections. The MUTCD suggests that temporary traffic control signals should be used with other traffic control devices, such as warning and regulatory signs, pavement markings, and channelizing devices. Some analyses of work zone fatal crashes showed that certain temporary traffic control signals, such as STOP/GO signals, were effective in reducing fatal crashes in work zones (Hill, 2003).

In summary, a wide range of TTC methods have been utilized in highway work zones. Results of previous research projects found that many of them could effectively control speeds or reduce numbers of crashes when properly installed. However, the authors did not find a study that quantified the measurement of TTC effectiveness in mitigating crash severity. In addition, there was no straightforward measurement on the effectiveness of individual TTC in the work zones. Outcomes of such a study would provide valuable knowledge for traffic engineers to design more cost-effective traffic control mechanisms in the work zones.

4. Data collection

The researchers extracted a total of 655 severe work zone crashes, including 29 fatal cases and 626 injury cases, from the KDOT accident database, which was based on the crash information from accident reports. The original data included a wide range of variables describing drivers, crash vehicles, crash location characteristics, and environmental conditions. Among them, the variables that were used in this study included crash severity, driver errors, and TTC methods. Because the observations in the database were in text format, a numerical value was assigned to each observation to facilitate the regression analyses. At the end of data collection, crash information represented by numerical values was compiled into a spreadsheet where a crash was described in one data row, where multiple columns were used to represents multiple traffic control devices and human errors. In the spreadsheet, fatal crashes were assigned with a severity outcome of 1 and injury crashes were assigned with an outcome of 0. In addition, the traffic control and driver error observations were assigned with binary values (1 represent presence and 0 represent none-presence). Then, the spreadsheet was inputted into the SAS software for anal-

Table 1
Crash Variables and Their Frequencies

Variable	Observation	Fatal crashes	Percent of fatal	Injury crashes	Percent of injury
Traffic control	Flagger/officer	5	17.2	25	4.0
	Stop sign/signal	2	6.9	37	5.9
	Flasher	1	3.4	4	0.6
	No passing zone control	6	20.7	83	13.3
	Center/edge lines	26	89.7	458	73.2
Driver error	Inattentive driving[a]	14	48.3	291	46.5
	Disregarded traffic signs, signals, or markings	3	10.3	50	8.0
	Followed too closely	1	3.4	152	24.3
	Exceeded speed limit or too fast for conditions	5	17.2	123	19.6

Note: Because crashes frequently involve multiple traffic control and driver error observations, the percentages do not add up to 100% and the numbers of crashes do not add up to the totals of fatal crashes and injury crashes.

[a] Inattentive driving includes such human errors as fell asleep, inattention, distraction-cell phone, distraction-other electronic devices, and other distraction in or on vehicle.

yses. Table 1 shows the traffic control and driver error observations and their frequencies.

5. Binary logistic regression method

This study used binary logistic regression technique to evaluate the effectiveness of the TTC methods commonly used in work zones. Binary logistic regression is a statistical method developed specifically for describing the relationships between a set of independent explanatory variables and a dichotomous response variable or outcome. A binary logistic regression model is a direct probability model that has no requirements on the distributions of the explanatory variables or predictors (Harrell, 2001). It is flexible and is more likely to yield accurate results when applied to traffic crash analysis in which the safety effectiveness of TTC measures needs to be quantified. The significance of logistic regression technique in the analyses of traffic safety has been recognized by some researchers. Hill (2003) utilized this technique in the analysis of work zone fatal crashes to quantify the effectiveness of traffic control devices, though the study was based on only fatal crashes and focused on a very limited number of TTCs. The technique was also used to model the relationships between crash severity and wide ranges of crash variables (Lu et al., 2006; Chang and Yeh, 2006; Kim et al., 2000; Dissanayake and Lu, 2002). These studies developed multivariate models for crash severity analyses rather than concentrating on the effectiveness of TTCs on reducing crash severities in work zones.

The following briefly describes the theoretical basis of the binary logistic regression method. Let Y be an event ($Y = 1$ and $Y = 0$ denote occurrence and nonoccurrence, respectively) and let a vector $\boldsymbol{X}$ be a set of predictors $\{X_1, X_2, \ldots, X_k\}$. The expected value of Y given $\boldsymbol{X}$ is the probability (P) of the occurrence of Y given $\boldsymbol{X}$, which can be expressed in linear regression form as follows:

$$E\{Y|X\} = P\{Y = 1|X\} = X\beta$$

where $\boldsymbol{\beta}$ is the regression parameter vector and $\boldsymbol{X\beta}$ stands for $\beta_0 + \beta_1X_1 + \ldots + \beta_kX_k$.

Because the probability determined by this equation can exceed one, the following binary logistic regression model is generally preferred for the analysis of binary responses:

$$P\{Y = 1|X\} = [1 + \exp(-X\beta)]^{-1} = \exp(X\beta)/[1 + \exp(X\beta)]$$

The above equation can be expressed in the following logistic form:

$$\text{Logit}\{Y = 1|X\} = \log[P/(1-P)] = \beta_0 + \beta_1X_1 + \cdots + \beta_kX_k$$

For the above model, given the estimated β's as $\hat{\beta}_0, \hat{\beta}_1, \cdots, \hat{\beta}_k$, the estimated probability $\hat{P}$ that an event Y happens, can be computed as follows:

$$\hat{P}\{Y = 1|X\} = exp(X\hat{\beta})/[1 + exp(X\hat{\beta})]$$

where $\boldsymbol{X}\,\hat{\beta}$ stands for $\hat{\beta}_0 + \hat{\beta}_1X_1 + \cdots + \hat{\beta}_kX_k$.

The significance of a predictor can be tested using the methods of the likelihood ratio test, the Wald test, and the score test (Hosmer and Lemeshow, 2000). The likelihood ratio test compares the deviation of the model with the predictor to that without the predictor. The Wald test is obtained by comparing the maximum likelihood estimate of the slope parameter, β_1, to an estimate of its standard error. The score test is based on the distribution theory of the derivatives of the log likelihood. Nevertheless, the three tests were all used in the study to minimize the probability of missing significant predictors. A predictor was determined to be significant when at least one test showed a p-value less than or equal to 0.1. Quantifying the safety impact of an explanatory variable can be treated as a special logistic regression case:

$$\text{logit}\{Y = 1|X = 0\} = \beta_0$$
$$\text{logit}\{Y = 1|X = 1\} = \beta_0 + \beta_1$$

Accordingly, the estimated probability that an event happens ($Y = 1$) when the test factor is present ($X = 1$) is as follows:

$$\hat{P}\{Y = 1|X = 1\} = \exp\{\hat{\beta}_0 + \hat{\beta}_1\}/(1 + \exp\{\hat{\beta}_0 + \hat{\beta}_1\})$$

The estimated probability that this event happens ($Y = 1$) when the test factor is absent ($X = 0$) is

$$\hat{P}\{Y = 1|X = 0\} = \exp\{\hat{\beta}_0\}/(1 + \exp\{\hat{\beta}_0\})$$

In this study, odds ratio was used to measure the difference between the univariate logistic regression model pairs. Odds ratio is defined as the ratio of the two odds given the two values of the test variable. Given the estimated odds of an event $\{Y = 1|X\}$ as

$$\text{Odds}\{Y = 1|X\} = \hat{P}\{Y = 1|X\}/(1-\hat{P}\{Y = 1|X\})$$

the odds ratio for the single-variable case is

$$Odds \quad ratio(X = x_1 : X = x_2) = exp[\hat{\beta}_1(x_1 - x_2)]$$

6. Evaluating the effectiveness of work zone TTC methods

Based on the available crash information, the effectiveness of several commonly used work zone TTC methods was evaluated. The effectiveness was assessed in terms of reducing the severity of work zone crashes and lowering the odds that a given severe work crash was caused by major human errors. The crash data used for the evaluation included the fatal and injury work zone crashes in Kansas highway work zones between January 2003 and December 2004. The evaluated TTC methods included flagger/officer, stop sign/signal, flasher, no passing zone, and center/edge lines; the major human errors that were included in the evaluation were "inattentive driving," "disregarded traffic control," "followed too closely," and "exceeded speed limit or too fast for condition."

6.1. Effectiveness of flagger/officer control

For estimating the effectiveness of flagger/officer control in reducing the severity of work zone crashes, the response variable Y represented a severe crash ($Y = 1$ for fatal crashes and $Y = 2$ for injury crashes) and the explanatory variable X represented the presence of a flagger ($X = 1$ for presence and $X = 0$ for absence). The logistic regression model was estimated as follows:

$$\text{Logit}\{Y = 1|X\} = -2.42 - 0.81X$$

The three test-of-significance statistics (likelihood ratio, score, and Wald) all indicated a high level of significance (i.e., 0.01) for the flagger variable.

According to this model, the conditional probability of having fatalities, given the occurrence of a severe crash (either fatal or injury) when flagger control was present, was estimated as follows:

$$\hat{P}\{Y = 1|X = 1\} = \exp\{\hat{\beta}_0 + \hat{\beta}_1\}/(1 + \exp\{\hat{\beta}_0 + \hat{\beta}_1\}) = 0.04$$

The corresponding probability without a flagger control was as follows:

$$\hat{P}\{Y = 1|X = 0\} = \exp\{\hat{\beta}_0\}/(1 + \exp\{\hat{\beta}_0\}) = 0.08$$

The estimated odds ratio between the occurrence of a fatal crash with flagger control and without flagger control was:

$$\begin{aligned}\text{Odds} \quad ratio(X = 1 : X = 0) &= exp[\hat{\beta}_1(x_1 - x_2)] \\ &= \exp[-0.81 \times (1 - 0)] = 0.44\end{aligned}$$

Hence, statistically, using a flagger in a work zone could reduce the odds of having fatalities in a given severe crash by 56%. In terms of probability, the presence of a flagger in a work zone could lower the probability of causing fatalities by 4% (or from 0.08 to 0.04) when a severe crash occurred.

Previous work zone crash studies (Bai and Li, 2007, 2008) have shown that human errors contribute to a significant proportion of work zone severe crashes. Reducing risky driver errors is an important objective for work zone TTC methods. The effectiveness of the flagger/officer control in work zones in preventing major human errors from causing severe (fatal and injury) crashes was also evaluated in this study. In the evaluations, the response variable Y represented a severe crash that was either caused by a studied human error ($Y = 1$) or not caused by this human error ($Y = 0$). For example, to evaluate the effectiveness of a flagger in preventing "disregarded traffic control" from causing fatal or injury crashes, the logistic regression model was developed as follows:

$$\text{Logit}\{Y = 1|X\} = -1.78 - 0.77X$$

According to this model, the conditional probability of the crash caused by "disregarded traffic control," given the occurrence of this severe crash, when flagger control was present was estimated as follows:

$$\hat{P}\{Y = 1|X = 1\} = \exp\{\hat{\beta}_0 + \hat{\beta}_1\}/(1 + \exp\{\hat{\beta}_0 + \hat{\beta}_1\}) = 0.07$$

The corresponding probability without a flagger control was as follows:

$$\hat{P}\{Y = 1|X = 0\} = \exp\{\hat{\beta}_0\}/(1 + \exp\{\hat{\beta}_0\}) = 0.14$$

The estimated odds ratio between the severe crash being caused by "disregarded traffic control" human error with flagger control and without flagger control was as follows:

$$\begin{aligned}&\text{Odds ratio}(X = 1 : X = 0) \\ &\quad = \exp[\hat{\beta}_1(x_1 - x_2)] = \exp[-0.77 \times (1 - 0)] = 0.46\end{aligned}$$

These results indicate that using a flagger in a work zone could reduce the odds of having a severe crash caused by "disregarded traffic control" human error by 54% (1–0.46). In terms of conditional probability, the presence of a flagger in a work zone could lower the probability of causing a severe crash due to "disregarded traffic control" by 7% (or from 0.14 to 0.07) when a severe crash occurred. Table 2 lists the parameters and the estimated probabilities and odds ratio of the fitted logistic regression models for the effectiveness of the flagger/officer control in reducing crash severity and the odds that a given severe crash was caused by human errors such as "disregarded traffic control," "inattentive driving," and "exceeded speed limit or too fast for condition." As illustrated in the table, using a flagger/officer in a highway work zone could lower the odds of having a severe crash caused by "inattentive driving" or "exceeded speed limit or too fast for condition" by about 40%. The effectiveness of a flagger/officer in preventing the impact of "followed too closely" was not determined because none of the statistical tests supported the significant relationship between the traffic control and the driver error.

6.2. Effectiveness of stop sign/signal

The stop sign/signal control was tested for its effectiveness in reducing crash severity and preventing the major human errors

Table 2
Model parameters and evaluation results for flagger control

Parameter	Coefficient		*p*-Value of significance test*			Probability		Odds ratio ($X = 1$: $X = 0$)[a]
	$\hat{\beta}_0$	$\hat{\beta}_1$	LR[b]	Score	Wald	$X = 1$	$X = 0$	
Effectiveness in reducing crash severity	−2.42	−0.81	<u>0.01</u>	<u>≤0.01</u>	<u>≤0.01</u>	0.04	0.08	0.44
Effectiveness in preventing "disregarded traffic control"	−1.78	−0.77	<u>≤0.01</u>	<u>≤0.01</u>	<u>≤0.01</u>	0.07	0.14	0.46
Effectiveness in preventing "inattentive driving"	0.34	−0.51	<u>0.01</u>	<u>0.01</u>	<u>0.01</u>	0.46	0.58	0.60
Effectiveness in preventing "exceeded speed limit or too fast for condition"	−1.01	−0.46	<u>0.03</u>	<u>0.02</u>	<u>0.02</u>	0.19	0.27	0.63

* *p*-Value is the output value of the statistical tests of significance. A *p*-value less than 0.1 indicates that the test variable is significant at 0.1 level of significance, and is underlined in the table.
[a] $X = 1$ when the traffic control was present and $X = 0$ when it was absent.
[b] Likelihood ratio.

Table 3
Model parameters and evaluation results for stop sign/signal control

Parameter	Coefficient		*p*-Value of significance test*			Probability		Odds ratio ($X = 1$: $X = 0$)[a]
	$\hat{\beta}_0$	$\hat{\beta}_1$	LR[b]	Score	Wald	$X = 1$	$X = 0$	
Effectiveness in preventing "followed too closely"	−2.38	1.26	<u>≤0.01</u>	<u>≤0.01</u>	<u>0.01</u>	0.25	0.08	3.53

* *p*-Value is the output value of the statistical tests of significance. A *p*-value less than 0.1 indicates that the test variable is significant at 0.1 level of significance, and is underlined in the table.
[a] $X = 1$ when the traffic control was present and $X = 0$ when it was absent.
[b] Likelihood ratio.

Table 4
Model parameters and evaluation results for flasher control

Parameter	Coefficient		*p*-Value of significance test*			Probability		Odds ratio ($X = 1$: $X = 0$)[a]
	$\hat{\beta}_0$	$\hat{\beta}_1$	LR[b]	Score	Wald	$X = 1$	$X = 0$	
Effectiveness in reducing crash severity	−2.24	−.86	0.20	0.09	0.13	0.04	0.10	0.42

* *p*-Value is the output value of the statistical tests of significance. A *p*-value less than 0.1 indicates that the test variable is significant at 0.1 level of significance, and is underlined in the table.
[a] $X = 1$ when the traffic control was present and $X = 0$ when it was absent.
[b] Likelihood ratio.

Table 5
Model parameters and evaluation results for no passing zone control

Parameter	Coefficient		p-Value of significance test*			Probability		Odds ratio ($X = 1$: $X = 0$)[a]
	$\hat{\beta}_0$	$\hat{\beta}_1$	LR[b]	Score	Wald	$X = 1$	$X = 0$	
Disregarded traffic control	−2.20	−0.35	0.06	0.04	0.05	0.07	0.10	0.71

* *p*-Value is the output value of the statistical tests of significance. A *p*-value less than 0.1 indicates that the test variable is significant at 0.1 level of significance, and is underlined in the table.
[a] $X = 1$ when the traffic control was present and $X = 0$ when it was absent.
[b] Likelihood ratio.

Table 6
Model parameters and evaluation results for center/edge lines

Parameter	Coefficient		p-Value of significance test*			Probability		Odds ratio ($X = 1$: $X = 0$)[a]
	$\hat{\beta}_0$	$\hat{\beta}_1$	LR[b]	Score	Wald	$X = 1$	$X = 0$	
Effectiveness in reducing crash severity	−3.63	−0.80	0.01	0.02	0.03	0.01	0.03	0.45
Effectiveness in preventing "exceeded speed limit or too fast for condition"	−1.61	−0.35	<0.01	0.01	0.01	0.12	0.17	0.71
Effectiveness in preventing "followed too closely"	−1.30	−0.20	0.06	0.07	0.07	0.18	0.21	0.81

* *p*-Value is the output value of the statistical tests of significance. A *p*-value less than 0.1 indicates that the test variable is significant at 0.1 level of significance, and is underlined in the table.
[a] $X = 1$ when the traffic control was present and $X = 0$ when it was absent.
[b] Likelihood ratio.

from causing severe crashes. The tests of significance showed that the presence of a stop sign/signal control device in a work zone was not significantly related to the fatal crashes. In addition, the tests showed that the presence of this traffic control resulted in a dramatic increase of the odds that a given severe crash was caused by "followed too closely". This result may indicate that this TTC method could actually catalyze the "followed too closely" human error to cause severe crashes. As listed in Table 3, when a stop sign/signal was used, the odds of having crashes caused by "following too closely" was roughly two and a half times (3.53–1) higher than the odds without such a device.

6.3. Effectiveness of flasher device

Statistical tests showed that the use of flashers in work zones was not directly related to the severe work zone crashes that were caused by the four major human errors. However, the effectiveness of flashers in mitigating the severity of work zone crashes was determined. Using the SAS software, the following logistic regression model was generated:

$$\text{Logit}\{Y = 1|X\} = -2.24 - 0.86X$$

Listed in Table 4 are the results of the three tests of significance and the respective probabilities of a severe crash resulting in fatalities with and without a flasher control device. The odds ratio of having a fatal crash with and without a flasher control device is also included in the table. The results indicated that using a flasher device in a work zone could reduce the odds of a severe crash resulting in fatalities by 58% (1–0.42).

6.4. Effectiveness of "no-passing-zone" control

The results of the three tests of significance, including likelihood ratio test, score test, and Wald test, all suggested that the use of no-passing-zone control was significantly related to the odds of a severe crash caused by "disregarded traffic control" human error. Table 5 lists the evaluation results for no-passing-zone controls. The results indicated that, in a work zone with no-passing-zone control, the odds of a severe crash caused by "disregarded traffic control" human error would be 29% less than that in work zones without such control.

6.5. Effectiveness of pavement center/edge lines

Statistical study showed that the use of center/edge lines in work zones was effective not only for reducing crash severity, but also in preventing human errors such as "exceeded speed limit or too fast for condition" and "followed too closely" from causing severe crashes. Table 6 shows the results in terms of the estimated probabilities and the odds ratio. The results of regression analyses suggested that the use of center/edge lines in work zones may reduce the odds of causing fatalities when severe crashes occurred by 55%. In addition, having center/edge lines in work zones may also lower the odds of a severe crash caused by speeding by 29%, and the odds of a severe crash caused by "followed too closely" by 19%.

7. Conclusion

Work zone safety has been a research focus for many years and improving the safety in highway work zones is a high-priority task for traffic engineers. Evaluating the effectiveness of the TTC methods used in highway work zones would help traffic engineers identify traffic control deficiencies, and thus, make continuous improvement in safety. In this study, the effectiveness of several TTC methods, including flagger/officer, stop sign/signal, flasher, no passing zone, and center/edge lines, in mitigating work zone crash severity and preventing common human errors from causing severe work zone crashes was quantified using a logistic regression technique. The findings may provide valuable knowledge for traffic engineers in understanding the effects of the TTC methods on the severity or involvement of certain human errors in work zone crashes. They may also provide insights on safety implications of the work zone environment associated with each evaluated TTC method. According to the logistic regression analyses, the presence of a flagger or officer directing traffic could reduce the odds of having fatalities in a severe crash by 56%; having flashers or center/edge lines in work zones could reduce the odds by more than 50% as well. However, based on the available crash data, the statistics did not support close associations between the usage of stop signs/signals and no-passing-zone control in work zones and fatality involvement in severe crashes.

Regarding the effectiveness TTC methods in preventing common human errors from causing severe crashes in work zones, the evaluation showed that flaggers/officers could considerably lower the odds of severe work zone crashes caused by human errors such as "disregarded traffic control," "inattentive driving," and "exceeded speed limit or too fast for condition." No-passing-zone control in work zones was effective in reducing the odds of having severe crashes caused by "disregarded traffic control". In addition, having center/edge lines in work zones could lower the odds of having severe work zone crashes caused by human errors such as "exceeded speed limit or too fast for condition" and "followed too closely." However, having stop signs/signals in work zones would dramatically increase the odds of having severe crashes caused by "followed too closely" human error.

In this study, logistic regression analyses were used to assess individual TTC methods so that quantified estimations of the effectiveness of each TTC could be obtained. The actual effectiveness of these methods may vary when used in combination with other traffic control devices and/or work zone conditions. This research can be extended in several ways. First, fatal crash data from other sources could be added to increase the total number of fatal cases in order to improve the reliability of the analysis. In this project, the researchers only examined data from the state of Kansas due to limited resource. In the future, researchers could collect data from the work zones in other states to enrich the fatal crash information. Second, evaluating the effectiveness of the TTC methods may be extended to property-damage-only crashes. When possible, the evaluation should also consider the data such as traffic volume and vehicle-miles traveled so that the effectiveness of TTC measures in reducing the total number of crashes can be determined. Finally, there is a need to evaluate the effectiveness of certain combinations of TTC methods that are commonly used in work zones. The results of such multivariate analyses will provide a comprehensive understanding on how these TTC measures interactively affect safety in work zones. It should be also noticed that researchers of this study used the driver error information from the police accident reports. Errors might occur during the crash investigation. Especially, the determination of driver errors might have a certain degree of bias that was unavoidable in a human-controlled process.

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