Flagger Effects in Reducing the Likelihood of Rear-End Collisions for In-Platoon Vehicles in Work Zones

K. A. Avrenli, R. Benekohal, and H. Ramezani

Rear-end collisions are among the most dominant crash types in work zones. Three factors may increase the potential of rear-end collisions in work zones: following too closely, speeding, and faster trailing. This study explores the effectiveness of flaggers in reducing the frequency of these three factors. Eleven data sets were collected from five single-lane work zones with no lane change opportunity. Time gap and speed data for around 4,600 in-platoon vehicles were used. Statistical analyses were based on the frequency of the three factors. According to the results, during flagger presence and a 45 mph speed limit, the probability that a vehicle in platoon would follow too closely was reduced by 60% to 69% compared with a 45 mph or 55 mph speed limit and no flagger. The probability that a vehicle would speed by at least 5 mph at short time gaps was reduced by 28% to 72% during flagger presence and a 45 mph speed limit compared with a 55 mph speed limit and no flagger and by 85% to 95% during flagger presence and a 45 mph speed limit compared with a 45 mph speed limit and no flagger. Work zones with a 45 mph speed limit and no flagger were also found to be more hazardous for speeding at short time gaps than work zones with a 55 mph speed limit and no flagger. Only two of the vehicles were found to faster trail at short time gaps. Because of the low frequency, no statistical analysis was conducted for faster-trailing vehicles.

In 2009, 28% of all crashes in Illinois were rear-end collisions, which accounted for the highest number of injury crashes (*1*). Because of the higher degree of interaction between vehicles, rear-end collisions may constitute a higher percentage of work zone crashes. For instance, around 45% of the work zone crashes were rear-end collisions in Ohio from 2005 to 2007 (*2*). The occurrence of short time headways may increase the potential and severity of rear-end collisions because of the shorter time available for the trailing vehicle to avoid a rear-end collision. Davis and Swenson reported short time headways as one of the causal factors for work zone rear-end collisions (*3*).

Following too closely (short time headways) and speeding are two major factors associated with work zone crashes. For instance, following too closely was the most commonly reported factor contributing to the work zone crashes in Ohio (*2*). Raub et al. reported following too closely as the second most common cause (by 24%) of work zone crashes in Illinois work zones (*4*). Chambless et al. found following too closely to be the primary contributing factor that accounted for 7% of the work zone crashes in Alabama, Michigan, and Tennessee (*5*). In addition, speeding was reported as the second most dominant type of driver error in Kansas work zone crashes (*6*). Bushman et al. reported excessive speed as a contributing factor in around 30% of the work zone crashes in Canada (*7*).

This study explores the effects of flaggers on the frequency of short time gaps and speeding in single-lane work zones. Reduction of the frequency of short time headways and speeding could be considered as a safety improvement. This study is not advocating putting flaggers on the road for the sole purpose of increasing headways. Flaggers are placed in work zones based on the information in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*8*) to slow down traffic and alert drivers to the crew working nearby. The flaggers observed in this study were holding "Slow" paddles in the work zone, which could lead to reduction in vehicle speeds and increase in time headways. This study analyzes the frequency of the following three types of driving behavior in single-lane work zones during flagger presence and no flagger presence:

1. Maintaining short time gaps (i.e., following too closely),
2. Speeding by 5 mph or more at short time gaps (i.e., speeding by 5 mph or more while following too closely), and
3. Faster trailing (traveling faster than the immediate leader) by 5 mph or more at short time gaps.

The three types of driving behavior listed above may increase the likelihood of rear-end collisions. In this study, vehicle time gaps of vehicles are considered in preference to time headways. While time headways are influenced by vehicle length, time gaps directly indicate the available time for a driver to avoid colliding with the vehicle ahead. Thus drivers are generally more concerned about time gaps than time headways.

In view of the three above mentioned risky driving behaviors, the objectives of this study are to find out and quantify how the following change when a flagger is present in the work zone:

- Frequency of vehicles with short time gaps,
- Frequency of vehicles speeding by at least 5 mph at short time gaps, and
- Frequency of vehicles faster trailing by at least 5 mph at short time gaps.

K. A. Avrenli and H. Ramezani, Room B106, and R. Benekohal, Room 1213, Department of Civil and Environmental Engineering, Newmark Civil Engineering Laboratory, University of Illinois at Urbana–Champaign, 205 North Mathews Avenue, Urbana, IL 61801. Corresponding author: K. A. Avrenli, avrenli2@illinois.edu.

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BACKGROUND

To the authors' best knowledge, studies on the detailed effects of flagger presence in work zones are very limited. Bai and Li analyzed the work zone crash data that took place between 1992 and 2004 and found that 89% of the work zone crashes happened when there was no officer or flagger in the work zone (*6*). Li and Bai also analyzed a total of 655 severe work zone crashes that occurred between January 2003 and December 2004 in Kansas (*9*). They found that flagger presence could reduce the odds of having fatalities in a severe crash by 56%. Likewise, they concluded that flagger presence could lower the odds of a severe crash caused by "disregarded traffic control" human error by 54%. Another conclusion they drew from the results was that flagger presence could decrease the odds of a severe crash caused by "inattentive driving" or "exceeded speed limit" by around 40%.

DATA COLLECTION AND REDUCTION

Eleven data sets were collected from five work zones in Illinois. All five work zones had the same two-to-one lane configuration. The work zones were all on Interstate highways. In the area in which the data were collected, two lanes serving the same direction of traffic were reduced to one lane, and the other lane was closed. Therefore, there was a single direction of traffic in one lane at the work zones. The research team did not alter the typical work zone setup that the Illinois Department of Transportation used. No data collection was made during the evening or night traffic. As Table 1 shows, the volume ranged from 631 to 913 vehicles per hour per lane (vphpl) at the study sites during data collection. Details regarding the work zone setup are also summarized in Table 1.

As Table 1 shows, some of the data sets were collected during flagger presence in the work zone. Section 6D.03 of the MUTCD recommends use of a flagger through a temporary traffic control zone as one of the key elements to improve worker safety (*8*). Also the *Flagger Handbook* of the Illinois Department of Transportation states that flagger usage is recommended on multilane roadways to "protect workers while maintaining traffic speeds at a reasonable level" (*10*).

For each data set, a video camera was used to collect the traffic flow data to obtain information on individual vehicles. The video camera was situated such that it did not interfere with the work zone traffic flow. The location of the camera was close to the work space. Two markers around 250 ft apart from each other were placed near the shoulder by the research team. The video camera was used to videotape the vehicles passing the two markers. The video files had time stamps and frame numbers that enabled accurate reading of a particular frame within the 1/30th of a second. The following data were obtained for each vehicle from the video files:

1. Vehicle type:
   – Cars: passenger cars, motorcycles, minivans, and pickup trucks and
   – Trucks: single-unit trucks, Interstate semitrailers, and buses;
2. Times at which the vehicle passed the two markers; and
3. Type of leading vehicle (i.e., car or truck).

To compute the speed of a particular vehicle, the times at which it passed the two markers were used. The time gaps were computed by using the times at which successive vehicles passed one of the selected markers.

ANALYSIS AND RESULTS

Determining the Thresholds for Short Time Gaps

This study focuses on the risky driving behavior of the vehicles with short time gaps. However, the question is, what would be a reasonable threshold to define short time gaps? In other words, what threshold should be selected as the maximum allowable length to define short time gaps? The threshold for short time gaps can be determined with respect to the distribution of driver reaction times. On the basis of some past studies (*11–13*), the median reaction time for alerted drivers was found to be around 0.64 to 0.66 s. For unalerted drivers, these numbers would be about 30% longer. Thus for work zone conditions, the first threshold for short time gaps is set at 0.70 s.

Furthermore, it would be useful to use one or two more alternative thresholds for short time gaps and conduct the same type of analysis for each short time gap threshold. One can then see the results of risky driving behaviors with regard to different short time gap thresholds. So in addition to the threshold of 0.70 s, two more short time gap thresholds are selected.

Normann found that the brake reaction time of drivers ranged up to 1.7 s (*13*). However, Johansson and Rumar observed that only 10% of the alerted drivers had a reaction time of 1.5 s or longer (*11*). In another study, only 5% of the alerted drivers exhibited a reaction

TABLE 1 Summary of Data Sets Used in This Study

Data Set	Site and Data Collection Period	Work Zone Speed Limit (mph)	Flagger Present?	Length of Work Zone (mi)	Duration of Data Collection (min)	Total No. of Vehicles Observed	Volume (vphpl)	% Trucks
1	I-74EB (a.m.)	55	No	0.5	46.5	563	726	21.1
2	I-74EB (p.m.)	55	No	0.5	44.3	599	811	28.0
3	I-72EB (p.m.)	45	No	1.9	43.6	620	853	14.2
4	I-39NB (p.m.)	55	No	2.7	42.3	644	913	21.6
5	I-80WB (a.m.)	45	No	5.5	59.9	729	730	37.7
6	I-80EB (p.m.)	45	No	5.5	44.4	484	654	45.2
7	I-80WB (a.m.)	45	Yes	5.5	44.1	464	631	38.8
8	I-80WB (p.m.)	45	Yes	5.5	45.7	508	667	42.7
9	I-80EB (a.m.)	45	Yes	5.5	43.3	460	637	43.3
10	I-80EB (p.m.)	45	Yes	5.5	46.1	555	722	31.4
11	I-39NB (a.m.)	45	Yes	2.7	48.1	632	788	28.3

NOTE: No. = number; EB = eastbound; NB = northbound; WB = westbound.

time of 1.0 s or longer (*12*). Thus, vehicles with time gaps greater than 1.0 s may not be considered in the short time gap category. Therefore, the second (and the highest) threshold for short time gaps is set at 1.00 s. Finally, the third threshold for short time gaps is taken as the average of the first and the second thresholds (i.e., 0.85 s).

Data Categorization

The data were classified into three categories on the basis of work zone traffic control as follows:

- Speed limit (SL) = 55. The work zone speed limit was 55 mph (88 km/h). There was only the standard MUTCD signage in the work zone.
- SL = 45. The work zone speed limit was 45 mph (72 km/h). There was only the standard MUTCD signage in the work zone and no flagger.
- Flagger. The work zone speed limit was 45 mph (72 km/h). In addition to the standard MUTCD signage, there was also a flagger in the work zone during the entire data collection period.

A flagger may be used on multilane roadways to improve safety for workers. Each flagger was stationed at least 100 ft from the work crew and was visible to oncoming traffic for a minimum of 500 ft. Depending on the work zone configuration, the flaggers stood either on the shoulder or in the closed lane. Each flagger was equipped with a "Slow" paddle and high-visibility safety apparel that meets Performance Class 2 requirements of American National Standards Institute/International Safety Equipment Association Standard 107-2004. Each flagger had the responsibility of controlling the traffic flow with the "Slow" paddle to ensure safe passage of traffic in the work area (*14*).

Table 2 shows the number of in-platoon vehicles observed in each category of work zone temporary traffic control. Out of the 6,258 vehicles observed, 4,595 of them (73.4%) were in platoon. This study uses the same platooning criteria as Benekohal et al. (*15*). A vehicle is considered to be in platoon if it maintained a time headway of less than 4.0 s or a space headway of less than 250 ft (76 m). Moreover, categorized by work zone traffic control, the number of vehicles that displayed risky driving behavior is tabulated in Table 2 for the short time gap thresholds of 0.70 s, 0.85 s, and 1.00 s. Based on the number of observations given in Table 2, the percentage of frequency of the three risky driving behaviors is illustrated by work zone traffic control in Figure 1. In Table 2, the numerals in the headings indicate how the last three columns are computed. For instance, the last column is computed by dividing the fourth column by the second column in Table 2.

The data were not categorized on the basis of vehicle type because time gaps are considered in data analysis. As already mentioned in the introductory section, time gaps are independent of vehicle length and vehicle type because they directly indicate the available time for a driver to avoid rear-end colliding with the vehicle ahead.

Tendency to Maintain Short Time Gaps

Results of the χ^2 Tests

Figure 1*a* shows the observed percentage of frequency of short time gaps by work zone traffic control for each short time gap threshold. No matter what short time gap threshold is selected, a remarkable reduction in the frequency of short time gaps is observed in the presence of a flagger. To compare the frequency of short time gaps based on work zone traffic control, contingency tables are prepared from the data given in Table 2 and chi-square (χ^2) tests are made. Table 3 is a contingency table for the short time gap threshold of 1.00 s.

Because of space constraints, the other contingency tables are not shown and only the results of the χ^2 tests are given in Table 4. For each short time gap threshold and two particular study groups, Table 4 gives the odds ratio, χ^2, and *p*-value. For two particular data categories, the odds ratio is the ratio of the odds of an event occurring in the first data category to the odds of the same event occurring in the second data category (*16*). The odds ratio is computed as given in Equation 1:

$$\text{odds ratio}_{1,2} = \frac{p_1/(1-p_1)}{p_2/(1-p_2)} \qquad (1)$$

where p_i is the probability of observing a particular event in the *i*th study group.

TABLE 2 Number of Observations for Risky Driving Behavior Categorized by Work Zone Traffic Control for Short Time Gap Thresholds of 0.70 s, 0.85 s, and 1.00 s

Work Zone Traffic Control	No. of In-Platoon Vehicles (1)	All (2)	Speeding by at Least 5 mph (3)	Faster Trailing by at Least 5 mph (4)	% In-Platoon Vehicles with Short Time Gaps (2/1)	% Speeding (by ≥5 mph) Vehicles at Short Time Gaps (3/2)	% Faster Trailing (by ≥5 mph) Vehicles at Short Time Gaps (4/2)
$T_G < 0.70$ s							
SL = 55	1,226	36	2	0	2.9	5.6	0.0
SL = 45	1,331	46	12	0	3.5	26.1	0.0
Flagger	2,038	25	1	1	1.2	4.0	4.0
$T_G < 0.85$ s							
SL = 55	1,226	83	3	0	6.8	3.6	0.0
SL = 45	1,331	109	26	0	8.2	23.9	0.0
Flagger	2,038	46	1	1	2.3	2.2	2.2
$T_G < 1.00$ s							
SL = 55	1,226	157	6	1	12.8	3.8	0.6
SL = 45	1,331	204	44	0	15.3	21.6	0.0
Flagger	2,038	92	1	1	4.5	1.1	1.1

NOTE: T_G = time gap.

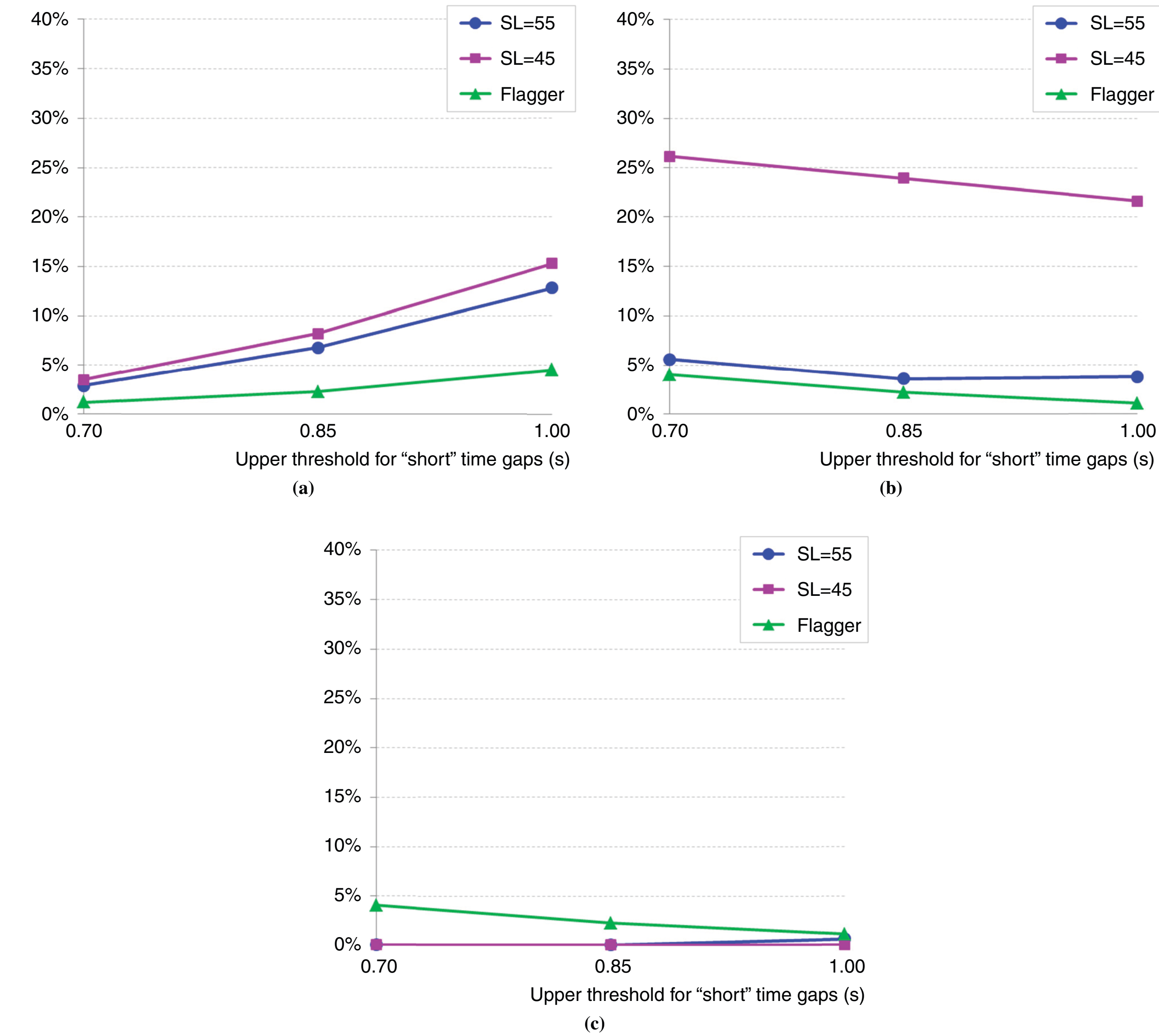

FIGURE 1 Percentage of frequency of the three risky driving behaviors: (*a*) percentage of in-platoon vehicles that maintain short time gaps, (*b*) percentage of drivers with short time gaps who were speeding by at least 5 mph, and (*c*) percentage of drivers with short time gaps who were faster trailing by at least 5 mph.

In Table 4, the odds ratios are computed based on the odds of observing short time gaps in a particular data category. For instance, the fourth row of Table 4 compares the work zones with a flagger versus the work zones with a 55 mph speed limit with respect to the odds of short time gaps. If the short time gap threshold is taken as 0.70 s, the odds ratio is 0.41, the χ^2 is 12.20, and the *p*-value associated with the χ^2 is less than .001. So the odds of observing short time gaps in the work zones with flaggers equals 0.41 times the odds of that in the work zones with a 55 mph speed limit and no flagger, and the difference is significant at $\alpha = .05$.

According to the results of the χ^2 tests given in Table 4, the following conclusions can be made at a .05 probability of Type I error ($\alpha = .05$):

- For all short time gap thresholds, the percentage of in-platoon drivers who maintained short time gaps changed significantly in the following order: SL = 45 ≈ SL = 55 > flagger.
- The work zones with no flagger were associated with the highest frequency of short time gaps, regardless of the speed limit. So work zone speed limit alone was not associated with any significant change in the frequency of short time gaps. It was during flagger presence when there was a significant reduction in the frequency of short time gaps.
- Flagger presence was associated with significant reductions in the frequency of short time gaps. This may be attributed to the slowing down of the vehicles in response to the waving movement of the flagger or the presence of a human being adjacent to the roadway.

Results of the Binary Logistic Regression Models

To further quantify the effects of flaggers in reducing the likelihood of short time gaps, a binary logistic regression model has to be built. Because the speed limit is found to have no significant effect on the

TABLE 3 Contingency Table for Three Scenarios of Traffic Control Versus Percentage of Frequency of Time Gaps < 0.70 s

Traffic Control	No. of Vehicles in Platoon $T_G < 0.70$ s	$T_G \geq 0.70$ s	Sum
SL = 55 versus SL = 45[a]			
SL = 55	36 (2.9%)	1,190 (97.1%)	1,226 (100%)
SL = 45	46 (3.5%)	1,285 (96.5%)	1,331 (100%)
Flagger versus SL = 45[b]			
Flagger	25 (1.2%)	2,013 (98.8%)	2,038 (100%)
SL = 45	46 (3.5%)	1,285 (96.5%)	1,331 (100%)
Flagger versus SL = 55[c]			
Flagger	25 (1.2%)	2,013 (98.8%)	2,038 (100%)
SL = 55	36 (2.9%)	1,190 (97.1%)	1,226 (100%)

[a] $\chi^2 = 0.56$; *p*-value = .456.
[b] $\chi^2 = 19.40$; *p*-value = <.001.
[c] $\chi^2 = 12.20$; *p*-value = <.001.

frequency of short time gaps, the binary logistic regression model shown in Equation 2 is appropriately built for each short time gap threshold:

$$\text{logit}\{Y = 1|\bar{X}\} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \tag{2}$$

where

Y = binomial response variable that takes 1 if a vehicle is maintaining a short time gap, and 0 otherwise;
$\bar{X}$ = $[X_1, X_2]$ = binomial predictors such that X_1 takes 1 for flagger presence in the work zone and 0 otherwise; X_2 takes 1 for a work zone speed limit of 55 mph, and 0 for 45 mph; and
$\beta_0, \beta_1, \beta_2$ = binary logistic regression constants.

According to the model given in Equation 2, the conditional probabilities of $P\{Y = 1|\bar{X}\}$ are estimated as given in Equation 3 (*9, 15*):

$$P\{Y = 1|\bar{X} = [x_1, x_2]\} = \frac{\exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2)}{1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2)} \tag{3}$$

According to the binary logistic regression model given in Equation 2,

- $P\{Y = 1|X_1 = 0; X_2 = 0\}$ is the probability of a motorist maintaining a short time gap at a speed limit of 45 mph and during no flagger presence,
- $P\{Y = 1|X_1 = 0; X_2 = 1\}$ is the probability of a motorist maintaining a short time gap at a speed limit of 55 mph and during no flagger presence, and
- $P\{Y = 1|X_1 = 1; X_2 = 0\}$ is the probability of a motorist maintaining a short time gap at a speed limit of 45 mph and during flagger presence.

Stepwise binary logistic regression is carried out to fit the model given in Equation 2 for each short time gap threshold. For all three short time gap thresholds, the predictor X_2 (i.e., work zone speed limit) is not found to be significant at $\alpha = .05$. This matches with the results presented in Table 4 because speed limit is not found to be significantly associated with the frequency of short time gaps. Therefore, only the predictor X_1 (i.e., flagger presence) is found to be significant at $\alpha = .05$ and included in the model. Table 5 shows the binary logistic regression models and the estimates of $P\{Y = 1|X_1 = x_1\}$ for each short time gap threshold. All three binary logistic regression models and all regression coefficients were found to be statistically significant at $\alpha = .05$. For instance, the probability of motorists maintaining time gaps shorter than 1.00 s is estimated as .141 in the work zones with no flagger and .045 in the work zones with a flagger. According to the probabilities given in Table 5, the probability of maintaining short time gaps ranges from 1.3% to 14.1%, depending on the short time gap threshold and work zone temporary traffic control.

Flagger Effects in Reducing the Probability of Short Time Gaps

Table 6 gives the estimate of the reduction in the probability of an in-platoon vehicle maintaining a short time gap during flagger presence. Consider the case of the short time gap threshold of 0.70 s, for instance. According to Table 5, the estimate of the probability of an in-platoon vehicle maintaining a short time gap (i.e., <0.70 s) is .032 when there is no flagger and .013 when there is a flagger. Thus, when there is a flagger, it is estimated that the probability of an in-platoon vehicle maintaining a short time gap may be reduced by (.032 − .013)/.032 = 60%. Using the same procedure, one can conclude from Table 6 that

- When the work zone had a flagger and a 45 mph speed limit compared with when it had no flagger and a 45 mph speed limit, the probability that a vehicle in platoon would maintain a short time gap was reduced by 60% to 69% and
- When the work zone had a flagger and a 45 mph speed limit compared with when it had no flagger and a 55 mph speed limit, the

TABLE 4 Results of χ^2 Tests for Work Zone Traffic Control Versus Percentage of Frequency of Short Time Gaps

Data Category 1	Data Category 2	$UT_G = 0.70$ s Odds Ratio	χ^2	*p*-Value	$UT_G = 0.85$ s Odds Ratio	χ^2	*p*-Value	$UT_G = 1.00$ s Odds Ratio	χ^2	*p*-Value
SL = 55	SL = 45	0.85	0.56	.456	0.81	1.85	.174	0.81	3.34	.067
Flagger	SL = 45	0.35	19.40	<.001	0.26	64.56	<.001	0.26	117.46	<.001
Flagger	SL = 55	0.41	12.20	<.001	0.32	41.07	<.001	0.32	74.69	<.001

NOTE: UT_G = upper threshold to define short time gaps.

TABLE 5 Binary Logistic Regression Models Quantifying the Effects of Flagger on Frequency of Short Time Gaps

Upper Threshold for Short Time Gaps	Binary Logistic Regression Model	Probability That Vehicle in Platoon Would Maintain Short Time Gaps: During No Flagger Presence (SL = 45 mph or 55 mph) $P\{Y = 1 \mid X_1 = 10\}$	During Flagger Presence (SL = 45 mph) $P\{Y = 1 \mid X_1 = 1\}$
0.70	$\text{Logit}\{Y = 1 \mid X_1\} = -3.42 - 0.93\,X_1$	.032	.013
0.85	$\text{Logit}\{Y = 1 \mid X_1\} = -2.52 - 1.23\,X_1$	.075	.023
1.00	$\text{Logit}\{Y = 1 \mid X_1\} = -1.81 - 1.25\,X_1$	.141	.045

probability that a vehicle in platoon would maintain a short time gap was reduced by 60% to 69%.

Tendency to Speed by at Least 5 mph at Short Time Gaps

Results of the χ^2 Tests

For each short time gap threshold, the percentage of frequency of the vehicles with short time gaps and speeding by at least 5 mph is shown by work zone traffic control in Figure 1*b*. Figure 1*b* indicates the following:

- The percentage of frequency of the drivers who both maintained short time gaps and sped by at least 5 mph was around 21.6% to 26.1% for SL = 45, which is considerably higher than that for SL = 55 and flagger.
- In the flagger category, only one vehicle with a short time gap was observed to exceed the speed limit by at least 5 mph. The corresponding percentage of frequency ranged from 1.1% to 4.0% based on the short time gap threshold.
- In the case of SL = 55, the percentage of frequency of the drivers who both maintained short time gaps and sped by at least 5 mph ranged from 3.6% to 5.6% based on the short time gap threshold.

Therefore, flagger presence is associated with a substantial reduction in the frequency of the drivers who sped by at least 5 mph at short time gaps. To determine if the percentage of frequencies differed significantly with respect to work zone traffic control, contingency tables were prepared and χ^2 tests were made. Table 7 summarizes the results of the χ^2 tests. All the odds ratios given in Table 7 are computed based on the odds of speeding by at least 5 mph at short time gaps. For instance, the second row of Table 7 compares the work zones with a flagger versus the work zones with a 45 mph speed limit and no flagger. If the short time gap threshold is selected as 0.85 s, the odds ratio is 0.07, the χ^2 is 11.36, and the *p*-value associated with the χ^2 is .001. So the odds of observing a motorist speeding by at least 5 mph at short time gaps in the work zones with flaggers equals 0.07 times the odds of that in the work zones with a 45 mph speed limit and no flagger, and the difference is significant at $\alpha = .05$.

From the results of the χ^2 tests, the following conclusions can be made at a .05 probability of Type I error:

- For all three short time gap thresholds, the percentage of drivers who both maintained short time gaps and sped by at least 5 mph changed numerically in the following order:
  SL = 45 > SL = 55 > flagger
- For all three short time gap thresholds, the percentage of drivers who both maintained short time gaps and sped by at least 5 mph changed significantly in the following order:
  SL = 45 > SL = 55 ≈ flagger
- No matter what short time gap threshold is taken, work zones with a 45 mph speed limit and no flagger exhibited the highest frequency of drivers who sped by at least 5 mph at short time gaps. A reason for that may be the drivers' unwillingness to reduce their speeds below a relatively lower speed limit.
- The frequency of drivers speeding by at least 5 mph at short time gaps was significantly lower in the work zones with a 55 mph speed limit and no flagger than in those with a 45 mph speed limit and no flagger.
- The frequency of drivers speeding by at least 5 mph at short time gaps was the lowest in the work zones with a flagger. Therefore, flagger presence seems to be the key factor to substantially reduce the frequency of speeding by at least 5 mph at short time gaps. The reason for this may be human presence adjacent to the roadway or the waving movement of the flagger.

TABLE 6 Percentage of Reduction in Probability of Maintaining Short Time Gaps and of Speeding During Flagger Presence

Upper Threshold for Defining Short Time Gaps (s)	Compared to SL = 55 mph, No Flagger	Compared to SL = 45 mph, No Flagger
Reduction in the Probability of Maintaining Short Time Gaps During Flagger Presence and 45 mph SL (%)		
0.70	60	60
0.85	69	69
1.00	68	68
Reduction in the Probability of Speeding by at Least 5 mph at Short Time Gaps During Flagger Presence and 45 mph SL (%)		
0.70	28	85
0.85	40	91
1.00	72	95

Results of the Binary Logistic Regression Models

To quantify further the effects of flaggers on reducing the frequency of speeding by at least 5 mph at short time gaps, binary logistic regression models as given in Equation 4 are built as follows:

$$\text{logit}\left\{Z = 1 \mid \overline{X}\right\} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \tag{4}$$

where Z = binomial response variable that takes 1 if a vehicle is speeding by at least 5 mph at short time gap, and 0 otherwise.

TABLE 7 Results of χ^2 Tests for Work Zone Traffic Control Versus Percentage of Frequency of Speeding by at Least 5 mph at Short Time Gaps

Data Category 1	Data Category 2	$UT_G = 0.70$ s Odds Ratio	χ^2	p-Value	$UT_G = 0.85$ s Odds Ratio	χ^2	p-Value	$UT_G = 1.00$ s Odds Ratio	χ^2	p-Value
SL = 55	SL = 45	0.17	6.01	.014	0.12	15.05	<.001	0.14	23.59	<.001
Flagger	SL = 45	0.12	5.28	.022	0.07	10.57	.001	0.04	20.76	<.001
Flagger	SL = 55	0.78	0.08	.782	0.65	0.20	.651	0.28	1.59	.208

According to the model given in Equation 4, the conditional probabilities of $P\{Z = 1|\bar{X}\}$ are estimated as given in Equation 5 (*9, 15*):

$$P\left\{Z = 1|\bar{X} = [x_1, x_2]\right\} = \frac{\exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2)}{1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2)} \quad (5)$$

According to the binary logistic regression model given in Equation 4,

- $P\{Z = 1|X_1 = 0; X_2 = 0\}$ is the probability of a motorist speeding at a short time gap at a speed limit of 45 mph and during no flagger presence,
- $P\{Z = 1|X_1 = 0; X_2 = 1\}$ is the probability of a motorist speeding at a short time gap at a speed limit of 55 mph and during no flagger presence, and
- $P\{Z = 1|X_1 = 1; X_2 = 0\}$ is the probability of a motorist speeding at a short time gap at a speed limit of 45 mph and during flagger presence.

Stepwise binary logistic regression is carried out to fit the model given in Equation 4 for each short time gap threshold. For all three short time gap thresholds, both predictors of X_1 (i.e., flagger presence) and X_2 (i.e., work zone speed limit) are found to be significant at $\alpha = .05$. This matches with the results presented in Table 7 because speed limit is found to be significantly associated with the frequency of speeding by at least 5 mph at short time gaps. Table 8 shows the binary logistic regression models and the estimates of $P\{Z = 1|X_1 = x_1; X_2 = x_2\}$ for each short time gap threshold. All three binary logistic regression models and all regression coefficients were found to be statistically significant at $\alpha = .05$. Consider the case of the short time threshold of 1.00 s, for instance. According to Table 8, the probability of motorists speeding by at least 5 mph at time gaps shorter than 1.00 s is estimated as .217 in the work zones with a 45 mph speed limit and no flagger, .038 in the work zones with a 55 mph speed limit and no flagger, and .011 in the work zones with a flagger. According to Table 8, the probability of speeding by at least 5 mph at short time gaps ranges from 1.1% to 26.1%, depending on the short time gap threshold and work zone temporary traffic control.

Tendency to Faster Trail by at Least 5 mph at Short Time Gaps

For each short time gap threshold, Figure 1*c* shows the percentage of frequency of drivers who faster trailed by at least 5 mph at short time gaps. According to Figure 1*c*,

- For all short time gap thresholds, the frequency of the drivers who faster trailed by at least 5 mph at short time gaps was very low;
- When the work zone had a flagger and a 45 mph speed limit, only one out of 2,038 vehicles was observed to faster trail by at least 5 mph while it maintained a short time gap; and
- When the work zone had no flagger and a 55 mph speed limit, only one out of 1,226 vehicles was observed to faster trail by at least 5 mph while it maintained a short time gap.

The results show that faster trailing by at least 5 mph at short time gaps does happen even though the frequency is rather low. Because the frequency is too low for a statistical analysis, no statistical analysis was conducted regarding this risky driving behavior. However, it should be noted that every time a vehicle faster trails by at least 5 mph at a short time gap, it may be a potential rear-end collision.

Flagger Effects in Reducing the Probability of Speeding by at Least 5 mph at Short Time Gaps

Table 6 gives the estimate of the reduction in the probability of a motorist speeding by at least 5 mph at a short time gap during flagger presence and a 45 mph speed limit. Consider the case of the short time gap threshold of 0.85 s, for instance. According to Table 8, the estimate of the probability of a motorist speeding by at least 5 mph at a short time gap (i.e., < 0.85 s) is .238 during no flagger presence and a 45 mph speed limit, .036 during no flagger presence and 55 mph speed limit, and .022 during flagger presence and a 45 mph speed limit. Thus, compared with a work zone with a 45 mph speed limit and no flagger, the probability of a motorist speeding by at least

TABLE 8 Binary Logistic Regression Models Quantifying Effects of Flagger on Frequency of Speeding by at Least 5 mph at Short Time Gaps

Upper Threshold for Short Time Gaps	Binary Logistic Regression Model	Probability That Vehicle Would Speed by at Least 5 mph at Short Time Gaps: During No Flagger Presence (SL = 45 mph) $P\{Z = 1|X_1 = 0; X_2 = 0\}$	During No Flagger Presence (SL = 55 mph) $P\{Z = 1|X_1 = 0; X_2 = 1\}$	During Flagger Presence (SL = 45 mph) $P\{Z = 1|X_1 = 1; X_2 = 0\}$
0.70	$\text{Logit}\{Z = 1|\bar{X}\} = -1.04 - 2.14\,X_1 - 1.79\,X_2$	.261	.056	.040
0.85	$\text{Logit}\{Z = 1|\bar{X}\} = -1.16 - 2.65\,X_1 - 2.12\,X_2$	.238	.036	.022
1.00	$\text{Logit}\{Z = 1|\bar{X}\} = -1.29 - 3.23\,X_1 - 1.94\,X_2$	.217	.038	.011

5 mph at short time gap is reduced by (.238 − .022)/.238 = 91%. By using the same procedure, it can be concluded from Table 6 that

- When the work zone had a flagger and a 45 mph speed limit compared with when it had no flagger and a 45 mph speed limit, the probability that a vehicle would speed by at least 5 mph at short time gaps was reduced by 85% to 95% and
- When the work zone had a flagger and a 45 mph speed limit compared with when it had no flagger and a 55 mph speed limit, the probability that a vehicle would speed by at least 5 mph at short time gaps was reduced by 28% to 72%.

CONCLUSIONS AND RECOMMENDATIONS

For maintaining short time gaps:

- When the work zone had a flagger and a 45 mph speed limit compared with no flagger and a 45 mph speed limit, the probability that a vehicle in platoon would maintain short time gaps was reduced by 60% to 69%;
- When the work zone had a flagger and a 45 mph speed limit compared with no flagger and a 55 mph speed limit, the probability that a vehicle in platoon would maintain short time gaps was reduced by 60% to 69%; and
- The probability that a vehicle in platoon would maintain short time gaps did not differ significantly between the work zones with no flagger and a 45 mph speed limit and the work zones with no flagger and a 55 mph speed limit.

For speeding by at least 5 mph at short time gaps:

- When the work zone had a flagger and a 45 mph speed limit compared with no flagger and a 45 mph speed limit, the probability that the a vehicle would speed by at least 5 mph at short time gaps was reduced by 85% to 95%;
- When the work zone had a flagger and a 45 mph speed limit compared with no flagger and a 55 mph speed limit, the probability that a vehicle would speed by at least 5 mph at short time gaps was reduced by 28% to 72%; and
- The frequency of vehicles speeding by at least 5 mph at short time gaps was significantly greater in work zones with no flagger and a 45 mph speed limit than in work zones with no flagger and a 55 mph speed limit. Thus work zones with no flagger and a 45 mph speed limit were found to be more hazardous for speeding at short time gaps.

On the basis of the above results, the following conclusions can be made:

- Flagger presence seems to be the key factor to significantly reduce the frequency of short time gaps and speeding by at least 5 mph at short time gaps. The reason might be either human presence adjacent to the road or the waving movement of the flagger.
- Rear-end collisions are directly related to short time gaps and speeding (*2–7*). Because flagger presence can effectively reduce the probability of the combination of short time gaps and speeding, it may effectively reduce the probability of rear-end collisions as well.

The following are some other conclusions and recommendations:

- The frequency of faster trailing by at least 5 mph at short time gaps is found to be too low in all data sets for a statistical analysis.
- The volume at the study sites ranged from 631 to 913 vphpl during the data collection. Future studies can conduct the same analysis at different volume ranges.
- As a future study, how the results changed over the length of lane closure can be explored. To observe this, traffic flow data can be collected from multiple locations over the lane closure.
- This research can be extended by using field data from other work zones with other types of work zone traffic control (e.g., intelligent transportation systems) and different lane configurations.

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