MIDWEST SMART WORK ZONE DEPLOYMENT INITIATIVE

MwSWZDI

FHWA POOLED FUND STUDY

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Removable Orange Rumble Strips

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Supplemental Notes

Abstract

REMOVABLE ORANGE RUMBLE STRIPS

Objectives

The primary goal of the study was to determine the effectiveness of the rumble strips as located in the approach to a highway work zone. Rumble strips are intended for use both with stationary long-term work zones and with short-term moving projects. The specific research objectives were:

1. To test the effectiveness of the rumble strips in merging the traffic into one lane before the work zone starts;
2. To test and evaluate the effectiveness of the rumble strips in reducing the average speeds and speed variance approaching the work zone;
3. To determine whether the rumble strips changed the accident rate; and
4. To determine the ease of installation and removal, and the durability of the rumble strips.

Measures Of Effectiveness

The rumble strips were expected to provide an advance warning of the lane closure, to encourage motorists to reduce vehicle speed, to reduce the speed variance, to perform for the life of the project, and to be safe for motorists. Table 4-1 shows the measures of effectiveness associated with each objective.

Lane distribution and speed measurements were disaggregated by vehicle type (passenger vehicles vs. non-passenger vehicles) and by time of day (day, night, and dawn/dusk).

TABLE 4-1 Measures of effectiveness.

Objective	Measures
Provide advance warnings	Lane distribution
Reduce speed	Mean speed 85^{th} percentile speed Mean speed of fastest 15% of vehicles 10-mph pace
Reduce speed variance	Standard deviation of speed % of vehicles in 10-mph pace
Perform for life of project	Observed ease of installation Observed condition before removal Observed ease of removal
Provide for safety	Number of accidents related to rumble strips

Data Collection And Analysis Procedures

The field research was conducted at a stationary, long-term work zone on eastbound Interstate 70 (I-70) near Columbia, Missouri.

Site Description

The highway normally has a 70-mph speed limit, but the posted speed limit approaching the work zone was reduced first to 60-mph and then to 50-mph. On the first installation attempt, six sets of rumble strips were installed at locations approaching the work zone (Figure 4-1). On the second attempt, only four sets of rumble strips were installed (Figure 4-2).

The rumble strips, which can be cut to length, are 4 inches wide and 0.15 inches thick. A vehicle passing over the rumble strips experiences a slight bump, which alerts a driver to hazards ahead. The orange color designates the construction site. Each set contained six rumble strips, which were placed on 10 foot centers at the site farthest from the lane drop (Figure 4-3), 5 foot centers at the next site (Figure 4-4), and 2 foot centers at the remaining sites (Figure 4-5). At the first 3 sites (farthest upstream from the work zone), the rumble strips spanned both lanes, while at the 3 sites closest to the work zone they spanned only the closed lane. In addition, a rumble strip warning sign was placed in advance of the first set of rumble strips to alert drivers.

The pavement-related work at this site included cold milling, pavement repair, and resurfacing. The average daily traffic was approximately 14,600 vehicles, with 25.6% non-passenger vehicles (three or more axles) in the eastbound direction of travel. The right lane (driving lane) was closed during the first installation attempt, and the left lane (passing lane) of the eastbound highway was closed during the second attempt.

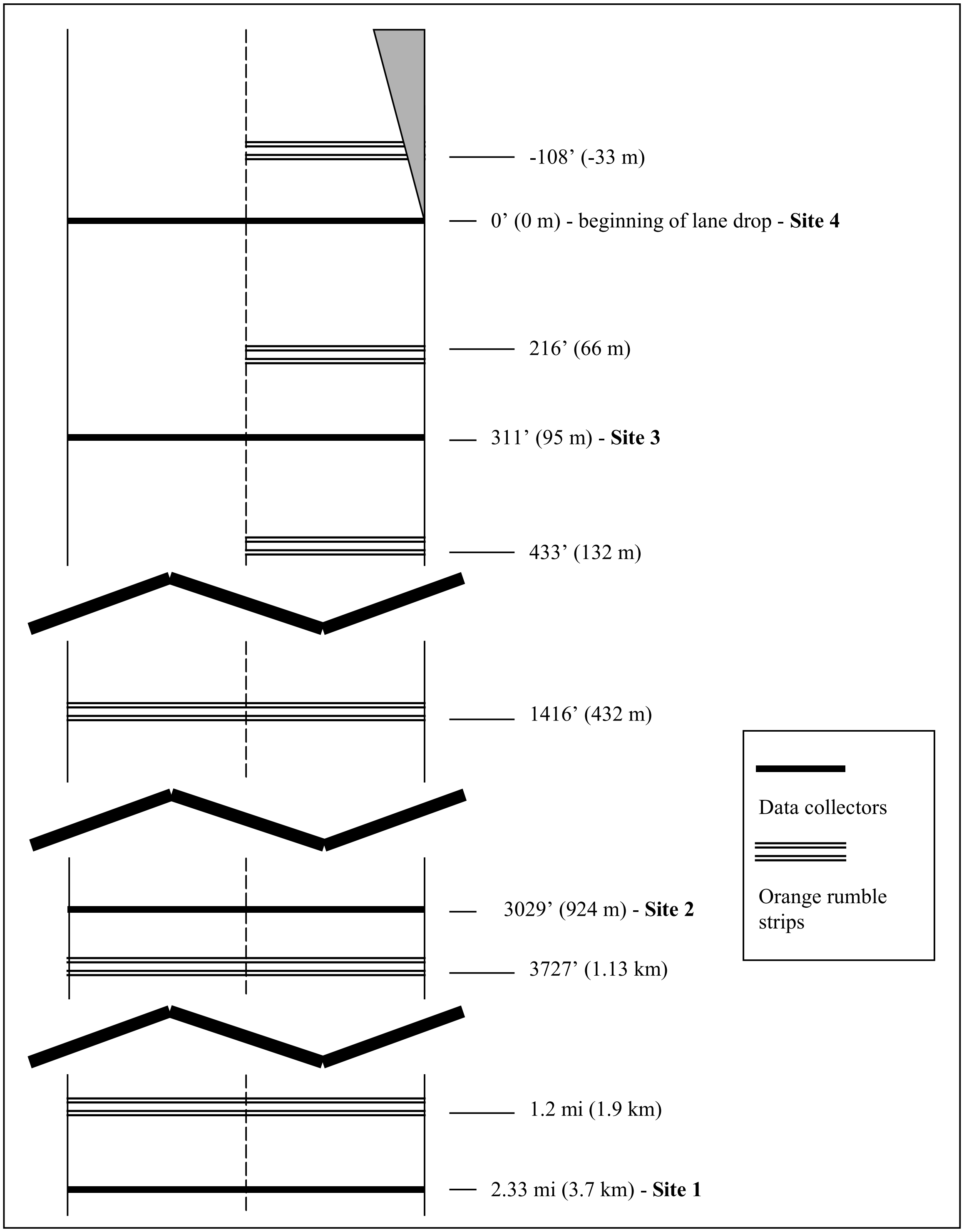

FIGURE 4-1 Schematic location of detectors and rumble strips in work zone (1st attempt).

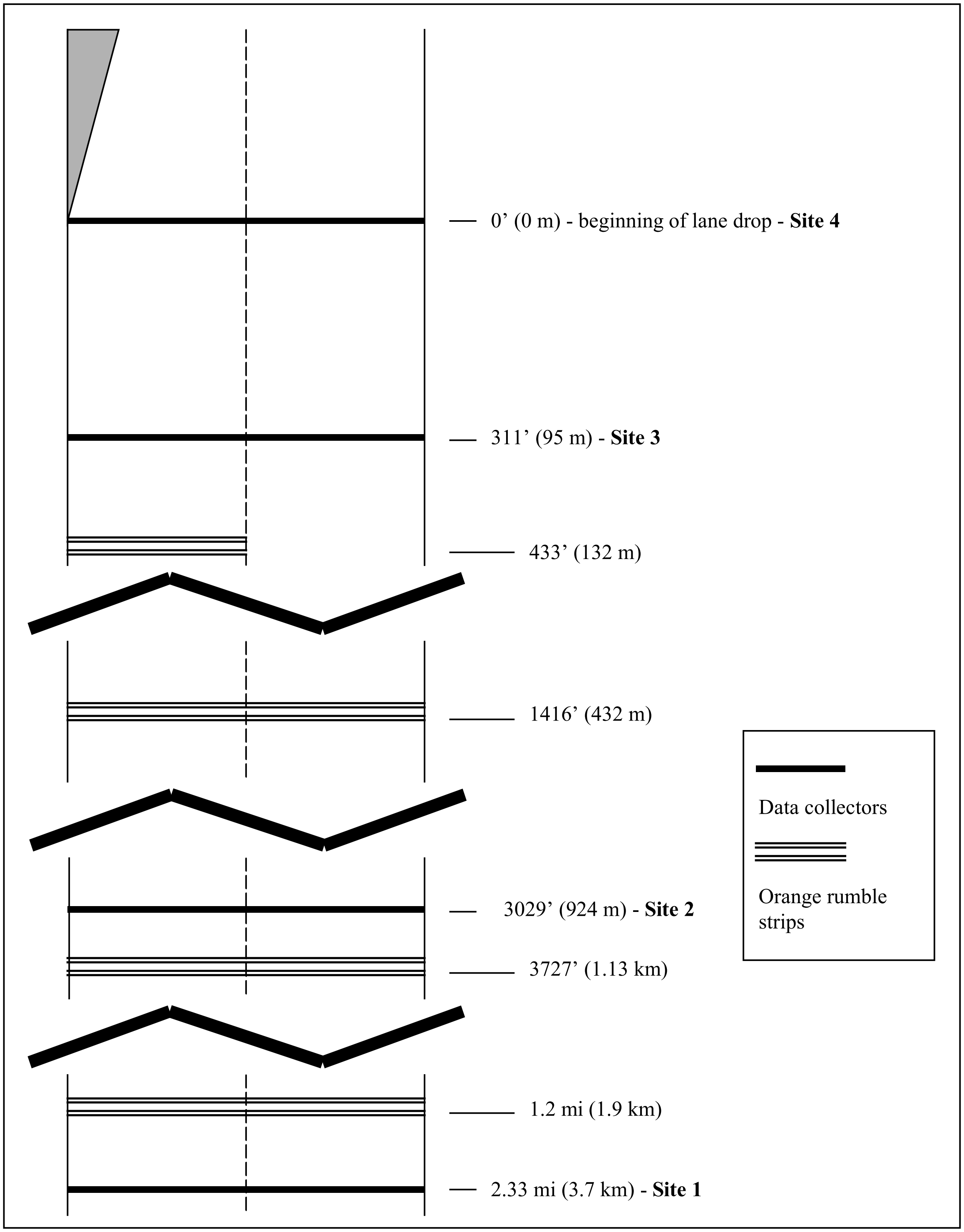

FIGURE 4-2 Schematic location of detectors and rumble strips in work zone (2nd attempt).

FIGURE 4-3 Installation of rumble strips on 10' centers with 200-lb roller.

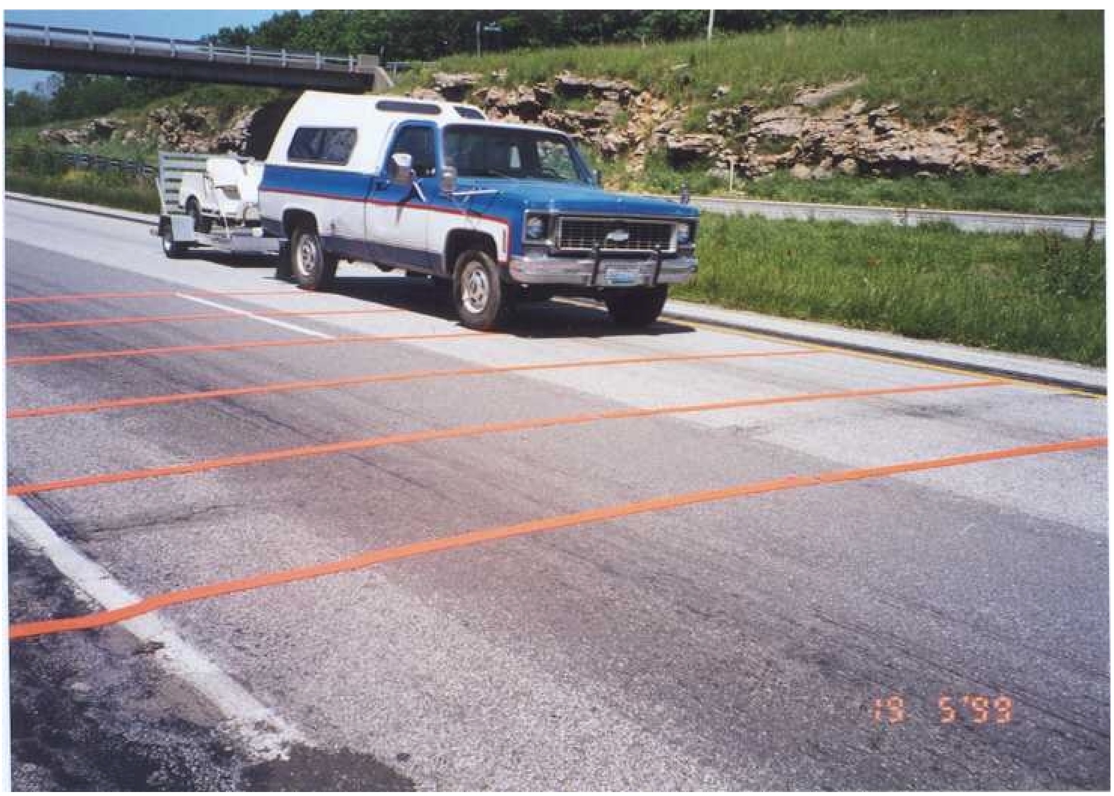

FIGURE 4-4 Rumble strips on 5' centers.

FIGURE 4-5 Rumble strips on 2' centers.

Data Collection

Data were collected at four locations along the approach to the work zone, as shown in Figure 4-2, while only the CB Wizard Alert System was operating (before case), and again after the rumble strips were installed, while the CB alert system was still operating (after case). Vehicle speeds, volumes, and vehicle classifications were collected in 15-minute intervals. Due to breaks in the pneumatic tubes, it was not always possible to collect data at all four sites during all time periods, but approximately 24 hours of data were collected for both the before and after cases. The rumble strips were initially installed on April 13, 1999, and removed the next day. The second installation occurred on May 19, 1999. Data for the analysis were collected on May 18, 1999, for the before case, and on May 20, 1999, for the after case. The second installation of rumble strips was removed on May 27, 1999. All data analyzed were collected during the second installation, as it is unknown how long the rumble strips were in place before they detached from the pavement on the first attempt.

Accident data were collected from one mile upstream of the first data collection site through the end of the work zone. Observations were made regarding the ease of installing and removing the rumble strips and their durability.

Data Analysis

The primary measures of effectiveness used to analyze the data were lane distribution, mean speed, and speed variance upstream of the work zone. Along with these parameters, the percentage of vehicles below the speed limit, the 10-mph pace, the percentage of vehicles in the

10-mph pace, the 85th percentile speed**,** and the mean speed of the fastest 15% of vehicles were calculated to evaluate the traffic control devices in detail. The analysis examined the difference in the parameters before and after the device was installed. Significance testing of the parameters used a two-tailed Student's t-test with a level of significance α = 0.05. An F-test was also conducted, at the same level of significance, to find any significant differences in the speed variance.

Each "before and after" comparison is a test of the hypothesis that the characteristic under study is the same in the before and after cases (i.e., the characteristic did not change). The level of significance (α) used was 0.05. This means that when there was no change, the test can be expected to reach that conclusion correctly (that there is no statistically significant difference) in 95% of the comparisons. However, in 5% of the cases in which there was no change, the test can be expected to indicate a statistically significant difference (this is called a Type I error).

The analysis methods, as well as classification procedures, are explained in the following sections.

Mean Speed

The mean indicates the general speed of vehicles. A greater mean speed has been associated with increased accident potential at a site (*1*). The data were analyzed to identify significant differences in mean speed with the mean was calculated as shown in Equation 4-1.

$$\mu = \frac{F_i X_i}{F_i} \qquad (Eq. 4-1)$$

where: μ = mean speed
F_i = frequency of observations in speed interval *i*
X_i = midpoint of speed interval *I*

The speed data were collected in 15-minute intervals as the frequencies of vehicles in the speed intervals shown in Table 4-2. The midpoint of the speed intervals was taken as the value of X_i, except for the speed interval 1-30 mph, where 20 mph was used to approximate X_i. The speed data in the interval of 85-147 were neglected because very few vehicles fell in this interval, and their mean speed would be difficult to estimate.

TABLE 4-2 Speed intervals for data collection.

Speed Intervals (mph)												
1-30	31-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	70-75	75-80	80-85	85-147

Mean speeds were calculated for each 15-minute interval, and the time intervals were later grouped into the categories of day, night, and dawn/dusk. The 15-minute intervals were also categorized under different levels of service conditions. Final mean speeds and standard deviations were calculated as a weighted average of the 15-minute intervals, using the number of vehicles as the weighting factor.

Speed Variance

Speed variance has been shown to be related to the probability of occurrence of an accident (*1*). At a given mean speed, a higher speed variance is more hazardous than a low variance. With a high variance, many motorists travel at higher and lower speeds than the mean speed, increasing the potential for conflicts. An F-test was conducted on the speed variance to determine any significant differences.

The variance of speed was calculated for each 15-minute interval using Equation 4-2.

$$S^2 = \frac{F_i X_i^2 - N\mu^2}{N-1} \qquad (Eq.4-2)$$

where: S^2 = variance

F_i = frequency of observations in speed interval i

X_i = midpoint of speed interval i

N = number of observations

μ = mean speed

The results report the average standard deviation (the square root of variance), weighted by the volume in each 15-minute interval.

Density

Density (in units of passenger cars per mile per lane or pcpmpl) was used to classify the time intervals as either uncongested or congested. Density equals flow rate (in units of passenger cars per hour per lane) divided by space mean speed (in miles per hour). To calculate flow rate, each non-passenger vehicle was considered equivalent to 1.5 passenger vehicles.

Time mean speed, rather than space mean speed, was measured in the field. Previous research has shown that there is little significant difference between the time mean speed and space mean speed for freeways (*2*). Therefore, the time mean speed estimate value was used for the space mean speed. From the values of density, the level of service of each 15-minute interval was assigned as shown in Table 4-3.

TABLE 4-3 Level of service and density.

Level of Service	Density (pcpmpl)
A	0-10
B	10-16
C	16-24
D	24-32
E	32-45
F	>45

85th Percentile Speed and Mean Speed of Fastest 15% of Vehicles

The 85^{th} percentile speed and the mean speed of the fastest 15% of vehicles were estimated by assuming that the distribution of speeds within a speed range was uniform (e.g., 60% of the vehicles in the speed interval of 60 to 65 mph would have speeds between 60 and 63 mph).

10-mph Pace

The 10-mph pace of each 15-minute interval was grouped to determine the frequencies of each 10-mph pace in each lane. A 2xC contingency table Chi-squared test was performed to determine any significant differences in the distribution of speed.

Data Classification

The vehicles were grouped into *passenger vehicles* (two axles), *non-passenger vehicles* (more than two axles), and *all vehicles.* The times of the observations were classified according to light conditions as day, night, and twilight (dawn/dusk). The U.S. Naval observatory readings of sunset and sunrise were used for this classification.

Finally, the levels of service in the closed and passing lanes were used to group the data into uncongested conditions (both lanes had levels of service A, B, C, or D) or congested conditions (at least one of the lanes had level of service E or F). Due to the unavailability of further details of speed profile in the range 1-30 mph and the approximate use of time mean speed for space mean speed, the actual densities might be greater than the values calculated.

Results

Results related to lane distribution, speed, speed variance, rumble strip performance, and safety are presented below. All comparisons described are the after case compared to the before case, and after cells that show a statistically significant difference from the before case ($\alpha = 0.05$) are shaded in the tables. A blank cell indicates that there were no such conditions observed, and a dash (–) indicates that it was not possible to calculate the particular parameter. For example, if only one vehicle was observed in a 15-minute interval, it would not be possible to calculate a standard deviation of speed.

Due to problems with the data collection device at Site 3, data are only reported for Sites 1, 2, and 4. Data collection Site 1 was 2.33 miles upstream from the lane closure, where drivers would not yet have seen the first set of rumble strips. Data collection Sites 2 and 4 were 3029 feet and 0 feet upstream of the lane closure, respectively.

Lane Distribution

The lane distribution is considered to have improved if there are fewer vehicles in the closed lane in the after case than there were in the before case.

Figures 4-6 to 4-8 present profiles of the percentage of traffic in the right side or driving lane (the lane closed downstream) for the before and after cases for day, night, and dawn/dusk, for *all vehicles, passenger vehicles*, and *non-passenger vehicles*. The percentage of vehicles in the passing (closed) lane generally decreases from Site 1 to Site 4. However, in several cases (particularly for *non-passenger vehicles*), a sharp increase was observed at Site 4. One possible explanation for this is an informal observation that some *non-passenger vehicles* tended to travel in the middle of the two lanes, perhaps hoping to prevent vehicles from passing close to the work zone.

Tables 4-4 to 4-6 show the results for lane distribution during the day, night, and dawn/dusk.

During the day (Table 4-4), for uncongested conditions, lane distribution improved at Site 2 when the rumble strips were in place. For congested conditions, lane distribution improved at Site 4.

During the night (Table 4-5), while there was only one statistically significant difference (at Site 2 for *all vehicles*), lane distributions at Site 4 were all somewhat improved with the rumble strips in place.

During periods of dawn and dusk (Table 4-6), no significant differences were found.

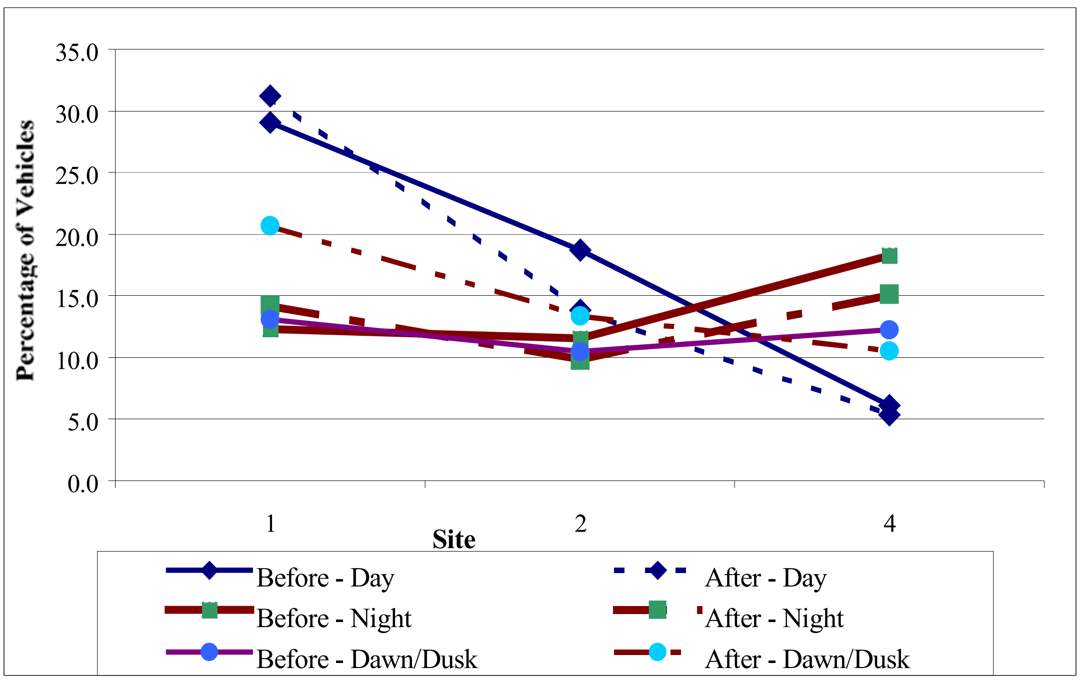

FIGURE 4-6 Profile of percentage of traffic in closed lane – *all vehicles.*

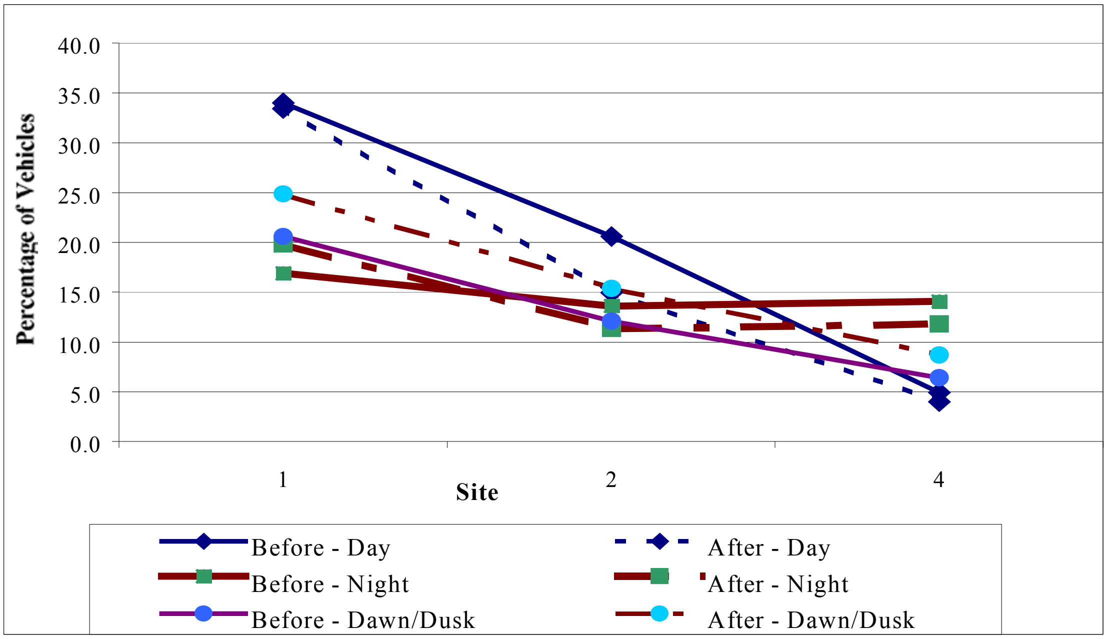

FIGURE 4-7 Profile of percentage of traffic in closed lane – ***passenger vehicles.***

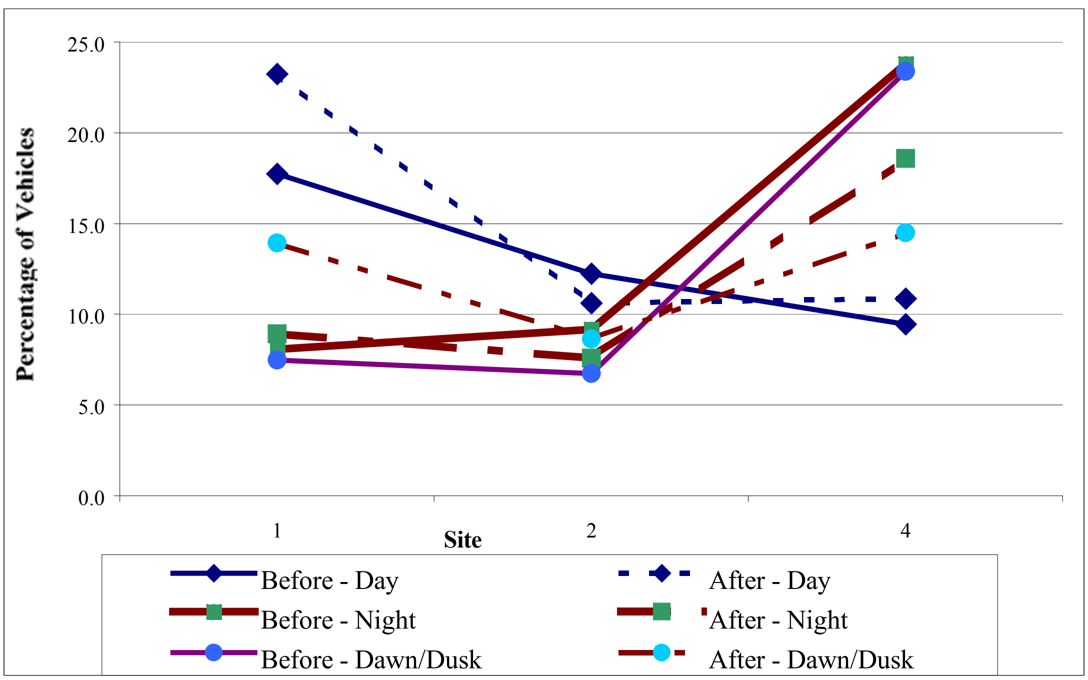

FIGURE 4-8 Profile of percentage of traffic in closed lane – ***non-passenger vehicles.***

TABLE 4-4 Percentage of vehicles in the closed lane – day.

Vehicle Type	Case	Uncongested Conditions at Site			Congested Conditions at Site		
		1	**2**	**4**	**1***	**2**	**4**
All vehicles	**Before**	29.1	18.7	6.1		16.6	17.8
	After	**31.2**	**13.8**	5.4		14.6	**7.6**
Passenger vehicles	**Before**	34.0	20.6	4.9		19.4	11.2
	After	33.4	**15.0**	4.0		17.2	**6.0**
Non-passenger vehicles	**Before**	17.8	12.2	9.4		8.7	33.5
	After	**23.2**	10.6	10.8		11.5	**12.1**
* No congested conditions were observed at Site 1							

TABLE 4-5 Percentage of vehicles in the closed lane – night.

Vehicle type	Case	Uncongested Conditions at Site*		
		1	**2**	**4**
All vehicles	**Before**	12.3	11.5	18.3
	After	14.2	**9.8**	15.1
Passenger vehicles	**Before**	16.9	13.6	14.1
	After	19.8	11.3	11.8
Non-passenger vehicles	**Before**	8.1	9.2	23.8
	After	8.9	7.6	18.6
*No congested conditions were observed				

TABLE 4-6 Percentage of vehicles in the closed lane – dawn/dusk.

Vehicle type	Case	Uncongested Conditions at Site*		
		1	**2**	**4**
All vehicles	**Before**	13.1	10.5	12.2
	After	20.7	13.4	10.5
Passenger vehicles	**Before**	20.6	12.1	6.4
	After	24.9	15.4	8.7
Non-passenger vehicles	**Before**	7.5	6.7	23.4
	After	13.9	8.6	14.5
*No congested conditions were observed				

Average Speed Characteristics

This section presents the results for mean speed, percentage of vehicles below the speed limit, 10-mph pace, 85th percentile speed, and mean speed of the fastest 15% of vehicles, during the day, night, and dawn/dusk. An improvement has occurred if the mean speed, 10-mph pace, 85th percentile speed, and mean speed of the fastest 15% of vehicles decreases from the before case to the after case, or if the percentage of vehicles traveling below the speed limit increases from the before case to the after case.

<u>Mean Speeds</u>

Figures 4-9 to 4-11 show the mean speed profiles for the open lane for the before and after cases. Mean speeds decreased from Site 1 to Site 4 for all after cases.

Tables 4-7 to 4-9 show the results for mean speed during the day, night, and awn/dusk periods.

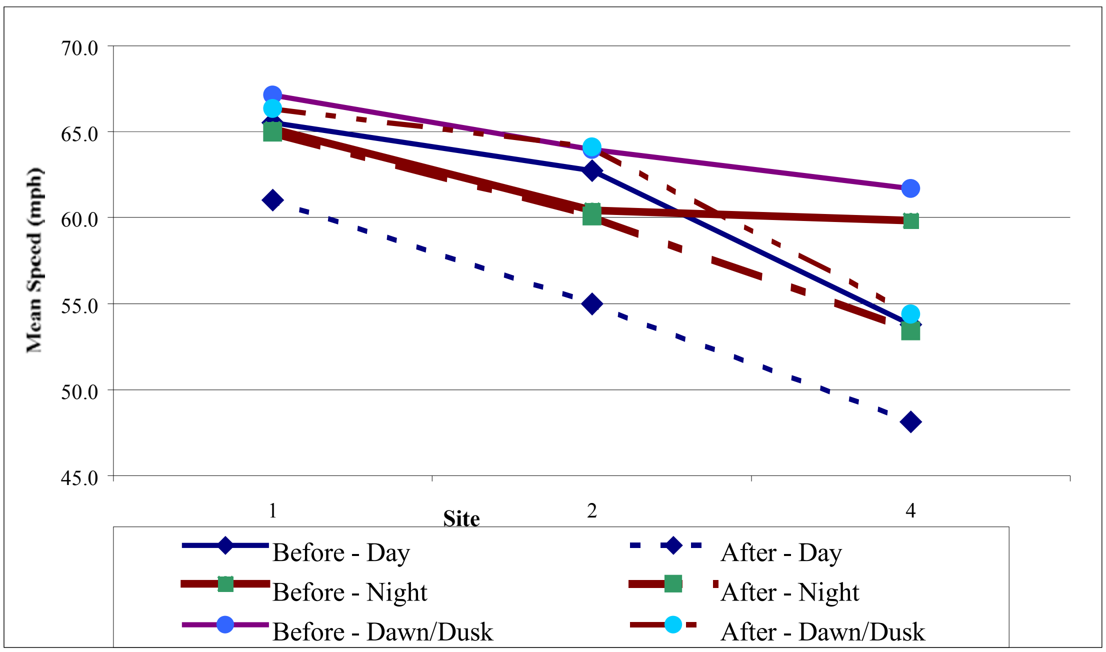

FIGURE 4-9 Mean speed profiles for open lane – *all vehicles.*

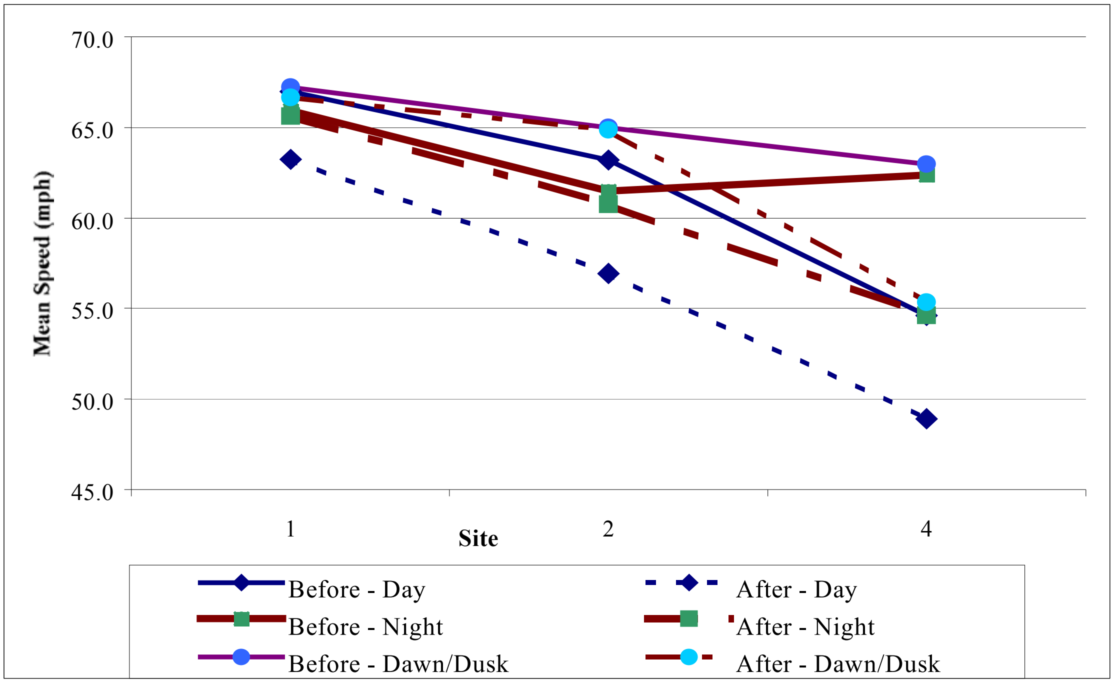

FIGURE 4-10 Mean speed profiles for open lane – ***passenger vehicles.***

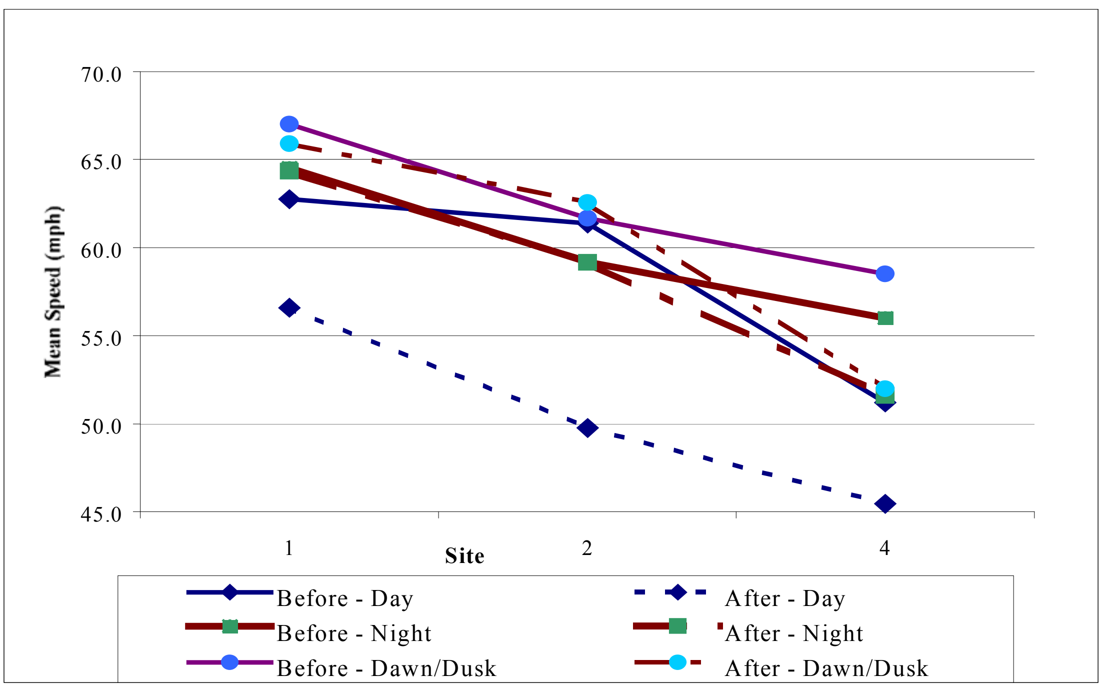

FIGURE 4-11 Mean speed profiles for open lane – ***non-passenger vehicles.***

With the rumble strips in place, mean speed during the day decreased at Sites 2 and 4 under uncongested conditions (Table 4-7). The average speeds were also lower at Site 1, perhaps not influenced by the rumble strips. The prevailing speed may have been lower on the after day. However, since the after speeds at Sites 2 and 4 show greater reductions than the after speed at Site 1, it is likely that the rumble strips caused some speed reduction. For congested conditions, the rumble strips were associated with lower speeds at Site 2 and mixed changes in speeds at Site 4.

During the night (Table 4-8), changes in mean speed were mixed at Site 2 but were significantly improved (lower) at Site 4.

During dawn and dusk (Table 4-9), while the only statistically significant difference in mean speed was for *non-passenger vehicles* at Site 4, *passenger vehicles* and *all vehicles* also showed improvement (lower speeds) at Site 4.

TABLE 4-7 Mean speeds – day.

Vehicle Type	Case	Lane	Uncongested Conditions at Site			Congested Conditions at Site		
			1	**2**	**4**	**1***	**2**	**4**
All vehicles	**Before**	**Driving**	65.5	62.7	53.8		30.3	26.5
		Passing	73.0	71.6	60.3		38.1	34.0
	After	**Driving**	**61.0**	**55.0**	**48.1**		**24.4**	**28.8**
		Passing	69.7	**64.2**	**44.2**		**30.7**	**31.1**
Passenger vehicles	**Before**	**Driving**	67.0	63.2	54.6		33.1	26.8
		Passing	73.9	72.3	60.4		41.0	32.4
	After	**Driving**	**63.2**	**56.9**	**48.9**		**25.4**	**29.3**
		Passing	71.8	**66.3**	**46.2**		**33.0**	32.1
Non-passenger vehicles	**Before**	**Driving**	62.8	61.4	51.2		25.3	25.1
		Passing	69.2	67.6	60.2		32.9	37.0
	After	**Driving**	**56.6**	**49.7**	**45.5**		**23.3**	**27.4**
		Passing	61.0	**54.4**	**40.5**		**27.8**	**29.7**
* No congested conditions were observed at Site 1								

TABLE 4-8 Mean speeds – night.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	65.2	60.4	59.8
		Passing	71.8	68.4	64.5
	After	**Driving**	65.0	60.1	**53.4**
		Passing	72.3	**70.4**	**55.2**
Passenger vehicles	**Before**	**Driving**	65.9	61.5	62.4
		Passing	72.9	69.4	64.8
	After	**Driving**	65.6	**60.7**	**54.6**
		Passing	73.0	**70.7**	**56.3**
Non-passenger vehicles	**Before**	**Driving**	64.5	59.2	56.0
		Passing	69.4	66.5	64.3
	After	**Driving**	64.3	59.2	**51.6**
		Passing	70.4	**69.7**	**54.5**
*No congested conditions were observed					

TABLE 4-9 Mean speeds – dawn/dusk.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	67.1	64.0	61.7
		Passing	73.9	71.8	71.2
	After	**Driving**	66.3	64.1	54.4
		Passing	75.1	71.4	46.0
Passenger vehicles	**Before**	**Driving**	67.2	65.0	63.0
		Passing	74.5	72.3	71.0
	After	**Driving**	66.6	64.9	55.3
		Passing	75.3	72.0	46.7
Non-passenger vehicles	**Before**	**Driving**	67.0	61.7	58.5
		Passing	71.7	69.4	71.4
	After	**Driving**	65.9	62.6	**52.0**
		Passing	74.4	69.2	**45.3**
*No congested conditions were observed					

Percentage of Vehicles Below Speed Limit

Tables 4-10 to 4-12 show the percentages of vehicles below the speed limit. The speed limit was 60-mph at Site 1 and 50-mph at Site 2 and Site 4.

Under uncongested conditions during the day (Table 4-10), the percentage of vehicles below the speed limit appeared to improve (increase). No significant differences were found for congested conditions.

During the night (Table 4-11), observance of the speed limit in the driving (open) lane improved at Site 4.

During dawn and dusk (Table 4-12), while only one statistically significant difference was found at Site 4, all of the Site 4 observations showed improved compliance with the speed limit.

TABLE 4-10 Percentage of vehicles below speed limit – day.

Vehicle Type	Case	Lane	Uncongested Conditions at Site			Congested Conditions at Site		
			1	**2**	**4**	**1***	**2**	**4**
All vehicles	**Before**	**Driving**	14.7	3.6	34.7		92.5	99.8
		Passing	5.2	0.8	21.8		74.7	85.6
	After	**Driving**	**27.4**	**26.6**	**50.2**		98.3	98.0
		Passing	14.3	**18.1**	**50.5**		89.1	84.0
Passenger vehicles	**Before**	**Driving**	14.4	3.7	32.7		91.6	99.8
		Passing	5.2	0.7	20.1		72.9	87.5
	After	**Driving**	**27.1**	**24.9**	**48.0**		98.1	98.0
		Passing	13.8	**15.8**	**46.1**		87.3	83.5
Non-passenger vehicles	**Before**	**Driving**	14.7	3.4	41.2		95.0	100.0
		Passing	5.6	1.7	27.7		79.5	80.0
	After	**Driving**	**27.8**	**29.1**	**57.6**		98.9	98.3
		Passing	**16.9**	**24.6**	**59.3**		92.0	84.6

*No congested conditions were observed at Site 1

TABLE 4-11 Percentage of vehicles below speed limit – night.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	16.1	4.5	19.2
		Passing	6.8	0.9	10.9
	After	**Driving**	16.9	5.1	**30.2**
		Passing	4.3	0.2	9.8
Passenger vehicles	**Before**	**Driving**	17.8	4.1	11.6
		Passing	5.2	0.9	10.1
	After	**Driving**	19.4	4.5	**22.7**
		Passing	3.3	0.3	5.8
Non-passenger vehicles	**Before**	**Driving**	15.1	5.4	26.3
		Passing	4.6	1.8	12.0
	After	**Driving**	15.0	6.4	**39.1**
		Passing	8.3	0.0	12.4
* No congested conditions were observed					

TABLE 4-12 Percentage of vehicles below speed limit – dawn/dusk.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	9.5	0.6	11.4
		Passing	0.0	0.0	16.7
	After	**Driving**	12.3	0.6	28.7
		Passing	0.0	0.7	37.3
Passenger vehicles	**Before**	**Driving**	11.2	0.6	9.1
		Passing	0.0	0.0	25.0
	After	**Driving**	17.1	0.2	23.7
		Passing	0.0	0.9	53.1
Non-passenger vehicles	**Before**	**Driving**	6.6	0.5	17.0
		Passing	0.0	0.0	12.5
	After	**Driving**	6.7	1.3	**40.3**
		Passing	0.0	0.0	31.0
* No congested conditions were observed					

10-mph Pace

The speed distributions (that is, the proportion of vehicles in each speed interval) were analyzed to determine whether a significant difference existed in the before and after distributions. Changes in the 10-mph pace are reported only when the changes in the distribution were significant.

Significant differences in the speed distributions occurred at Site 2 during the day for all vehicles and during the night for non-passenger vehicles. In the former case, the 10-mph pace increased from 60-70 mph to 65-75 mph, and in the latter case, it decreased from 60-70 mph to 55-65 mph. At Site 4, significant differences were found during both day and night for all vehicle classes. In all cases, the 10-mph pace decreased. No other significant differences in the distributions occurred.

85th Percentile Speeds

Tables 4-14 to 4-16 show the results of the 85th percentile speed in the before and after cases.

During the day (Table 4-14), just as mean speed tended to decrease, the 85th percentile speed tended to decrease, under uncongested conditions, when the rumble strips were in place.

During the night (Table 4-15), while results were mixed at Sites 1 and 2, the 85th percentile speed was significantly lower (improved) at Site 4.

During dawn and dusk (Table 4-16), while only one statistically significant difference was found, the 85th percentile speeds were uniformly lower (better) at Site 4.

TABLE 4-13 85th Percentile speeds – day.

Vehicle Type	Case	Lane	Uncongested Conditions at Site			Congested Conditions at Site		
			1	2	4	1*	2	4
All vehicles	**Before**	**Driving**	72.2	70.2	63.8		30.9	35.8
		Passing	79.3	78.8	68.0		54.6	48.2
	After	**Driving**	67.0	**65.1**	**59.6**		21.4	37.5
		Passing	76.1	**74.5**	**61.1**		38.3	39.3
Passenger vehicles	**Before**	**Driving**	72.2	71.1	64.8		31.2	35.8
		Passing	80.0	79.3	69.8		56.3	45.6
	After	**Driving**	68.3	**66.3**	**60.6**		22.6	37.8
		Passing	77.5	**75.3**	**62.6**		43.4	40.5
Non-passenger vehicles	**Before**	**Driving**	69.6	67.2	59.8		22.9	30.4
		Passing	76.7	75.2	61.6		44.2	47.2
	After	**Driving**	64.5	**61.3**	**55.9**		18.3	34.9
		Passing	72.2	**67.9**	**50.5**		32.3	38.1
* No congested conditions were observed at Site 1								

TABLE 4-14 85th Percentile speeds – night.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	71.6	67.8	66.2
		Passing	77.5	74.7	64.5
	After	**Driving**	**67.4**	67.5	**61.8**
		Passing	77.4	75.7	**60.1**
Passenger vehicles	**Before**	**Driving**	73.7	70.5	69.6
		Passing	78.7	76.7	65.1
	After	**Driving**	73.5	70.2	**64.6**
		Passing	78.0	77.4	**61.5**
Non-passenger vehicles	**Before**	**Driving**	69.9	65.1	61.5
		Passing	73.4	70.6	64.2
	After	**Driving**	69.4	65.6	**58.4**
		Passing	**75.4**	**74.3**	**58.7**
* No congested conditions were observed					

TABLE 4-15 85th Percentile speeds – dawn/dusk.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	73.7	71.2	69.2
		Passing	82.0	79.0	67.9
	After	**Driving**	72.4	71.8	63.9
		Passing	79.6	77.2	55.8
Passenger vehicles	**Before**	**Driving**	74.3	72.6	71.3
		Passing	82.4	79.7	75.2
	After	**Driving**	73.8	73.1	65.5
		Passing	80.2	77.8	53.1
Non-passenger vehicles	**Before**	**Driving**	71.7	67.3	64.0
		Passing	77.1	74.3	68.2
	After	**Driving**	70.8	68.9	60.6
		Passing	79.3	73.7	**56.4**
* No congested conditions were observed					

Mean Speed of Fastest 15% of Vehicles

Tables 4-16 to 4-18 show the mean speeds of the fastest 15% of vehicles.

Just as mean speed tended to decrease during the day, the mean speed of the fastest 15% of vehicles tended to decrease during the day (Table 4-16), particularly under uncongested conditions, when the rumble strips were in place.

During the night (Table 4-17), the mean speed of the fastest 15% of vehicles was significantly lower (improved) at Site 4.

During dawn and dusk (Table 4-18), while only one statistically significant difference was found, the mean speeds of the fastest 15% of vehicles were uniformly lower (better) at Site 4.

TABLE 4-16 Mean speed of fastest 15% of vehicles – day.

Vehicle Type	**Case**	**Lane**	**Uncongested Conditions at Site**			**Congested Conditions at Site**		
			1	**2**	**4**	**1***	**2**	**4**
All vehicles	**Before**	**Driving**	74.5	73.3	68.0		38.8	38.0
		Passing	81.2	80.9	71.6		62.5	52.7
	After	**Driving**	70.5	**68.8**	**63.9**		31.6	39.7
		Passing	79.0	**77.3**	**64.9**		**47.4**	44.1
Passenger vehicles	**Before**	**Driving**	75.3	74.1	69.0		40.1	37.9
		Passing	81.6	81.2	73.0		64.9	50.9
	After	**Driving**	71.4	**69.8**	**64.8**		32.5	40.0
		Passing	79.43	**77.9**	**66.1**		**49.2**	44.6
Non-passenger vehicles	**Before**	**Driving**	71.7	69.4	62.6		35.8	37.5
		Passing	77.8	75.9	62.5		53.2	47.4
	After	**Driving**	67.4	**64.5**	**59.0**		29.8	37.8
		Passing	**74.7**	**70.2**	**52.6**		38.4	42.1
* No congested conditions were observed at Site 1								

TABLE 4-17 Mean speed of fastest 15% of vehicles – night.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	74.2	71.3	70.7
		Passing	79.0	76.3	66.4
	After	**Driving**	74.0	71.1	**65.6**
		Passing	78.4	77.3	**61.8**
Passenger vehicles	**Before**	**Driving**	75.9	73.6	73.3
		Passing	79.9	77.9	67.1
	After	**Driving**	75.8	73.1	**68.0**
		Passing	78.9	78.7	**62.6**
Non-passenger vehicles	**Before**	**Driving**	71.8	67.3	64.2
		Passing	73.9	70.8	64.9
	After	**Driving**	71.4	67.5	**60.7**
		Passing	75.9	**74.5**	**59.6**
* No congested conditions were observed					

TABLE 4-18 Mean speed of fastest 15% of vehicles – dawn/dusk.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	75.4	74.0	73.2
		Passing	82.9	80.6	68.3
	After	**Driving**	74.1	74.9	67.3
		Passing	80.8	78.8	59.1
Passenger vehicles	**Before**	**Driving**	76.0	75.1	74.5
		Passing	83.0	81.0	75.1
	After	**Driving**	75.0	75.9	68.5
		Passing	81.5	79.2	58.0
Non-passenger vehicles	**Before**	**Driving**	73.7	69.1	66.2
		Passing	78.4	74.6	68.5
	After	**Driving**	71.9	**71.1**	62.6
		Passing	80.3	74.3	**56.9**
* No congested conditions were observed					

Speed Variance Characteristics

This section presents the results for standard deviation of speed and percentage of vehicles traveling within the 10-mph pace during the day, night, and dawn/dusk, respectively. A smaller standard deviation and an increased percentage of vehicles traveling within the 10-mph pace indicate an improvement from the before to the after case.

Standard Deviation of Speed

Figures 4-12 to 4-14 show generally increasing standard deviations of speed in the open lane from Site 1 to Site 4. For day, for all vehicle classes, the standard deviation is greater in the after case than in the before case.

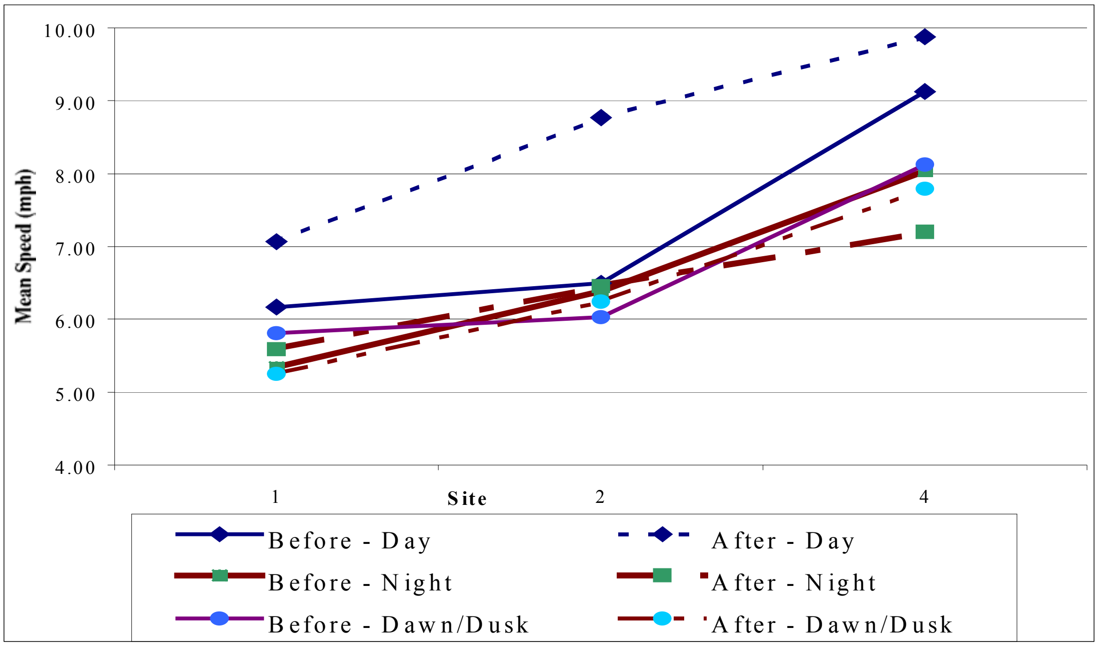

FIGURE 4-12 Profile of standard deviation of speed for open lane– *all vehicles.*

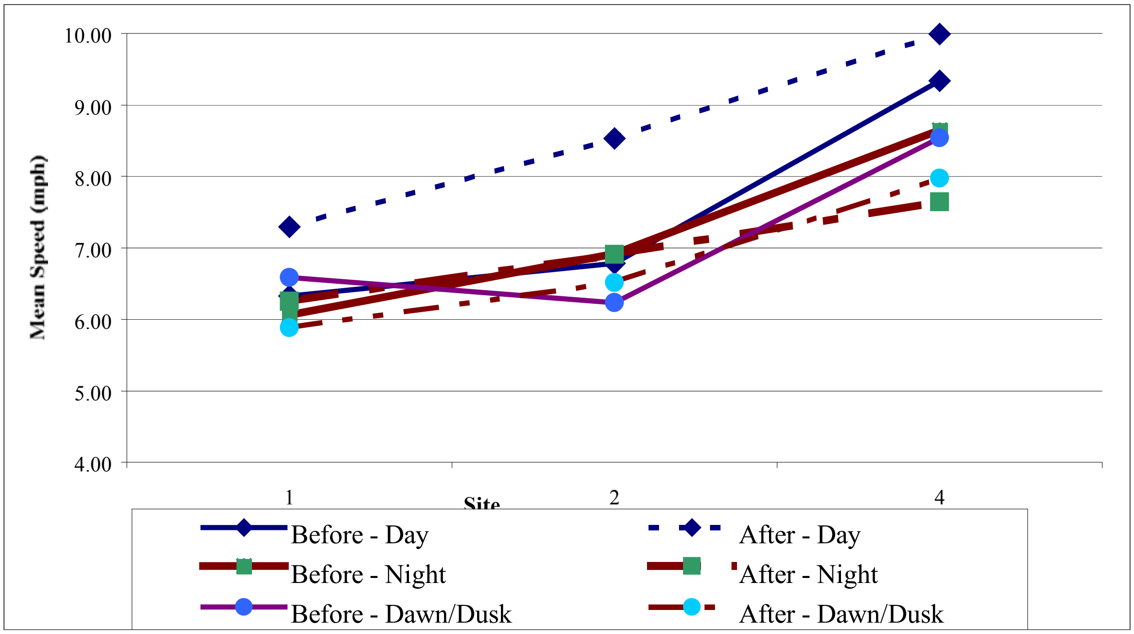

FIGURE 4-13 Profile of standard deviation of speed for open lane– ***passenger vehicles.***

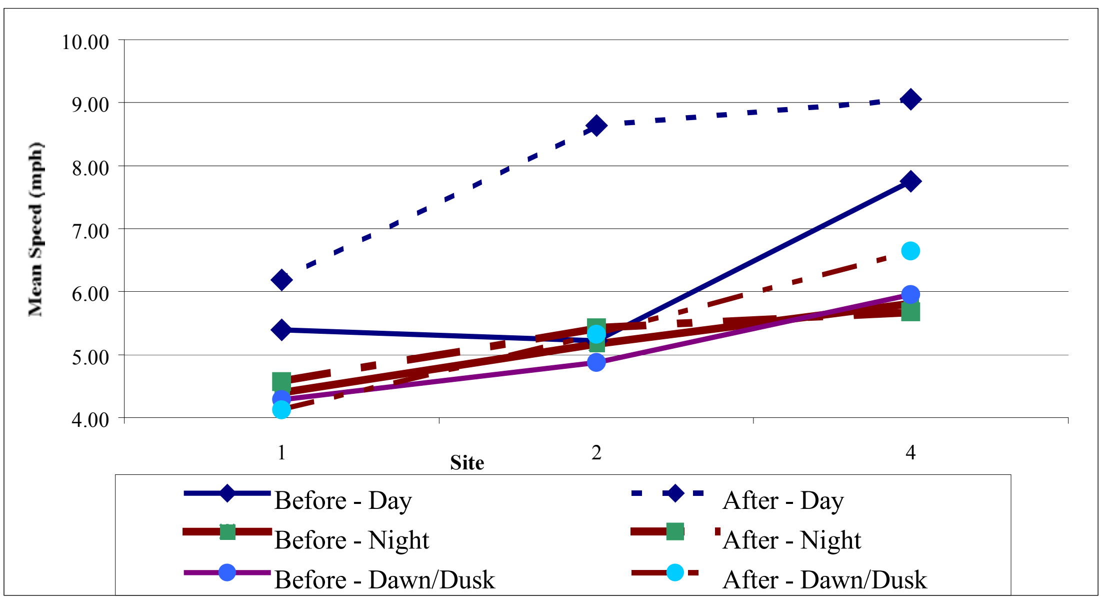

FIGURE 4-14 Profile of standard deviation of speed for open lane– ***non-passenger vehicles.***

Tables 4-19 to 4-21 show the standard deviations of speed for the before and after cases.

During the day (Table 4-19), no statistically significant differences were found in standard deviation of speed. However, under uncongested conditions, all of the standard deviations were higher with the rumble strips in place. Under congested conditions, no consistent pattern emerged.

During the night (Table 4-19), no statistically significant differences were found.

During dawn and dusk (Table 4-21), no statistically significant differences were found.

TABLE 4-19 Standard deviation of speed – day.

Vehicle Type	Case	Lane	Uncongested Conditions at Site			Congested Conditions at Site		
			1	2	4	1*	2	4
All vehicles	Before	Driving	6.17	6.49	9.13		7.91	7.27
		Passing	5.44	6.11	6.55		15.97	11.61
	After	Driving	7.07	8.77	9.88		5.74	7.46
		Passing	6.90	9.29	13.03		10.47	8.58
Passenger vehicles	Before	Driving	6.32	6.78	9.34		8.83	7.22
		Passing	5.22	6.06	8.25		15.84	11.75
	After	Driving	7.29	8.53	9.99		6.71	7.52
		Passing	6.50	8.68	13.63		11.39	8.45
Non-passenger vehicles	Before	Driving	5.40	5.22	7.76		5.20	7.26
		Passing	5.33	5.18	3.28		14.29	7.63
	After	Driving	6.19	8.64	9.05		4.23	6.93
		Passing	7.51	10.10	8.98		7.39	8.31
* No congested conditions were observed at Site 1								

TABLE 4-20 Standard deviation of speed – night.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	2	4
All vehicles	Before	Driving	5.34	6.39	8.04
		Passing	5.47	5.42	3.87
	After	Driving	5.59	6.45	7.20
		Passing	5.26	5.48	4.44
Passenger vehicles	Before	Driving	6.06	6.91	8.65
		Passing	5.30	5.81	4.66
	After	Driving	6.25	6.91	7.64
		Passing	5.19	5.43	4.67
Non-passenger vehicles	Before	Driving	4.39	5.17	5.81
		Passing	3.86	3.14	2.64
	After	Driving	4.57	5.42	5.68
		Passing	4.21	4.41	3.47
* No congested conditions were observed					

TABLE 4-21 Standard deviation of speed – dawn/dusk.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	2	4
All vehicles	**Before**	**Driving**	5.81	6.03	8.12
		Passing	5.59	4.98	2.34
	After	**Driving**	5.25	6.24	7.79
		Passing	4.18	6.31	8.60
Passenger vehicles	**Before**	**Driving**	6.58	6.23	8.54
		Passing	5.42	5.10	2.77
	After	**Driving**	5.88	6.51	7.97
		Passing	3.96	6.39	7.66
Non-passenger vehicles	**Before**	**Driving**	4.29	4.88	5.95
		Passing	4.79	4.15	1.66
	After	**Driving**	4.12	5.32	6.64
		Passing	4.51	5.65	9.37
* No congested conditions were observed					

Percentage of Vehicles Traveling within the 10-mph Pace

Tables 4-22 to 4-24 show the percentage of vehicles within the 10-mph pace in the before and after cases.

During the day (Table 4-22), under uncongested conditions, the percentage of vehicles within the 10-mph pace tended to decrease, particularly at Site 2. This would be expected, since every category of standard deviation of speed tended to increase. For congested conditions, the plurality of vehicle speeds fell below 30-mph (i.e. in the 1-30 mph interval); therefore, it was impossible to calculate a 10-mph pace.

During the night (Table 4-23), no statistically significant differences were found

In the dawn/dusk period (Table 4-24), while only one statistically significant difference was found, the percentage of vehicles within the 10-mph pace tended to be worse (lower) at Site 4.

TABLE 4-22 Percentage of vehicles within the 10-mph pace – day.

Vehicle Type	Case	Lane	Uncongested Conditions at Site		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	61.7	60.1	47.4
		Passing	71.0	65.6	57.7
	After	**Driving**	62.3	**54.6**	45.7
		Passing	65.8	**54.4**	48.1
Passenger vehicles	**Before**	**Driving**	58.9	57.2	45.0
		Passing	69.4	66.5	56.8
	After	**Driving**	58.1	**52.1**	44.9
		Passing	64.901	**51.8**	**39.6**
Non-passenger vehicles	**Before**	**Driving**	74.4	70.1	56.5
		Passing	77.7	72.8	77.9
	After	**Driving**	73.9	**63.8**	52.9
		Passing	71.9	68.7	75.5

TABLE 4-23 Percentage of vehicles within the 10-mph pace – night.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	69.3	61.5	55.2
		Passing	69.2	75.4	79.9
	After	**Driving**	71.4	59.8	55.8
		Passing	73.6	74.2	84.2
Passenger vehicles	**Before**	**Driving**	59.5	56.1	52.7
		Passing	73.9	71.1	84.4
	After	**Driving**	60.0	55.1	51.4
		Passing	77.2	71.9	81.2
Non-passenger vehicles	**Before**	**Driving**	78.0	68.3	66.2
		Passing	86.7	88.2	84.1
	After	**Driving**	77.2	65.3	64.8
		Passing	78.4	82.1	87.3
* No congested conditions were observed					

TABLE 4-24 Percentage of vehicles within the 10-mph pace – dawn/dusk.

Vehicle Type	Case	Lane	Uncongested Conditions at Site*		
			1	**2**	**4**
All vehicles	**Before**	**Driving**	66.9	59.7	50.6
		Passing	60.1	78.0	85.4
	After	**Driving**	71.6	58.3	47.2
		Passing	80.6	62.7	66.5
Passenger vehicles	**Before**	**Driving**	60.7	59.9	49.2
		Passing	68.5	76.2	95.7
	After	**Driving**	61.2	57.2	48.1
		Passing	81.6	68.4	69.0
Non-passenger vehicles	**Before**	**Driving**	77.2	69.1	64.7
		Passing	72.5	80.6	80.6
	After	**Driving**	84.2	66.6	**51.6**
		Passing	78.4	83.3	84.6
* No congested conditions were observed					

Rumble Strip Performance

The traffic control contractor's first attempt to install the rumble strips occurred on April 13, 1999. Although it had recently rained lightly, the pavement surface appeared to be dry. The personnel laid out the rumble strips, walked on the surface area of the strips to apply pressure (Figure 4-15), then rolled their pickup truck tires over the surface area (Figure 4-16). By the next morning and after a heavy rain, most of the rumble strips had lost adhesion and had been removed from the pavement by traffic. Figure 4-17 shows the remnants of some of those rumble strips.

FIGURE 4-15 Rumble strips initial installation.

FIGURE 4-16 Rumble strips initial installation.

FIGURE 4-17 Failure of rumble strips when improperly installed.

On May 19, 1999, on thoroughly dry pavement, the contractor's installation was successful. The rumble strips were laid in place and a 200-lb (90-kN) roller was used to apply pressure, per the manufacturer's instructions (Figure 4-3). The process, including temporary lane closures for both lanes and installation of the rumble strips, required approximately three-and-one-half hours for a two-person installation team. The rumble strips remained in good condition for eight days (Figures 4-3 to 4-5, Figures 4-18 and 4-19). Rumble strip removal exhibited no particular difficulties and required approximately two hours, including temporary lane closures, for a two-person team with no special tools (Figure 4-20).

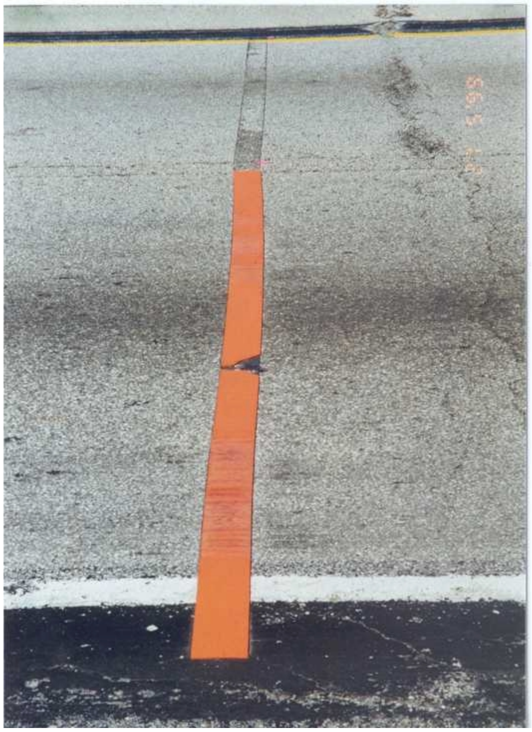

FIGURE 4-18 Second-worst material loss after eight days.

FIGURE 4-19 Worst material loss after eight days.

FIGURE 4-20 Rumble strip removal.

Safety

The time periods when the devices were in place were too short to indicate a statistically significant reduction in accidents. However, a sharp rise in accidents could indicate that the rumble strips are hazardous. No accidents were found to have occurred because of the rumble strips. The rumble strips were expected to warn drivers still in the closed lane and traveling at high speeds to slow down and change lanes. If the rumble strips were to cause an accident, it would be expected to be either a changing lane or out of control type accident. No accidents of either type occurred while the rumble strips were in place.

Conclusions

This study examined the effect of rumble strips on lane distributions, vehicle speeds, and vehicle conflicts at a long-term work zone in Missouri. The rumble strips were primarily intended to reduce the percentage of vehicles in the closed lane, traffic speeds, and speed variability. The data analysis examined the difference in the parameters before and after the devices were installed. The primary measures of effectiveness were lane distributions, speed mean, and speed variance; however, other parameters were also studied for significance in the evaluation of the traffic control devices. For the before and after studies, the analysis took into consideration the effects of time of day and class of vehicle.

The rumble strips were associated with improved lane distribution at the beginning of the lane drop during both the day and night. The mean, 85^{th} percentile, and mean speeds of the fastest 15% of vehicles all showed improvement with the rumble strips in place. The only negative change in traffic flow characteristics associated with the rumble strips was a tendency for increased speed variance, exhibited in some of the observations through an increase in the standard deviation of speed and a decrease in the percentage of vehicles within the 10-mph pace.

The study also examined the ease of installation and removal and the durability of the rumble strips. Installation required approximately 3.5 hours for a two-person team, including temporary lane closures for both lanes, while removal required approximately 2.0 hours. In general, the rumble strips maintained their structural integrity under eight days of traffic, with about 14,600 vehicles per day, including 25.6% vehicles with three or more axles. The first, failed installation attempt indicated that installing the rumble strips on possibly damp pavement without the use of a 200-lb roller can result in nearly immediate failure. The second, successful installation indicated that the rumble strips can adhere well when applied to dry pavement with a 200-lb roller.

Finally, the study examined the safety of the rumble strips. No adverse effect on traffic safety was found.

Recommendations

Removable orange rumble strips can be used on an interstate highway construction zone when applied to dry pavement with a 200-lb roller. If one-way traffic is being reduced from two lanes to one lane, the rumble strips can be expected to encourage earlier merging and to reduce speeds slightly. However, there may be an increase in the standard deviation of speed and a reduction in the percentage of traffic traveling within the 10-mph pace.

The primary costs of the rumble strips include the material, several hours of labor for installation and removal, and any additional traffic delay or hazard caused by the temporary lane closures required for installation and removal.