MIDWEST SMART WORK ZONE DEPLOYMENT INITIATIVE

MwSWZDI

FHWA POOLED FUND STUDY

Report Title

Report Date: 2002

Preformed Rumble Strips

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Supplemental Funding Agency Name and Address (if applicable)

Supplemental Notes

Abstract

EFFECTIVENESS OF SWARCO RUMBLER® ON US 65 IN SPRINGFIELD, MISSOURI

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1. TECHNOLOGY

The Swarco Rumbler® is a removable rumble strip intended to provide auditory, visual, and vibratory warnings for highway construction zones, as tested in this study. According to the manufacturer's promotional literature, the Rumbler provides:

- Auditory warning by generating a distinct level of audible transmissions that alert the motorist to upcoming changes in traffic flow
- Visual warning by white or yellow coloring (reflectorized or unreflectorized).
- Vibratory warning by a controlled distinct vibration as the motorist travels across the designated rumble strip area.

The manufacturer's promotional literature also states that the Rumbler can provide advance warning for "blind stop signs, traffic signals, dangerous curves and exit ramps" and that it can be used in "parking garages, schools, railroad crossings, churches and residential areas." These latter characteristics were not tested in this study.

The manufacturer's contact information is:

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Objectives

The primary objective of this study was to evaluate the effectiveness of rumble strips in reducing the mean speed and speed variance of vehicles along the northbound and southbound directions of US 65 in the Sunset Boulevard region of Springfield, Missouri. A second objective was to observe the ease of installation and removal of the rumble strips. The final objective was to

document the longevity of the rumble strips, as they can be used in work zones for both short-term and long-term projects.

Measures of Effectiveness

This study is similar to a study performed by the University of Missouri-Columbia with the help of the Missouri Department of Transportation (MoDOT) in the first year of the Midwest Smart Work Zone Deployment Initiative (MwSWZDI@ 2000). The study, which evaluated removable orange rumble strips on Interstate 70 in Columbia, Missouri, showed that the rumble strips tended to reduce speed at the project site. The encouraging results of the I-70 study prompted the use of the same approach to study the effectiveness of the rumble strips in this project. The same measures of effectiveness that were used in the I-70 study have been used to test the speed reducing effects of the rumble strips in this project.

Table 1 lists the measures of effectiveness used. The primary measures of effectiveness for the rumble strips were before and after mean speeds and before and after speed variances of vehicles. Significant differences between before and after mean speeds and speed variances have been verified by means of statistical tests. Conclusions regarding the effectiveness of the rumble strips were drawn based on the outcome of these statistical tests.

TABLE 1 Measures of effectiveness

Objective	Measures
Reduce Speed	Mean Speed 85th percentile speed Mean speed of the 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 durability Observed ease of removal

2. STUDY SITE

The Missouri Department of Transportation wanted to reduce traffic speed in advance of a work-zone on a section of US 65 in Springfield, Missouri. Vehicle speed data were collected in the northbound and southbound directions of US 65 in the Sunset Boulevard area. Missouri Department of Transportation (MoDOT) maintenance crews assisted with the data collection.

The northbound and southbound directions were observed in this study. There were two lanes in each direction; referred to here as the passing lane and the driving lane. Lane shifts were

implemented in the work-zone to keep the traffic flowing during construction. Figure 1 shows the site layout. Three sets of rumble strips were installed, one set each at the Road Work Ahead, Reduced Speed Ahead and Speed Limit signs. This report refers to the Road Work Ahead sign as Location 1, the Reduced Speed Ahead sign as Location 2 and the Speed Limit sign as Location 3. Each set of rumble strips contained six rows at a 36-inch spacing. Each row included two strips in each of the two lanes. An adhesive was applied to both the pavement surface and the under side of the rumble strip before installation. After the rumble strips were placed at their exact locations, they were tamped using a 200-lb roller (Figures 2 and 3).

Three sets of speed detectors with pneumatic hoses were used to collect speed data separately for each lane at each of the three locations in both directions of traffic flow. The first set of detectors was placed before the rumble strip sets, the second set after the first set of rumble strips, and the third set of detectors after the last set.

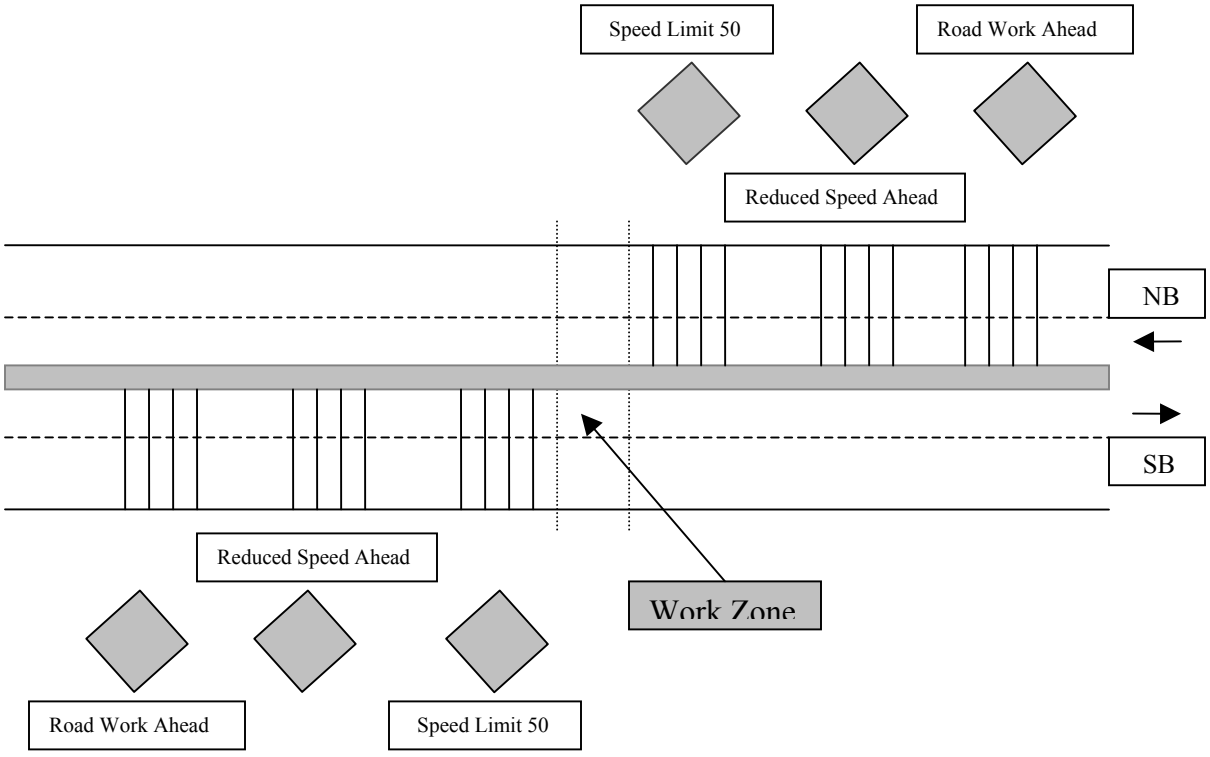

FIGURE 1 Site layout

FIGURE 2 Installation of rumble strips with 200-lb roller

FIGURE 3 Driving lane after installation of the rumble strips

3. DATA COLLECTION

Before and after speed data were collected for the driving and the passing lanes at each of the three locations in the northbound and southbound directions of the highway. Data at each location were classified by vehicle types as specified in the Data Classification section of this report. Speed data were collected in 15- minute intervals over a span of 48-hours at each location. However, temporary application of oil coating at a few locations caused the malfunction of some of the pneumatic hoses, resulting in less than 48-hours of data in such cases. It was desired that at least 24-hours of data be available for consideration for an effective and

accurate analysis. Thus, data were cleaned and 24 hours of good data for each location were chosen from existing data sets to represent a full day.

The rumble strips were installed on both southbound lanes and the northbound passing lane on September 19th, 2001 and along the northbound driving lane on September 20th, 2001. Both before and after speed data were collected. The before data were collected between 4:15 p.m. on Monday, September 17, 2001 and 9:15 a.m. on Wednesday, September 19, 2001 for the northbound lanes. For the southbound lanes, the data were collected between 4:15 p.m. on Monday, September 17, 2001 and 9:00 a.m. on Wednesday, September 19, 2001. Automatic vehicle counters with pneumatic hoses were laid down to collect the before case vehicular speeds. One set of detectors was placed before the rumble strip sets, the second set after the first set of rumble strips while the third set of detectors was placed after the last set of rumble strips. The detectors were placed at the same locations after the rumble strip installation to collect after case data. The after data were collected between 1:15 p.m. on Monday, September 24, 2001 and 3:15 p.m. on Tuesday, September 25, 2001 for northbound lanes and between 1:15 p.m. on Monday, September 24, 2001 and 7:30 a.m. on Wednesday, September 26, 2001 for southbound lanes.

4. DATA ANALYSIS

Speed variance and mean speed were used as the two main measures of effectiveness during data analysis. 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 additional measures used to evaluate the fulfillment of the desired objectives. Values of these parameters before and after the installation of the rumble strips were calculated and indicated the effectiveness of the strips. A two-tailed student's t-test with level of significance α=0.05 was used to determine the statistical significance of differences in mean speeds. A statistical F-test with a significance level of α=0.05 was conducted to verify significant differences in speed variances. The hypothesis tested in these cases was that there was no significant difference in the measured before and after parameters. A significance level of 0.05 means that, in cases where the hypothesis is true, an incorrect conclusion will be reached only 5% of the time.

The following sections explain the analysis procedures and the formulae used.

Mean Speed

Mean speed values indicate the nature of the traffic flow at the site and also serve as good indicators of potential accident locations. Mean speeds were calculated for each 15-minute interval using Equation 1 (May 1990).

$$\bar{x} = \frac{\sum_{i=1}^{g} f_i \bar{x}_i}{N} \qquad (Eq.1)$$

where: $\bar{x}$ = estimated mean speed of population
f_i = frequency of observations in speed interval i

$\bar{x}_i$ = midpoint of speed interval I
g = number of speed intervals
N = total number of vehicles observed

Mean speeds for all intervals of the before and the after data were calculated using the same formula. Table 2 shows the speed intervals adopted to classify speed data. The student's t-test was then applied to the mean of the before and after values of interval mean speeds derived for a single location. The 15-minute time intervals were also classified as day and night. For the before case, 7:00 a.m. to 7:15 p.m. was considered to be day-time and 7:30 p.m. onwards was classified as night-time. For the after case, 7:15 a.m. to 7:00 p.m. was considered to be day-time and 7:15 p.m. onwards was classified as night-time .

TABLE 2 Speed intervals adopted during data collection

Speed Intervals (mph)												
1-30	31-35	36-40	41-45	46-50	51-55	56-60	61-65	66-70	71-75	76-80	81-85	86-147

Speed Variance

Speed variance is the square of standard deviation of speed. Higher variances are associated with higher crash rates. Speed variances were calculated for all 15-minute intervals of the before and after cases using Equation 2 (May 1990).

$$s^2 = \frac{\sum_{i=1}^{g} f_i (x_t)^2 - N(\bar{x})^2}{N-1} \qquad (Eq.\ 2)$$

where: s^2 = estimated variance of speeds
$\bar{x}_i$ = interval mean speed
$\bar{x}$ = estimated population mean
f_i = interval frequency

An F-test was conducted on the mean of the before and after interval speed variances to determine significant differences.

Data Classification

The analysis was performed based on counts of all vehicles types combined, passenger vehicles (two axles) and non-passenger vehicles (three or more axles). Times at which data were recorded were classified under day and night times, as described above.

5. RESULTS

The rumble strips were intended to reduce the mean speed and speed variance along the northbound and southbound directions of US 65. Detectors were placed in each of these two directions (in both the driving and the passing lanes) at locations 1, 2, and 3. Location 1 was upstream of the rumble strips, so one might expect that the rumble strips would not have a large effect on speed and speed variance at Location 1. As a result, Location 1 can be viewed as a control site for factors that might affect prevailing speed (e.g., weather). Analysis includes examination of the before and after speed characteristics at the downstream locations (Locations 2 and 3) and also changes in prevailing speed due to the rumble strips (i.e., the speeds at Locations 2 and 3 compared to the speed at Location 1). These results are described below, along with a description of the ease of installation and longevity of the rumble strips.

Mean Speed Characteristics

Mean Speeds along Northbound Lanes

Figures 4 to 9 show plots for mean speeds as observed for the driving and passing lanes at all three locations for vehicles traveling along the northbound direction during the day and during the night.

For the Northbound passing lane, the after mean speeds during both night and day times were lower than the before mean speeds for all locations, although the after mean speeds during the day were only marginally lower than the corresponding mean speed during the day (Figure 4). For the Northbound driving lane, the after speeds during both day and night were marginally lower than the mean speeds recorded during the corresponding before conditions for all locations (Figure 5).

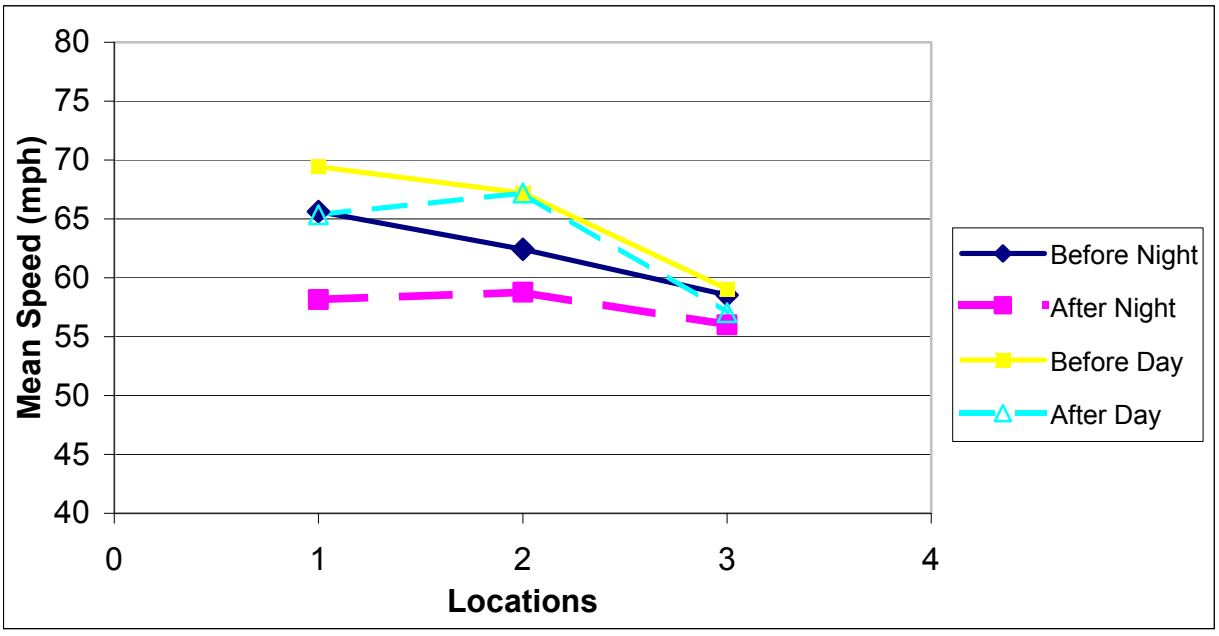

FIGURE 4 Mean speed profiles for northbound passing lane – *all vehicles*

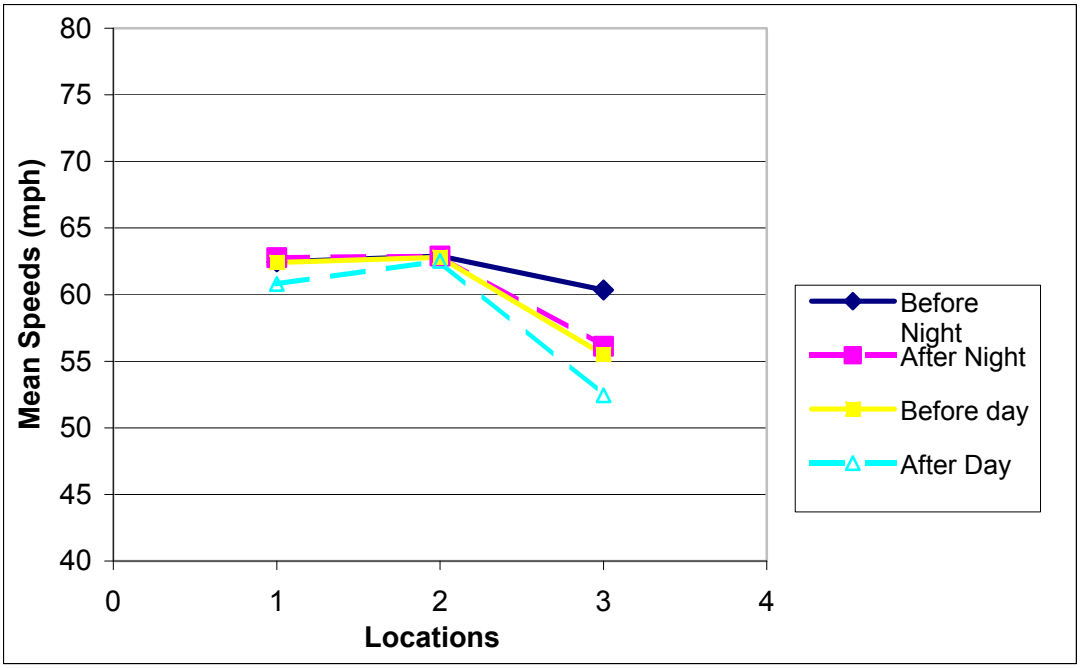

FIGURE 5 Mean speed profiles for northbound driving lane – *all vehicles*

For the Northbound passing lane, Figure 6 shows that the after speeds during both day and night were considerably lower than the mean speeds recorded during the corresponding before conditions for most locations. The before mean speed at the third location was lower than the corresponding after mean speed recorded at night. Figure 7 shows that the after mean speeds and the before mean speeds during both day and night do not differ much for the first two locations, whereas the after mean speeds were considerably lower than the corresponding before mean speeds during both day and night for the third location.

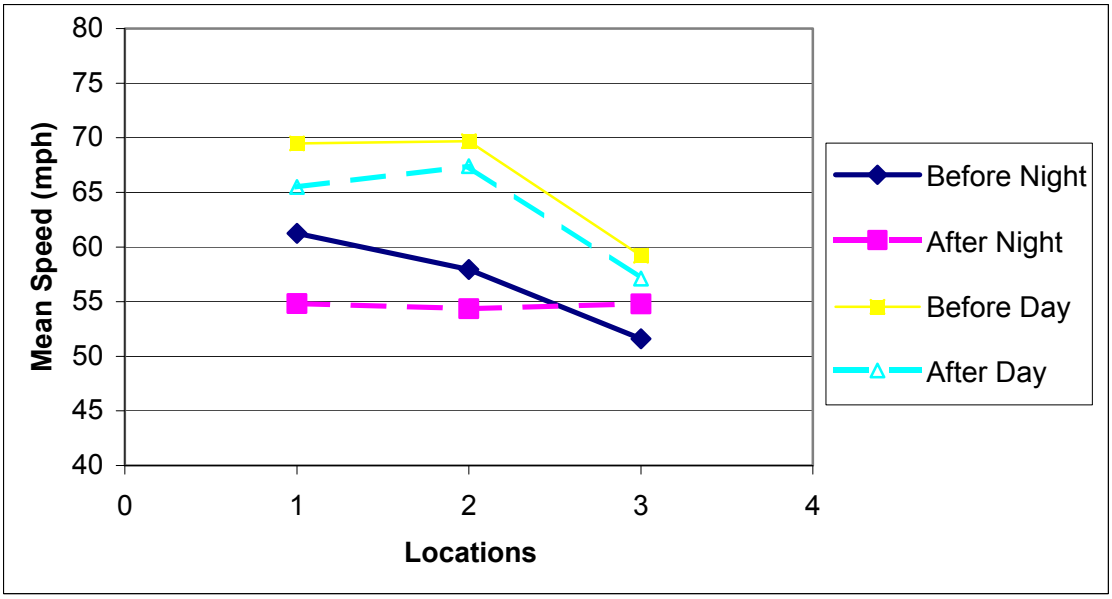

FIGURE 6 Mean speed profiles for northbound passing lane – *passenger vehicles*

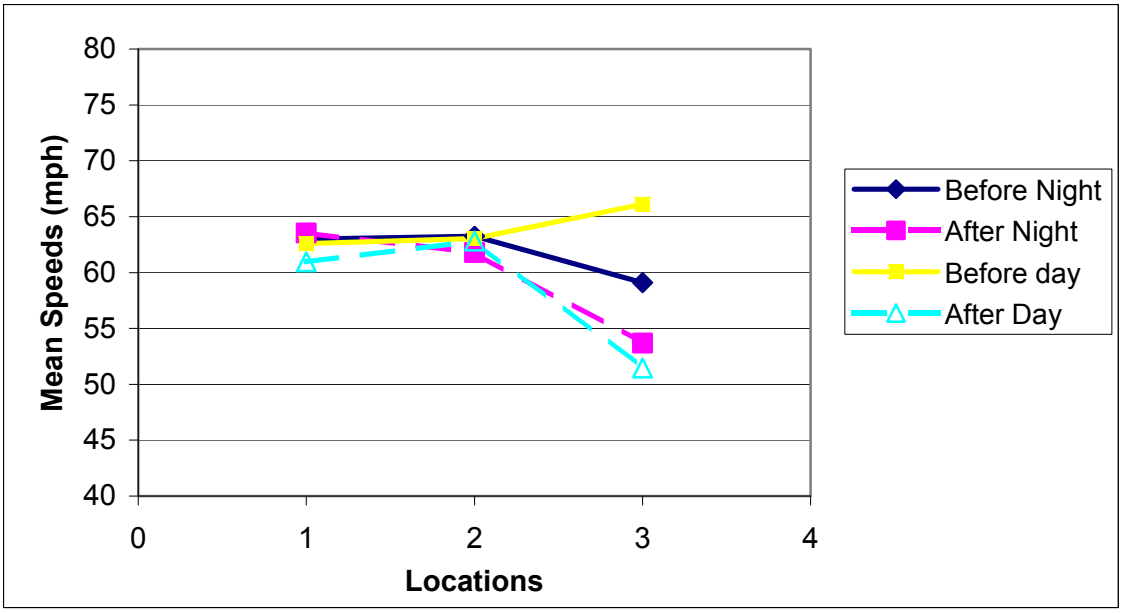

FIGURE 7 Mean speed profiles for northbound driving lane – *passenger vehicles*

Figure 8 shows that while before mean speeds were considerably lower than the after speeds during the night, they were considerably greater than the corresponding mean speeds during the day for all locations. Figure 9 shows that the after mean speeds and the before mean speeds during both day and night do not differ much for the first two locations, whereas the after mean speeds were considerably lower than the corresponding before mean speeds during both day and night for the third location.

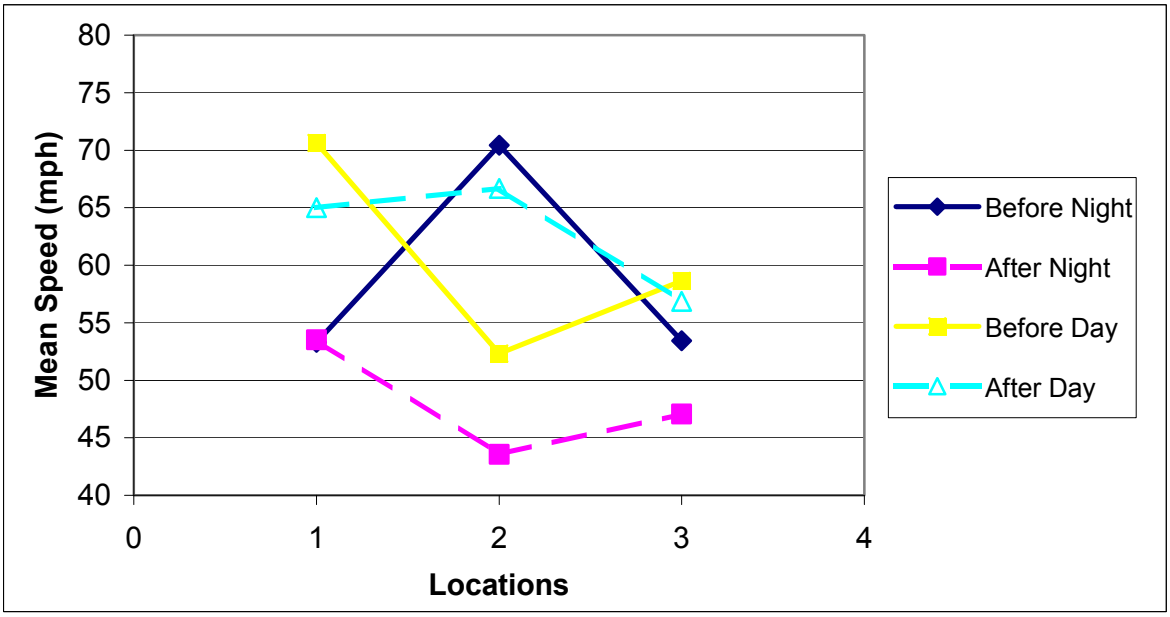

FIGURE 8 Mean speed profiles for northbound passing lane – *non-passenger vehicles*

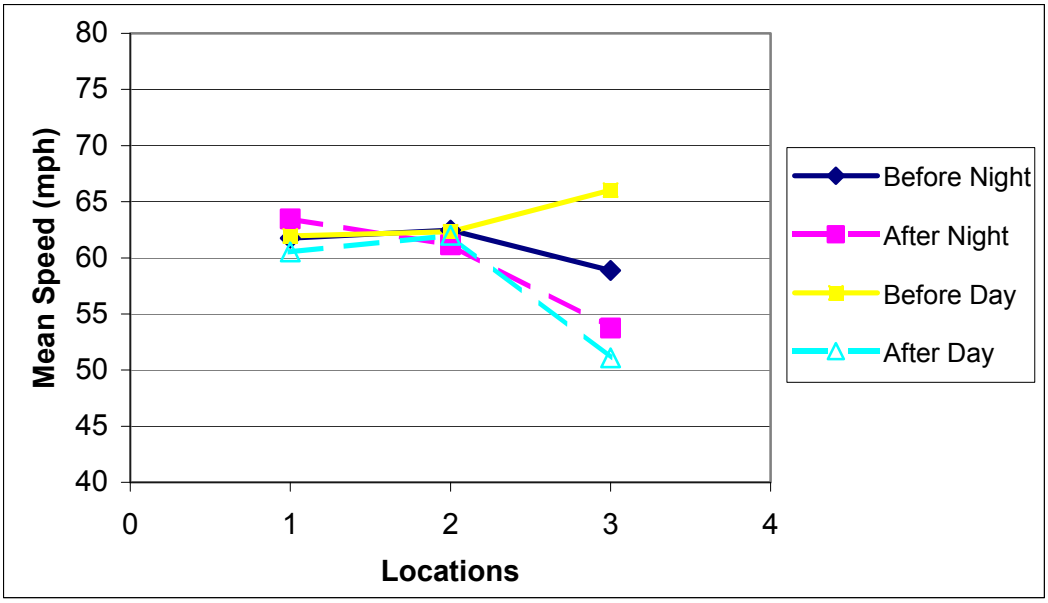

FIGURE 9 Mean speed profiles for northbound driving lane – *non-passenger vehicles*

The data points for the above graphs were derived from Tables 3 through 5. The "P" in the column reading "Lanes" refers to passing lanes, and the "D" in the same column refers to a driving lane. So, for example, NB1P means northbound, Location 1, passing lane.

TABLE 3 Day and night mean speeds- *all vehicles, northbound direction*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	65.64	69.42	58.16	65.36
	NB1D	62.46	62.41	62.78	60.80
2	NB2P	62.43	67.20	58.78	67.20
	NB2D	62.90	62.80	62.90	62.53
3	NB3P	58.54	59.04	55.99	57.04
	NB3D	60.34	55.49	56.12	52.43

TABLE 4 Day and night mean speeds – *passenger vehicles, northbound direction*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	61.26	69.47	54.82	65.50
	NB1D	62.98	62.58	63.55	60.95
2	NB2P	57.93	69.69	54.37	67.40
	NB2D	63.25	63.06	61.80	62.82
3	NB3P	51.59	59.19	54.80	57.12
	NB3D	59.11	66.10	53.69	51.45

TABLE 5 Day and night mean speeds – *non-passenger vehicles, northbound direction*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	53.31	70.62	53.52	65.01
	NB1D	61.75	61.94	63.46	60.53
2	NB2P	70.42	52.33	43.55	66.67
	NB2D	62.46	62.32	61.16	62.01
3	NB3P	53.44	58.63	47.07	56.85
	NB3D	58.86	66.04	53.75	51.09

Mean Speeds along Southbound Lanes

Figures 10 to 15 show plots for mean speeds as observed for the driving and passing lanes at all three locations for vehicles traveling along the southbound direction during the day and during the night.

Figure 10 shows that the before and after mean speeds during the day and night were marginally different with after speeds being equal to or lower than the corresponding before speeds for all locations. Figure 11 shows that the after mean speeds were greater than the corresponding before mean speeds for all locations during both day and night times.

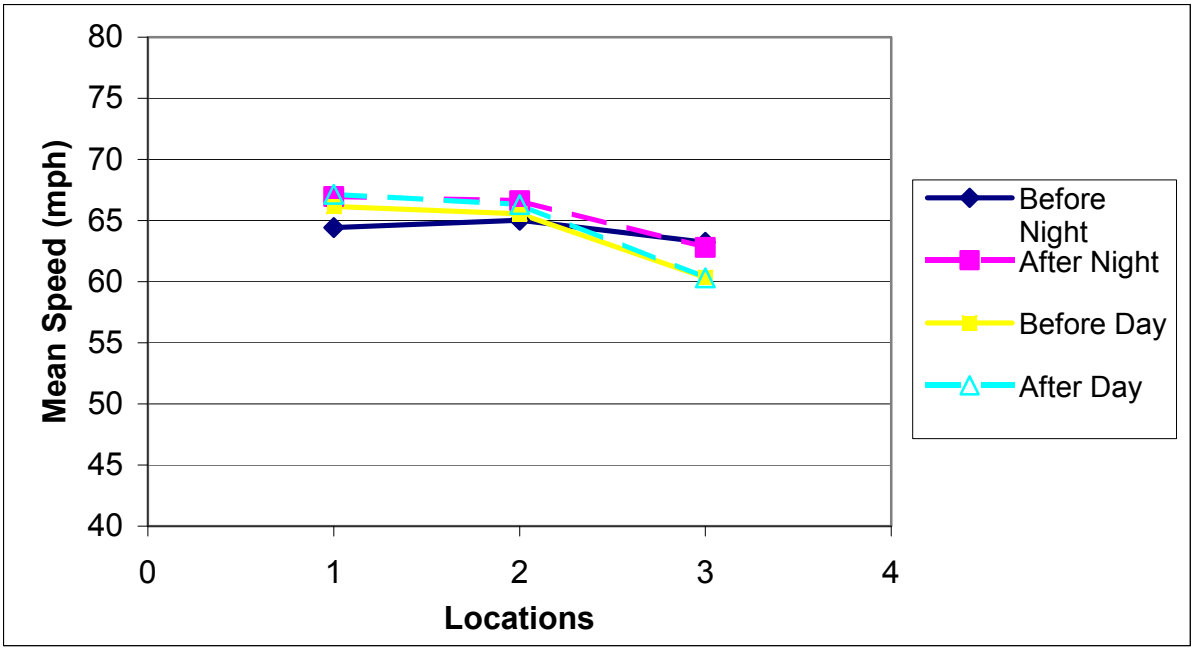

FIGURE 10 Mean speed profiles for southbound passing lane – *all vehicles*

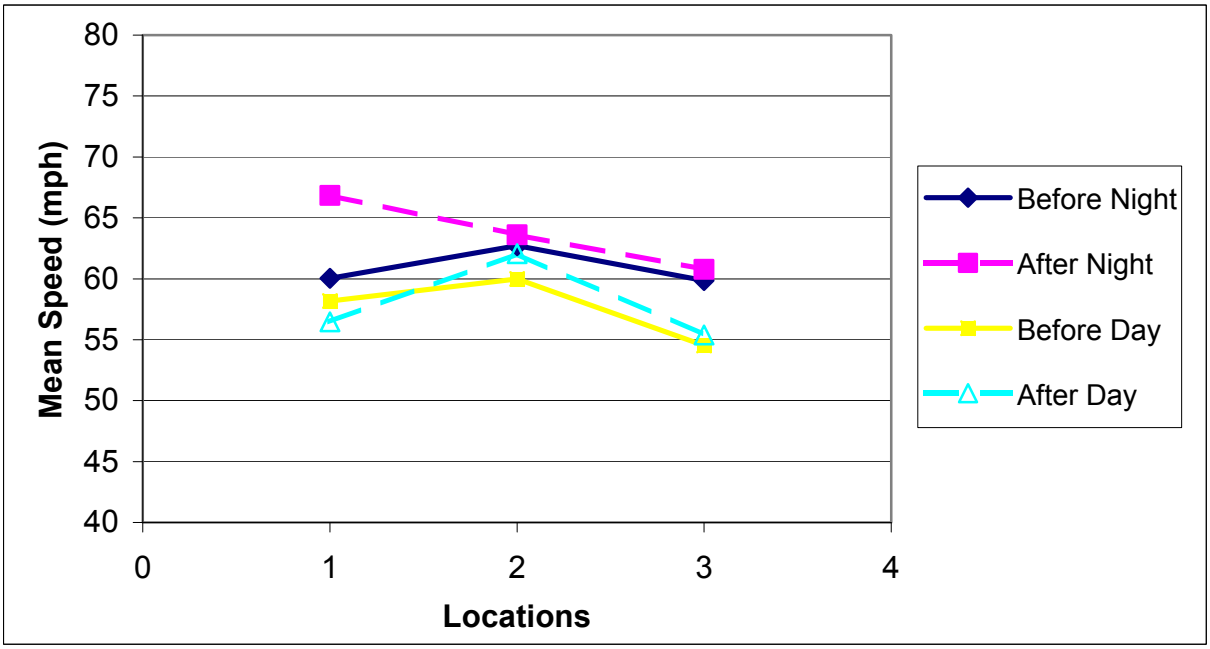

FIGURE 11 Mean speed profiles for southbound driving lane – *all vehicles*

Figure 12 shows that the before and after mean speeds during the day and night were marginally different with after speeds being equal to or less than the corresponding before speeds for all locations. Figure 13 shows that the after mean speeds were greater than the corresponding before mean speeds for all locations except the first location during both day and night times.

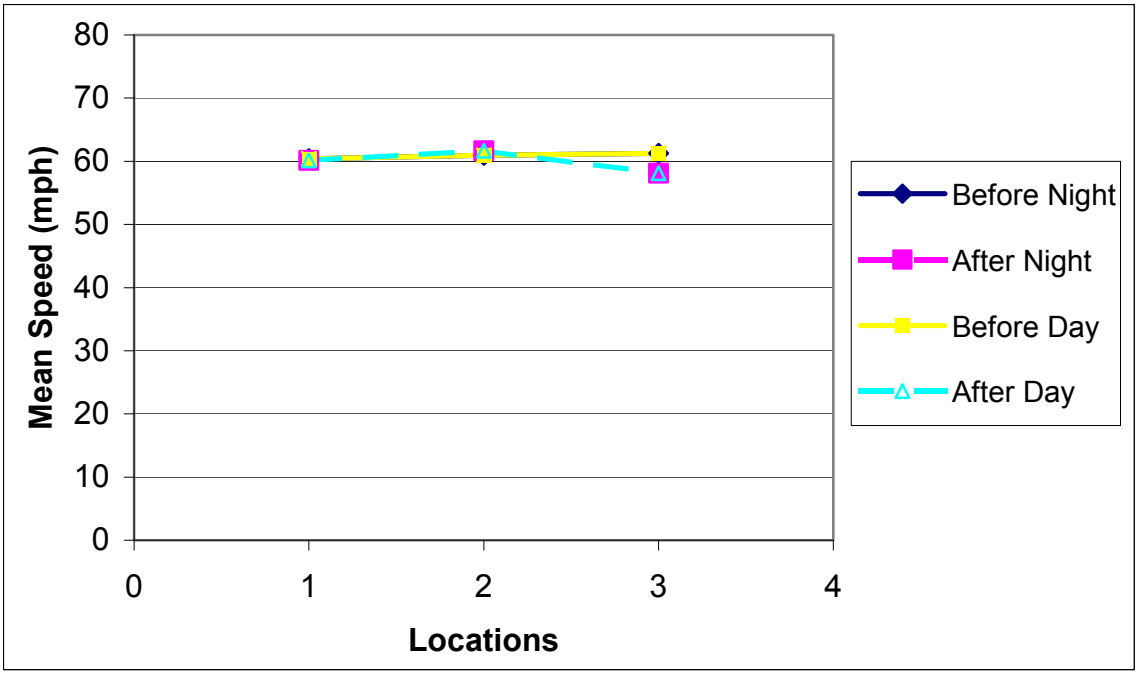

FIGURE 12 Mean speed profiles for southbound passing lane – *passenger vehicles*

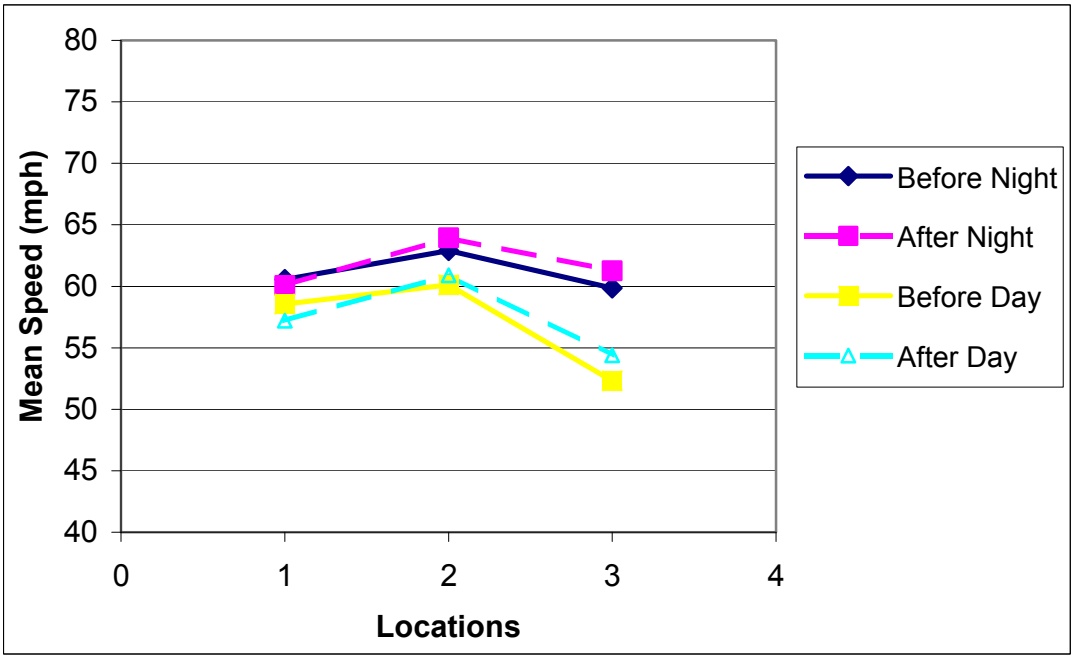

FIGURE 13 Mean speed profiles for southbound driving lane – *passenger vehicles*

Figure 14 shows that the before mean speeds recorded during the night were higher than the corresponding after mean speeds for the first two locations, whereas the before and after speeds were equal at the third location. The day-time plots show that there was not much difference in the before and after values of mean speed during the day at all locations. Figure 15 shows that the after mean speeds were higher than the corresponding before mean speeds, only marginally for the second and third locations during both day and night.

The data points for the above graphs were derived from Tables 6 through 8.

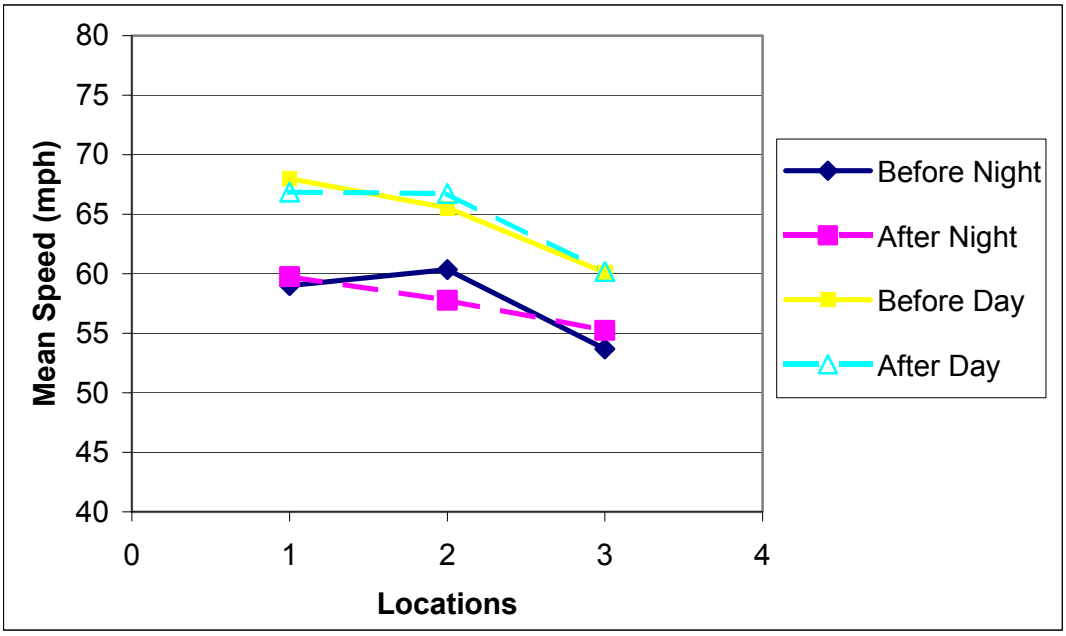

FIGURE 14 Mean speed profiles for southbound passing lane – *non-passenger vehicles*

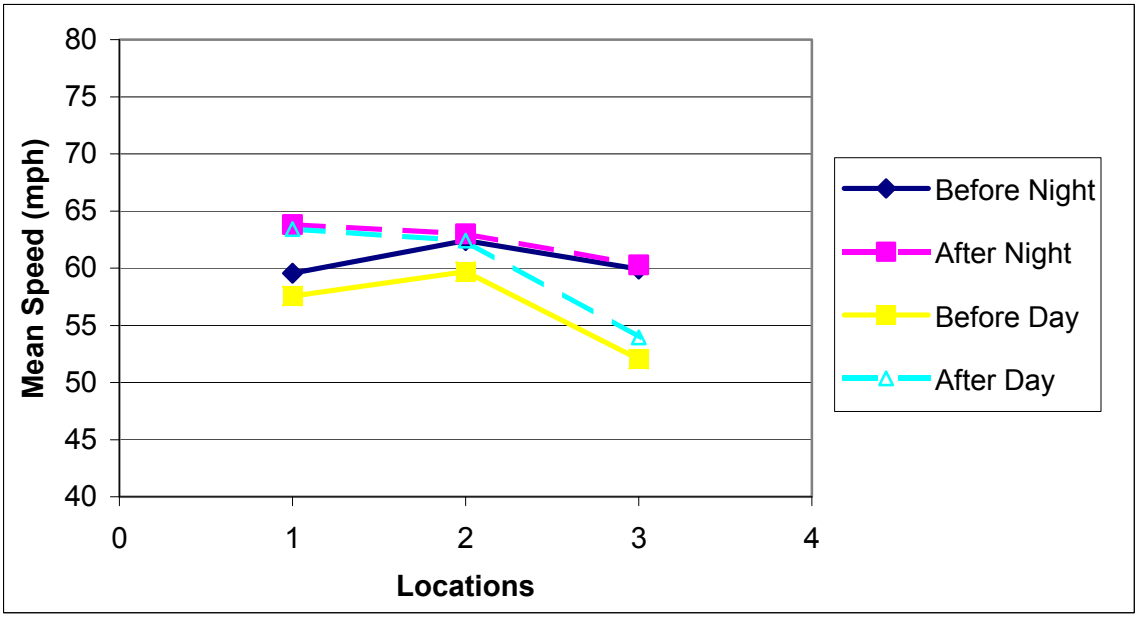

FIGURE 15 Mean speed profiles for southbound driving lane – *non-passenger vehicles*

TABLE 6 Day and night mean speeds – *all vehicles, southbound direction*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	SB1P	64.43	66.14	66.97	67.15
	SB1D	60.05	58.17	66.85	56.47
2	SB2P	65.03	65.54	66.62	66.31
	SB2D	62.72	59.99	63.6	62.05
3	SB3P	63.22	60.34	62.79	60.32
	SB3D	59.85	54.52	60.77	55.39

TABLE 7 Day and night mean speeds – *passenger vehicles, southbound direction*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	SB1P	60.38	66.29	60.12	67.29
	SB1D	60.56	58.55	60.06	57.19
2	SB2P	60.95	65.54	61.65	64.4
	SB2D	62.91	60.13	63.94	60.89
3	SB3P	61.26	60.44	58.09	60.88
	SB3D	59.86	52.32	61.26	54.38

TABLE 8 Day and night mean speeds – *non-passenger vehicles, southbound direction*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	SB1P	59.00	67.99	59.75	66.86
	SB1D	59.56	57.55	63.82	63.43
2	SB2P	60.34	65.53	57.78	66.75
	SB2D	62.42	59.69	62.99	62.42
3	SB3P	53.69	60.11	55.23	60.19
	SB3D	59.91	52.04	60.29	53.96

85th Percentile Speeds

85th Percentile Speeds along Northbound lanes

The 85th percentile speed is the speed at which fewer than 85% or less of the vehicles travel. Tables 9, 10 and 11 show the 85th percentile speeds for the northbound lanes during day and night times. For most of the cases shown in the table, the after value of the 85th percentile speed was lower than the before value. However, some 85th percentile speeds in the after case were greater than the corresponding values in the before cases. These cases are marked with an asterisk (*) in the tables.

TABLE 9 85th percentile speeds along the northbound direction – *all vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	73.25	73.50	69.17	69.19
	NB1D	66.81	66.48	67.42	64.90
2	NB2P	69.77	71.32	69.94	71.11
	NB2D	67.16	67.54	66.82	66.18
3	NB3P	66.22	64.08	64.24	62.49
	NB3D	64.84	60.92	61.12	57.47

TABLE 10 85th percentile speeds along the northbound direction – *passenger vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	73.38	73.59	69.25	69.30
	NB1D	67.17	66.77	67.60*	65.19
2	NB2P	69.81	71.49	67.17	66.63
	NB2D	67.41	67.79	67.17	66.63
3	NB3P	66.09	64.20	64.33	62.55
	NB3D	64.76	61.13	61.19	57.71

TABLE 11 85th percentile speeds along the northbound direction – *non-passenger vehicles*

Location	Lanes	Before Condition Night	Before Condition Day	After Condition Night	After Condition Day
1	NB1P	73.00	73.31	69.04	68.86
	NB1D	65.74	65.80	66.93*	64.61
2	NB2P	69.66	70.80	66.03	65.19
	NB2D	66.63	67.01	66.03	65.19
3	NB3P	66.48	63.75	64.02	62.27
	NB3D	64.97	60.59	60.97	58.29

85th Percentile Speeds along Southbound lanes

Tables 12, 13 and 14 show the 85th percentile speeds for the southbound lanes during day and night times. Unlike the northbound direction, for most of the cases the after value of the 85th percentile speed was greater than the before value. These cases are marked with an asterisk. There were very few cases in all vehicles, passenger vehicle and non-passenger vehicle categories where the after case 85th percentile values were less than the corresponding before case values. However, it may be noted that these cases were largely outnumbered by the cases where after case values were greater than the before case values.

TABLE 12 85th percentile speeds along the southbound direction – *all vehicles*

Location	Lanes	Before Condition Night	Before Condition Day	After Condition Night	After Condition Day
1	SB1P	72.69	69.96	73.11*	72.04*
	SB1D	64.11	62.96	67.59*	72.76*
2	SB2P	71.33	69.17	71.35*	70.64*
	SB2D	67.10	64.08	68.05*	66.21*
3	SB3P	69.24	64.80	68.82	65.44*
	SB3D	64.53	59.07	64.87*	60.99*

TABLE 13 85th percentile speeds along the southbound direction – *passenger vehicles*

Location	Lanes	Before Condition Night	Before Condition Day	After Condition Night	After Condition Day
1	SB1P	70.01	70.09	73.35*	72.31*
	SB1D	64.27	63.18	67.05*	67.09*
2	SB2P	71.70	69.20	71.90*	69.73*
	SB2D	67.25	64.16	68.31*	65.12*
3	SB3P	69.90	64.89	69.15	65.83*
	SB3D	64.47	59.68	64.88*	61.18*

TABLE 14 85th percentile speeds along the southbound direction – *non-passenger vehicles*

Location	Lanes	Before Condition Night	Before Condition Day	After Condition Night	After Condition Day
1	SB1P	71.86	69.80	72.52*	71.44*
	SB1D	63.81	62.30	68.30*	79.90*
2	SB2P	70.36	69.13	69.71	74.39*
	SB2D	66.77	63.95	67.50*	68.50*
3	SB3P	68.18	64.56	67.97	64.75
	SB3D	64.65	59.43	64.83*	60.55*

Speed Variance Characteristics

The standard deviation of speed is a primary indicator of the speed variation at a location. The standard deviation of speed is expressed as the square root of speed variance. A lower standard deviation is associated with a lower probability of crashes. The percentage of vehicles traveling within the 10-mph pace is also an important speed variance characteristic. A greater percentage of vehicles traveling within the 10-mph pace in an after case compared to the corresponding before case is considered an improvement of traffic conditions.

Standard Deviation of Speed along Northbound Lanes

Figures 16 and 17 show plots for average values of standard deviation along the northbound lanes for day and night times. Figure 16 shows that the standard deviations of speed in the before

case during the nights were lower than the corresponding values recorded in the after case. The after values during the day were less than the corresponding values in the before case for the first and third locations, whereas they were greater for the second location. Figure 17 shows that the after case values were less than the before case values for the second and third locations but were greater in case of the first location during the night. During the day, all standard deviation values in the after case were less than the corresponding values recorded in the before case.

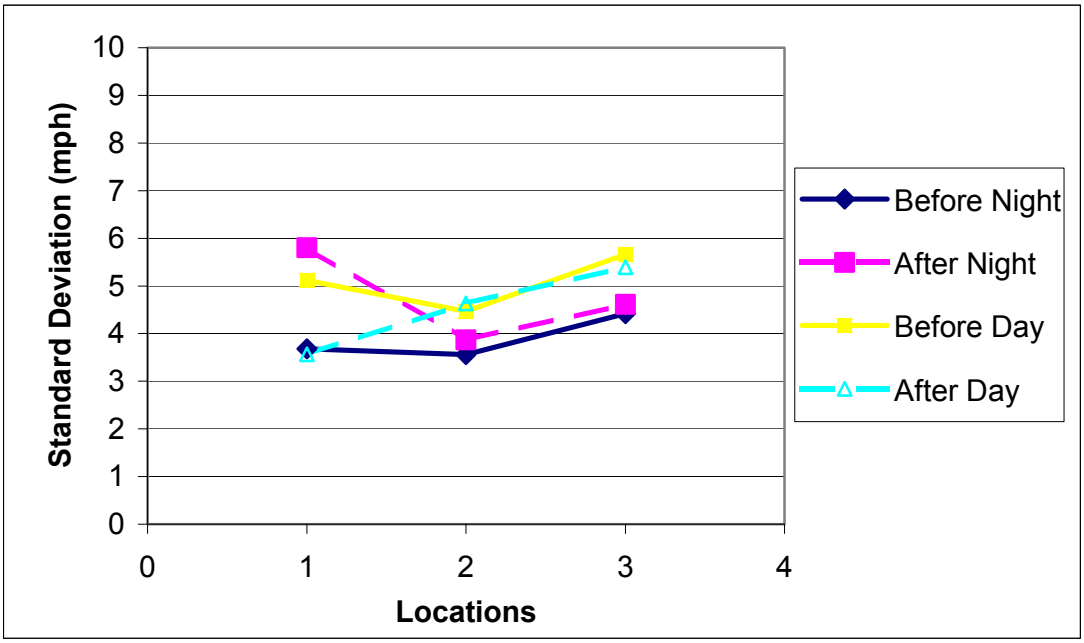

FIGURE 16 Standard deviation profiles for northbound passing lanes – *all vehicles*

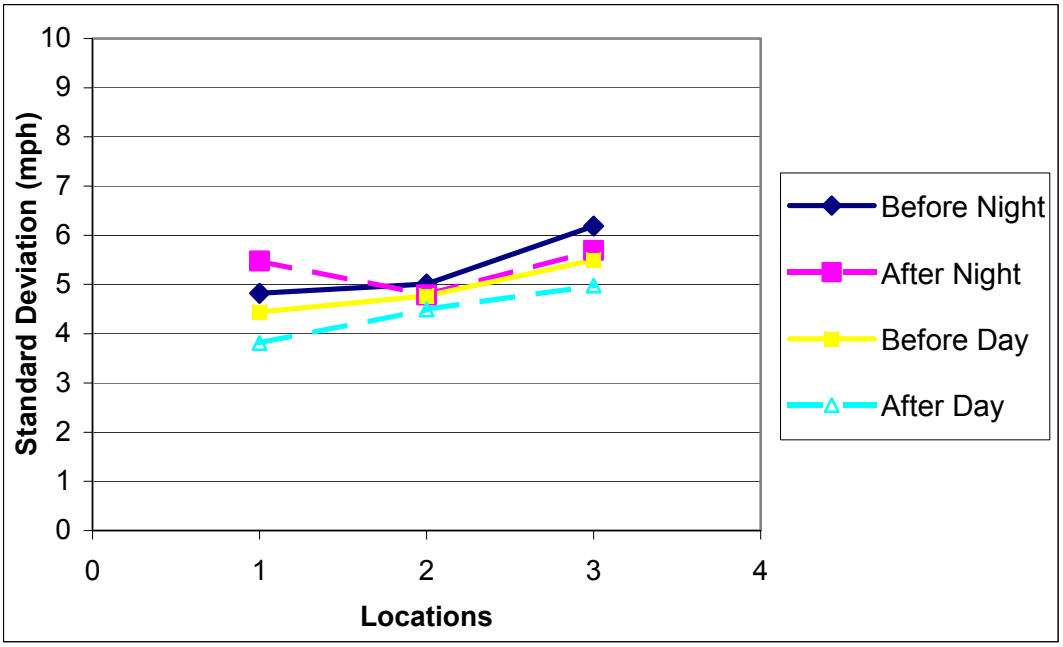

FIGURE 17 Standard deviation profiles for northbound driving lanes – *all vehicles*

Standard Deviation of Speed along Southbound Lanes

Figures 18 and 19 show plots for average values of standard deviation along the southbound lanes for day and night times. The standard deviations of speed in the after case were considerably greater than the corresponding values of standard deviation in the before case. There was just one case – the southbound first location passing lane – in which the after case standard deviation recorded during the night was less than the corresponding value in the before case. The plots have been derived from Tables 15 through 20.

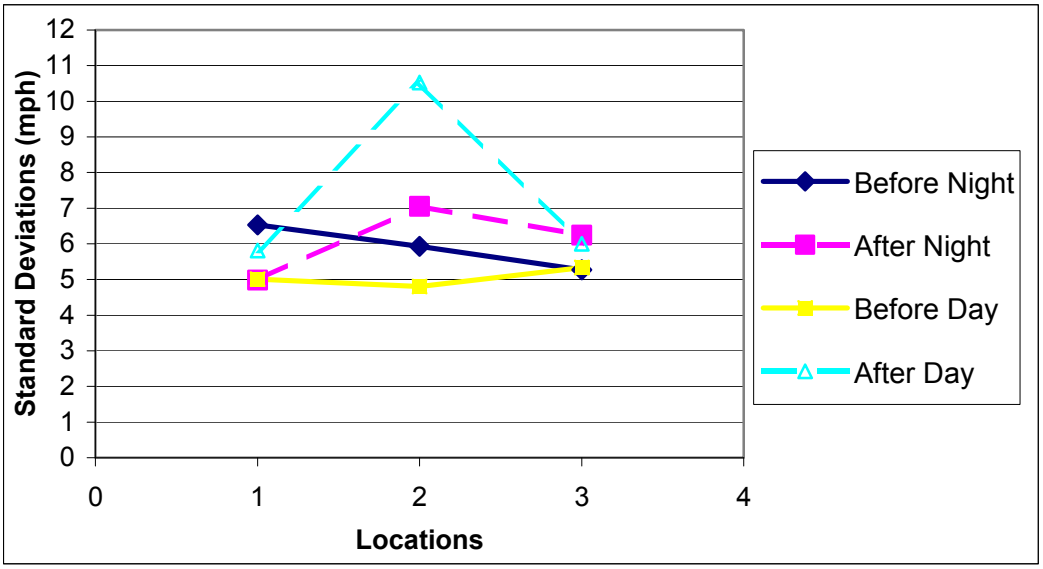

FIGURE 18 Standard deviation profiles for southbound passing lanes – *all vehicles*

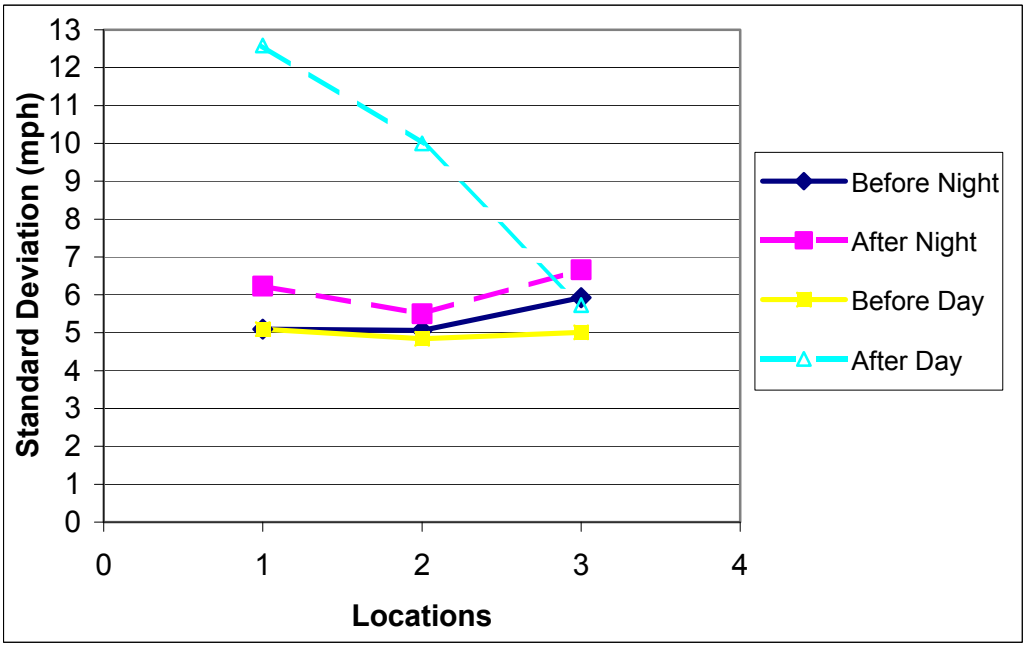

FIGURE 19 Standard deviation profiles for southbound driving lanes – *all vehicles*

TABLE 15 Standard deviation along the northbound direction – *all vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	3.68	5.12	5.80	3.57
	NB1D	4.82	4.44	5.48	3.81
2	NB2P	3.56	4.47	3.87	4.64
	NB2D	5.01	4.77	4.79	4.50
3	NB3P	4.42	5.66	4.61	5.39
	NB3D	6.19	5.50	5.70	4.98

TABLE 16 Standard deviation along the northbound direction – *passenger vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	4.73	5.37	10.14	4.23
	NB1D	5.03	4.47	5.91	4.56
2	NB2P	4.24	4.58	4.73	4.90
	NB2D	4.73	4.73	5.79	4.51
3	NB3P	4.51	5.74	4.88	5.42
	NB3D	6.47	5.60	5.74	5.02

TABLE 17 Standard deviation along the northbound direction – *non-passenger vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	NB1P	3.33	4.93	3.45	4.06
	NB1D	4.95	4.53	5.95	4.28
2	NB2P	3.44	4.26	4.20	4.41
	NB2D	4.92	4.74	4.45	4.62
3	NB3P	5.09	5.56	4.18	5.35
	NB3D	6.05	5.38	5.36	4.72

TABLE 18 Standard deviation along the southbound direction – *all vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	SB1P	6.53	5.01	4.98	5.81
	SB1D	5.09	5.10	6.23	12.58
2	SB2P	5.92	4.81	7.05	10.52
	SB2D	5.06	4.85	5.51	9.99
3	SB3P	5.28	5.34	6.24	6.00
	SB3D	5.93	5.01	6.66	5.73

TABLE 19 Standard deviation along the southbound direction – *passenger vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	SB1P	6.61	4.53	4.95	5.92
	SB1D	4.73	4.51	4.90	10.40
2	SB2P	6.28	4.66	7.15	10.02
	SB2D	5.15	4.93	5.70	10.49
3	SB3P	5.40	5.47	6.05	6.06
	SB3D	6.25	4.98	7.20	5.75

TABLE 20 Standard deviation along the southbound direction – *non-passenger vehicles*

		Before Condition		After Condition	
Location	Lanes	Night	Day	Night	Day
1	SB1P	6.49	4.17	4.05	5.79
	SB1D	4.03	4.55	7.31	12.23
2	SB2P	4.01	4.93	3.82	9.36
	SB2D	4.92	4.62	5.17	9.08
3	SB3P	4.41	5.06	4.82	5.56
	SB3D	5.46	4.79	6.03	5.51

Fastest 15% of Vehicles

Mean Speed of the Fastest 15% of Vehicles in the Northbound Direction

Tables 21 to 23 show the values for the before and after mean speeds of the fastest 15% of vehicles along each lane in the northbound direction for day and night times. The general trend shows a decrease in the mean speeds, but there were only a few cases where the decrease was significant.

TABLE 21 Mean speed of the fastest 15% of vehicles – *all vehicles, northbound direction*

		Before Condition		After Condition	
Location	Lanes	Day	Night	Day	Night
1	NB1P	74.35	74.32	69.29	69.26
	NB1D	69.02	69.23	65.41	70.68
2	NB2P	73.92	69.44	73.9	69.58
	NB2D	69.34	69.37	69.23	69.45
3	NB3P	64.85	69.18	64.25	69.47
	NB3D	64.32	65.22	59.66	64.27

TABLE 22 Mean speed of the fastest 15% of vehicles – *passenger vehicles, northbound direction*

		Before Condition		After Condition	
Location	Lanes	Day	Night	Day	Night
1	NB1P	79.92	79.85	74.13	74.97
	NB1D	69.06	69.30	68.92	69.90
2	NB2P	74.01	73.93	69.95	69.60
	NB2D	69.41	69.43	69.26	69.55
3	NB3P	69.20	69.21	64.27	69.74
	NB3D	64.41	69.95	59.78	64.34

TABLE 23 Mean speed of the fastest 15% of vehicles – *non-passenger vehicles, northbound direction*

		Before Condition		After Condition	
Location	Lanes	Day	Night	Day	Night
1	NB1P	79.98	78.68	73.56	74.87
	NB1D	68.9	69.06	68.95	72.75
2	NB2P	73.63	73.93	69.52	69.51
	NB2D	69.18	69.23	69.15	69.22
3	NB3P	69.26	69.12	64.13	68.51
	NB3D	59.78	64.34	63.83	64.09

Mean Speed of the Fastest 15% of Vehicles in the Southbound Direction

Tales 24 through 26 show that the southbound mean speeds in the after cases were consistently greater than the corresponding before cases.

TABLE 24 Mean speed of the fastest 15% of vehicles – *all vehicles, southbound direction*

		Before Condition		After Condition	
Location	Lanes	Day	Night	Day	Night
1	SB1P	73.71	74.96	74.13	79.61
	SB1D	63.62	63.92	85.35	70.72
2	SB2P	69.25	74.1	84.33	75.09
	SB2D	63.95	69.31	79.89	69.7
3	SB3P	64.83	70.03	69.32	70.13
	SB3D	60.26	64.96	64.25	65.37

TABLE 25 Mean speed of the fastest 15% of vehicles – *passenger vehicles, southbound direction*

		Before Condition		After Condition	
Location	Lanes	Day	Night	Day	Night
1	SB1P	73.73	75.13	74.19	79.63
	SB1D	68.88	69.17	71.29	71.29
2	SB2P	74.14	74.31	75.37	75.15
	SB2D	69.08	69.43	71.3	74.72
3	SB3P	69.28	74.3	69.37	74.28
	SB3D	63.86	69.64	64.23	70.34

TABLE 26 Mean speed of the fastest 15% of vehicles – *non-passenger vehicles, southbound direction*

		Before Condition		After Condition	
Location	Lanes	Day	Night	Day	Night
1	SB1P	73.66	74.45	73.98	73.93
	SB1D	63.6	69.18	107.86	87.82
2	SB2P	74.53	73.44	110.54	74.81
	SB2D	68.7	69.04	106.31	69.38
3	SB3P	68.99	73.53	69.13	69.68
	SB3D	73.31	69.43	63.95	69.81

10-mph Pace

Percentage of vehicles traveling within the 10-mph Pace along the northbound direction

Tables 27 to 29 show the 10-mph pace and the percentage of vehicles traveling along the northbound direction that fall within the 10-mph pace. The before and after cases are described with the suffixes (B) and (A), respectively. The percentage of vehicles in the 10-mph pace increase consistently in most cases for the northbound direction.

TABLE 27 Percent of vehicles within 10-mph pace – *all vehicles,* northbound

All Vehicles				
Location	Day		Night	
	10 mph Pace	% Vehicles	10 mph Pace	% Vehicles
NB 1P(B)	65-75	67.51	65-75	72.34
NB 1P(A)	60-70	83.13	60-70	83.91
NB 1D(B)	55-65	73.28	55-65	74.95
NB 1D(A)	55-65	78.44	55-65	73.63
NB 2P(B)	60-70	72.93	60-70	83.37
NB 2P(A)	60-70	77.56	60-70	80.86
NB 2D(B)	55-65	69.52	55-65	73.10
NB 2D(A)	55-65	76.62	55-65	74.46
NB 3P(B)	50-60	55.32	55-65	60.51
NB 3P(A)	50-60	62.89	55-65	59.67
NB 3D(B)	50-60	64.04	55-65	58.23
NB 3D(A)	45-55	71.65	50-60	64.35

TABLE 28 Percent of vehicles within 10-mph pace – *passenger vehicles, northbound*

Passenger Vehicles				
Location	Day		Night	
	10 mph Pace	% Vehicles	10 mph Pace	% Vehicles
NB 1P(B)	65-75	66.68	65-75	71.44
NB 1P(A)	60-70	82.67	60-70	83.33
NB 1D(B)	55-65	72.63	55-65	74.24
NB 1D(A)	55-65	77.24	55-65	72.31
NB 2P(B)	60-70	72.57	60-70	82.83
NB 2P(A)	60-70	76.58	60-70	81.23
NB 2D(B)	60-70	69.11	55-65	72.33
NB 2D(A)	55-65	75.57	55-65	73.28
NB 3P(B)	50-60	54.75	55-65	61.30
NB 3P(A)	50-60	62.28	55-65	57.97
NB 3D(B)	50-60	63.27	55-65	57.94
NB 3D(A)	45-55	70.68	55-65	63.17

TABLE 29 Percent of vehicles within 10-mph pace – *non-passenger vehicles, northbound*

Non-Passenger Vehicles				
Location	Day		Night	
	10 mph Pace	% Vehicles	10 mph Pace	% Vehicles
NB 1P(B)	65-75	69.12	65-75	74.14
NB 1P(A)	60-70	84.43	60-70	87.12
NB 1D(B)	55-65	74.59	55-65	77.07
NB 1D(A)	55-65	80.48	55-65	76.66
NB 2P(B)	60-70	73.92	60-70	84.83
NB 2P(A)	60-70	80.43	60-70	79.91
NB 2D(B)	55-65	67.01	55-65	66.63
NB 2D(A)	55-65	78.45	55-65	76.65
NB 3P(B)	50-60	56.97	55-65	58.59
NB 3P(A)	50-60	64.78	55-65	64.14
NB 3D(B)	50-60	65.18	55-65	58.69
NB 3D(A)	50-60	80.97	55-65	67.03

Percentage of vehicles traveling within the 10-mph pace along the southbound direction

Tables 30 to 32 show the 10-mph pace and the percentage of total vehicles traveling along the northbound direction that fall within the 10-mph pace. The percentage of vehicles in the 10-mph pace increases consistently in most cases for the southbound direction.

TABLE 30 Percent of vehicles within 10-mph pace – *all vehicles, southbound*

All Vehicles				
Location	Day		Night	
	10 mph Pace	% Vehicles	10 mph Pace	% Vehicles
SB 1P(B)	60-70	78.20	60-70	71.85
SB 1P(A)	60-70	69.16	65-75	73.64
SB 1D(B)	55-65	71.68	55-65	78.61
SB 1D(A)	55-65	45.41	60-70	79.42
SB 2P(B)	60-70	77.31	60-70	75.00
SB 2P(A)	60-70	64.27	60-70	75.68
SB 2D(B)	55-65	72.73	55-65	70.19
SB 2D(A)	55-65	64.58	60-70	67.33
SB 3P(B)	55-65	62.91	60-70	60.82
SB 3P(A)	55-65	58.96	55-65	61.98
SB 3D(B)	50-60	64.00	55-65	60.29
SB 3D(A)	50-60	63.91	55-65	60.01

TABLE 31 Percent of vehicles within 10-mph pace – *passenger vehicles, southbound*

Passenger Vehicles				
Location	Day		Night	
	10 mph Pace	% Vehicles	10 mph Pace	% Vehicles
SB 1P(B)	60-70	78.20	60-70	71.85
SB 1P(A)	60-70	69.16	65-75	73.64
SB 1D(B)	55-65	74.14	55-65	79.45
SB 1D(A)	55-65	52.09	60-70	79.90
SB 2P(B)	60-70	76.26	60-70	73.70
SB 2P(A)	60-70	67.01	60-70	73.82
SB 2D(B)	55-65	71.84	55-65	69.80
SB 2D(A)	55-65	66.82	60-70	67.21
SB 3P(B)	55-65	61.58	60-70	65.35
SB 3P(A)	55-65	57.68	55-65	61.42
SB 3D(B)	50-60	63.89	55-65	58.60
SB 3D(A)	50-60	64.26	55-65	63.90

TABLE 32 Percent of vehicles within 10-mph pace- *non-passenger vehicles, southbound*

Non-Passenger Vehicles				
Location	Day		Night	
	10 mph Pace	% Vehicles	10 mph Pace	% Vehicles
SB 1P(B)	60-70	78.74	60-70	75.36
SB 1P(A)	60-70	71.76	65-75	76.81
SB 1D(B)	50-60	67.26	55-65	77.07
SB 1D(A)	55-65	36.67	60-70	78.73
SB 2P(B)	60-70	79.92	60-70	78.22
SB 2P(A)	60-70	58.15	60-70	80.22
SB 2D(B)	55-65	74.50	55-65	70.98
SB 2D(A)	55-65	60.82	55-65	68.00
SB 3P(B)	55-65	66.35	60-70	62.29
SB 3P(A)	55-65	62.21	60-70	65.59
SB 3D(B)	50-60	63.30	55-65	59.35
SB 3D(A)	50-60	65.21	55-65	61.20

Rumble Strip Performance

The rumble strips were installed on both southbound lanes and the northbound passing lane on September 19th, 2001. The strips were installed along the northbound driving lane on September 20th, 2001. Not considering the time to set up traffic control, the rumble strips were laid down in 10 to15 minutes at each location. The installation of the rumble strips was performed in the following five steps.

Step 1. Lay out rumble strip location.
Step 2. Lay out and prepare materials.
Step 3. Apply first coat of adhesive to pavement surface.
Step 4. Apply second coat of adhesive to pavement surface and first coat of adhesive to back of rumble strips.
Step 5. Install rumble strips at pre-decided locations and tamp with 200-lb roller.

Photographs taken four weeks after the installation of the rumble strips show that the strips were in good condition. As shown in Figure 20, no wear and tear or curling of the edges was observed. According to the District Engineer's Office, the rumble strips remained functional and in place until removed by snow plows in March of 2002.

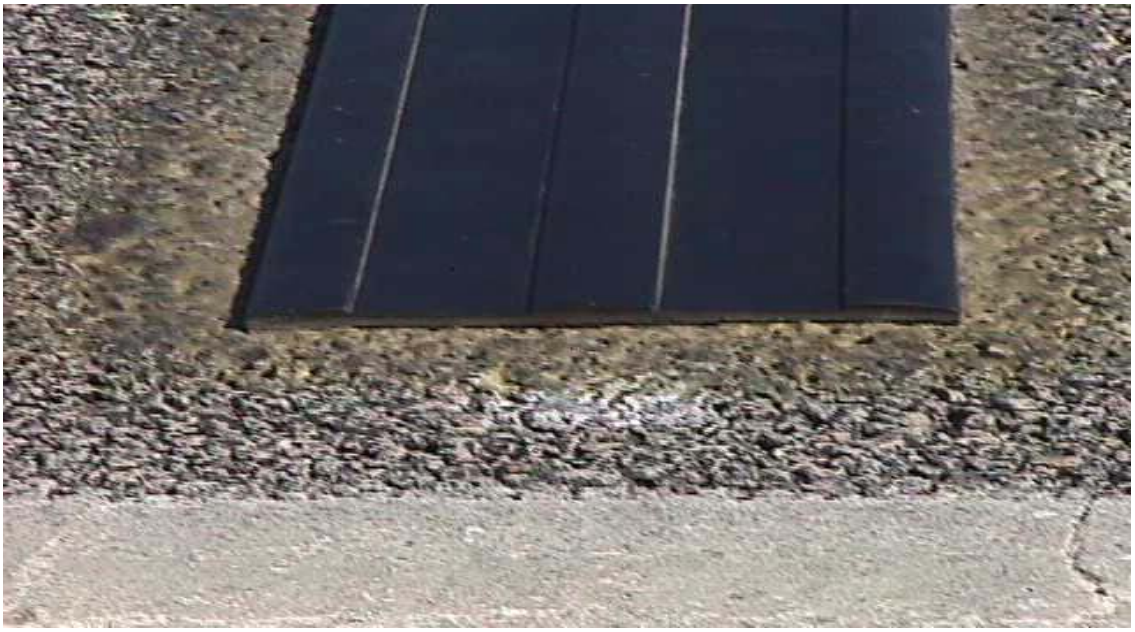

FIGURE 20 Rumble strip condition four weeks after installation

Statistical Tests of Mean and Variance

Tables 33 and 35 show the results of the statistical tests on the mean speeds. The mean speeds were subject to a two tailed student's t-test with a level of significance of 0.05. The standard deviation of the difference of means, s_p, was calculated using Equation 3 (May 1990).

$$s_p = \left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2} \right)^{1/2} \qquad (Eq.\ 3)$$

where: s_1, n_1 = standard deviation and number of observations in the before condition,
s_2, n_2 = standard deviation and number of observations in the after condition.

If the difference in mean speeds between the before and after cases is less than $1.96*s_p$, there was no significant difference between the before and after mean speeds. If the case is otherwise, the after mean speeds were significantly different from the before mean speeds.

The results of the F test on the speed variances are shown in Tables 34 and 36. The ratios of the before and after variances are compared to an F-value derived from the F distribution table. The greater value of variance always stays at the numerator of the ratio, which avoids values less than 1. A value of the ratio of variances less than the value derived from the F distribution table implies that the before and after case variances were not significantly different. An otherwise case implies that the before and after case variances were significantly different.

TABLE 33 Statistical two-tailed students t-test for the northbound lanes.

Lane	Standard Deviation(s)	1.96*s	Difference in Means	Inference
NB1D	0.6706	1.3146	0.2013	Speeds not significantly different
NB1P	0.7208	1.4128	5.8465	Speeds significantly different
NB2D	0.6877	1.3479	0.1345	Speeds not significantly different
NB2P	0.6326	1.2399	1.9265	Speeds significantly different
NB3D	0.8067	1.5811	3.5391	Speeds significantly different
NB3P	0.7591	1.4879	2.2790	Speeds significantly different

TABLE 34 Statistical F test for speed variances along the northbound lanes.

Lane	Ratio of variances	F ratio for significance	Inference
NB1D	1.3311	1.4020	Variances not significantly different
NB1P	2.4588	1.4476	Variances significantly different
NB2D	1.0973	1.3403	Variances not significantly different
NB2P	1.2754	1.3403	Variances not significantly different
NB3D	1.2156	1.3403	Variances not significantly different
NB3P	1.0312	1.4116	Variances not significantly different

TABLE 35 Statistical two-tailed students t-test for the southbound lanes.

Lane	Standard Deviation(s)	1.96*s	Difference in Means	Inference
SB1D	0.8107	1.5890	-1.7400	Speeds significantly different
SB1P	0.9354	1.8333	-2.5920	Speeds significantly different
SB2D	0.8178	1.6029	-1.5289	Speeds not significantly different
SB2P	0.8181	1.6034	-1.1666	Speeds not significantly different
SB3D	0.8230	1.6131	-1.0048	Speeds not significantly different
SB3P	0.7937	1.5556	-0.3115	Speeds not significantly different

TABLE 36 Statistical F test for speed variances along the southbound lanes

Lane	Ratio of variances	F ratio for significance	Inference
SB1D	1.1438	1.4200	Variances not significantly different
SB1P	3.7973	1.3449	Variances significantly different
SB2D	2.6597	1.3770	Variances significantly different
SB2P	2.7720	1.4110	Variances significantly different
SB3D	1.2922	1.3403	Variances not significantly different
SB3P	1.3310	1.4063	Variances not significantly different

6. CONCLUSIONS

This study examined the effect of rumble strips on traffic speeds along the northbound and southbound directions of US 65 in Springfield, Missouri. The mean speeds and standard deviation of speed served as the two main measures of effectiveness in this study. The other measures of effectiveness –85^{th} percentile speed, mean speed of the fastest 15% of vehicles, 10-mph pace and percentage of vehicles in 10-mph pace – were used to see if they supported the results indicated by the mean speed and standard of speed. The observed ease of installation and the observed durability of the rumble strips were also used to verify the performance of the rumble strips during course of the project.

- Mean speeds along the northbound driving and passing lanes were lower in the after case than in the before case. However, the rumble strips did not have a similar effect on the southbound traffic. There were cases when the southbound mean speeds were greater in the after case when compared to the corresponding before case values. This result indicates that a reduction in mean speed was not found.

- The 85th percentile speeds along northbound lanes were reduced after the installation of the rumble strips, whereas the post-installation values show an increase in the case of the southbound lanes. The 85th percentile speeds confirm the lack of consistency in reducing speed.

- In some cases, the after standard deviation of speed was less than that of the before condition, but in other cases the after standard deviation of speed was greater than that of the before condition. The data therefore do not indicate a consistent reduction in speed variation.

- The mean speeds of the fastest 15% of vehicles traveling along the northbound direction were lower in the after case, whereas there was an increase in the after case for southbound vehicles.

These results indicate that reductions in mean speed and standard deviation of speed were not consistently present.

7. RECOMMENDATIONS

The results indicate that the rumble strips can be placed in a reasonable amount of time and can remain visible and attached to the pavement for several months. However, the desired reductions in speed and speed variability did not occur. The rumble strips should not be expected to reduce speed or speed variability on multilane highway work zones.

References

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