University at Buffalo

The State University of New York

Department of Civil, Structural and Environmental Engineering

223 Ketter Hall, Buffalo, NY 14260

Effectiveness of Active Speed Controls in Highway Work Zones

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Principal Investigator:

Satish B. Mohan

Graduate Research Assistants:

Bhavana S. Ghorpade

Wesley C. Zech

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ABSTRACT

The objective of this project was to evaluate the effectiveness of two interventions on the reduction of travel speeds in highway work zones: (i) Rumble Strips, and (ii) Variable Message Signs (VMSs).

While the injury rate in total U.S construction has declined @ 2.9% per year, and the fatality rate in U.S. transportation has declined @ 3.2% per year, the severe injuries in highway work zones have stayed constant at approximately 37,000, and fatalities at 800, for the last several years, costing about $4.0 billion per year. 'Excessive Speed', and 'Driver Inattention' have been found as the two major causes of highway work zone accidents accounting for 41.9% of the work zone injuries. The effectiveness of the proposed interventions was evaluated in mitigating these two major causes. The proposed interventions have the potential of reducing 168 fatalities, and 7,752 severe injuries; and save $838 million.

Three field studies were conducted. A field study was done in the first year of this research on the effectiveness evaluation of Variable Message Signs (VMSs) in reducing vehicle speeds in highway work zones. Three types of VMSs: (i) **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN, (ii) WORK ZONE 45 MPH ~ STATE POLICE ENFORCED, AND (iii) YOUR SPEED 'X' MPH,** were tested on highway repaving jobs on Interstate-90 in the western New York region, all of the sections having a speed limit of 65 mph, with a posted speed limit of 45 mph in the work zones. All of the tests were conducted in the night-time because the repaving work was scheduled during nights when the traffic volumes were light. The tests showed that a VMS can effectively reduce speeds by about 5 mph. The VMS: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN,** reduced mean speeds by 6mph, against 5 mph by the VMS: **YOUR SPEED "X" MPH.** The tests also showed that the VMS reduced the percentage of vehicles above 45 mph by about 8%. On this attribute, the VMS: **WORK ZONE 45 MPH ~ STATE POLICE ENFORCED,** performed the best. It reduced the percentage of vehicles above 45 mph by 25% in the driving lane. The VMS control also reduced the percent of vehicles above 55 mph by 25% in the driving lane and 20% in the passing lane, and decreased the percent of vehicles traveling above 65 mph by 8% in the driving lane and by 4% in the passing lane. The speed variances, were however, slightly

increased by the application of the VMS's. The VMS's: **WORK ZONE 45 MPH ~ STATE POLICE ENFORCED**, and **YOUR SPEED 'X' MPH**, reduced the 85th percentile speeds of all vehicles by at least 5.5 mph.

Another field study was conducted on Interstate-90 in western New York State (NYS). The study included speed measurements of nearly 180,000 vehicles. The three types of CMS messages tested were: (i) *RIGHT LANE CLOSED ~ KEEP LEFT*, (ii) *WORK ZONE MAX SPEED 45 MPH ~ BE PREPARED TO STOP*, and (iii) *LEFT LANE CLOSED ~ KEEP RIGHT*. Of the three CMS messages tested, the CMS message stating '*WORK ZONE MAX SPEED 45 MPH ~ BE PREPARED TO STOP*' proved the best, significantly reducing vehicle speeds by 3.3 mph to 6.7 mph (5.3 km/h to 10.8 km/h). The other two VMSs were not very effective.

The third field study was conducted on two highways located in western New York State (NYS) to evaluate two types of speed control devices: (i) Rumble Strips, and (ii) Police Presence. The study included speed measurements of approximately 554,400 vehicles. Two types of rumble strips, composed of preformed rumble strip materials were installed using different patterns, and evaluated. The rumble strips utilized on Interstate-86 were effective in reducing vehicle speeds in the range of approximately 1.4 mph to 2.9 mph (2.25 km/h to 4.67 km/hr), the passenger cars (PC) speeds were reduced by approximately 2.4 mph (3.86 km/h), the 2-axle 4-tire vehicle speeds by as little as 1.4 mph (2.25 km/h). The 5A-ST vehicles were reduced by as small as 2.0 mph (3.22 km/h) but were dependent upon the type of lane closure setup. The other type of rumble strip installed on Interstate-990, was not effective in reducing vehicle speeds in either lane.

Police Presence combined with rumble strips was utilized as another speed control measure and was proven to be most effective, reducing speeds of all major vehicle types anywhere from 3.0 mph to 6.0 mph (4.83 km/h to 9.66 km/h). The results of this field research indicate that properly selected speed control devices can be effective in reducing vehicle speeds in highway work zones. The study also proved that rumble strips are at most partially effective, and the police presence combined with rumble strips was the most effective speed control device.

Three organizations collaborated in this research: (i) Construction Safety and Health Institute (CSHI), State University of New York at Buffalo, (ii) Thruway Authority, New York State Department of Transportation (NYSDOT), and (iii) Flasher Handling Corporation.

SIGNIFICANT FINDINGS

The results of this research show that, if properly selected, active speed controls can be significantly effective in reducing speeds of all classes of vehicles, in highway work zones. Of the three VMS types used in this research, VMS 2:'WORK ZONE MAX SPEED 45 MPH ~ BE PREPARED TO STOP' was very effective in reducing vehicle speeds. It reduced vehicle speeds by 3 mph to 5 mph (4.83 km/h to 8.05 km/h) in the driving lane and 4 mph to 6 mph (6.44 km/h to 9.66 km/h) in the passing lane. This VMS, however, increased the speed variances from 13% to 35%. The other two VMSs: (i) 'RIGHT LANE CLOSED ~ KEEP LEFT' and (ii) 'LEFT LANE CLOSED ~ KEEP RIGHT' were not very effective.

The 3M™ rumble strips proved effective as an active speed control in the driving lane only, for all vehicle types. The 3M™ rumble strip produced on average a 1.0 mph to 2.0 mph (1.61 km/h to 3.22 km/h) reduction in vehicular speeds in the driving lane. Vehicles in the passing lane were not significantly affected by the 3M™ rumble strips. The other set of rumble strips: Swarco™ rumble strips had partial success. In the driving lane they reduced the speeds of PC and 2A-4T vehicles only. In the passing lane the speed reduction was minor.

The police presence along with Swarco™ rumble strips proved to be the most effective active speed control, reducing speeds from 4.0 mph to 6.0 mph (6.44 km/h to 9.66 km/h). This control also reduced the speed variances by about 25%, a very desirable attribute in reducing rear-end accidents.

This research, using field experiments, has proven that active speed controls, if properly selected and implemented can be significantly effective in reducing vehicle speeds as well as speed variances.

The results of this research show that, if properly selected, speed control devices can be significantly effective in reducing speeds of all classes of vehicles, in highway work zones.

The 3M™ rumble strips proved effective as a speed control device but it was dependent upon the lane closure setup. Vehicles having to execute a merging maneuver from the closed lane of traffic to the open traffic lane, had greater speed reductions when compared against the vehicles that did not have to execute a merging maneuver. This should be an area of concern, due to the speed differential created, which may increase the likelihood of accidents occurring between merging and non-merging vehicles in highway work zones. 3M™ rumble strips effectively reduced the speed of merging vehicles in the range of 1.4 mph to 2.9 mph (2.25 km/h to 4.67 km/h). The other set of rumble strips: Swarco™ rumble strips had partial success. In the driving lane they reduced the speeds of PC and 2A-4T vehicles only. In the passing lane the speed reduction was minor.

The police presence along with Swarco™ rumble strips proved to be the most effective speed control device, reducing speeds from 4.0 mph to 6.0 mph (6.44 km/h to 9.66 km/h). This control also reduced the speed variances by about 25%, a very desirable attribute in reducing rear-end accidents.

This research, using field experiments, has proven that speed control devices, if properly selected and implemented can be significantly effective in reducing vehicle speeds as well as speed variances.

USEFULNESS OF FINDINGS

This research has identified those Variable Message Signs (VMS) that significantly reduce speeds in highway workzones.

This research has also evaluated the effectiveness of two popularly used rumble Strips.

Both of the above results will guide the transportation professionals in using the more effective controls, and save money and accidents.

SCIENTIFIC REPORT

(i) Effectiveness of Variable Message Signs

The construction work zones were located on the Interstate-90. The highway comprised of two lanes in each direction, with a single lane closure (left lane or right lane) for work activity. Portable Traffic Counters: *Classifiers - Phoenix* ^{TM} with Pneumatic Road Tubes were used to measure speeds. The counters were hooked to a pair of Pneumatic Tubes, placed 12 feet apart across both lanes: the Driving Lane (DL) and the Passing lane (PL). Figure 1 represents the location of the Pneumatic Road Tubes and Portable Traffic Counters. The construction work comprised of pavement and shoulder rehabilitation. In one day's work, approximately 2.0 miles were covered over a work period of 10 hours to 12 hours. Speed limit outside the work zone was 65 mph and statutory speed limit in the work zone was 45 mph. Speed Studies were conducted only during the night (19:00 to 07:00) as daytime construction in this stretch of the Interstate was not considered possible due to high traffic volumes.

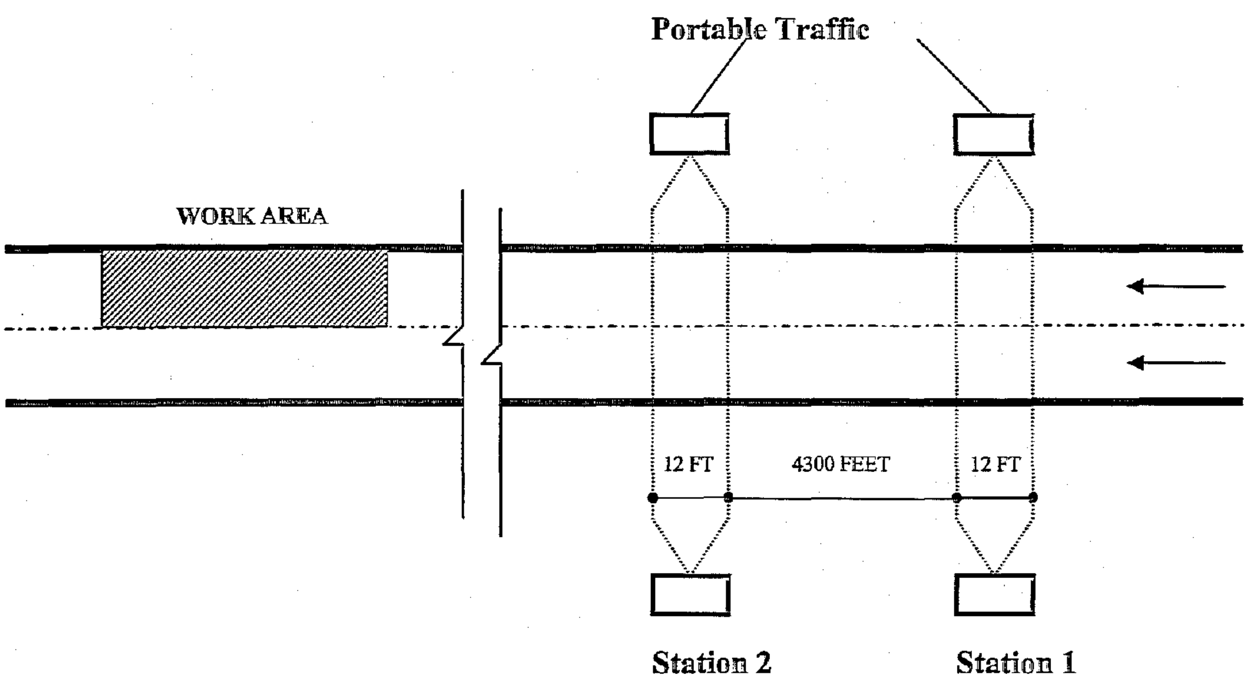


FIGURE 1: Location Details of Portable Traffic Counters.

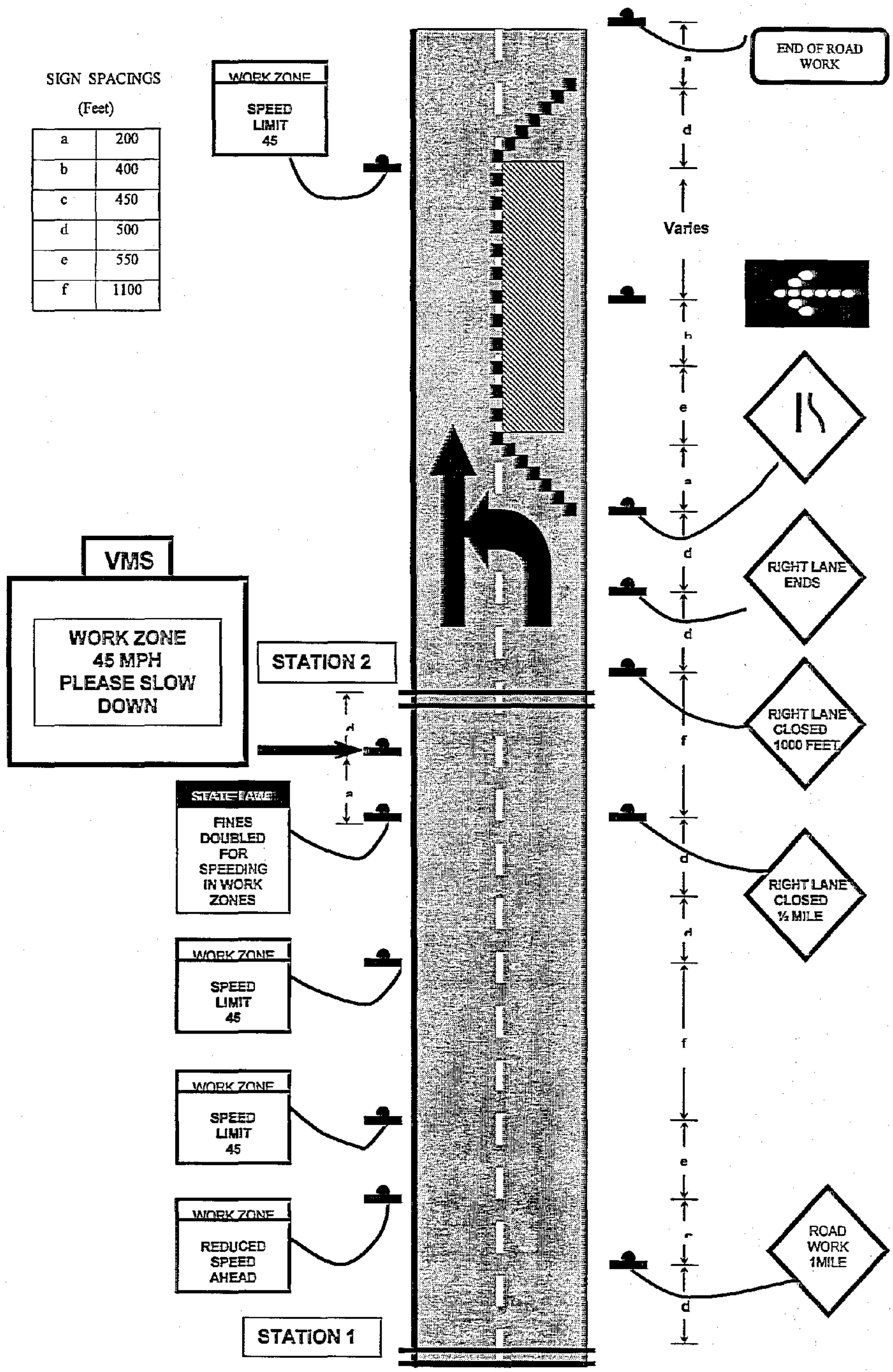


FIGURE 2 Locations of the Variable Message Sign (VMS) on a Typical Study

Site. The pneumatic road tubes were set up at two locations: (i) at 500 feet ahead of the first passive sign, ROAD WORK ~ 1 MILE. This location of the traffic counters was designated as STATION 1 in the study and (ii) 1900 feet ahead of the start of the work area taper. This location was designated as STATION 2. The detailed layout of the signage including the VMS location is shown in Figure 2.

1.1 Location of Variable Message Signs

Each of the three VMS's were located 500 feet ahead of the second set of counters (Station 2), approximately 3800 feet after the first set of counters. This 500 feet distance included the safe deceleration distance for reducing speeds from 65 mph to 45 mph after the drivers have seen the VMS. The VMS letters were 8 inches high, thus visible from a distance of 480 feet for normal vision. Figure 4 shows the location of the VMS on a typical study site. The three VMS types tested in the study are as follows:

1. VMS_A: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN**
2. VMS_B: **WORK ZONE SPEED LIMIT 45 MPH ~ STATE POLICE ENFORCED**
3. VMS_C: **YOUR SPEED 'X' MPH**

Seven sections (7) were tested in this study. The three VMS's were applied to four different study sites (Test Sections), and three study sites were tested without any intervention (Control Sections). Data was collected on weekdays and under normal weather conditions. For the purpose of referencing in this paper, the above three VMS's are termed as type A, type B, and type C, as shown above.

1.2 Data Collection

For each of the 7 sections: (i) those with a VMS intervention (Test Sections), and (ii) those without any intervention (Control Sections), speed observations were made at both of the two stations and for each of the two lane types. The speed-sample size on study sites ranged from 135 vehicle speeds to 3792 vehicle speeds. The *Traffman*^{TM} software was used to download the speed and volume data from the counters. The traffic counters classified the data into 13 vehicle types. An analysis of the speed data revealed that 90% of the observations belonged to three of the 13 vehicle types.

1. Passenger Cars (PCs) vehicles
2. 2-Axle, 4-Tire (2A-4T) vehicles
3. 5-Axle, Single-Trailer (5A-ST) vehicles

The speed analysis was therefore limited to each these three major vehicle types, and the remaining observations were grouped into one vehicle class named: 'Other Vehicles'. Speeds were analyzed separately for each of the two lanes: (i) Driving Lane (DL) and (ii) Passing Lane (PL), because the initial data obtained revealed a significant difference between the two lane- mean speeds and the two lane-variances, for each of the two stations. Data was classified into two categories:

i. Speed characteristics and other measurements without the presence of active speed controls (VMSs) – Control Sections.
ii. Speed characteristics and other measurements after the installation of a VMS – Test Sections.

Data stratified by Station Number and Lane Type, were used in the analyses. The various statistics computed from the field data for the 7 sections were organized as in example Table 1, for Test Section #2, that displayed VMS_A: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN**. The speed statistics computed from each set of data included: (i) average speeds (ii) 85^{th} percentile speeds (iii) variances, and (iv) percent vehicles traveling above 45 mph, 55 mph, and 65 mph. The ***Z-test*** was used to evaluate significant reductions in the speeds of vehicles between Stations 1 and 2, for each of the three vehicle types and for the total vehicles, as they traveled through the work zone. Individual speeds of the three classes of vehicles, and their vehicle frequency data were used for calculating speed variances.

1.3 Statistical Data Analyses

Four types of statistical tests were done on the speed data:

i. Z-tests on mean speeds
ii. F-tests on significance on speed variances
iii. Z-tests on 85th percentile speeds, and
iv. Percent of vehicles conforming to speed limits.

Each of the tests are described in the following sections.

TABLE 1 Test Section #2 Statistics

Station 1 Statistics

Statistics	Vehicle Types				
	Cars	2A-4T	5A-ST	Others	Total
1. Number of Vehicles	375	52	83	71	581
Percentage of Total	64.50%	8.90%	14.20%	12.40%	100%
2. Modal Speed (i) Speed Class (mph)	65.0-69.69	65.0-69.69	65.0-69.69	65.0-69.69	65.0-69.69
(ii) % in Modal Class	34.9	34.6	50.6	40.0	35.4
3. 85th Percentile Speed	74.9	72.9	72.2	74.6	74.3
4. Average Speed	70.6	68.2	66.3	68.4	69
5. Standard Deviation in Speeds	5.8	6.6	5.7	6.7	7.0

Station 2 Statistics

Statistics	Cars	2A-4T	5A-ST	Others	Total
1. Number of Vehicles	583	105	323	176	1187
Percentage of Total	70.40%	7.30%	11.80%	10.50%	100%
2. Modal Speed (i) Speed Class (mph)	45.0-45.9	45.0-45.9	45.0-45.9	45.0-45.9	45.0-45.9
(ii) % in Modal Class	26.7	32.3	31.2	33.3	29.2
3. 85th Percentile Speed	59.0	57.6	57.7	57.5	58.3
4. Average Speed	55.5	52.7	50.2	38.4	51.0
5. Standard Deviation in Speeds	8.6	7.7	6.7	18.1	7.0

1.3.1 Z-Tests on Mean Speeds

The vehicle speeds, were measured before-and-after each of the VMS's was installed. The number of speed measurements ranged from 135 to 3792. Since the number of observations was large, Z-tests were performed on the before-and-after measurements to test any significant reduction in speeds caused by the VMS. The following hypothesis was tested:

$$H_0 : (X_{1C} - X_{2C}) \leq (X_{1T} - X_{2T})\text{, against}$$

$$H_1 : (X_{1C} - X_{2C}) > (X_{1T} - X_{2T})$$

Where,

X_{1C} = Mean speed at Station 1 (before the work zone started) on a Control Section

X_{2C} = Mean speed at Station 2 (after the VMS location) on a Control Section

X_{1T} = Mean speed at Station 1 (before the work zone started) on a Test Section

X_{2T} = Mean speed at Station 2 (after the VMS location) on a Test Section

Since it had been observed that the speed variances are different in the two lanes: (i) DL, and (ii) PL, the speed data was analyzed separately for each of the two lane types. Z-statistics for each of the three VMS's was calculated, an example of the Z-statistics for VMS_A is given below:

$$Z_A = \frac{(X_{TA1} - X_{TA2}) - (X_{Control(1)} - X_{Control(2)})}{\sqrt{\alpha^2_{Control} + \alpha^2_A}}$$

Where,

X_{TA} = Mean speed of Average Test Sections at Station 1

X_{TA2} = Mean speed of Average Test Sections at Station 2

$X_{Control1}$ = Mean speed of Average Control Sections at Station 1

$X_{Control2}$ = Mean speed of Average Control Sections at Station 2

$\alpha^2_{Control}$ = Average Variance of the Control Sections.

α^2_A = Average Variance of the Test Sections, with the VMS_A: **WORK ZONE 45 MPH, PLEASE SLOW DOWN**

The tests of significance at α = 0.05 and α = 0.01 were performed; the Z-statistics and all the critical values for passenger cars are shown in Table 2, for each of the three VMS types. Z-statistics for 2A-4T, 5A-ST, and total vehicles are available with the authors. All of the three VMS types reduced the vehicle speeds significantly.

TABLE 2 Z-Test on Mean Speeds: Passenger Cars

VMS TYPE	LANE	Difference in Mean Speeds	Standard Error	Z-Statistic	Z-Value	
					0.05	0.01
WORK ZONE 45 MPH ~ PLEASE SLOW DOWN	DL	8.55	0.49	17.47	1.645	2.346
	PL	3.58	0.43	8.24	1.645	2.346
WORK ZONE 45 MPH ~ STATE POLICE ENFORCED	DL	12.52	0.53	23.66	1.645	2.346
	PL	--	--	--	--	--
YOUR SPEED 'X' MPH	DL	5.25	0.58	9.08	1.645	2.346
	PL	-8.95	0.91	-9.88	1.645	2.346

VMS_A: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN** significantly reduced the mean speeds of PCs by 8.5 mph, the mean speeds of 2A-4T vehicles by 6 mph, mean speeds of 5A-ST vehicles by 6 mph, and the total mean speeds of all vehicles by 7.7 mph, in the DL. The PL showed a reduction in mean speeds by 3.5 mph for PCs, by 5.5 mph for 2A-4T vehicles, by 4.5 mph for 5A-ST vehicles, and by 5 mph for total vehicles.

VMS_B: **WORK ZONE 45 MPH ~ STATE POLICE ENFORCED** also significantly reduced the mean speeds of PCs by 12.5 mph, mean speeds of 2A-4T vehicles by 4 mph, mean speeds of 5A-ST vehicles by 4 mph, and mean speeds of all vehicles by 5.5 mph, in the DL. Speed measurements in the PL had some machine errors while counting the data, and therefore mean speeds in the passing lane could not be computed.

VMS_C: **YOUR SPEED 'X' MPH** reduced the mean speeds of PCs by 5.5 mph, mean speeds of 2A-4T vehicles by 2.5 mph, mean speeds of 5A-ST vehicles by 3.5 mph, and mean speeds of all vehicles by 4 mph, in the DL. The PL did not show a reduction in the mean speeds of PCs, 2A-4T vehicles, 5A-STvehicles, or total vehicles, using VMS_C.

1.3.2 The Tests of Significance on the Variance of Speeds

To study if the VMSs had a significant impact on the variance of speeds, F-tests of significance were conducted on the speed variances of Test Sections at Station 2, and compared with the speed variances of Control Sections at Station 2.

The computations for the F-test conducted on VMS_B are given as:

$$\sigma^2_{Test(B)(2)} = \frac{\sigma^2_{TB(2)}}{n_{(T2)}}$$

$$f = \frac{\sigma^2_{Test(B)(2)}}{\sigma^2_{Controls(2)}}$$

Where,

$\sigma^2_{Controls(2)}$ = Pooled Speed variance of cars in Control Section #1 and Control Section #3, at Station #2, having a degree of freedom of $(n_{c1}+n_{c3}-2)$

$\sigma^2_{Test(B)(2)}$ = Pooled Speed variance of cars in Test Section #2 and Test Section #5, at Station #2, having a degree of freedom of (n_B-1)

The F-test results for passenger cars are tabulated in Table 3 and show the following:

TABLE 3 F-Test Results: Passenger Cars

VMS TYPE	LANE	F-Statistic	Significance of F at 0.05 level
WORK ZONE 45 MPH ~ PLEASE SLOW DOWN	DL	1.023	1.000
	PL	0.674	1.000
WORK ZONE 45 MPH ~ STATE POLICE ENFORCED	DL	3.017	1.134
	PL	--	--
YOUR SPEED 'X' MPH	DL	2.754	1.1332
	PL	0.178	1.383

VMS_A: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN** increased the standard deviation of speeds of PCs by 0.5 mph, standard deviation of 2A-4T vehicles decreased by 0.7 mph, standard deviation of speeds of 5A-ST vehicles increased by 5 mph, and standard deviation of speeds of all vehicles reduced by 1 mph in the DL. In the PL, PCs did not show any change in standard deviation; standard deviation of speeds of 2A-4T vehicles decreased by 1 mph, standard deviation of speeds of 5A-ST vehicles did not show any change, and standard deviation of speeds of all vehicles decreased by 1 mph.

VMS_B: **WORK ZONE 45 MPH ~ STATE POLICE ENFORCED** increased the standard deviation of speeds of PCs by 1 mph, the standard deviation of speeds of 2A-4T vehicles decreased by 0.5 mph, standard deviation of speeds of 5A-ST vehicles decreased by 0.5 mph, and standard deviation of speeds of all vehicles decreased by 1 mph, in the DL.

And, VMS_C: **YOUR SPEED 'X' MPH** increased the standard deviation of speeds of PCs by 1 mph. Standard deviation of speeds of 2A-4T vehicles decreased by 1 mph, standard deviation of speeds of 5A-ST vehicles increased by 0.2 mph, and standard deviation of speeds of all vehicles increased by 0.2 mph in the DL. In the PL, the PCs showed a reduction in standard deviation of speeds by 1 mph, 2A-4T vehicles showed an increase by 1.5 mph, the standard deviation of 5A-ST vehicles decreased by 1 mph, and standard deviation of speeds of all vehicles increased by 5 mph.

1.3.3 Z-Tests on 85th Percentile Speeds

To evaluate the reduction in 85th percentile speeds in the work zones, Z-tests were performed on the before-and-after speeds to test any significant reduction in 85th percentile speeds caused by the installation of the VMSs. The 85th percentile speeds were automatically computed by the Portable Counter Classifiers at both the Station 1 and Station 2 and for both the lane types. The Z-test statistics on 85th percentile speeds of passenger cars are reported in Table 4. Z-test statistics for all other vehicle types are available with the authors. The Z-tests show the following:

TABLE 4 Z-Test on 85% Speed: Passenger Cars

VMS TYPE	LANE	Difference in Mean Speeds	Standard Error	Z-Statistic	Z-Value	
					0.05	0.01
WORK ZONE 45 MPH ~ PLEASE SLOW DOWN	DL	8.60	0.49	17.57	1.645	2.346
	PL	-0.85	0.43	-1.96	1.645	2.346
WORK ZONE 45 MPH ~ STATE POLICE ENFORCED	DL	4.75	0.53	8.98	1.645	2.346
	PL	--	--	--	--	--
YOUR SPEED 'X' MPH	DL	4.75	0.58	8.22	1.645	2.346
	PL	-9.15	0.91	-21.87	1.645	2.346

The VMS_A: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN** significantly reduced the 85th percentile speeds of PCs by 8.6 mph, the 85th percentile speeds of 2A-4T vehicles by 1.2 mph. The 85th percentile speeds of 5A-ST vehicles, and all vehicles did not show any change, in the DL. The PL did not show any reduction in 85th percentile speeds for PCs, 2A-4T vehicles, 5A-STvehicles, and all vehicles, using VMS_A.

The VMS_B: **WORK ZONE 45 MPH ~ STATE POLICE ENFORCED** significantly reduced the 85th percentile speeds of PCs by 4.7 mph, of 2A-4T vehicles reduced by 8 mph, of 5A-ST vehicles reduced by 3.3 mph, and of all vehicles by 5.6 mph, in the DL. Speed measurements in the PL had some machine errors while counting the data, and therefore 85th percentile speeds could not be computed.

The VMS_C: **YOUR SPEED 'X' MPH** reduced the 85th percentile speeds of PCs by 4.75 mph, of 2A-4T vehicles by 5.5 mph, for 5A-ST vehicles by 3.1 mph, and of all vehicles by 5.4 mph, in the DL. The PL did not show a reduction in the 85th percentile speeds of PCs, 2A-4T vehicles, 5A-ST vehicles, or total vehicles, using VMS_C.

1.3.4 Percent of Vehicles Conforming To Speed Limits

The vehicle speeds data was also analyzed to determine the reduction, if any, in the number of vehicles traveling above the 45 mph posted speed limit, above 55 mph, and above 65 mph. This statistic was computed separately for each of the three VMS types, and was compared with the Control Section. The analysis was further stratified for each of the three major vehicle types as well as for the total number of vehicles. Tables 5, 6, and 7 give the statistics on the percentage of each class of vehicles traveling above the 45mph, above 55mph and above 65mph, respectively, for each of the two lanes.

TABLE 5 Percent Vehicles Above 45 MPH Posted Speed Limits

VMS Type	% Vehicles above 45 MPH at Station #2								Remarks
	Cars		2A–4T		5A–ST		Total		
	DL	PL	DL	PL	DL	PL	DL	PL	
WORK ZONE 45 MPH ~ PLEASE SLOW DOWN	88.6	84.7	89.2	85.4	84.3	78.2	84.4	81.7	
WORK ZONE 45 MPH ~ STATE POLICE ENFORCED	84.1	--	89.0	--	84.0	--	81.0	--	
YOUR SPEED 'X' MPH	63.0	89.0	88.6	82.5	84.0	81.3	86.0	88.0	Most Effective
Control Sections	97.6	91.6	97.5	93.2	92.8	91.0	93.2	90.5	

Notes: -- No data available

TABLE 6 Percent Vehicles Above 55 MPH Posted Speed Limits

VMS Type	% Vehicles above 45 MPH at Station #2								Remarks
	Cars		2A–4T		5A–ST		Total		
	DL	PL	DL	PL	DL	PL	DL	PL	
WORK ZONE 45 MPH ~ PLEASE SLOW DOWN	38.2	28.9	27.5	24.5	29.9	19.6	34.3	23.5	
WORK ZONE 45 MPH ~ STATE POLICE ENFORCED	30.0	--	20.5	--	24.5	--	26.7	--	Most Effective
YOUR SPEED 'X' MPH	30.0	32.6	27.0	21.5	22.0	16.6	25.0	25.3	
Control Sections	66.7	50.7	55.0	52.3	49.4	39.8	63.7	45.3	

Notes: -- No data available

TABLE 7 Percent Vehicles Above 65 MPH Posted Speed Limits

VMS Type	% Vehicles above 45 MPH at Station #2								Remarks
	Cars		2A–4T		5A–ST		Total		
	DL	PL	DL	PL	DL	PL	DL	PL	
WORK ZONE 45 MPH ~ PLEASE SLOW DOWN	5.6	4.1	4.9	2.5	2.2	0.9	5.0	2.5	Most Effective
WORK ZONE 45 MPH ~ STATE POLICE ENFORCED	3.1	--	0.0	--	2.7	--	2.3	--	
YOUR SPEED 'X' MPH	4.5	4.4	1.1	2.1	1.8	1.6	2.6	3.3	
Control Sections	18.1	10.8	15.0	11.1	6.0	4.4	27.7	6.1	

Notes: -- No data available

The statistics given in the above tables conclude the following:

Using VMS_A: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN** the number of PCs above 45 mph decreased from 97.6% in the Control Section to 88.6% in the DL (9% reduction), and from 91.6% to 84.7% (7% decrease) in the PL. The 2A-4T vehicles showed an 8.5% decrease in the DL and 8% decrease in the PL. The 5A-ST vehicles showed an 8.5% decrease in the DL and a significant 13% decrease in the PL. All of the vehicles combined showed a reduction of 9% in both the DL and the PL.

The number of PCs traveling above 55 mph in the work zone decreased by 29% in the DL, and 22% in the PL due to the VMS. Similarly, 2A-4T vehicles decreased by 28% in both the DL and PL. The number of 5A-ST vehicles reduced by 20% in both the DL and the PL. All of the vehicles showed a reduction of 30% in the DL and 22% in the PL.

The number of PCs traveling above 65 mph decreased from 18% in the Control Section to 5.6% by using the VMS, resulting in a 13% decrease in the DL. The number of PCs in the PL, however, decreased by only 7%. The 2A-4T vehicles showed a 10% decrease in the DL and 9% decrease in the PL. The 5A-ST vehicles showed a 4% decrease in the DL and a 3% decrease in the PL. All of the vehicles combined showed a significant reduction of 22% in the DL and 3.5% reduction in the PL.

Using VMS_B: **WORK ZONE 45 MPH ~ STATE POLICE ENFORCED**, the number of PCs traveling above 45 mph in the work zone decreased by 14%. The 2A-4T vehicles decreased by 7.5% in the DL. The 5A-ST vehicles by 8%, and all of the vehicles by 12%.

The number of PCs traveling above 55 mph in the work zone showed a significant decrease of 36%. Similarly, the 2A-4T vehicles decreased by 35%. The 5A-ST vehicles reduced by 25%. All of the vehicles showed a reduction of 37%.

The number of PCs traveling above 65 mph showed a decrease of 16% using the VMS. The 2A-4T vehicles showed a 10% decrease, the 5A-ST vehicles by 4%, and all of the vehicles combined showed a reduction of 25%.

Using VMS_C: **YOUR SPEED 'X' MPH**, the number of PCs above 45 mph decreased from 97.5% in the Control Section to 63% in the DL (25% reduction), and from 91.6% to 89% (2% decrease) in the PL. The 2A-4T vehicles showed a 9% decrease in both the DL and the PL. The 5A-ST vehicles showed a 12% decrease in both the DL and the PL. All of the vehicles combined showed a reduction of 7% in the DL and 8% in the PL.

The number of PCs traveling above 55 mph in the work zone decreased by 36% in the DL, and 18% in the PL due to the VMS. Similarly, 2A-4T vehicles decreased by 28% in the DL and 31% PL. The 5A-ST vehicles reduced by 28% in the DL and 24% in the PL. All of the vehicles showed a reduction of 38% in the DL and 20% in the PL.

The number of PCs traveling above 65 mph decreased from 18% in the Control Section to 4.5%, therefore by using VMS_C, a 13.5% decrease occurred in the DL, but the number of cars in the PL, however, decreased by only 6%. The 2A-4T vehicles showed a 14% decrease in the DL and 9% decrease in the PL. The 5A-ST vehicles showed a 5% decrease in the DL and a 3% decrease in the PL. All of the vehicles combined showed a significant reduction of 25% in the DL and 3% reduction in the PL.

In terms of the reduction of the percentage of vehicles above 45 mph in the work zone, the VMS_B: **WORK ZONE 45 MPH ~ STATE POLICE ENFORCED** showed the best performance in reducing the percentage of all vehicles by 12%. VMS_A: **WORK ZONE 45 MPH ~ PLEASE SLOW DOWN** was effective in reducing the percentage of all vehicles by 9%, and lastly, VMS_C: **YOUR SPEED "X" MPH** reduced the percentage of vehicles by 7%. The statistics also indicated that the percentage reduction of vehicle speeds is more in the DL, than in the PL.

(ii) Effectiveness of Rumble Strips

The effectiveness of the following speed control devices implemented to reduce vehicular speeds and variances in highway work zones:

4. Two (2) rumble strip types, and
5. Police presence in combination with rumble strips

Two separate test locations on western New York State (NYS) highways with a statutory speed limit of 55 mph (88.55 km/h) or faster were selected, and each of the test locations utilized one or more of the above two interventions. The field data was collected from August 2001 through November 2001. The objective of this study was to measure the effectiveness of the two speed control measures implemented to reduce vehicular speeds and variances, in highway work zones, with a vision of enhancing work zone safety. The following field data was collected:

6. The speed characteristics of vehicles traveling through the study locations using the Manual of Uniform Traffic Control Devices (MUTCD) regulatory work zone speed limit and advisory signage only. These sections were considered 'Control Sections', and

7. The speed characteristics of vehicles traveling through the study locations after one or two of the speed control devices were implemented. These sections were considered 'Test Sections'. Description of the two site locations is provided below:

Speed measurements were taken at two locations: (i) Station 1, which was located in the advanced warning area upstream of the transition zone lane taper, and (ii) Station 2, located 528 downstream from the rumble strip intervention. The interventions were positioned downstream in advance of the transition lane taper, to provide advance warning to motorists.

Interstate-86 Test Site

Rumble Strip Study I

The construction site on Interstate-86 Eastbound (I-86 EB), located in Jamestown, NY was selected as a test location for the rumble strip study. Figure 3 illustrates the permanent work zone layout showing the locations of the MUTCD work zone signage, the rumble strip intervention, and the location of the speed measurement devices. I-86 is a four-lane divided rural freeway with a speed limit of 65 mph (104.65 km/h) and a work zone speed limit of 45 mph (72.45 km/h). The construction operation on I-86 consisted of rehabilitating the existing roadway. Alternating right lane and left lane closures were necessary to construct both sides of the roadway. Therefore, this test site had two different test section configurations:

8. Right Lane Closed (RLC), and
9. Left Lane Closed (LLC)

3M™ Rumble Strips were used on the I-86 EB test site, which were located before the actual work zone lane closure. The rumble strips were 6 inches (152.4 mm) wide and 0.4 inch (10.16mm) (± .12 inches (304.8 mm)) thick, and extended across both the driving and passing lanes. Each set of rumble strips was 50 feet (15.25 m) long comprising of six rumble strips spaced 10 feet (3.05 m) apart. A plan view and cross section of the rumble strips are displayed in Figure 4. Two rumble strip sets were placed between Station 1 and Station 2, 1050 feet (320.25 m) apart from each another. Station 1 was 529 feet (161.35 m) upstream from the first set of rumble strips and Station 2 was 528 feet (161.04 m) downstream from the second set of rumble strips.

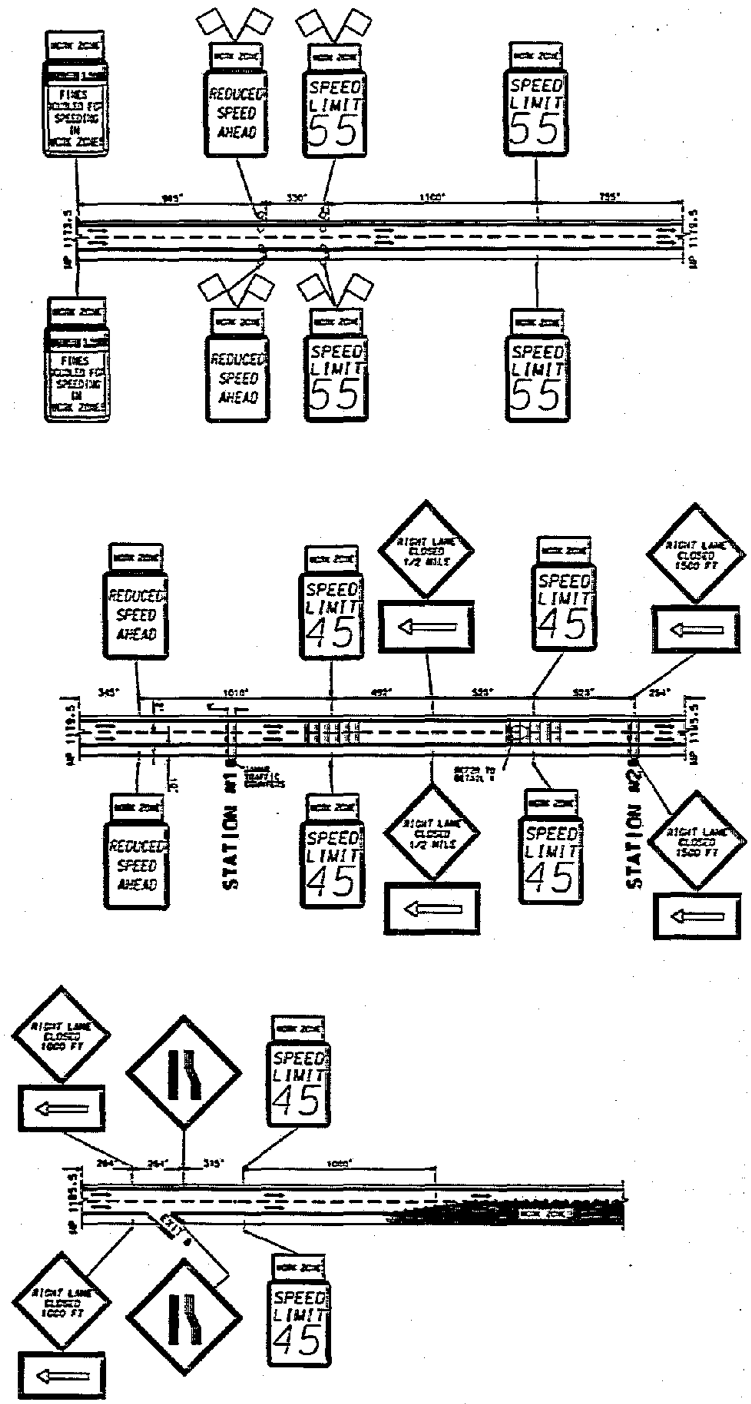


FIGURE 3 I-86 Work Zone Layout.
[Not to Scale]

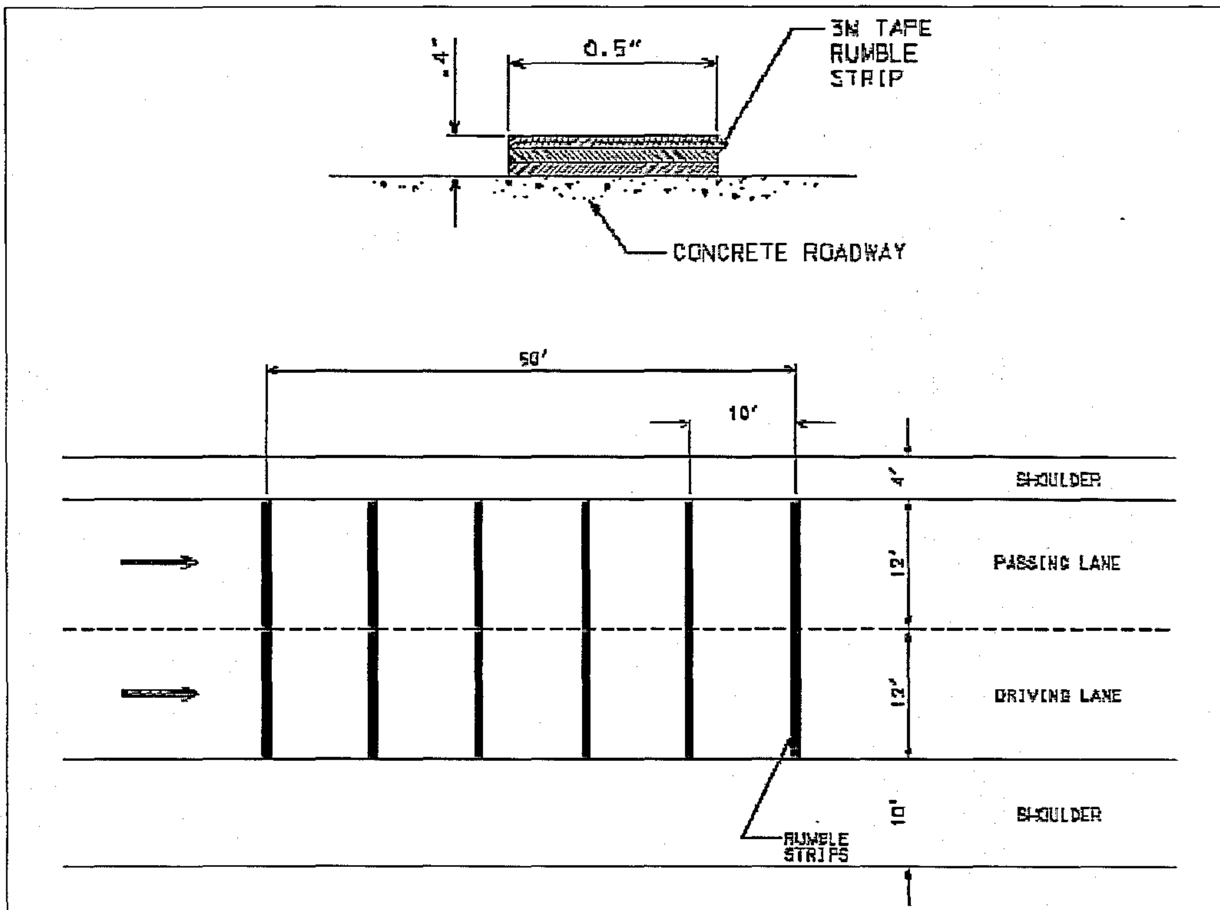


FIGURE 4 3M™ Rumble Strip Layout.

Interstate-990 Test Site

Rumble Strip Study II

Interstate-990 Northbound (I-990 NB) was another construction site selected for the rumble strip study, and for police presence combined with rumble strips. Figure 5 illustrates the I-990 work zone layout showing the orientation of the MUTCD work zone signage, the location of the rumble strips, the position of the police car, and the location of the speed measurement devices. I-990 is a 6-lane divided urban expressway with a speed limit of 55 mph (88.55 km/h) and a work zone speed limit of 45 mph (72.45 km/h). The construction site on the I-990 NB was a permanent work zone consisted of bridge and spot road rehabilitation for the entire northbound traveled way.

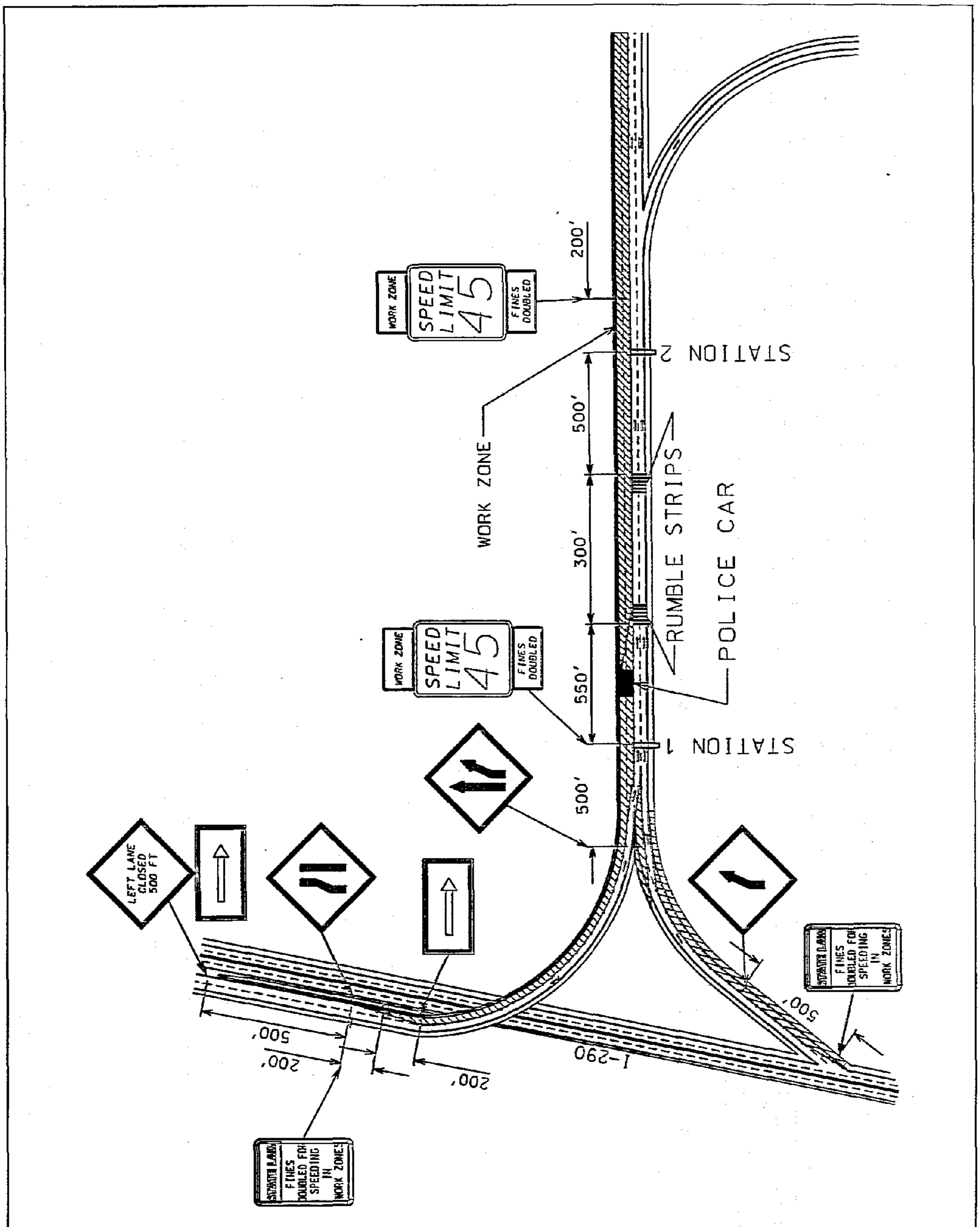


FIGURE 5: I-990 Work Zone Layout.
[Not to Scale]

The rumble strip by Swarco™ Industries Inc. was tested. The preformed rumble strips were a black non-reflective high quality high carbon resin. Each rumble strip was 6 inches x .25 inches (152.4 mm x 6.35 mm), which was placed over both travel lanes perpendicular to the traffic flow. Adhesive glue was used to install the rumble strips to the concrete pavement. Details of the rumble strip cross section and the rumble strip layout are shown in Figure 6. There were 2 sets of rumble strips between Station 1 and Station 2, spaced 300 feet (91.5 m) from each other. Each set of rumble strips contained six rumble strips spaced 40 feet (12.2 m) apart. Station 1 was located 550 ft (167.64 m) upstream from the first set of rumble strips while Station 2 was 500 ft (152.40 m) downstream from the second set of rumble strips.

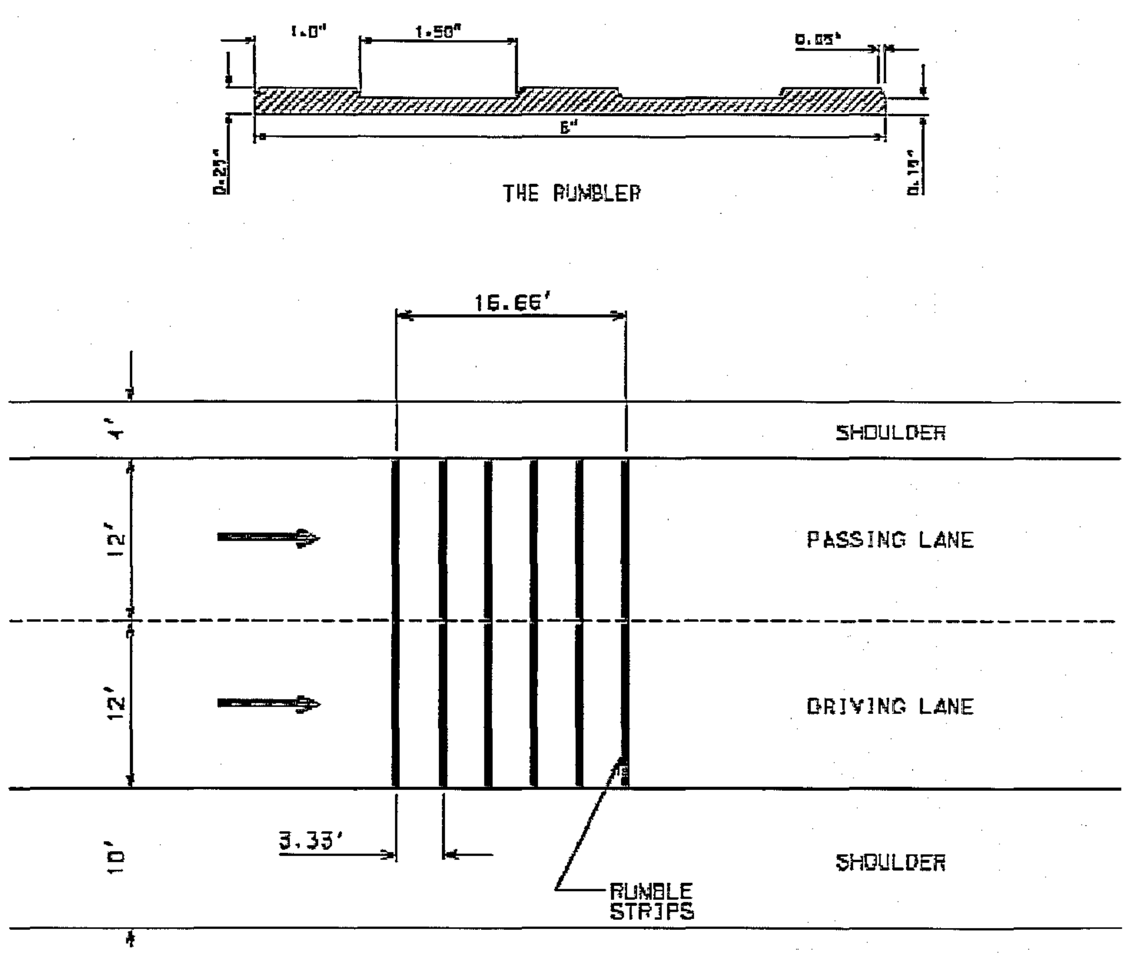


FIGURE 6 Swarco™ Rumble Strip Layout.

Police Presence with Swarco™ Rumble Strip Study

During this phase of data collection on the I-990 NB site, a police patrol car was positioned adjacent to Station 1, remaining stationary the entire time, and was located 1,350 ft (411.48 m) upstream from Station 2. The police car in combination with the Swarco™ rumble strips was evaluated as a speed control device. The patrol car was positioned from 7:00 am to 4:00 pm with the flashing light bar active the entire time. The rumble strips and data collection locations were configured as described in section 3.2.1.

Data Collection

Data collection included a total of thirty collection periods, but four of the periods were deleted from the data analyses because of tube failure which resulted in erroneous data. Speed data for control sections was measured for both sites when the rumbles strips were removed from the pavement and the police car was not present. All test data was collected on weekdays, during both the day and the night, while construction operations were active and inactive, and under normal weather conditions.

Speed Measurement Devices

Portable Trax I Traffic Counter/Classifiers made by Jamar™ Technologies, were used to collect speed data. Each test site contained two counters and two sets of pneumatic tubes. One set of tubes and a counter was placed upstream from the intervention at Station 1, and the second set was placed downstream from the intervention, at Station 2.

TEST DATA ANALYSES

The Trax I counters produced raw data files with the vehicles speed data classified by date, time, lane designation, number of axles, vehicle specification, vehicle class, length of vehicle, vehicle speed, gap, follow, and axle spacing. The raw data files were sorted using the S AS^{TM} s oftware b y date, l ane, a nd v ehicle c lass for s tatistical a nalyses. T hree o f t he vehicle classes: (i) Passenger Cars (PC), (ii) Two-axle Four-Tire vehicles (2A-4T), and (iii) Five-Axle Single-Trailer vehicles (5A-ST) accounted for 76.05% of the data (Table 8). Therefore, for studying the speed characteristics, and for evaluating the effectiveness of speed control devices, only these three vehicle classes were considered in this research and are categorized as below.

10. All Vehicles 100% of measured vehicles

2. Selected Vehicles

a. Class #2– Passenger Cars	(PC)	63.25% of measured vehicles
b. Class #3– Two-Axle Four-Tire	(2A-4T)	9.71% of measured vehicles
c. Class #9 – Five-Axle Single-Trailer	(5A-ST)	3.09% of measured vehicles

The distributions of the speed data were left-skewed. For example, Figures 7(a) and 7(b) illustrate the speed distributions of Station 1 speeds, for passenger cars, for lane #1, and lane #2, respectively. Figures 8(a) and 8(b) show the corresponding speed fluctuations over the time-of-day. To eliminate traffic congestion and/or other errors in measured speeds, the data was processed as below:

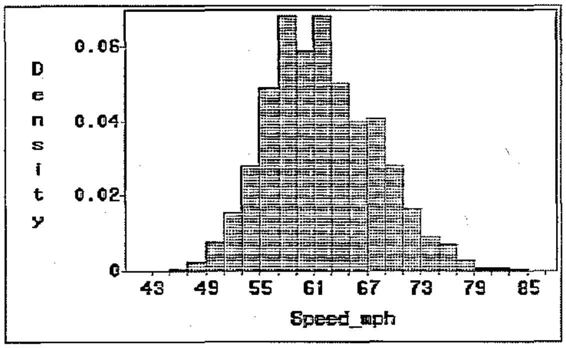
TABLE 8 Distribution of Vehicle Types* in the Test Data

Vehicle Classification		TEST AND CONTROL LOCATIONS				TOTALS	
		I-990		I-86			
Bin	Type	Total Vehicles	% Veh.	Total Vehicles	% Veh.	Vehicles	% Veh.
#1	Cycle	9,710	2.32	6,916	5.10	16,626	3.00
#2	Cars (PC)	283,432	67.65	67,361	49.66	350,793	63.28
#3	2A-4T	38,932	9.29	14,932	11.01	53,864	9.72
#4	Buses	1,573	0.38	1,657	1.22	3,230	0.58
#5	2A-SU	4,953	1.18	3,749	2.76	8,702	1.57
#6	3A-SU	6,618	1.58	3,197	2.36	9,815	1.77
#7	4A-SU	627	0.15	238	0.18	865	0.16
#8	4A-ST	2,391	0.57	2,955	2.18	5,346	0.96
#9	5A-ST	3,792	0.91	13,356	9.85	17,148	3.09
#10	6A-ST	16	0.00	20	0.01	36	0.01
#11	5A-MT	2	0.00	214	0.16	216	0.04
#12	6A-MT	0	0.00	0	0.00	0	0.00
#13	7^{+}A-MT	189	0.05	68	0.05	257	0.05
#14	Unknown	66,658	15.91	20,832	15.36	87,490	15.78
ALL	ALL	418,961	100.00	135,651	100.00	554,388	100.00

Note: * The number of vehicles in this table represent the total number of vehicles measured by the Trax I Traffic Counters. The counters were installed in most cases about one hour before the construction started, therefore the counts include a small percentage of vehicles that passed the counters during non-work zone conditions. The speed data, given later, includes the number of vehicles measured only during construction periods. The number of vehicles in the speed data calculations are therefore lesser

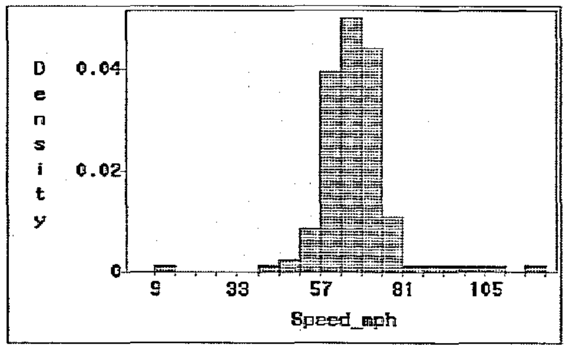
8/13/01 - Test Section - STATION 1
Class 2 - Passenger Cars
RAW DATA

Class = 2
Lane = 1



Moments			
N	1738.0000	Sum Wgts	1738.0000
Mean	61.4638	Sum	106824.000
Std Dev	6.1413	Variance	37.7157
Skewness	0.3832	Kurtosis	0.1061
USS	6631316.00	CSS	65512.2163
CV	9.9918	Std Mean	0.1473

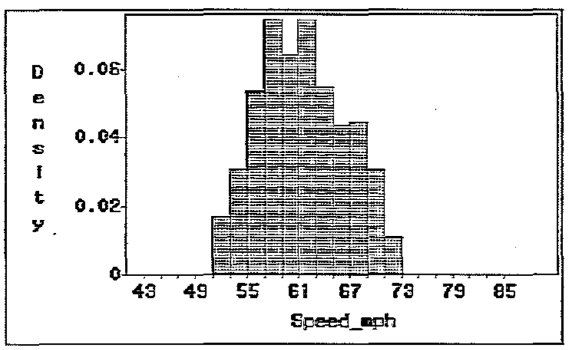
Class = 2
Lane = 2



Moments			
N	135.0000	Sum Wgts	135.0000
Mean	66.2741	Sum	8947.0000
Std Dev	11.0875	Variance	122.9318
Skewness	0.5118	Kurtosis	9.0393
USS	609427.000	CSS	16472.8593
CV	16.7297	Std Mean	0.9543

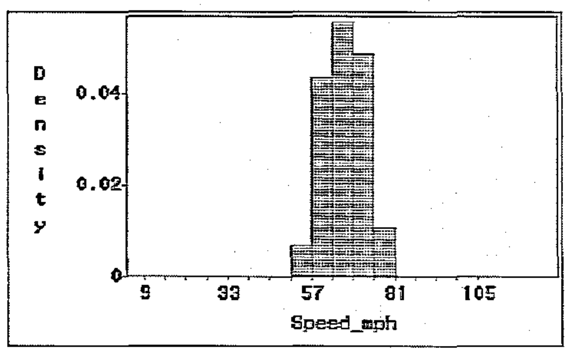
8/13/01 - Test Section - STATION 1
Class 2 - Passenger Cars
PROCESSED DATA

Class = 2
Lane = 1



Moments			
N	1596.0000	Sum Wgts	1596.0000
Mean	60.9148	Sum	97220.0000
Std Dev	4.9743	Variance	24.7438
Skewness	0.1144	Kurtosis	-0.8009
USS	5961602.00	CSS	39466.4110
CV	8.1660	Std Mean	0.1245

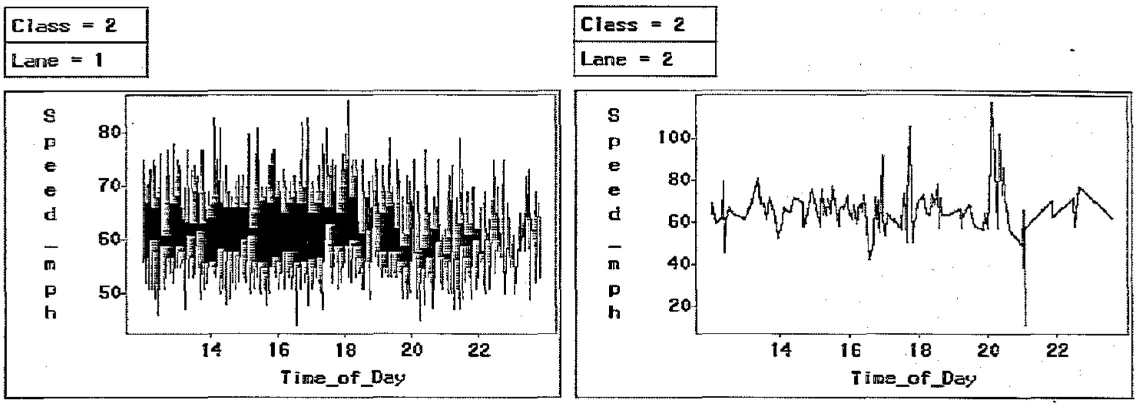
Class = 2
Lane = 2



Moments			
N	122.0000	Sum Wgts	122.0000
Mean	65.7705	Sum	8024.0000
Std Dev	5.9859	Variance	35.8312
Skewness	0.0696	Kurtosis	-0.5338
USS	532078.000	CSS	4335.5738
CV	9.1012	Std Mean	0.5419

FIGURE 7 Sample Speed Distribution of Passenger Cars.
[Source: Interstate-86, Rumble Strip Study Data]

8/13/01 - Test Section - STATION 1
Class 2 - Passenger Cars
RAW DATA



8/13/01 - Test Section - STATION 1
Class 2 - Passenger Cars
PROCESSED DATA

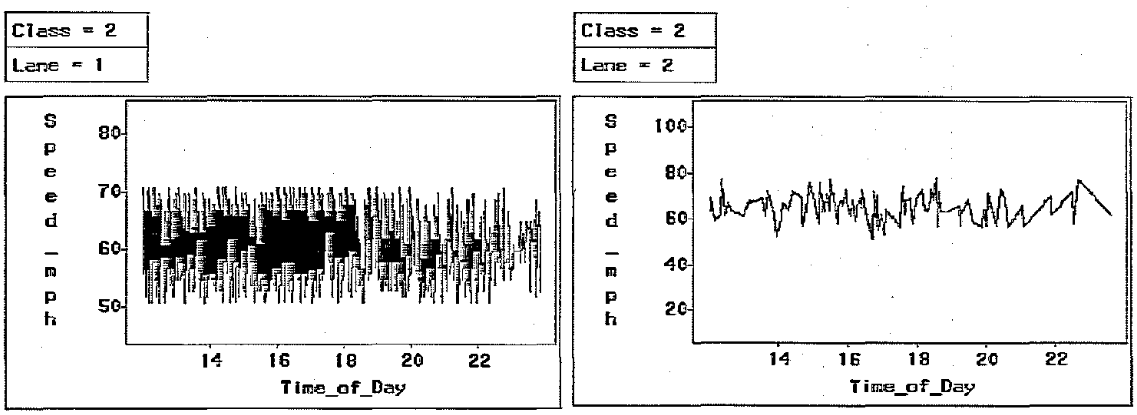


FIGURE 8 Sample Line Plots of Vehicle Speeds (Passenger Cars).
[Source: Interstate-86, Rumble Strips Study Data]

11. Vehicles beyond the range of mean speed $\pm 2 \times$ standard deviation ($\bar{x} \pm 2s$) were eliminated from the database, which was done separately for: (i) all vehicles and (ii) class 2, 3, and 9 vehicles. Figures 5(a), 5(b) and 6(a), and 6(b) illustrate an example of processed data for passenger cars at measured at Station 1 on the I-86 test site.

The outliers ($\bar{x} \pm 2s$) were eliminated in two iterations. An example of processed data for Station 2, passenger cars, is presented in Figures 5(c), 5(d); and 6(c) and 6(d). Similar procedures were followed for the speed distributions for the other types of vehicle classes: 3, and 9.

Tests of Significance – Rumble Strips

The effectiveness of the two types of rumble strip interventions on reducing vehicle speeds through highway work zones was the primary focus of the research. The true effectiveness of the intervention, thus, can be calculated by the difference between the speeds at Station 1 and Station 2 of the test sections, and the control sections. The number of vehicles used in speed measurements ranged from 105 to 16,002 for a test section. This data was then reduced by deletion of outliers corresponding to traffic congestion or other errors such as: tube failure or improper placement of the tubes. Due to the high volume of vehicles (>>30), z-tests were performed to test any significant effect that the interventions had on the reduction of speeds. The weighted averages of the vehicular mean speeds and their standard errors were used to calculate the z-scores. The vehicle speed data at Station 1, Station 2, the z-test statistics, and the p-values were organized into 7 tables, two each for the 3M™ rumble strips, two for the Swarco™ rumble strips, and one for police presence combined with Swarco™ rumble strips. Results from all tables are discussed in section 5.

The comparison of mean speeds for testing any significant difference in speed reduction between Station1 and Station 2 vehicle speeds before and after the rumble strip interventions, was performed using a z-test. The null hypothesis and the alternative hypothesis for the rumble strip interventions are stated below:

$$H_o : (\mu_{C1} - \mu_{C2}) \leq (\mu_{T1} - \mu_{T2}) \quad \text{.................................} \quad (1)$$

$$H_1 : (\mu_{C1} - \mu_{C2}) > (\mu_{T1} - \mu_{T2}) \quad \text{..................................} \quad (2)$$

where,

$\mu_{C1 \text{ or } C2}$ = Mean Vehicle Speed at Station 1 or Station 2 for a Control Section

$\mu_{T1 \text{ or } T2}$ = Mean Vehicle Speed at Station 1 or Station 2 for a Test Section

Effectiveness of Rumble Strips

Two rumble strip types were tested:

12. 3M™ on Interstate 86 (I-86)
13. Swarco™ on Interstate 990 (I-990):

Since the sample size in each of the tests was >>30 and since the speeds were approximately normally distributed (Figure 5(c), 5(d)), the following z-statistic was used to test the effectiveness of the 3M™ rumble strips against the null hypothesis: H_o,

$$z_{ijk} = \frac{(\bar{X}_{T1} - \bar{X}_{T2}) - (\bar{X}_{C1} - \bar{X}_{C2})}{\sqrt{\frac{s^2_{C1}}{n_{C1}} + \frac{s^2_{C2}}{n_{C2}} + \frac{s^2_{T1}}{n_{T1}} + \frac{s^2_{T2}}{n_{T2}}}} \quad \text{.................................} \quad (3)$$

z_{ijk} = Test Statistic for Lane Closure (i), vehicle class (j), and lane type (k)

where,

i = Designation for RS type: 1=Left Lane Closed (LLC), 2=Right Lane Closed (RLC)

j = Vehicle class designation: 1=All vehicles; 2=P.C.'s; 3=2A-4T's; and 4=5A-ST's

k = Lane type designation: 1=Driving Lane, 2=Passing Lane

$\bar{X}_{Tn}$ = Mean Vehicle Speed for a Test Section at Station n

$\bar{X}_{Cn}$ = Mean Vehicle Speed for a Control Section at Station n

s^2_{Tn} = Variance of Vehicle Speeds for a Test Section at Station n

s^2_{Cn} = Variance of Vehicle Speeds for a Control Section at Station n

n_{Tn} = Number of Vehicles in a Test Section at Station n

n_{Cn} = Number of Vehicles in a Control Section at Station n

TABLE 9 Effectiveness of 3M™ Rumble Strips (RLC*)					
VEHICLE TYPE	DRIVING LANE				Intervention Effectiveness? $\alpha = 0.05$
	$\bar{X}_T$-$\bar{X}_C$	s_T-s_C	Z-Value	P-Value	
All Vehicles	2.66	-0.36	22.99	<0.0001	Yes*
PC	2.46	-0.61	16.04	<0.0001	Yes*
2A-4T	2.89	-0.08	9.01	<0.0001	Yes*
5A-ST	2.63	-0.62	7.00	<0.0001	Yes*
VEHICLE TYPE	PASSING LANE				Intervention Effectiveness? $\alpha = 0.05$
	$\bar{X}_T$-$\bar{X}_C$	s_T-s_C	Z-Value	P-Value	
All Vehicles	-3.70	-0.54	-9.89	2.0000	No
PC	-4.05	-1.64	-8.28	2.0000	No
2A-4T	-8.48	-3.11	-7.12	2.0000	No
5A-ST	-1.00	-0.66	-0.75	1.5464	No

Notes:

RLC* = Right Lane Closed

X_T = Difference between the Test Section Station 1 and Station 2 Mean Speeds (mph)

X_C = Difference between the Control Section Station 1 and Station 2 Mean Speeds (mph)s_T = Difference between the Test Section Station 1 and Station 2 Standard Deviations (mph)

s_C = Difference between the Control Section Station 1 and Station 2 Standard Deviations (mph)

Yes* = significant at α=0.05

1.0 mph = 1.61 km/h

s_T = Difference between the Test Section Station 1 and Station 2 Standard Deviations (mph)

s_C = Difference between the Control Section Station 1 and Station 2 Standard Deviations (mph)

Yes* = significant at α=0.05

1.0 mph = 1.61 km/h

For Swarco™ rumble strips tested on I-990, the z-statistic was calculated using Equation (3), with the following designation of subscripts:

z_{ij} = Test Statistic for the Rumble Strip for vehicle class (i), and lane type (j)

where,

i = Vehicle class designation: 1=All vehicles; 2=P.C.'s; 3=2A-4T's; and 4=5A-ST's

j = Lane type designation: 1=Driving Lane, 2=Passing Lane

The level of significance selected for our hypothesis testing was $\alpha=0.05$, for which the critical values of the test statistic, $z_{ijk} = 1.645$ for one sided tests. In other words, if $z_{ijk} \leq 1.645$, the rumble strips tested are not significantly effective in reducing speeds. The values of z_{ijk} statistic for all rumble strips types, for extracted vehicle classes, are given in Table 9, 10, and 11 for each of the two lane types.

TABLE 10 Effectiveness of 3M™ Rumble Strips (LLC*)

VEHICLE TYPE	DRIVING LANE				Intervention Effectiveness? $\alpha = 0.05$
	$\bar{X}_T$-$\bar{X}_C$	s_T-s_C	Z-Value	P-Value	
All Vehicles	-1.77	-0.34	-14.49	2.0000	No
PC	-0.82	-0.80	-4.79	2.0000	No
2A-4T	-0.32	0.49	-0.96	1.6620	No
5A-ST	-0.49	0.18	-1.17	1.7576	No
VEHICLE TYPE	**PASSING LANE**				**Intervention Effectiveness? $\alpha = 0.05$**
	$\bar{X}_T$-$\bar{X}_C$	s_T-s_C	Z-Value	P-Value	
All Vehicles	2.21	0.32	9.00	<0.0001	Yes*
PC	2.38	-0.07	7.62	<0.0001	Yes*
2A-4T	1.38	0.84	2.05	0.0404	Yes*
5A-ST	1.93	-1.04	3.46	0.0005	Yes*

Notes:
RLC* = Right Lane Closed
X_T = Difference between the Test Section Station 1 and Station 2 Mean Speeds (mph)
X_C = Difference between the Control Section Station 1 and Station 2 Mean Speeds (mph)
s_T = Difference between the Test Section Station 1 and Station 2 Standard Deviations (mph)
s_C = Difference between the Control Section Station 1 and Station 2 Standard Deviations (mph)
Yes* = significant at α=0.05
1.0 mph = 1.61 km/h

TABLE 11 Effectiveness of Swarco™ Rumble Strips					
VEHICLE TYPE	DRIVING LANE				Intervention Effectiveness? $\alpha = 0.05$
	$\bar{X}_T - \bar{X}_C$	$s_T - s_C$	Z-Value	P-Value	
All Vehicles	-1.00	-0.34	-16.33	2.0000	No
PC	-0.21	-0.74	-2.61	1.9910	No
2A-4T	0.15	-1.05	0.63	0.5291	No
5A-ST	-0.91	-0.69	-1.48	1.8610	No
VEHICLE TYPE	PASSING LANE				Intervention Effectiveness? $\alpha = 0.05$
	$\bar{X}_T - \bar{X}_C$	$s_T - s_C$	Z-Value	P-Value	
All Vehicles	-0.15	-0.33	-2.81	1.9951	No
PC	-0.25	-0.16	-4.29	2.0000	No
2A-4T	0.66	-0.22	4.50	0.0000	Yes*
5A-ST	1.07	-0.25	2.47	0.0135	Yes*

Notes:
X_T = Difference between the Test Section Station 1 and Station 2 Mean Speeds (mph)
X_C = Difference between the Control Section Station 1 and Station 2 Mean Speeds (mph)
s_T = Difference between the Test Section Station 1 and Station 2 Standard Deviations (mph)
s_C = Difference between the Control Section Station 1 and Station 2 Standard Deviations (mph)
Yes* = significant at α=0.05
1.0 mph = 1.61 km/h

Test of Significance – Police Presence in Combination with Rumble Strips

The presence of a police patrol car on the test site created a unique testing situation in which a separate hypothesis was developed to analyze the speed data collected. Due to the location of the police car, motorists traveling through the work zone could see well in advance the stationed car position adjacent to Station 1. Therefore the motorists were already in compliance with the work zone speed limit upon traversing Station 1 and reductions in vehicle speeds between Station 1 and Station 2 could not be properly analyzed. Therefore it was determined to develop an alternative hypothesis in order to statistically analyze the difference in mean vehicle speeds at Station 2 only, of the test and control sections, to observe the effectiveness of the intervention in speed reduction contributed by the presence of a stationary patrol car in the work zone.

The comparison of mean speeds for testing any significant difference between Station 2 vehicle speeds before and after the police presence combined with the Swarco™ rumble strip intervention, was also performed using a z-test. The null hypothesis and the alternative hypothesis for this intervention are stated below:

$$H_{o(PP)} : \mu_{C2} - \mu_{T2} = 0 \quad \text{...} \quad (4)$$

$$H_{1(PP)} : \mu_{C2} - \mu_{T2} > 0 \quad \text{...} \quad (5)$$

where,

μ_{C2} = Mean Vehicle Speed at Station 2 for a Control Section

μ_{T2} = Mean Vehicle Speed at Station 2 for a Test Section

Effectiveness of Police Enforcement along with Rumble Strips (PE+RS)

The following z-statistic was used to test the null hypothesis: $H_{o(PP)}$, to evaluate the police presence in conjunction with the Swarco™ rumble strip intervention and is shown below in Equation (6).

$$z_{ij} = \frac{(\overline{X}_{C2} - \overline{X}_{T2})}{\sqrt{\frac{s^2_{C2}}{n_{C2}} + \frac{s^2_{T2}}{n_{T2}}}} \quad \text{...} \quad (6)$$

z_{ijk} = Test Statistic for (PP+RS) of vehicle class (i), and lane type (j)

where,

i = Vehicle class designation: 1=All vehicles; 2=P.C.'s; 3=2A-4T's; and 4=5A-ST's

j = Lane type designation: 1=Driving Lane, 2=Passing Lane

$\overline{X}_{T2}$ = Mean Vehicle Speed for a Test Section at Station 2

$\overline{X}_{C2}$ = Mean Vehicle Speed for a Control Section at Station 2

s^2_{T2} = Variance of Vehicle Speeds for a Test Section at Station 2

s^2_{C2} = Variance of Vehicle Speeds for a Control Section at Station 2

n_{T2} = Number of Vehicles in a Test Section at Station 2

n_{C2} = Number of Vehicles in a Control Section at Station 2

The values of z_{ijk} statistic for the police presence in combination with Swarco™ rumble strips types, for extracted vehicle classes, is given in Table 12 for each of the two lane types.

TABLE 12 Police Presence + Swarco™ RS* Speed Statistics Summary

Vehicle Type	Section Type	DRIVING LANE - STATION 2							
		n	$\bar{X}$	s	X_{C2}-X_{T2}	s_{T2}/s_{C2}	Z-Value	P-Value	Intervention Effectiveness? $\alpha = 0.05$
All Vehicles	Test	23370	46.48	3.80	3.07	0.74	72.33	<0.0001	Yes*
	Control	22361	49.55	5.15					
P.C.	Test	14791	47.81	3.89	4.16	0.77	65.98	<0.0001	Yes*
	Control	8648	51.97	5.02					
2A-4T	Test	1317	47.76	3.56	3.82	0.69	18.82	<0.0001	Yes*
	Control	831	51.59	5.13					
5A-ST	Test	179	46.25	3.35	3.68	0.81	7.20	<0.0001	Yes*
	Control	86	49.93	4.14					

Vehicle Type	Section Type	PASSING LANE - STATION 2							
		n	$\bar{X}$	s	X_{C2}-X_{T2}	s_{T2}/s_{C2}	Z-Value	P-Value	Intervention Effectiveness? $\alpha = 0.05$
All Vehicles	Test	22865	46.02	3.45	3.48	0.74	95.87	<0.0001	Yes*
	Control	27087	49.50	4.65					
P.C.	Test	16366	46.35	3.30	3.40	0.74	80.63	<0.0001	Yes*
	Control	17797	49.76	4.46					
2A-4T	Test	2568	45.71	3.33	4.12	0.78	39.37	<0.0001	Yes*
	Control	2737	49.83	4.26					
5A-ST	Test	287	45.04	2.72	4.52	0.79	16.11	<0.0001	Yes*
	Control	226	49.56	3.46					

Notes: Tables above contain processed data after outliers were deleted

RS* = Rumble Strips

$\bar{X}_{T2}$ = Mean Speed at Sta. 2, of the Test Section (mph)

$\bar{X}_{C2}$ = Mean Speed at Sta. 2, of the Control Section (mph)

s_{T2} = Std. Deviation at Sta. 2, of the Test Section (mph)

s_{C2} = Std. Deviation at Sta. 2, of the Control Section (mph)

Yes* = significant at α=0.05

1.0 mph = 1.61 km/h

P-Value Test Statistic

In order to determine the degree to which the data supports or does not support the null hypothesis, the p-values of the test data were computed. The p-values for each test were calculated using the following formula:

$$\text{p-value} = P(Z > z_c) \quad \text{.................................... (7)}$$

z_c = computed value of the test statistic

P-values for each of the tests are given in Tables 5, 6, 7, and 8. The significance level of the test was set at α=0.05. The null hypothesis is rejected if the p-value is less than 0.05.

DISCUSSION OF THE TEST RESULTS

Effectiveness of 3M™ Rumble Strips

The 3M™ rumble strips proved effective in the Right Lane Closed (RLC) scenario in the driving lane only. Overall the 3M™ rumble strips reduced all vehicles by 2.7 mph (4.35 km/h) over the entire vehicle population. They reduced PC speeds by 2.4 mph (3.86 km/h), 2A-4T vehicle speeds by 2.9 mph (4.67 km/h), and 5A-ST speeds by 2.6 mph (4.18 km/h). P-values for the 3M™ rumble strips are statistically significant in the driving lane, for all vehicle classes. Also, in the driving lane, the speed standard deviations showed reductions ranging from 0.08 mph to 0.62 mph (0.13 km/h to 1.0 km/hr). The 3M™ rumble strips were not effective in the passing lane for any of the vehicle classes, in the RLC situation. [Table 9]

In the Left Lane Closed (LLC) scenario, the 3M™ rumble strips had no significant reduction in speed in the driving lane for all vehicle classes. All vehicles in the passing lane had significant reductions in speed. In the passing lane, all the vehicles overall experienced a significant reduction in speed by 2.2 mph (3.54 km/h). The rumble strips proved effective in reducing PC by 2.4 mph (3.86 km/h), 2A-4T vehicles by 1.4 mph (2.25 km/h) and 5A-ST vehicles by 1.9 mph (3.05 km/h). Also, in the passing lane, the overall standard deviation increased by 0.32 mph (0.51 km/h), indicating little differences in speed variation between the test and the control sections. [Table 6]

Effectiveness of Swarco™ Rumble Strips

In the driving lane, the Swarco™ rumble strips display no significant reduction of vehicle speeds over the entire vehicle population. The passing lane experienced speed reductions for 2A-4T vehicles of 0.7 mph (1.13 km/h), and 5A-ST vehicles of 1.1 mph (1.77 km/h). The standard deviations of speeds show no sign of increase before and after the rumble strips. [Table 11]

Effectiveness of Police Enforcement + Swarco™ Rumble Strips (PE+RS)

The presence of a police car combined with Swarco™ rumble strips reduced speeds of all vehicle classes by 3.1 mph to 4.5 mph (4.98 km/h to 7.25 km/h). In the driving lane, PC experienced a reduction in speeds by 4.2 mph (6.76 km/h), 2A-4T vehicles reduced speeds by 3.8 mph (6.12 km/h), and 5A-ST's slowed by 3.7 mph (5.96 km/h). The passing lane also experienced reduced speeds of PCs by 3.4 mph (5.47 km/h), 2A-4T vehicles by 4.1 mph (6.60 km/h), and 5A-ST vehicles by 4.5 mph (7.25 km/h). Also, the standard deviation of vehicle speeds showed a reduction of about 25% for all vehicles both in the driving lane and in the passing lane. [Table 12]

PUBLICATIONS

Ghorpade, Bhavana S. and Satish B. Mohan *"Effectiveness of Variable Message Signs (VMSs) for Highway Work Zone Safety"*, Journal of the Institute of Transportation Engineers (ITE), submitted on: May 4, 2004

Zech, Wesley C., Satish B. Mohan, and Jacek Dmochowski *"Evaluation of Rumble Strips and Police Presence as Speed Control Measures in Highway Work Zones"* Journal of the Institute of Transportation Engineers (ITE), submitted on: May 4, 2004

Zech, Wesley C., Satish B. Mohan, and Jacek Dmochowski *"Evaluation of Changeable Message Signs as a Speed Control Measure in Highway Work Zones"*, ASCE Journal of Transportation Engineering, submitted on: May 4, 2004