Evaluation of Rumble Strips and Police Presence as Speed Control Measures in Highway Work Zones

Wesley C. Zech[1]; Satish Mohan[2]; and Jacek Dmochowski[3]

Abstract: This paper presents the results of a field study conducted on western New York State (NYS) highway work zones to evaluate two types of speed control devices: (1) rumble strips, and (2) police presence in combination with rumble strips. The study included speed measurements of approximately 554,400 vehicles. The most commonly used rumble strips comprise of either raised asphalt humps, or grooves cut in the pavement. In both of these two practices, the pavement is damaged, and the layout requires closing the road for extended periods. This project tested the effectiveness of two types of rumble strips: 3M and Swarco. These rumble strips do not damage the pavement, have the potential of repeated use, and are installed in a short period of time. The 3M rumble strips utilized on Interstate-86 were effective in reducing the passenger car (PC) speeds by approximately 3.86 km/h (2.4 mph), the two-axle four-tire vehicle speeds by 2.25 km/h (1.4 mph), and the five-axle single trailer vehicles by 3.22 km/h (2.0 mph). The speed reductions were dependent upon the type of lane closure setup. The Swarco rumble strips installed on Interstate-990, were not effective in reducing vehicle speeds, in either lane. The results of this field research indicate that properly selected rumble strips can be cost-effective in reducing vehicle speeds in highway work zones. Police presence combined with rumble strips was proven to be most effective, reducing speeds of all major vehicle types from 4.83 to 9.66 km/h (from 3.0 to 6.0 mph).

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Introduction

U.S. highway construction and maintenance work zone accident data are alarming with an average of 745 fatalities and 40,700 severe injuries per year. Highway work zone fatalities per billion dollars spent are at least five times higher compared to the total U.S. construction. The following factors have been widely cited as the major causes of traffic accidents in highway work zones: (Daniel et al. 2000; Hall and Lorenz 1989; Ha and Nemeth 1995):

- Excessive vehicle speeds;
- Variation of speeds between different vehicles; and
- Driver inattention and erratic maneuvers.

The current work zone speed control practices, consisting of passive regulatory and advisory signage, are known to have low compliance (Migletz et al. 1999). This has led to innovative research on speed controls devices, such as: (1) police presence on site, (2) changeable message signs, (3) rumble strips, (4) drone radars, and (5) radar activated speed trailers. This paper reports the results of field tests conducted on western New York State highways to evaluate the effectiveness of two types of speed control devices: (1) rumble strips, and (2) police presence combined with rumble strips.

The most commonly used rumble strips comprise of either raised asphalt humps, or grooves cut in the pavement. In either of these two practices, the pavement is damaged, and the layout requires closing the road for extended periods. This project tested the effectiveness of two types of rumble strips which come in the form of tapes that glue to the pavement, and do not damage the pavement. They have the potential of repeated use, and are installed in a short period of time.

Literature Review

The following sections briefly describe the research conducted so far in respect of: rumble strips, and police presence.

Rumble Strips

Rumble strips produce an audible and vibratory warning, which draws the attention of the drivers to the existence of the speed control signs. Meyer (2000) evaluated the effectiveness of orange removable rumble strips versus the commonly used cold mix asphalt rumble strips on a rural two-way 104.65 km/h (65 mph) highway, with a reduced work zone speed limit of 48.30 km/h (30 mph). They used 3.175 mm (1/8 in.) thick and 100 mm (4 in.) wide orange removable rumble strips, which were self adhesive and were configured in a group of six strips spaced 304.8 mm (12 in.) apart. Meyer concluded that the use of these orange removable rumble strips significantly reduced mean

[1]Primary Contact, Assistant Professor, Dept. of Civil Engineering, Auburn Univ., 233 Harbert Engineering Center, Auburn, AL 36849. E-mail: zechwes@eng.auburn.edu

[2]Associate Professor, Dept. of Civil, Structural, and Environmental Engineering, SUNY at Buffalo, 223 Ketter Hall, Buffalo, NY 14260. E-mail: smohan@eng.buffalo.edu

[3]Assistant Professor, Dept. of Mathematics, Univ. of North Carolina at Charlotte, 396 Fretwell Bldg., 9201 University City Blvd., Charlotte, NC 28223-002. E-mail: jdmochow@uncc.edu

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speeds of both, cars and trucks by 1.61–3.70 km/h (1–2.3 mph). He also noted that the high visibility of the orange rumble strips had a positive effect in reducing vehicle speeds.

Fontaine and Carlson (2001) also evaluated the effectiveness of the orange rumble strips on two-lane, 112.7 km/h (70 mph) rural roads. The thickness of the rumble strips was 6.35 mm $(\frac{1}{4}$ in.), the width was 101.6 mm (4 in.), and six strips spaced at 457.2 mm (18 in.) were used. They found that the rumble strips had a greater impact on trucks than passenger cars, reducing the average truck speeds by 4.83–6.44 km/h (3–4 mph). Passenger cars experienced mean speed reductions of less than 3.2 km/h (2 mph).

Police Enforcement

The effectiveness of police enforcement to reduce vehicle speeds in highway work zones has been evaluated by several researchers (Noel et al. 1988; Sisiopiku and Patel 1999; Turochy and Sivanandan 1998). All of the several enforcement types: (1) static police presence, (2) cruising police enforcement or (3) drone radar have been found effective.

Noel et al. (1988) evaluated the use of a marked police car with the light bar and radar active on 88.55 km/h (55 mph) freeways with a work zone speed limit of 72.45 km/h (45 mph). Police presence reduced vehicle speeds by approximately 5.64–6.44 km/h (3.5–4.0 mph).

Sisiopiku and Patel (1999) investigated the effectiveness of police presence which consisted of stationary patrol cars and circulating patrol cars on 112.7 km/h (70 mph) Michigan highways. The research concluded that an initial decrease of 8.05 km/h (5 mph) was observed at the position of the patrol car, and a 4.35 km/h (2.7 mph) increase was measured after the motorists passed the patrol car. There was no significant lasting effect of the police presence after 1–3 h.

Turochy and Sivanandan (1998) evaluated the use of drone radar on three sites located in Virginia on Interstate-81. Drone radar is a simulation of police presence that activates a motorist's radar detector. Reductions of 1.29–3.70 km/h (0.8–2.3 mph) occurred in mean speeds, and 0.16–6.28 km/h (0.1–3.9 mph) in standard deviation. The drone radar also reduced the number of vehicles exceeding the speed limit by 6–20%; and the 85th percentile speed by 1.77–6.28 km/h (1.1–3.9 mph). They concluded that drone radar was effective in short term work zones.

Study Plan

The research was conducted by the Construction Safety and Health Institute at the State University of New York at Buffalo, in 2001 and 2002 to evaluate the effectiveness of the following speed controls:

1. Two removable rumble strip types: 3M, and Swarco; and
2. Police presence in combination with Swarco rumble strips.

The test locations were selected by the research team based on the construction schedule of the New York State Department of Transportation (NYSDOT). Two separate test locations on western New York State highways with a statutory speed limit of 88.55 km/h (55 mph) or faster were selected. The following field data was collected.

1. The speed characteristics of vehicles traveling through the study sections 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
2. The speed characteristics of vehicles after the speed control interventions were implemented in addition to the existing MUTCD regulatory work zone speed limit and advisory signage. These sections were considered test sections.

At each test location, speed measurements were taken at two stations: (1) Station 1, which was located in the advance warning area, upstream of the transition area lane taper, and (2) Station 2, located downstream from the rumble strip intervention, and also upstream from the transition area lane taper.

Interstate-86 Test Site—3M Rumble Strip Study

The construction site on Interstate-86 Eastbound (I-86 EB), located in Jamestown, N.Y. was selected as a test location. I-86 is a four-lane divided rural freeway with a speed limit of 104.65 km/h (65 mph) and a work zone speed limit of 72.45 km/h (45 mph). 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 configurations:

1. Right lane closed (RLC); and
2. Left lane closed (LLC).

The 3M rumble strip applications, already installed on-site by the contractor, were 152.4 mm (6 in.) wide and 10.16 mm (0.4 in.) [±304.8 mm (0.12 in.)] thick [Fig. 1(a)]. Each set of rumble strips was installed in a length of 15.25 m (50 ft), comprising of six rumble strips spaced 3.05 m (10 ft) apart. Two rumble strip sets were placed between Station 1 and Station 2, 320.25 m (1,050 ft) apart.

Interstate-990 Test Site—Swarco Rumble Strip Study

Interstate-990 Northbound (I-990 NB) was another construction site selected for the rumble strip study, and for the police presence combined with rumble strip intervention. Fig. 2 illustrates the I-990 work zone layout showing the MUTCD work zone signage, the location of the rumble strips, and the location of the speed measurement devices. I-990 is a six-lane divided urban expressway with a speed limit of 88.55 km/h (55 mph) and a work zone speed limit of 72.45 km/h (45 mph). The construction site on the I-990 NB was a permanent work zone for bridge reconstruction, and spot road rehabilitation.

The rumble strips by Swarco Industries Inc. was already installed by the contractor and therefore tested. The preformed rumble strips were made of black non-reflective high quality high carbon resin. Each rumble strip was 152.4 mm × 6.35 mm (6 in. × 0.25 in.), and 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 Fig. 1(b). There were two sets of rumble strips between Station 1 and Station 2, spaced 91.5 m (300 ft) apart. Each set of rumble strips contained six rumble strips spaced 1.2 m (10 ft) on center.

Police Presence Combined with Swarco Rumble Strip Study

During the 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 411.48 m (1,350 ft) upstream from

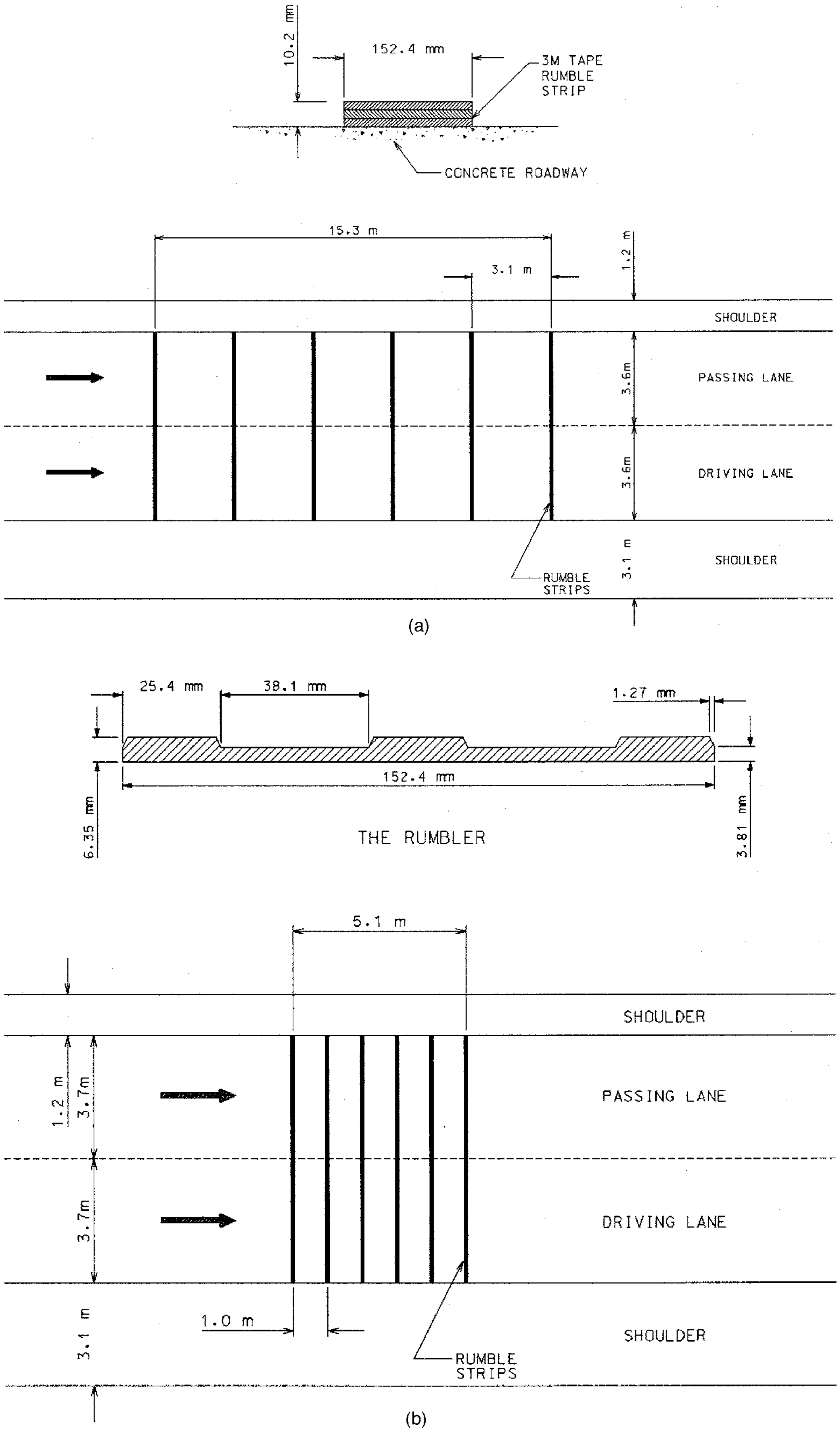

Fig. 1. (a) 3M and (b) Swarco rumble strip layouts.

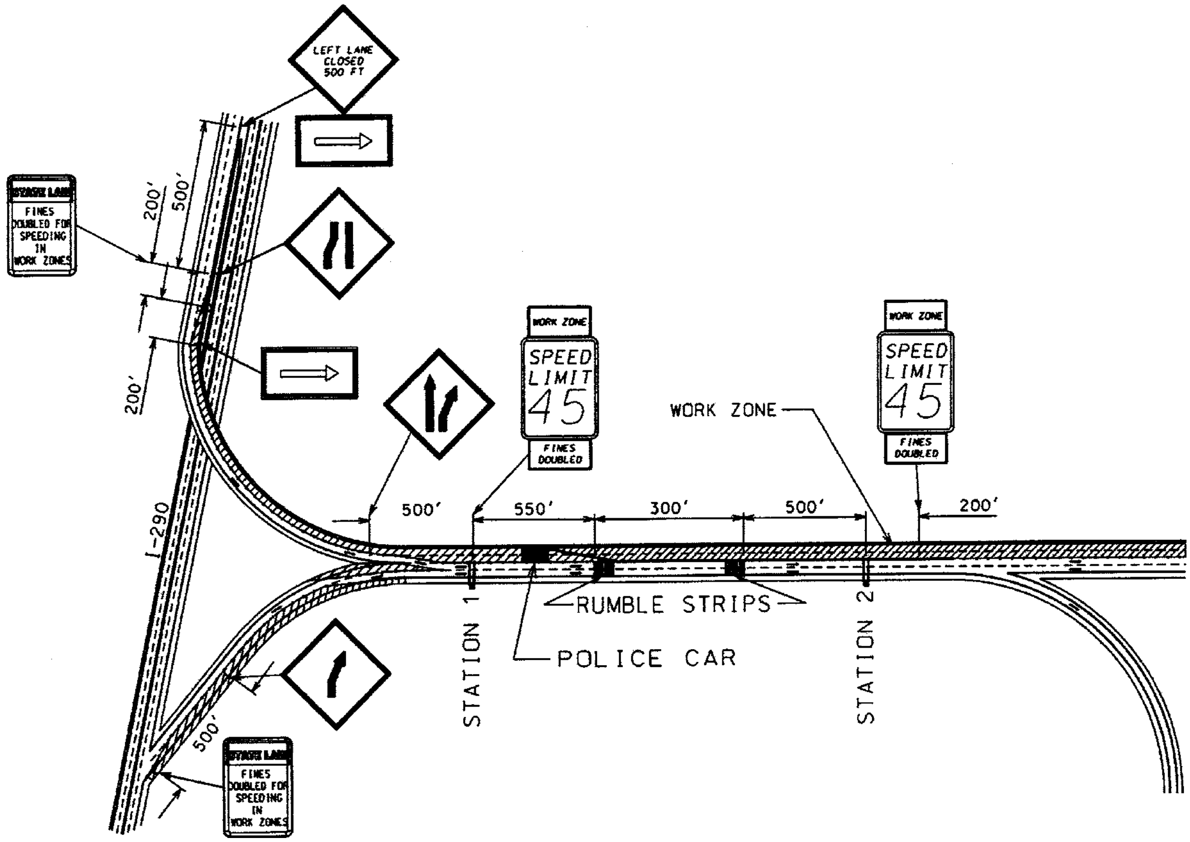

Fig. 2. I-990 work zone layout

Station 2. The police presence in combination with the Swarco rumble strips was evaluated as a speed control. The patrol car was positioned from 7:00 am to 4:00 pm with the flashing light bar active. Our intent in this paper is not to quantify the value of police presence alone, but to quantify it in combination with the Swarco rumble strip application. Due to the legal liability of the NYSDOT and the extensive labor required to remove and then re-install the rumble strips on this heavy traffic road, the police presence treatment was tested along with the rumble strips.

Data Collection

Data collection included a total of 30 collection periods, but four of the periods were deleted from the data analyses because of tube failure which resulted in erroneous data. Speed data during control sections, for comparison purposes, was measured at both sites when the rumble 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, whereas 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 SAS statistical software by date, lane, and vehicle class for analyses. Three of the vehicle classes accounted for 76.09% of the data: (1) passenger cars (PC—63.28%), (2) two-axle four-tire vehicles (2A-4T—9.72%), and (3) five-axle single-trailer vehicles (5A-ST—3.09%). Therefore, for evaluating the effectiveness of speed control devices, all vehicles along with the abovementioned three vehicle classes were considered individually. The frequency distributions of the speed data were right-skewed. For example, Figs. 3(a and b) illustrate the speed distributions of Station 1 speeds, for passenger cars, for Lane 1 and Lane 2, respectively. To eliminate the effect of traffic congestion and/or other errors in measured speeds, the data was processed. The following statement describes the data processing procedure. Vehicles beyond the range of the mean speed ±2 standard deviations ($\bar{x}\pm 2s$) were eliminated from the database, which was done separately for: all vehicles and Class 2, 3, and 9 vehicles. Figs. 3(c and d) illustrate an example of processed data for "class 2-passenger cars" as measured at Station 1 on the I-86 test site. The outliers ($\bar{x}\pm 2s$) were eliminated in two iterations. Similar procedures were followed for speed distributions at Stations 1 and 2 for the other vehicle classes considered: 3, 9, and "all-vehicles."

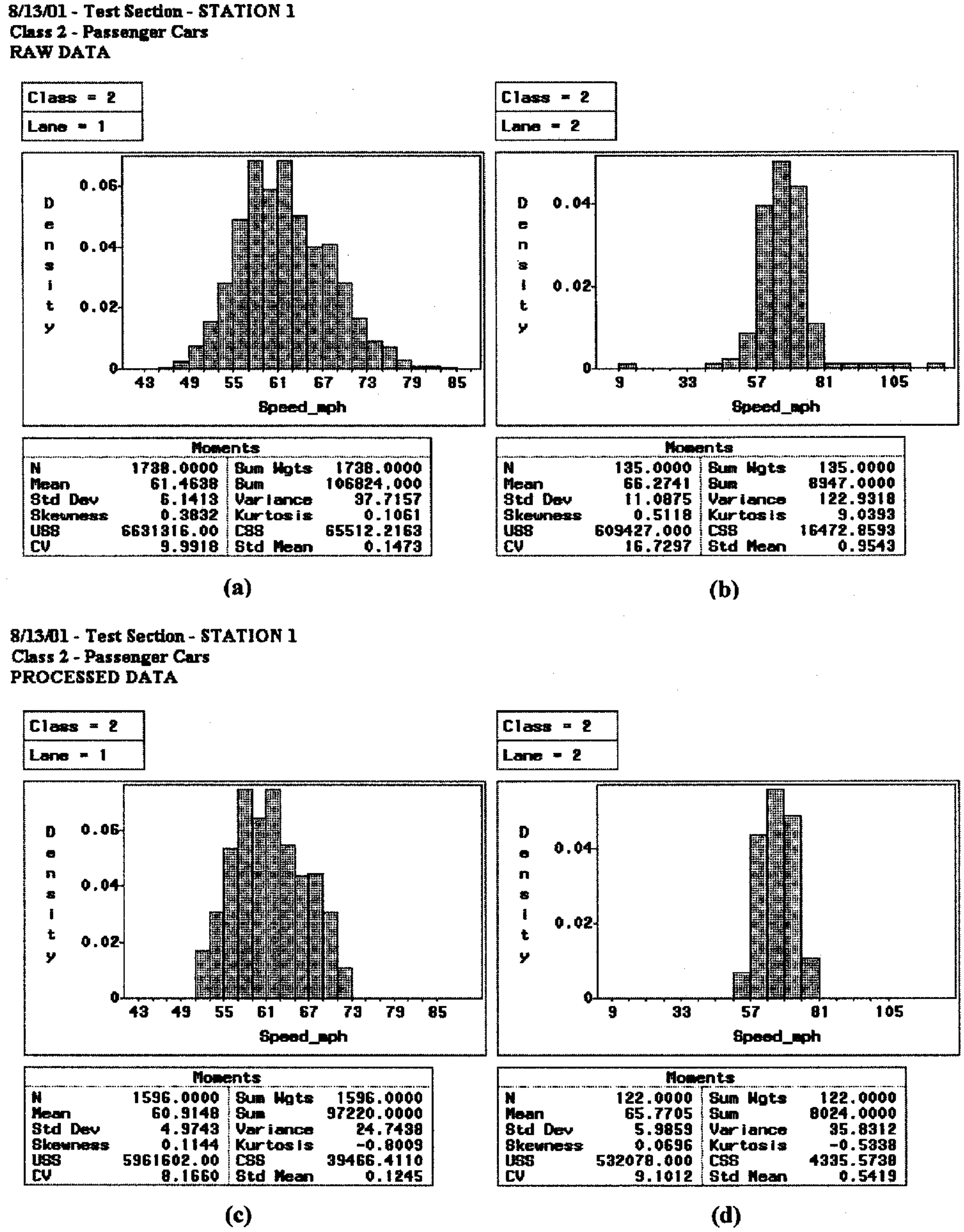

Fig. 3. Sample speed distribution of passenger cars

Test of Significance—Rumble Strips

The effectiveness of the two types of rumble strip interventions on reducing vehicle speeds in highway work zones, and the confounded effect of police presence in combination with rumble strips was the primary focus of the research. The effectiveness was calculated, using a before and after analysis, by taking the difference between the speeds at Station 1 and Station 2 of the test sections, vis-à-vis the control sections. The number of vehicles used in speed measurements ranged from 105 to 16,002 in a test section, and data therefore qualified for z tests. This data was then processed by deletion of outliers corresponding to traffic congestion or other errors (i.e. tube failure or improper placement of the tubes). The weighted averages of the vehicular mean speeds and their standard errors were used to calculate the z scores. The null hypothesis and the alternative hypothesis for the rumble strip interventions are stated as follows:

$$H_0\!:(\mu_{C1}-\mu_{C2}) \leqslant (\mu_{T1}-\mu_{T2}) \tag{1}$$

$$H_1\!:(\mu_{C1}-\mu_{C2}) > (\mu_{T1}-\mu_{T2}) \tag{2}$$

where $\mu_{C1 \text{ or } C2}$=mean vehicle speed at Station 1 or Station 2 for a control section and $\mu_{T1 \text{ or } T2}$=mean vehicle speed at Station 1 or Station 2 for a test section.

Since the sample size in each of the tests was $\geqslant$30 and since the speeds were approximately normally distributed [Figs. 3(c and d)], the following z statistic was used to test the effectiveness of the 3M rumble strips against the null hypothesis: H_0

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

where z_{ijk}=test statistic for lane closure (i), vehicle class (j), and lane type (k); i=designation for lane closure: 1=left lane closed (LLC), 2=right lane closed (RLC); j=vehicle class designation: 1=all vehicles; 2=PC's; 3=2A-4T's; and 4=5A-ST's;

Table 1. 3M Rumble Strips Statistics Summary (RLC*)

Vehicle class	Section type	Station 1 n	Station 1 $\bar{X}$	Station 1 s	Station 2 n	Station 2 $\bar{X}$	Station 2 S	$\bar{X}_T - \bar{X}_C$	$s_T - s_C$	Z value	P value	Effectiveness? $\alpha = 0.05$
						Driving Lane						
All vehicles	Test	17,826	98.22	8.16	18,102	88.52	8.57	4.29	−0.58	22.99	<0.0001	Yes
	Control	7,748	97.03	8.36	4,883	91.61	9.36					
PC	Test	10,730	98.31	8.42	11,030	88.46	8.50	3.97	−0.98	16.04	<0.0001	Yes
	Control	4,371	97.68	8.45	2,862	91.80	9.51					
2A-4T	Test	2,383	98.77	8.08	2,365	89.41	8.83	4.65	−0.13	9.01	<0.0001	Yes
	Control	1,036	97.52	8.64	676	92.81	9.52					
5A-ST	Test	2,198	98.64	7.36	2,152	89.14	8.19	4.23	−1.00	7.00	<0.0001	Yes
	Control	970	97.93	7.72	367	92.67	9.55					
						Passing Lane						
All vehicles	Test	2,113	97.09	15.32	1,072	97.16	12.60	−5.95	−0.87	−9.89	1.0000	No
	Control	1,593	96.91	11.46	4,601	91.03	9.61					
PC	Test	822	104.77	12.95	433	103.23	10.66	−6.51	−2.64	−8.28	1.0000	No
	Control	764	100.09	9.24	2,323	92.05	9.59					
2A-4T	Test	194	99.43	17.19	97	103.54	11.07	−13.64	−5.01	−7.12	1.0000	No
	Control	150	100.42	10.39	513	90.89	9.27					
5A-ST	Test	82	102.49	9.71	30	98.58	9.65	−1.62	−1.06	−0.75	0.7732	No
	Control	182	96.32	7.44	768	90.80	8.45					

Note: Contains processed data after outliers were deleted; RLC* = right lane closed; n = number of observations; $\bar{X}$ = mean vehicle speed (mph); s = standard deviation (mph); X_T = difference between the Test Section Station 1 and Station 2 mean speeds (km/h); X_C = difference between the Control Section Station 1 and Station 2 mean speeds (km/h); s_T = difference between the Test Section Station 1 and Station 2 standard deviations (km/h); s_C = difference between the Control Section Station 1 and Station 2 standard deviations (km/h); and 1 km/h = 0.62 mph.

k = lane type designation: type designation: 1 = driving lane and 2 = passing lane; $\bar{X}_{T1 \text{ or } T2}$ = mean vehicle speed for a test section at Station 1 or Station 2; $\bar{X}_{C1 \text{ or } C2}$ = mean vehicle speed for a control section at Station 1 or Station 2; $s^2_{T1 \text{ or } T2}$ = variance of vehicle speeds for a test section at Station 1 and or Station 2; $s^2_{C1 \text{ or } C2}$ = variance of vehicle speeds for a control section at Station 1 or Station 2; $n_{T1 \text{ or } T2}$ = number of vehicles measured in a test section at Station 1 or Station 2; and $n_{C1 \text{ or } C2}$ = number of vehicles measured in a control section at Station 1 or Station 2.

For Swarco rumble strips, the variable "lane closure" did not exist, so the z statistic was therefore calculated using Eq. (3), with z_{ij} = test statistic for the rumble strip for vehicle class (i), and lane type (j).

The level of significance selected for the hypothesis testing was 0.05, for which the critical value of the test statistic, z_{ijk} or $z_{ij} = 1.645$ for one sided tests. In other words, if z_{ijk} or $z_{ij} \leqslant 1.645$, the rumble strips tested are not significantly effective in reducing speeds. The values of z statistic for both rumble strips types, for the selected vehicle classes, are given in Tables1–3.

Test of Significance—Police Presence in Combination with Swarco Rumble Strips

The presence of a police patrol car on the test site created a unique situation in which a separate hypothesis was developed to analyze the speed data. Due to the location of the police car, motorists traveling through the work zone noticed, well in advance, the stationed car 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 intuitively used for effectiveness calculations. Therefore, it was determined to develop an alternative hypothesis in which vehicle speeds at Station 2 only, of the test section vis-à-vis control sections, were compared. The null hypothesis and the alternative hypothesis for this study are stated as follows:

$$H_{0(PP)}: \mu_{C2} - \mu_{T2} = 0 \tag{4}$$

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

where μ_{C2} = mean vehicle speed at Station 2 for a control section and μ_{T2} = mean vehicle speed at Station 2 for a test section.

The following z statistic was used:

$$z_{ij} = \frac{(\bar{X}_{C2} - \bar{X}_{T2})}{\sqrt{\frac{s^2_{C2}}{n_{C2}} + \frac{s^2_{T2}}{n_{T2}}}} \tag{6}$$

where z_{ij} = test statistic for police presence, and Swarco rumble strips of vehicle class (i), and lane type (j); i = vehicle class designation: 1 = all vehicles; 2 = PC's; 3 = 2A-4T's; and 4 = 5A-ST's; j = lane type designation: 1 = driving lane and 2 = passing lane; $\bar{X}_{T2}$ = mean vehicle speed for a test section at Station 2; $\bar{X}_{C2}$ = 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; and n_{C2} = number of vehicles in a control section at Station 2.

The values of z_{ij} statistic for the police presence in combination with Swarco rumble strips types, for selected vehicle classes, is given in Table 4 for each of the two lane types.

Table 2. 3M Rumble Strips Statistics Summary (LLC*)

Vehicle class	Section type	Station 1 n	Station 1 $\bar{X}$	Station 1 s	Station 2 n	Station 2 $\bar{X}$	Station 2 S	$\bar{X}_T - \bar{X}_C$	$s_T - s_C$	Z value	P value	Effectiveness? $\alpha = 0.05$
						Driving Lane						
All vehicles	Test	15,881	92.18	8.68	11,707	89.62	9.13	−2.86	−0.54	−14.49	1.0000	No
	Control	7,748	97.03	8.36	4,883	91.61	9.36					
PC	Test	6,797	94.45	9.63	6,437	89.89	9.40	−1.31	−1.29	−4.79	1.0000	No
	Control	4,371	97.68	8.45	2,862	91.80	9.51					
2A-4T	Test	1,503	94.31	7.39	1,580	90.13	9.07	−0.52	0.79	−0.96	0.8310	No
	Control	1,036	97.52	8.64	676	92.81	9.52					
5A-ST	Test	1,495	95.21	7.37	900	90.73	9.48	−0.78	0.28	−1.17	0.8788	No
	Control	970	97.93	7.72	367	92.67	9.55					
						Passing Lane						
All vehicles	Test	2,618	99.80	10.92	10,594	90.36	9.59	3.56	0.52	9.00	<0.0001	Yes
	Control	1,593	96.91	11.46	4,601	91.03	9.61					
PC	Test	1,100	103.36	9.42	4,365	91.48	9.64	3.84	−0.11	7.62	<0.0001	Yes
	Control	764	100.09	9.24	2,323	92.05	9.59					
2A-4T	Test	314	102.98	8.36	1,032	91.22	8.60	2.23	1.35	2.05	0.0202	Yes
	Control	150	100.42	10.39	513	90.89	9.27					
5A-ST	Test	210	99.12	8.84	1,572	90.48	8.17	3.11	−1.68	3.46	0.0003	Yes
	Control	182	96.32	7.44	768	90.80	8.45					

Note: Contains processed data after outliers were deleted; LLC* = left lane closed; n = number of observations; $\bar{X}$ = mean vehicle speed (mph); s = standard deviation (mph); X_T = difference between the Test Section Station 1 and Station 2 mean speeds (km/h); X_C = difference between the Control Section Station 1 and Station 2 mean speeds (km/h); s_T = difference between the Test Section Station 1 and Station 2 standard deviations (km/h); s_C = difference between the Control Section Station 1 and Station 2 standard deviations (km/h); and 1 km/h = 0.62 mph.

Table 3. Swarco Rumble Strips Statistics Summary

Vehicle class	Section type	Station 1 n	Station 1 $\bar{X}$	Station 1 s	Station 2 n	Station 2 $\bar{X}$	Station 2 S	$\bar{X}_T - \bar{X}_C$	$s_T - s_C$	Z value	P value	Effectiveness? $\alpha = 0.05$
						Driving Lane						
All vehicles	Test	27,609	83.14	7.36	29,143	78.74	8.24	−1.60	−0.54	−16.33	1.0000	No
	Control	20,573	85.73	6.87	22,361	79.73	8.29					
PC	Test	22,722	83.70	7.27	16,290	81.42	7.26	−0.33	−1.19	−2.61	0.9955	No
	Control	14,461	86.24	6.89	8,648	83.63	8.08					
2A-4T	Test	2,663	83.75	7.23	1,761	81.36	7.14	0.25	−1.69	0.63	0.2646	No
	Control	1,675	85.15	6.66	831	83.00	8.25					
5A-ST	Test	352	81.41	6.54	230	79.68	6.08	−1.47	−1.12	−1.48	0.9305	No
	Control	191	83.53	6.00	86	80.34	6.66					
						Passing Lane						
All vehicles	Test	37,843	83.00	7.60	37,179	78.18	7.55	−0.24	−0.54	−2.81	0.9975	No
	Control	25,577	84.71	7.01	27,087	79.65	7.49					
PC	Test	28,503	83.39	7.30	28,494	78.79	7.33	−0.41	−0.26	−4.29	1.0000	No
	Control	19,559	85.07	6.87	17,797	80.06	7.17					
2A-4T	Test	4,479	84.07	7.32	4,099	78.15	7.18	1.07	−0.35	4.50	<0.0001	Yes
	Control	2,982	85.03	6.64	2,737	80.17	6.85					
5A-ST	Test	377	80.84	6.63	401	76.89	5.64	1.72	−0.40	2.47	0.0067	Yes
	Control	246	81.97	6.15	226	79.74	5.56					

Note: Contains processed data after outliers were deleted; n = number of observations; $\bar{X}$ = mean vehicle speed (mph); s = standard deviation (mph); X_T = difference between the Test Section Station 1 and Station 2 mean speeds (km/h); X_C = difference between the Control Section Station 1 and Station 2 mean speeds (km/h); s_T = difference between the Test Section Station 1 and Station 2 standard deviations (km/h); s_C = difference between the Control Section Station 1 and Station 2 standard deviations (km/h); and 1 km/h = 0.62 mph.

Table 4. Police Presence+Swarco RS* Statistics Summary

Vehicle class	Section type	n	$\bar{X}$	s	$\bar{X}_{C2}-\bar{X}_{T2}$	s_{T2}/s_{C2}	Z value	P value	Effectiveness? $\alpha=0.05$
				Driving Lane—Station 2					
All vehicles	Test	23,370	74.78	6.11	4.94	0.74	72.33	<0.0001	Yes
	Control	22,361	79.73	8.29					
PC	Test	14,791	76.93	6.25	6.70	0.77	65.98	<0.0001	Yes
	Control	8,648	83.63	8.08					
2A-4T	Test	1,317	76.85	5.72	6.15	0.69	18.82	<0.0001	Yes
	Control	831	83.00	8.25					
5A-ST	Test	179	74.41	5.39	5.93	0.81	7.20	<0.0001	Yes
	Control	86	80.34	6.66					
				Passing Lane—Station 2					
All vehicles	Test	22,865	74.04	5.56	5.61	0.74	95.87	<0.0001	Yes
	Control	27,087	79.65	7.49					
PC	Test	16,366	74.58	5.31	5.48	0.74	80.63	<0.0001	Yes
	Control	17,797	80.06	7.17					
2A-4T	Test	2,568	73.55	5.36	6.63	0.78	39.37	<0.0001	Yes
	Control	2,737	80.17	6.85					
5A-ST	Test	287	72.47	4.38	7.27	0.79	16.11	<0.0001	Yes
	Control	226	79.74	5.56					

Note: Contains processed data after outliers were deleted; RS*=rumble strips; $\bar{X}_{T2}$=mean speed at Station 2, of the test section (km/h); $\bar{X}_{C2}$=mean speed at Station 2, of the control section (km/h); s_{T2}=standard deviation at Station 2, of the test section (km/h); s_{C2}=standard deviation at Station 2, of the control section (km/h); and 1 km/h=0.62 mph.

P-Value Test Statistic

In order to determine the degree to which the data supports the null hypothesis, the p values of the test data were computed. The p values for each test were calculated using the following formula:

$$p \text{ value} = P(Z > z_c) \tag{7}$$

where z_c=computed value of the test statistic.

P values for each of the tests are given in Tables 1–4. The significance level of the test was set at $\alpha=0.05$. The null hypothesis is rejected if the p value is less than 0.05.

Discussion of the Test Results

Effectiveness of 3M Rumble Strips

In the right lane closed (RLC) scenario, the 3M rumble strips proved effective in the driving lane only. The 3M rumble strips reduced the speeds of all vehicles by 4.35 km/h (2.7 mph). They reduced PC speeds by 3.86 km/h (2.4 mph), 2A-4T vehicle speeds by 4.67 km/h (2.9 mph), and 5A-ST speeds by 4.18 km/h (2.6 mph). P values for the 3M rumble strips were statistically significant in the driving lane, for all vehicle classes. Also, in the driving lane, the speed standard deviations showed reductions ranging from 0.13 to 1.0 km/hr (from 0.08 to 0.62 mph). The 3M rumble strips were not effective in the passing lane for any of the vehicle classes, in the RLC situation (Table 1).

In the left lane closed (LLC) scenario, the 3M rumble strips had no significant reduction in speeds in the driving lane for all vehicle classes. In the passing lane, all vehicles had significant reductions in speed, experiencing a significant reduction in speed by 3.54 km/h (2.2 mph).. The rumble strips proved effective in reducing speeds of PC's by 3.86 km/h (2.4 mph), 2A-4T vehicles by 2.25 km/h (1.4 mph) and 5A-ST vehicles by 3.05 km/h (1.9 mph). The overall standard deviation in the passing lane increased by 0.51 km/h (0.32 mph) (Table 2).

Effectiveness of Swarco Rumble Strips

In the driving lane, the Swarco rumble strips displayed no significant reduction of vehicle speeds over the entire vehicle population. The passing lane experienced speed reductions for 2A-4T vehicles of 1.13 km/h (0.7 mph), and 5A-ST vehicles of 1.77 km/h (1.1 mph). The standard deviations of speeds show no sign of increase before and after the rumble strips (Table 3).

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 4.98 to 7.25 km/h (3.1 to 4.5 mph). In the driving lane, PCs experienced a reduction in speeds by 6.76 km/h (4.2 mph), 2A-4T vehicles by 6.12 km/h (3.8 mph), and 5A-ST's by 5.96 km/h (3.7 mph). The passing lane also experienced reduced speeds of PCs by 5.47 km/h (3.4 mph), 2A-4T vehicles by 6.60 km/h (4.1 mph), and 5A-ST vehicles by 7.25 km/h (4.5 mph). 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 4). This intervention was the most effective, reducing both speeds and speed variances, significantly.

Summary and Conclusions

The 3M rumble strips proved effective as a speed control device but were dependent upon the lane closure setup. Vehicles having to execute a merging maneuver in the transition area of the work zone 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. The transition area should be an area of concern, due to the speed differentials 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 2.25–4.67 km/h (1.4–2.9 mph). The other set of rumble strips: Swarco rumble strips had partial success. In the driving lane they reduced the speeds of PCs and 2A-4T vehicles only. In the passing lane the speed reduction was minor. The police presence in combination with Swarco rumble strips proved to be the most effective speed control, reducing speeds from 6.44 to 9.66 km/h (from 4.0 to 6.0 mph). This control also reduced the speed variances by about 25%, a very desirable attribute in reducing rear-end accidents.

The speed reductions realized in the analysis, are reductions in speed over the entire population of vehicles. Since the vehicle population of the data set is quite large, this results in a very considerable reduction in vehicle speeds. This research, using field experiments, has proven that rumble strips and police presence, if properly selected and implemented can be effective in reducing vehicle speeds as well as speed variances, both sought-after objectives to enhancing work zone safety.

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