Evaluation of Messages on Changeable Message Signs as a Speed Control Measure in Highway Work Zones

Wesley C. Zech[1]; Satish B. Mohan, M.ASCE[2]; and Jacek Dmochowski[3]

Abstract: The objective of this study is to measure the effectiveness of three commonly used changeable message sign (CMS) messages in reducing vehicular speeds and variances in highway work zones. This paper presents the results of a field study conducted on Interstate-90 in western New York State to evaluate the use of three different types of messages displayed on a CMS, as a speed control measure. The study included speed measurements of nearly 180,000 vehicles. The three types of CMS messages tested were: (1) *RIGHT|LANE|CLOSED~KEEP|LEFT*; (2) *WORK ZONE|MAX SPEED|45 MPH~BE|PREPARED|TO STOP*; and (3) *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 most effective, significantly reducing vehicle speeds by 3.3–6.7 mi/h (5.3–10.8 km/h). The other two CMS messages were not as effective. The standard deviation of speed for the CMS message: *WORK ZONE|MAX SPEED|45 MPH~BE|PREPARED|TO STOP* increased by 1.1–1.7 mi/h (1.8–2.7 km/h) in the driving lane and 0.2–2.0 mi/h (0.3–3.2 km/h) in the passing lane. The speed variances for the other two CMS messages ranged from −2.00 to 1.13 mi/h (from −3.23 km/h to 1.83 km/h).

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Introduction

United States highway construction and maintenance work zone crash data are alarming with an average of 745 fatalities and 40,700 severe injuries per year (FARS 2005). Although highway traffic fatalities per hundred million vehicle miles have been steadily declining at the rate of 3.2% per year, the number of fatalities related with highway work zones have been rising at a rate of 2.3% per year, since 1981. Highway work zone fatalities per billion dollars spent are at least five times more than in the total United States construction industry. The following factors have been widely cited as the major causes of traffic crashes in highway work zones (Daniel et al. 2000; Fontaine and Carlson 2001; Hall and Lorenz 1989; Ha and Nemeth 1995; Migletz et al. 1999; Wang et al. 1996):

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

The current work zone speed control practices consist of passive regulatory and advisory signage but these practices are known to have low compliance (Fontaine and Carlson 2001). This has led to innovative research on speed control measures, such as: (1) police presence; (2) changeable message signs (CMSs); (3) rumble strips; (4) drone radar; and (5) radar activated speed trailers. Work zone speed control measures should be properly selected, while also considering possible adverse effects during and due to implementation. Possible adverse effects such as congestion and increases in speed variability between vehicles may increase the likelihood of a crash, thus having a negative impact on work zone safety. The degree of effectiveness of speed reduction interventions should also be evaluated during the selection and implementation of such control measures. This paper reports the results of field tests conducted on the New York State Thruway (I-90) to evaluate the effectiveness, as a speed control measure, of three different messages displayed using a CMS, located within the work zone.

[1]Assistant Professor, Dept. of Civil Engineering, Auburn Univ., 233 Harbert Engineering Center, Auburn, AL 36849-5337 (corresponding author). E-mail: zechwes@auburn.edu

[2]Amherst Town Supervisor, Amherst Municipal Building, 5583 Main St., Williamsville, NY 14221. E-mail: smohan@amherst.ny.us

[3]Associate Professor, Dept. of Mathematics, Univ. of North Carolina at Charlotte, 390D Fretwell Bldg., 9201 University City Blvd., Charlotte, NC 28223-0002. E-mail: jdmoch@uncc.edu

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Literature Review

CMSs are commonly used as a means of providing advisory information on congestion, traffic crashes, weather conditions, detour information, upcoming work situations, posted speed limits, or individual vehicle speeds. A search of the literature found that most research has focused on CMS displays integrated with radar units to alert drivers of their current speeds. Trailer mounted CMS boards equipped with radar devices have become a popular means of alerting drivers of excessive speeds by displaying the actual speeds of their vehicles along with an advisory notice to slow down. Limited studies have focused on the effect the message displayed on the CMS has on speed reduction, which is the motivation for this study. The primary reason for this research is to

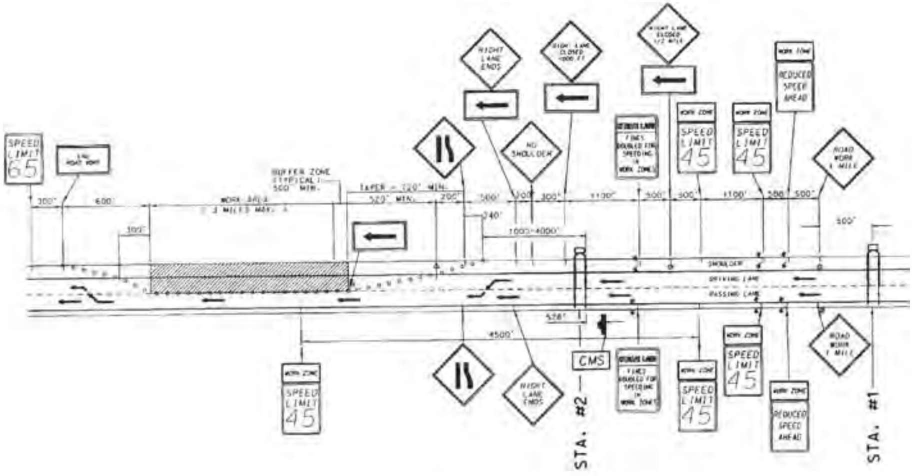

Fig. 1. Typical work zone layout; source: New York State Thruway Authority (NYSTA) [not to scale]

test and document the effect different CMS messages have on reducing vehicle speeds and their variances, upon entering the work zone. The following sections briefly summarize the research reported in the literature using CMSs as a speed control measure.

McCoy et al. (1995) evaluated the speed reduction effect of a trailer mounted speed display that was equipped with radar on a rural interstate in South Dakota. The study site was on a 55 mi/h (88.55 km/h) highway with a work zone speed limit of 45 mi/h (72.45 km/h). The speed display contained two static advisory signs mounted above the speed display that stated "*WORK ZONE*," "*45 MPH*," and the display was located off the left shoulder. Below the static signage, a plate stating "*YOUR SPEED*" was added above the dynamic speed display which alerted drivers of their current speeds. This study concluded that the speed display reduced the mean vehicle speeds of all vehicle classes by 4–5 mi/h (6.44–8.05 km/h). They also stated that the percent of vehicles exceeding the posted speed limit by 10 mi/h (16.1 km/h) were reduced by as much as 40%.

Garber and Srinivasan (1998) conducted a similar study using a CMS equipped with a radar unit on highways in Virginia. The CMS was placed within the work area at the beginning of the lane taper. Four different messages were evaluated during the course of the study and the message "YOU ARE SPEEDING SLOW DOWN" was the most effective. They concluded that the CMS with radar unit continued to be effective, for long durations.

Mohan and Ghorpade (2000) of the State University of New York at Buffalo evaluated the effectiveness of three CMS messages as active speed controls on four-lane rural interstate highways. The authors concluded that the CMS messages effectively reduced average speeds of the entire vehicle population by 5 mi/h (8.05 km/h). The CMS message: "*WORK ZONE|45 MPH—STATE POLICE|ENFORCED*" performed the best, by reducing the number of speeding vehicles in the total population over 45 mi/h (72.45 km/h) by 25% in the driving lane.

Fontaine and Carlson (2001) examined the effectiveness of a radar activated speed display, along with rumble strips, on two-lane rural roadways with 70 mi/h (112.70 km/h) speed limits. The speed display, which showed motorists their individual speeds, produced a 2–9 mi/h (3.2–14.5 km/h) reduction of the average speeds of passenger cars and a 3–10 mi/h (4.8–16 km/h) reduction in trucks, passing through the advance warning area of the work zone. The speed display also resulted in reducing the percentage of speeding passenger cars by 15 to 20%.

The research reported in this paper includes the testing of three CMS messages that have not been evaluated by any other research effort so far.

Study Plan

The research reported in this paper, was conducted by the Construction Safety and Health Institute at the State University of New York at Buffalo. The objective of this study was to measure the effectiveness of the three different messages displayed on a CMS in reducing vehicular speeds and speed variances in the advance warning area of highway work zones with a vision of enhancing work zone safety.

The test location, Interstate 90, located in the Western New York area was selected. The speed measurement data was collected from August 2001 through November 2001. The following field data were collected:

1. The speed characteristics of vehicles traveling through the study location using the typical work zone layout of the New York State Thruway Authority (NYSTA), as seen in Fig. 1. These sections were considered "control sections"; and
2. The speed characteristics of vehicles traveling through the study location, after one of the three CMS messages were

implemented. These sections were considered "test sections." A description of the research site location is provided in the following.

Interstate-90 Test Site

A construction project on Interstate-90 Eastbound (I-90 EB), between Batavia and Leroy, New York was selected for implementation of the CMS messages in addition to the static work zone speed limit and advisory signage. I-90 is a four-lane divided rural freeway with a statutory speed limit of 65 mi/h (104.65 km/h) and a posted work zone speed limit of 45 mi/h (72.45 km/h).

The construction project was a milling/paving operation for rehabilitating the roadway surface. A 2–3 mi (3.22–4.83 km) movable work zone was established for the daily milling/paving operation. The movable work zone consisted of temporary work zone traffic controls that were erected daily in the location of the construction operations. This required the researchers to position the CMS in a different location each day on the project before every data collection period. Construction operations began anytime after midnight and continued up to about 8:00 p.m., therefore the data consists of both night and day traffic conditions. The lane closure was either established in the right lane or the left lane, depending upon the construction operation for that particular day. The traffic control plan (TCP) was a typical work zone layout of the NYSTA. This TCP is comparable to typical application 33 (TA33) in Part 6 of the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA 2003).

Speed measurements were taken at two locations: (1) Station 1, which was located in the advance warning area approximately 5,700 ft (1,737.4 m) upstream of the transition zone lane taper; and (2) Station 2, located 528 ft (160.94 m) downstream from the CMS intervention. The CMS was positioned anywhere from 1,528 to 4,528 ft (from 465.7 to 1,380 m) upstream of the lane taper, to provide advance warning to motorists. A typical work zone layout of the NYSTA is illustrated in Fig. 1. The CMS letters were 8 in. (203.2 mm) in height, so that the CMS could be read from 480 ft (146.4 m) by a driver with 20/20 vision. The following three types of CMS messages were used in the study:

- CMS_1: *RIGHT|LANE|CLOSED~KEEP|LEFT*
- CMS_2: *WORK ZONE|MAX SPEED|45 MPH~BE|PREPARED|TO STOP*
- CMS_3: *LEFT|LANE|CLOSED~KEEP|RIGHT*

Each of the three CMS messages contained a two phase message, in compliance with the MUTCD, displayed to the motorists. For example, in CMS Message 1, the first phase displayed "*RIGHT|LANE|CLOSED,*" followed by the display, "*KEEP|LEFT.*"

Data Collection

Data collection included eight test sections, but three of the sections were deleted from the data analyses because of either improper tube placement or tube failure. Speed data for control sections could only be measured between the hours of 1:00 a.m. and 7:00 a.m. due to liability issues dealing with the CMS display being inactive during periods of high traffic volumes. Speed data for test sections were collected while the CMS board was active anytime between the hours of 1:00 a.m. and 8:00 p.m. All speed data were collected on weekdays, while the construction operation was in progress, and under normal weather conditions.

Speed Measurement Devices

Automatic pneumatic traffic data recorders 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 before the intervention at Station 1, and the second set was placed after the intervention, at Station 2, as shown in Fig. 1. Speed data was collected for both the driving lane (Lane 1) and the passing lane (Lane 2).

Test Data Analyses

The Trax I counters produced raw data files with the vehicle speed data classified by date, time, lane designation, number of axles, vehicle class, length of vehicle, vehicle speed, gap, and axle spacing. The raw data files were sorted using statistical software by date, lane, and vehicle class for analyses. Three of the vehicle classes: (1) passenger cars (PC); (2) two-axle four-tire vehicles (2A-4T); and (3) five-axle single-trailer vehicles (5A-ST) accounted for 65.58% of the data as given below:

1. All vehicles 100% of measured vehicles.
2. Selected vehicle classes
   a. Class 2—Passenger cars (PC) 47.98% of measured vehicles;
   b. Class 3—Two-axle four-tire (2A-4T) 7.48% of measured vehicles; and
   c. Class 9—Five-axle single-trailer (5A-ST) 10.12% of measured vehicles.

Therefore, for studying the speed characteristics and for evaluating the effectiveness of active speed control devices, "all vehicles" and the three vehicle classes stated above were individually analyzed. The distributions of the speed data were left-skewed, and in a few cases, the data were bimodal. For example, Figs. 2(a and b) illustrate the speed distributions of passenger cars traversing Station 2 for Lane 1, and Lane 2, respectively. Figs. 3(a and b) show the corresponding speed fluctuations over the time-of-day. Lane 1 speed characteristics of the passenger cars indicate that individual speeds over the time intervals of a particular study section can vary from 7.5 to 91.5 mi/h (from 12.08 to 147.32 km/h) with a standard deviation of 19 mi/h (30.59 km/h). A bimodal speed distribution illustrates a real world situation representative of traffic congestion occurring at the work zone over certain time periods resulting from high traffic volumes. To eliminate traffic congestion and/or other errors on measured speeds used in statistical analyses, the data were processed as in the following.

1. Vehicles beyond the range of mean speed ±2× standard deviation ($\bar{x}\pm2s$) were eliminated from the database, which was done separately for all vehicles and Classes 2, 3, and 9 vehicles.
2. Wherever a bimodal speed distribution occurred, a cut-off value of speed was utilized. The selection of a speed cut-off value was necessary to eliminate the effects of traffic congestion from the dataset before any statistical analysis could be performed. The cut-off value was determined on a case by case basis depending on the vehicle speed distribution. For example, in Figs. 2(a and b) and 3(a and b), a cut-off value of 45 mi/h (72.45 km/h) was chosen for the raw data in this particular case, below which all data points were eliminated.

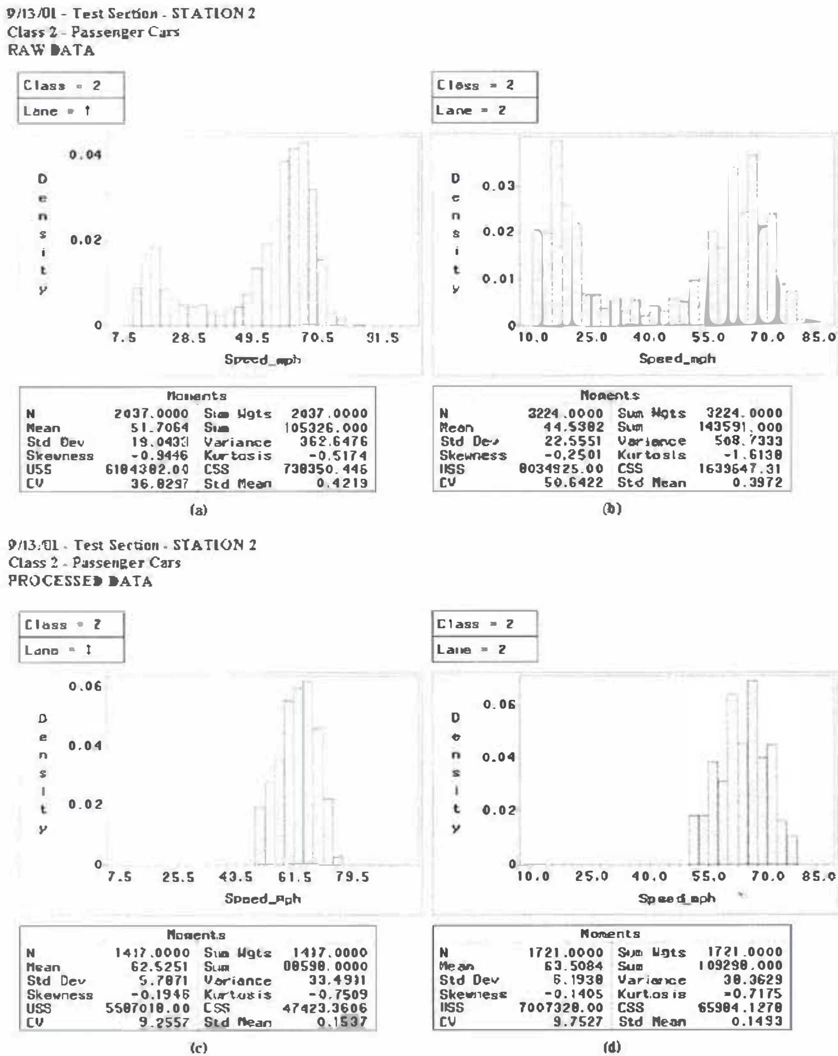

Fig. 2. Sample speed distribution of passenger cars [Source: Interstate-90, CMS Study Data]

The outliers ($\bar{x}\pm2s$) were eliminated in iterations. An example of processed data for Station 2, passenger cars, is presented in Figs. 2(c and d) and 3(c and d). Similar procedures were followed for the speed distributions for the other types of vehicle classes: 3, 9, and all vehicles.

Tests of Significance

The effectiveness of the three CMS message types on vehicle speeds through the work zone was the primary focus of the research. Reductions in vehicular speeds were determined by cal-

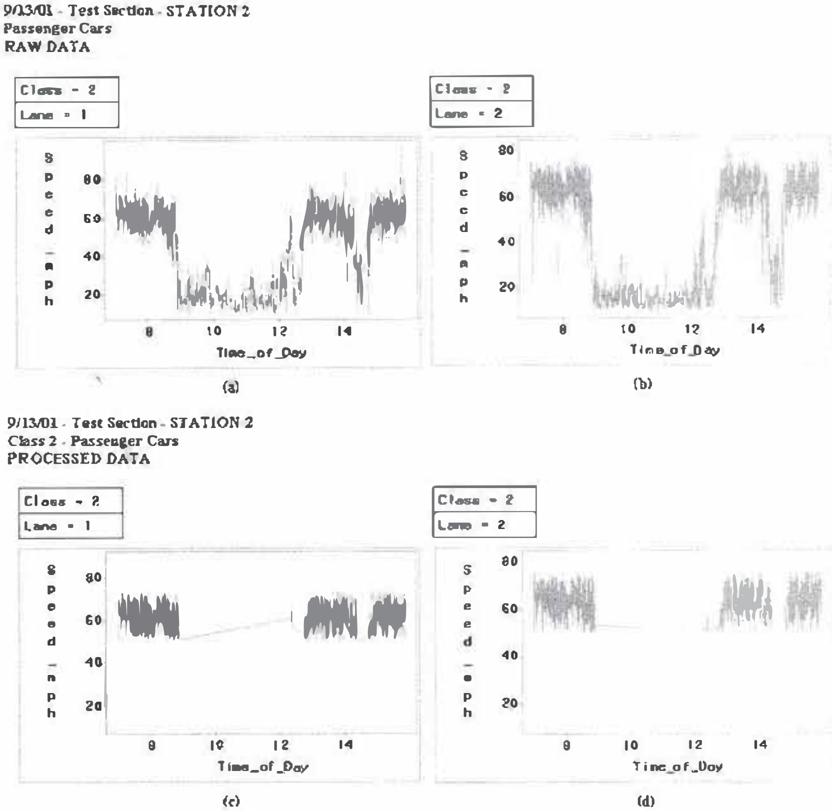

Fig. 3. Sample line plots of vehicle speeds (passenger cars) [Source: Interstate-90, CMS Study Data]

culating the differences in vehicle speeds between Stations 1 and 2. The true effectiveness of the intervention, thus, can be calculated by the difference between the speeds at Stations 1 and 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 were 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 ($n \gg 30$), z-tests were performed to test for any significant effect of the different messages. 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 tested are as

$$H_0: (\mu_{C1} - \mu_{C2}) \leq (\mu_{T1} - \mu_{T2}) \qquad (1)$$

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

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.

Z-Value Test Statistic

As the sample size in each of the tests were much greater than 30 and as the speeds were approximately normally distributed [Figs. 3(c and d)], the following z-statistic was used to test the null hypothesis: H_0:

Table 1. Interstate-90 CMS_1 Speed Statistics Summary

Vehicle class	Section type	Station 1			Station 2							
		n	$\bar{X}$	s	n	$\bar{X}$	s	$\Delta\bar{X}_T-\Delta\bar{X}_C$	s_T-s_C	Z-value	p-value	Effectiveness? $\alpha=0.05$
						Driving lane						
All vehicles	Test	5,492	65.30	4.91	2,719	60.90	5.97	−0.21	−0.62	−0.93	0.824	No
	Control	1,526	66.59	3.91	1,328	61.98	5.59					
PC	Test	2,727	66.68	4.38	1,417	62.53	5.79	0.46	−0.44	−1.44	0.925	No
	Control	471	68.99	3.91	430	64.30	5.76					
2A-4T	Test	392	65.23	4.61	181	62.12	5.43	−0.54	−0.47	0.04	0.484	No
	Control	140	67.54	3.49	100	64.46	4.78					
5A-ST	Test	446	64.47	3.62	147	59.83	5.00	1.58	−0.20	0.94	0.174	No
	Control	283	66.21	3.17	169	62.14	4.75					
						Passing lane						
All vehicles	Test	4,733	68.01	5.75	2,921	62.14	6.74	−3.07	−1.23	−8.34	1.000	No
	Control	424	70.93	4.81	846	61.99	7.03					
PC	Test	3,158	69.24	4.72	1,721	63.51	6.19	−1.70	−2.01	−3.49	1.000	No
	Control	223	72.44	3.35	296	65.01	6.83					
2A-4T	Test	413	68.16	4.99	266	63.42	6.01	−2.01	−0.08	−2.40	0.992	No
	Control	53	71.51	3.48	76	64.76	4.58					
5A-ST	Test	306	65.48	4.44	211	60.35	5.74	−3.65	−1.23	−5.15	1.000	No
	Control	37	69.49	2.23	153	60.71	4.76					

Note: Entries contain remaining data after outliers were deleted. CMS_1=*RIGHT|LANE|CLOSED~KEEP|LEFT* [alternating phases]; n=number of observations (vehicles); $\bar{X}$=mean vehicle speed (mi/h); s=standard deviation (mi/h); $\Delta\bar{X}_t$=difference between the test section Station 1 and Station 2 mean speeds (mi/h); $\Delta\bar{X}_c$=difference between the control section Station 1 and Station 2 mean speeds (mi/h); s_t=difference between the test section Station 1 and Station 2 standard deviations (mi/h); s_c=difference between the control section Station 1 and Station 2 standard deviations (mi/h); and 1.0 mi/h=1.61 km/h.

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

where z_{ijk}=test statistic for CMS (i), vehicle class (j), and lane type (k); i=designation for CMS type: 1=CMS_1, 2=CMS_2, and 3=CMS_3; 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 and 2=passing lane; $\bar{X}_{T_n}$=mean vehicle speed for a test section at Station n; $\bar{X}_{C_n}$=mean vehicle speed for a control section at Station n; $s_{T_n}^2$=variance of vehicle speeds for a test section at Station n; $s_{C_n}^2$=variance of vehicle speeds for a control section at Station n; n_{T_n}=number of vehicles measured in a test section at Station n; and n_{C_n}=number of vehicles measured in a control section at Station n.

The level of significance selected for hypothesis testing was $\alpha=0.05$, for which the critical value of the test statistic is, $z_{ijk}=1.645$ for one sided tests. In other words, if $z_{ijk}\leq 1.645$, the CMS message tested is not significantly effective in reducing speeds. The values of z_{ijk} statistics for all three CMS messages, for the three vehicle classes and for all vehicles, are given in Tables 1–3 for each of the two lane types. The null hypothesis is rejected if the z-value is less than 1.645.

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:

$$p\text{-value}=P(Z>z_c) \tag{4}$$

where z_c=computed value of the test statistic.

p-values for each of the tests are given in Tables 1–3. 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 Changeable Message Sign Messages

The three CMS messages tested in this study resulted in the following effectiveness: **CMS_1:*RIGHT|LANE|CLOSED ~KEEP|LEFT*** was not effective in reducing speeds in either the driving or the passing lane. Statistical results are summarized Table 1.

CMS_2:*WORK ZONE|MAX SPEED|45 MPH~BE| PREPARED|TO STOP* was effective for both driving and passing lanes for all vehicle classes. In the driving lane, speeds were reduced significantly, from 3.3 to 6.4 mi/h (from 5.3 to 10.3 km/h) (Table 2). Reduction in speeds in the driving lane for: (1) PCs was 5.3 mi/h (8.5 km/h); (2) for 2A-4T vehicles was 6.4 mi/h (10.3 km/h); and (3) for 5A-ST vehicles was 3.3 mi/h (5.3 km/h). Speed reductions also occurred in the passing lane, from 3.7 to 6.7 mi/h (from 5.9 to 10.8 km/h). In the passing lane, speed reductions: (1) for PCs were by 5.8 mi/h (9.3 km/h), (2) for 2A-4T vehicles, speeds reduced by 6.7 mi/h (10.8 km/h), and (3) for 5A-ST vehicles by 3.7 mi/h (5.9 km/h). p-values, for the driving and passing lane, of the all-vehicle class were less than 0.0001, much below 0.05. Thus the CMS_2 intervention is

Table 2. Interstate-90 CMS_2 Speed 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	$\Delta\bar{X}_T-\Delta\bar{X}_C$	s_T-s_C	Z-value	P-value	Effectiveness? $\alpha=0.05$
						Driving lane						
All vehicles	Test	5,910	68.37	3.76	2,796	59.12	6.57	4.64	1.13	20.17	<0.001	Yes
	Control	1,526	66.59	3.91	1,328	61.98	5.59					
PC	Test	2,737	70.13	3.04	1,574	60.13	6.59	5.31	1.70	14.16	<0.001	Yes
	Control	471	68.99	3.91	430	64.30	5.76					
2A-4T	Test	476	69.06	3.13	281	59.57	6.03	6.44	1.71	9.18	<0.001	Yes
	Control	140	67.54	3.40	100	64.46	4.78					
5A-5T	Test	872	66.43	2.71	257	59.02	5.39	3.34	1.10	6.20	<0.001	Yes
	Control	283	66.21	3.17	169	62.14	4.75					
						Passing lane						
All vehicles	Test	2,591	72.45	3.32	5,669	58.27	6.42	5.24	0.88	14.85	<0.001	Yes
	Control	424	70.93	3.81	846	61.99	7.03					
PC	Test	1,829	72.77	2.91	3,265	59.57	6.70	5.77	0.34	12.13	<0.001	Yes
	Control	223	72.44	3.35	206	65.01	6.83					
2A-4T	Test	249	72.43	2.98	543	58.94	6.08	6.74	2.00	8.64	<0.001	Yes
	Control	53	71.51	3.48	76	64.76	4.58					
5A-5T	Test	125	69.02	2.93	837	56.51	5.63	3.73	0.17	5.98	<0.001	Yes
	Control	37	69.49	2.23	153	60.71	4.76					

Note: Entries contain remaining data after outliers were deleted. CMS_2= *WORK ZONE* | *MAX SPEED* | *45 MPH* – *BE* | *PREPARED* | *TO STOP* [alternating phases]; n=number of observations (vehicles); $\bar{X}$=mean vehicle speed (mi/h); s=standard deviation (mi/h); $\Delta\bar{X}_T$=difference between the test section Station 1 and Station 2 mean speeds (mi/h); $\Delta\bar{X}_C$=difference between the control section Station 1 and Station 2 mean speeds (mi/h); s_T=difference between the test section Station 1 and Station 2 standard deviations (mi/h); s_C=difference between the control section Station 1 and Station 2 standard deviations (mi/h); and 1.0 mi/h=1.61 km/h.

Table 3. Interstate-90 CMS_1 Speed 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	$\Delta\bar{X}_T-\Delta\bar{X}_C$	s_T-s_C	Z-value	P-value	Effectiveness? $\alpha=0.05$
						Driving lane						
All vehicles	Test	12,884	68.79	3.79	10,864	67.45	4.04	1.11	0.31	5.90	<0.001	Yes
	Control	849	67.68	3.74	845	67.44	3.68					
PC	Test	6,658	70.42	3.28	4,207	68.89	3.49	−1.30	0.18	−0.57	0.715	No
	Control	184	71.11	3.79	167	69.34	3.82					
2A-4T	Test	1,060	69.23	3.65	737	68.11	3.78	−0.23	−0.74	0.72	0.237	No
	Control	53	69.36	2.91	57	68.72	3.79					
5A-5T	Test	2,011	66.85	2.93	1,258	66.16	2.81	0.65	−0.22	2.71	0.003	Yes
	Control	265	67.12	2.50	268	67.09	2.59					
						Passing lane						
All vehicles	Test	6,625	72.22	3.21	4,887	71.65	5.48	−1.69	−1.52	−2.70	0.997	No
	Control	153	71.30	3.81	218	69.04	7.60					
PC	Test	4,043	72.61	2.88	3,146	72.83	3.10	−0.52	0.27	−0.88	0.810	No
	Control	70	73.54	3.54	83	73.24	3.69					
2A-4T	Test	595	72.58	2.88	431	72.29	3.34	1.02	1.14	0.92	0.179	No
	Control	18	72.56	3.70	21	73.29	3.02					
5A-5T	Test	360	69.05	2.55	233	68.87	3.11	−0.96	−0.21	−1.40	0.932	No
	Control	21	69.50	1.79	30	68.37	2.55					

Note: Entries contain remaining data after outliers were deleted. CMS_1= *LEFT* | *LANE* | *CLOSED* – *KEEP RIGHT* [alternating phases]; n=number of observations (vehicles); $\bar{X}$=mean vehicle speed (mi/h); s=standard deviation (mi/h); $\Delta\bar{X}_T$=difference between the test section Station 1 and Station 2 mean speeds (mi/h); $\Delta\bar{X}_C$=difference between the control section Station 1 and Station 2 mean speeds (mi/h); s_T=difference between the test section Station 1 and Station 2 standard deviations (mi/h); s_C=difference between the control section Station 1 and Station 2 standard deviations (mi/h); and 1.0 mi/h=1.61 km/h.

effective in reducing vehicle speeds in both the driving and the passing lanes. Although significant speed reductions occurred, for all vehicle classes, the CMS_2: *WORK ZONE|MAX SPEED|45 MPH ~ BE|PREPARED|TO STOP*, increased the standard deviation of speeds by 1.1–1.7 mi/h (1.8–2.7 km/h) in the driving lane. In the passing lane, however, the increase in standard deviation was 0.2–2.0 mi/h (0.3–3.2 km/h). Statistical results are summarized in Table 2.

CMS_3: ***LEFT|LANE|CLOSED ~ KEEP|RIGHT*** was effective in reducing speeds in the driving lane for: (1) all vehicles by 1.1 mi/h (1.8 km/h) and (2) 5A-ST vehicles by 0.65 mi/h (1.1 km/h) over the entire vehicle population. No speed reductions occurred in the passing lane and therefore CMS_3 is not effective for the passing lane situation. The standard deviations between the test and control sections show an increase in the driving lane by 0.31 mi/h (0.50 km/h) for all vehicles, and a decrease of 0.22 mph (0.35 km/h) for 5A-ST vehicles. Statistical results are summarized in Table 3.

Summary and Conclusions

The results of this research show that, if properly selected, CMS messages can be significantly effective in reducing speeds of all classes of vehicles, in highway work zones. Of the three CMS types used in this research, CMS_2: "*WORK ZONE|MAX SPEED|45 MPH ~ BE|PREPARED|TO STOP*" was very effective in reducing vehicle speeds. It reduced vehicle speeds by 3.3–6.4 mi/h (5.3–10.3 km/h) in the driving lane and 3.7–6.7 mi/h (5.9–10.8 km/h) in the passing lane. This CMS_2 message, however, increased the speed standard deviation from approximately 1 to 2 mi/h (from 1.61 to 3.22 km/h). The other two CMS messages: (1) *RIGHT|LANE|CLOSED ~ KEEP|LEFT* and (2) *LEFT|LANE|CLOSED ~ KEEP|RIGHT* were not effective.

The speed reductions achieved in this study are quite considerable due to the fact that the vehicle population of the data set is quite large and these reductions in speed are experienced over the entire population of vehicles. This research, using field experiments, has proven that CMS messages, if properly selected and implemented can be effective in reducing vehicle speeds as well as the standard deviation of speed, both highly sought-after objectives to enhancing work zone safety.

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