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Title: **Long-Term Effectiveness of Speed Monitoring Displays in Work Zones on Rural Interstate Highways**

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ABSTRACT

The long-term effectiveness of Speed Monitoring Displays (SMDs) was evaluated as part of the Midwest States Smart Work Zone Deployment Initiative, a pooled-fund study sponsored by Iowa, Kansas, Missouri, Nebraska, and the Federal Highway Administration. Three SMDs were deployed for a five-week period along a 2.7-mile section between two work zones on I-80 near Lincoln, Nebraska. The mean, 85th percentile, and standard deviation of vehicle speeds, and the percentage of vehicles complying with the 55-mph speed limit and the 60 and 65-mph speed thresholds were used as measures of effectiveness (MOEs). The SMDs were found to be effective in lowering speeds, increasing the uniformity of speeds, and increasing speed-limit compliance over the five-week period. Statistically significant improvements in speed parameters and speed-limit compliance were observed at the measurement points downstream of the first two SMDs. The improvement in standard deviation and some compliance percentages were not statistically significant at the third SMD. Greater speed reductions and compliance increases were observed for passenger cars than for other vehicles. The combined long-term effect of the three SMDs was also assessed using spatially aggregated MOEs. Statistically significant improvement was found in terms of both speed reduction and speed-limit compliance. One week after the removal of the SMDs, there were still statistically significant speed-reductions and compliance increases, although they were less than during the deployment.
key words: work zones, speed control, speed monitoring display

INTRODUCTION

Speeding in work zone areas continues to be one of the major safety concerns on many of our roads, particularly on high-speed rural interstate highways. Excessive speed is among the major contributing factors most often reported for work zone accidents (*1,2*). To address this problem, various speed control strategies ranging from enforcement by patrol vehicles (*3,4*) to radar equipped speed monitoring devices (*5,6*) and more sophisticated changeable message sign systems (*7,8,9*) have been studied and field-tested. The speed monitoring display (SMD) developed in the late 1970s is one of the promising technologies that have been successfully applied both in the U.S. and abroad. An SMD informs drivers of their speeds and thereby encourages them to slow down if they are traveling above the speed limit. The objective of the system is to reduce the speed of traffic and increase speed limit compliance. Although some early studies (*10*) found it ineffective, the use of the SMD technology and the research directed to the evaluation of its effectiveness has grown in recent years.

Most recent studies (*5,6,11,12,13*) consistently found that vehicle speeds can be reduced by SMDs. For example, a recent study (*12*) evaluating the effectiveness of a SMD at a work zone on I-80 in Nebraska, found that the 85th-percentile speed, upper limit of the pace, and mean of the highest 15 percent of speeds were reduced significantly ($\alpha = 0.05$) by about 5 mph, which lowered the values of these parameters to, or below, the speed limit. However, the performance of the speed monitoring display had only been monitored during a relatively short period of time (i.e., less than a day), and over a relatively short length of roadway (i.e., 750 feet). Thus, the time period and the spatial extent, for which its effectiveness could be sustained, remained unknown.

A comparative study of photo-radar and SMD conducted in California (*6*) concluded that both devices significantly (i.e., by 7-8 km/h) reduced speed. They also found that supplementing an SMD with police enforcement can further increase the effectiveness. Another recent study (*13*) found that SMDs used at rural high speed temporary work zones can be expected to reduce vehicle speeds by about 5 mph. They also concluded that the speed reduction effect of SMDs is about 2 to 3 mph greater than that of the radar drone and speed advisory signs. But, the temporal and spatial effects of the devices were not evaluated.

OBJECTIVE

The primary objective of the present study is to evaluate the long-term effectiveness of SMDs in long-term work zones on rural interstate highways. To achieve this goal, three SMDs were deployed in a work zone area on I-80 near Lincoln, Nebraska. The effectiveness of the system was studied over a period of five weeks.

The SpeedGuard™ radar speed reporting system was the SMD used in this study. It is a portable, self-contained trailer unit, which is shown in Figure 1. It is equipped with radar to measure the speeds of approaching vehicles. The vehicle speeds are displayed on a panel with 24-inch LED numerals. The message YOUR SPEED is mounted on the trailer beneath the variable speed display. A speed limit sign is mounted on a rack above the display.

The SMD also featured a "Work Zone Alert", which simulates a camera taking pictures, and a "Violator Alert", which sounds an alarm if approaching speeds are above a preset threshold. However, these features were not activated during the study period.

STUDY SITE

The three SMDs were deployed along an approximately 2.7-mile section of eastbound I-80 near Lincoln, Nebraska. The section operated as a 4-lane divided interstate highway. It was located between two relatively long sections of the interstate with head-to-head operation (i.e., one roadway was closed for reconstruction and the other operated as a two-lane, two-way roadway). The location of the study area is shown in Figure 2.

Drivers often traveling at a relatively low speed for several miles in the head-to-head section tended to accelerate to a speed well above the 55-mph speed limit as they entered the two-lane section of the study area. Many of the drivers considered it as a good opportunity to pass slower moving vehicles and position themselves farther ahead before merging again into head-to-head operation. This setting created a situation with very low speed-limit compliance, which needed some type of speed control.

The average daily traffic volume on this section of I-80 was approximately 38,000 vehicles per day, of which 22 percent was commuting traffic. The truck percentage was 21 percent. The normal speed limit on I-80 is 75 mph, but the speed limit in the study area was 55 mph, because it was located between two work zones. The two work zones were for an interstate reconstruction project.

The traffic control plan within the study area is shown in Figure 3. The following sequence of signs was located on each side of the roadway:

1. SPEED LIMIT 55 sign with FINES DOUBLE sign plate about 13,000 feet before the lane closure taper;
2. SPEED LIMIT 55 sign with FINES DOUBLE sign plate about 9,000 feet before the lane closure taper;
3. LEFT LANE CLOSED AHEAD sign about 5,500 feet before the lane closure taper;

4. SPEED LIMIT 55 sign with FINES DOUBLE sign plate about 3,000 feet before the lane closure taper;
5. RIGHT LANE CLOSED ½ MILE sign about 2,750 feet before the lane closure taper;
6. Symbolic “lane reduction on the left” transition sign about 1,100 feet before the lane closure taper; and
7. SPEED LIMIT 55 sign with FINES DOUBLE sign plate about 625 feet before the lane closure taper.

In addition to the signs, there were two flashing arrow panels on the right shoulder. One arrow panel was located about 3,100 feet in advance of the lane closure taper, and the other arrow panel was located at the beginning of the lane closure taper. The lane closure taper was 900 feet long. It was delineated by reflectorized plastic drums spaced at 50-foot intervals and monodirectional yellow raised pavement markers at 5-foot centers.

To reduce speed and increase speed-limit compliance, the three SMDs were strategically deployed along the 2.7-mile road section. To identify the best locations for the SMDs, a speed profile was determined first. The profile shown in Figure 4 indicates the mean speed of vehicles observed at six points along the study area. It can be seen that vehicles entering the study area at a relatively low speed quickly accelerated and reached a mean speed higher than 60 mph within less than one-half mile. The lower entering speed was a consequence of the narrow lane width and the 45-mph advisory speed limit in the median crossover. To reduce the intensity of vehicle acceleration in this road section, the first SMD was deployed about 1,150 feet downstream of the crossover, on the left side of the road under the bridge. The second SMD was deployed about 1,000 feet upstream of the location where the highest mean speed of 61.6 mph was observed. The third SMD was deployed at the second arrow board to reduce the speed of vehicles approaching the lane closure in advance of the median crossover.

DATA COLLECTION

Traffic speeds were measured once before deployment, five times during the five-week deployment, and once after removal of the SMDs. The before studies were conducted four days before the SMDs were deployed. The SMDs were operated continuously for the next five weeks during which traffic speeds were measured once each week at one-week intervals. Finally, one week after the removal of the SMDs another set of speed measurements was conducted to determine if there were any residual speed-reduction effects of the system. The before and after studies took place on the same day of the week, during approximately the same time period of the day, and under very similar traffic and environmental conditions (i.e., comparable traffic volumes, dry weather and pavement). In addition to vehicle speeds, volume and truck percentages were also recorded.

The speed data were collected with ProLaser III Lidar units, which are capable of measuring the speed of vehicles with an accuracy of ±1 mph. Two of these units were used by two survey crews. Each unit was calibrated before and after data collection. As illustrated on Figure 5, vehicle speeds were measured at four locations: (1) upstream of the first SMD where vehicles entered the study area, (2) approximately 1,000 feet downstream of the first SMD, (3) approximately 1,000 ft downstream of the second SMD, and (4) at the beginning of the lane closure taper where vehicles passed the third SMD. Throughout the study, the same observers collected speed data at each location. To minimize the cosine-error of the speed measurements, they positioned themselves as close to the side of the roadway as possible while making every effort to remain inconspicuous. The angle between the line of traffic and the laser beam was less than 3 degrees resulting in a negligible cosine-error of less than 0.1 mph at each measurement location. Speeds were measured from vantage points behind the vehicles.

Since vehicle speeds during congested flow conditions are primarily influenced by the density of traffic, the speed data were collected only during uncongested flow conditions. For the same reason, only the speeds of vehicles with at least 5-second headways were measured. Also, at data collection point 3 shown in Figure 5, speed data were taken only at times when the on-ramp was empty (i.e., entering vehicles did not affect the speed and lane choice of vehicles traveling on the highway). Thus, the collected data include only desired speeds which were unaffected by any sort of vehicle interaction.

DATA ANALYSIS

The measures of effectiveness (MOEs) used to evaluate the SMDs included six speed parameters. They were determined from the speed samples collected at each measurement location before, during, and after the period when the SMDs were deployed. The six MOEs were:

- mean speed,
- standard deviation,
- 85^{th}-percentile speed,
- percentage complying with the speed limit, and
- percentage complying with the speed limit plus 5 mph.
- percentage complying with the speed limit plus 10 mph.

The statistical significance of the differences in these MOEs corresponding to the periods before, during and after the use of the SMDs was determined. The t-test was used to evaluate the differences in mean speeds. The binomial proportion test was used to evaluate the statistical significance of differences in the 85^{th}-percentile speeds, and the percentages complying with the speed limit and the speed thresholds of 5 and 10 mph above the speed limit. The F-test was used to check for statistically significant differences in the standard deviations of the speed distribution.

RESULTS

The MOE-profiles shown in Figure 6 correspond to the data collection periods before the deployment, during the first and last week of the operation, and after the removal of the SMDs. The profiles indicate an improvement in all MOEs at each observation point downstream of the SMDs during their deployment. The improvement was about 3 to 4-mph reduction in mean speed, 2 to 7-mph reduction in 85^{th} percentile speed, and about 20 to 40-point increase in the percentage of vehicles complying with the speed limit and the 60-mph speed threshold. As expected, much smaller changes were observed upstream of the first SMD.

Tables 1,2, and 3 summarize the MOEs calculated for both passenger cars and other vehicles at three measurement points downstream of the SMDs. For passenger cars the mean and 85^{th} percentile speeds were significantly lower (α=0.05), and with a few exceptions the three compliance percentages were significantly higher (α=0.05) at almost all locations during the operation, and also one week after the removal of the system. The standard deviation was also reduced, although the reduction was not statistically significant at the third SMD. The improvement in the MOEs for other vehicles is similar to those fore passenger cars, although many of the changes were not statistically significant, particularly at the third SMD.

To characterize the overall performance of the system, a set of spatially aggregated speed parameters were calculated for each study time by combining the speed data collected at all four locations. Two types of analyses were performed using these aggregated parameters.

First, their temporal variation was evaluated as shown in Figure 7. The graphs indicate persistent reductions of approximately 3 mph in mean speed, and 4 mph in the 85th percentile speed for passenger cars. The same tendency with approximately 2-mph reductions for both mean and 85th percentile speeds can be observed for other vehicles. The standard deviation of both passenger cars and other vehicles were also reduced during SMD operation, although the reduction for passenger cars was larger. The compliance with the speed limit and other two speed thresholds increased with approximately 10 to 20 percent for passenger cars during the use of SMDs. Similar improvement can be observed for other vehicles with respect to their compliance with the speed limit (i.e., 55 mph) and the 5-mph speed threshold above the speed limit (i.e., 60 mph). The compliance with the speed threshold of 10 mph above the speed limit (i.e., 65 mph) was much smaller than it was for passenger cars. However, it should be noted that this was also a consequence of their typically lower speed (i.e. their 85th percentile speed was 3 mph below the 65-mph speed threshold before the SMDs were deployed).

In the second analysis, the statistical significance of the improvements and the potential residual speed-reduction effect of the system were assessed using three sets of MOEs. They were calculated as the differences in the spatially aggregated speed parameters.

The first set of MOEs expressed how drivers behavior changed after 1, 2, 3, 4, and 5 weeks of SMD operation relative to the time period before they were deployed. The results shown in Table 5 indicate that a statistically significant (α=0.05) improvement was observed for all MOEs in the case of passenger cars. The same tendencies were observed for other vehicles, although the reduction in standard deviation during the 1st week, and the increase in the 65-mph compliance percentages on the 2nd and 3rd weeks were lower than in the other weeks of SMD deployment, and they were not statistically significant (α=0.05).

The second set of MOEs expressed how drivers behavior changed one week after the SMDs were removed compared to the last week when they were in operation. The results shown in column 1 of Table 5 indicate that a statistically significant (α=0.05) degradation was observed for all MOEs in the case of both passenger cars and other vehicles. However, it should be noted that none of the MOEs returned to the level observed before the deployment of the SMDs, which indicates that the system possesses some residual effects in vehicle-speed reduction.

To assess the significance of the residual effect of the system, a third set of MOEs were calculated. They expressed how driver behavior differed between the periods before the deployment and one week after the removal of the SMDs. The results shown in the second column of Table 5 indicate that a statistically significant improvement was observed for all MOEs in the case of passenger cars. Similar tendencies were observed for other vehicles, although the reduction in standard deviation, and the increase in the 60-mph compliance percentage were not statistically significant.

Previous research (*14*) suggests that lower speed reduces the frequency of fatal and injury crashes. Although none of the studies cited examined the relationship between speed and safety in work zones, a review of several international studies indicates that perhaps every 1-mph reduction in mean speed may reduce injury crashes by about 5 percent (*14*). If this relationship is applicable to work zones, one might expect the speed reductions associated with SMDs to result in a 15 to 20 percent reduction in injury crashes.

CONCLUSIONS

The SMDs were found to be effective in lowering speeds and increasing the uniformity of speeds over a period of five weeks.

Statistically significant (α=0.05) improvements in speed parameters (i.e., mean, 85th percentile speed, and standard deviation) and speed-limit compliance were observed at the measurement points downstream of the first two SMDs. The improvement in standard deviation and a some compliance percentages were not statistically significant at the third SMD. Greater speed reductions and compliance increases were observed for passenger cars than for other vehicles. Depending on the measurement location, the improvements were 3 to 4 mph for mean speed, 2 to 7 mph for 85th percentile speed, and 20 to 40 point in the percentage of vehicles complying with the 55-mph speed limit and the 60-mph speed threshold.

The combined long-term effectiveness of the three SMDs was assessed using spatially aggregated speed parameters. Persistent reductions of approximately 3 mph in mean speeds, and 4 mph in the 85th percentile speeds were observed for passenger cars over the 5-week period of SMD operations. A 2-mph reduction in both mean and 85th percentile speed was observed for other vehicles. The spatially averaged speed-limit compliance percentages increased with approximately 10 to 20 points for both passenger cars and other vehicles.

After removing the SMDs, the mean and 85th percentile speeds increased, and the speed-limit compliance percentages decreased. Although these changes were statistically significant (α=0.05), they did not reach the levels observed before the deployment of the SMDs. In fact, almost all speed parameters and compliance percentages measured after the removal of the SMDs were significantly (α=0.05) different than those measured before the deployment of the SMDs.

Thus, besides their long-term (i.e., five week) effectiveness, the SMDs also had some residual effect in terms of speed reduction and compliance improvement.

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DISCLAIMER

The contents of this paper reflect the viewers of the authors who are solely responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Iowa Department of Transportation, Kansas Department of Transportation, Missouri Department of Transportation, Nebraska Department of Roads, or Federal Highway Administration. The paper does not constitute a standard, specification, or regulation.

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TABLE 1: Measurement Location #2 1000 ft Downstream of the First SMD

Speed Parameter	BEFORE	DURING					AFTER
		week 1	week 2	week 3	week 4	week 5	
Passenger Cars							
Sample Size	253	242	205	136	264	232	224
Mean Speed (mph)	61.0	56.4	57.2	57.8	57.6	56.3	59.7
Standard Deviation (mph)	5.33	4.03	4.00	3.76	3.70	3.68	4.21
85^{th}-Percentile Speed (mph)	66	60.0	62.0	61.0	62.0	60.0	64.0
Compliance with Speed Limit (%)	16.60	44.63	36.10	24.26	30.68	45.26	16.07
Compliance with SL + 5 mph (%)	45.85	85.95	80.00	82.35	77.65	85.78	57.14
Compliance with SL + 10 mph (%)	80.24	97.52	97.54	96.32	98.86	98.28	90.52
Trucks							
Sample Size	109	93	92	106	69	83	108
Mean Speed (mph)	58.0	55.2	56.2	55.2	55.5	55.7	56.3
Standard Deviation (mph)	4.22	3.95	3.86	3.68	3.37	3.72	4.43
85^{th}-Percentile Speed (mph)	62	59	60	59	58	59	61
Compliance with Speed Limit (%)	32.11	53.76	47.83	56.60	53.62	49.40	43.52
Compliance with SL + 5 mph (%)	71.56	93.55	88.04	93.40	89.86	89.16	79.63
Compliance with SL + 10 mph (%)	94.50	98.92	98.91	99.06	100.00	100.00	97.22

Difference from BEFORE value is statistically not significant (α = 0.05).

TABLE 2: Measurement Location #3 1000 ft Downstream of the Second SMD

Speed Parameter	BEFORE	DURING					AFTER
		week 1	week 2	week 3	week 4	week 5	
				Passenger Cars			
Sample Size	194	212	196	127	189	153	184
Mean Speed (mph)	62.9	58.7	58.2	59.5	58.2	58.1	60.3
Standard Deviation (mph)	4.99	3.88	3.49	4.15	3.54	4.19	4.27
85th-Percentile Speed (mph)	68	63	62	63	62	63	65
Compliance with Speed Limit (%)	3.09	16.98	21.94	14.17	21.69	30.07	10.87
Compliance with SL + 5 mph (%)	38.66	72.17	75.51	62.20	75.66	75.82	56.52
Compliance with SL + 10 mph (%)	68.04	93.87	96.94	89.76	96.83	95.42	85.33
				Trucks			
Sample Size	108	91	101	49	91	97	70
Mean Speed (mph)	60.2	57.9	58.0	57.9	56.8	57.3	59.4
Standard Deviation (mph)	3.64	3.31	3.68	3.31	3.31	2.61	3.84
85th-Percentile Speed (mph)	64	62	62	61	60	60	63
Compliance with Speed Limit (%)	8.33	24.18	24.75	22.45	39.56	26.80	14.29
Compliance with SL + 5 mph (%)	55.56	76.92	80.20	83.67	86.81	91.75	57.14
Compliance with SL + 10 mph (%)	92.59	100.00	96.04	93.88	97.80	98.97	95.71

Difference from BEFORE value is statistically not significant (α = 0.05).

TABLE 3: Measurement Location #4 1000 ft Downstream of the Third SMD

Speed Parameter	BEFORE	DURING					AFTER
		week 1	week 2	week 3	week 4	week 5	
Passenger Cars							
Sample Size	105	110	111	81	121	90	105
Mean Speed (mph)	60.2	57.4	57.8	57.2	57.7	55.2	58.3
Standard Deviation (mph)	4.67	4.47	4.21	4.74	4.82	3.84	4.26
85^{th}-Percentile Speed (mph)	65	62	63	62	63	58	62
Compliance with Speed Limit (%)	14.29	37.27	33.33	38.27	35.54	53.33	26.67
Compliance with SL + 5 mph (%)	56.19	77.27	75.68	80.25	76.03	94.44	70.48
Compliance with SL + 10 mph (%)	87.62	96.36	94.59	92.59	95.04	97.78	96.19
Trucks							
Sample Size	76	69	53	32	42	62	57
Mean Speed (mph)	56.7	54.1	54.7	55.8	55.9	54.2	55.6
Standard Deviation (mph)	3.97	4.34	3.41	3.48	4.50	3.69	3.68
85^{th}-Percentile Speed (mph)	61	58	59	60	58	57	60
Compliance with Speed Limit (%)	36.84	60.87	50.94	50.00	42.86	61.29	43.86
Compliance with SL + 5 mph (%)	81.58	89.86	98.11	90.63	92.86	96.77	94.74
Compliance with SL + 10 mph (%)	100.00	100.00	100.00	100.00	97.62	100.00	100.00

Difference from BEFORE value is statistically not significant (α = 0.05).

TABLE 4 Temporal Variation of Differences in Speed Parameters After SMD Deployed.

SPEED PARAMETER	DIFFERENCE RELATIVE TO BEFORE STUDIES				
	Week 1	Week 2	Week 3	Week 4	Week 5
PASSENGER CARS					
Sample Size (DURING/BEFORE)	718/765	696/765	473/765	759/765	663/765
Mean Speed (mph)	-3.4	-2.7	-2.3	-2.9	-3.7
Standard Deviation (mph)	-0.9	-1.2	-1.0	-1.2	-1.1
85^{th}-Percentile Speed (mph)	-5	-4	-4	-4	-5
Compliance with Speed Limit (%)	21	14	11	15	25
Compliance with SL + 5 mph (%)	26	22	20	24	29
Compliance with SL + 10 mph (%)	13	14	11	15	14
OTHER VEHICLES					
Sample Size	298/397	309/397	264/397	272/397	361/397
Mean Speed (mph)	-2.0	-1.2	-1.7	-1.8	-2.1
Standard Deviation (mph)	-0.2	-0.5	-0.6	-0.6	-0.8
85^{th}-Percentile Speed (mph)	-2	-2	-2	-3	-3
Compliance with Speed Limit (%)	18	9	17	18	18
Compliance with SL + 5 mph (%)	13	12	14	15	18
Compliance with SL + 10 mph (%)	4	2	2	3	4

Difference is not significant (α = 0.05).

TABLE 5 Differences in Speed Parameters Before, During, and After SMD Deployment.

SPEED PARAMETER	AFTER - DURING (LAST WEEK) DIFFERENCE	AFTER - BEFORE DIFFERENCE
PASSENGER CARS		
Sample Size	765/697	663/697
Mean Speed (mph)	2.2	-1.5
Standard Deviation (mph)	0.4	-0.7
85^{th}-Percentile Speed (mph)	2	-3
Compliance with Speed Limit (%)	-18	7
Compliance with SL + 5 mph (%)	-19	10
Compliance with SL + 10 mph (%)	-5	9
OTHER VEHICLES		
Sample Size	397/345	361/345
Mean Speed (mph)	0.8	-1.3
Standard Deviation (mph)	0.9	-0.1
85^{th}-Percentile Speed (mph)	2	-1
Compliance with Speed Limit (%)	-9	9
Compliance with SL + 5 mph (%)	-11	7
Compliance with SL + 10 mph (%)	-2	2

Difference is not significant ($\alpha = 0.05$).

FIGURE 1 SpeedGuard Speed Monitoring Display.

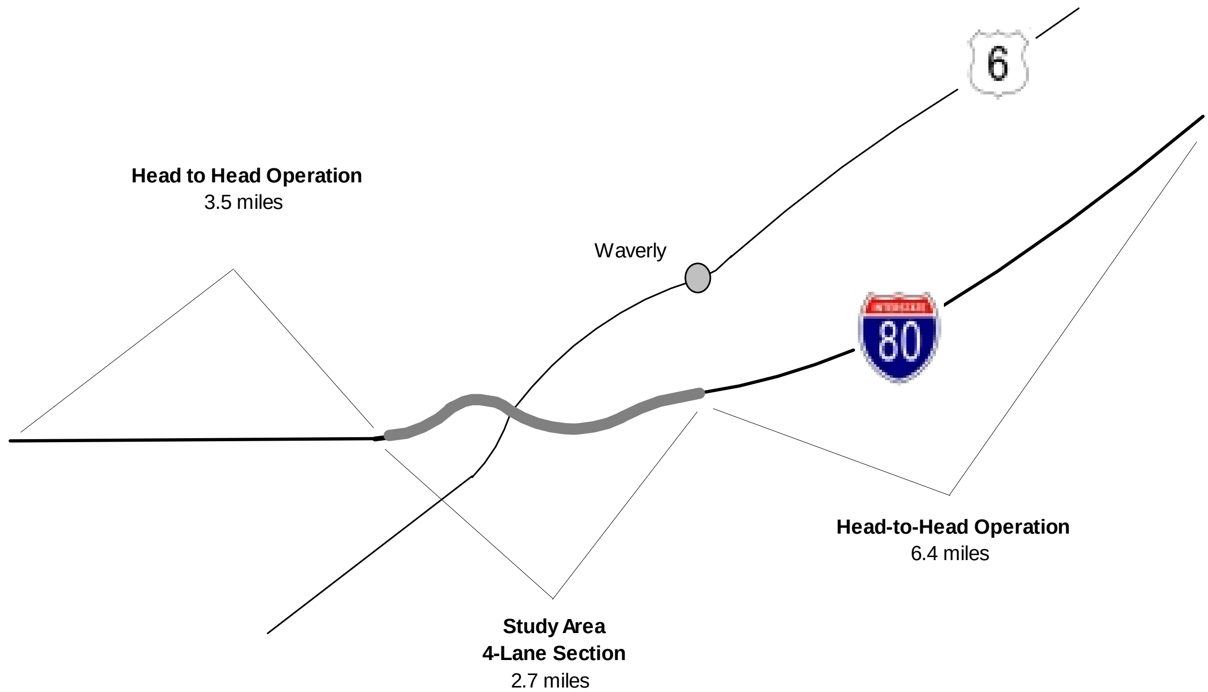

FIGURE 2 Location of the Study Site.

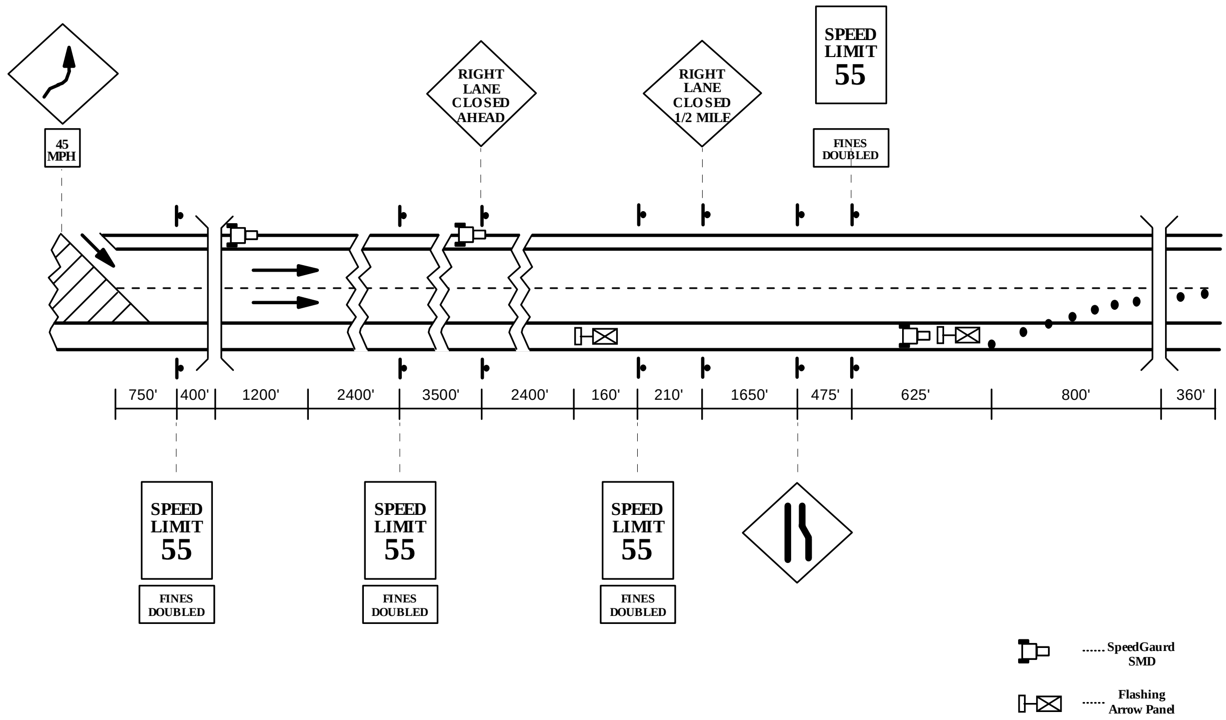

FIGURE 3 Traffic Control Plan at the Study Site.

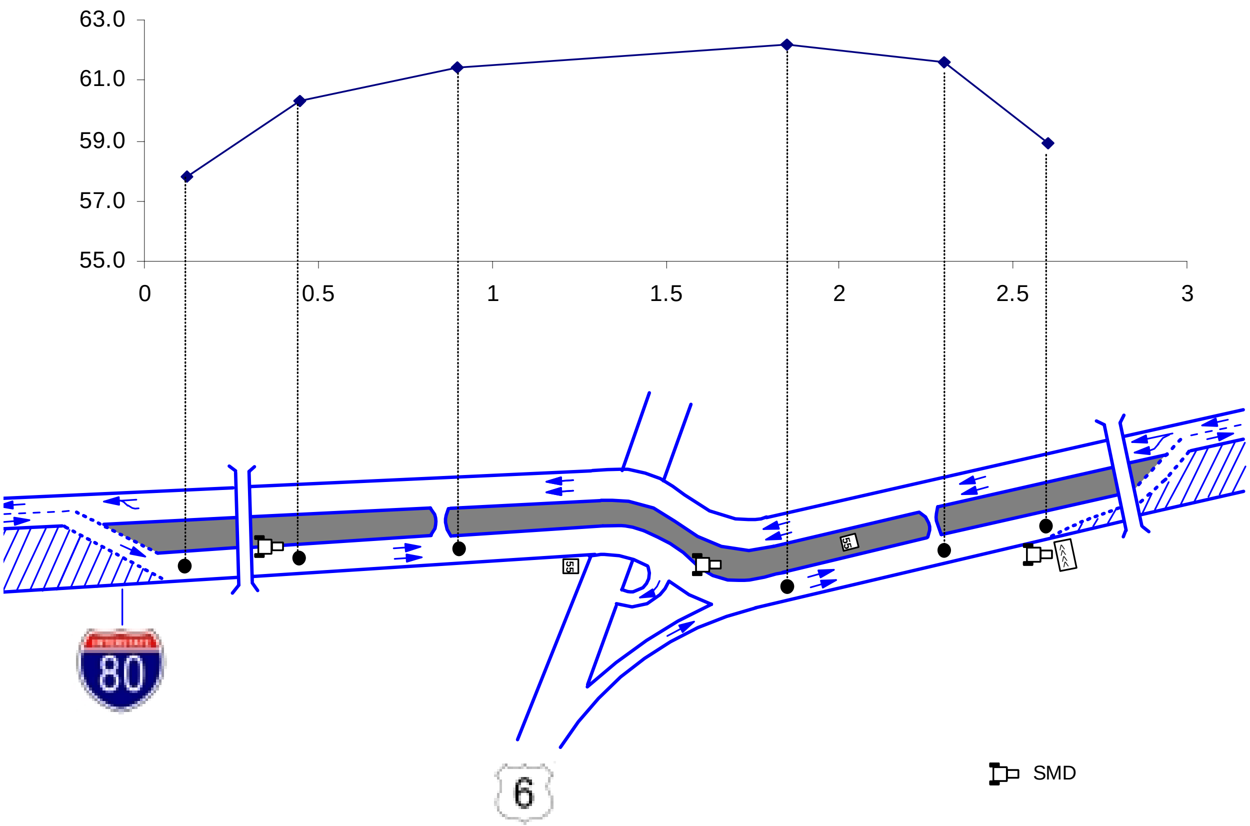

FIGURE 4 Speed Profile Before Deployment of the SMDs.

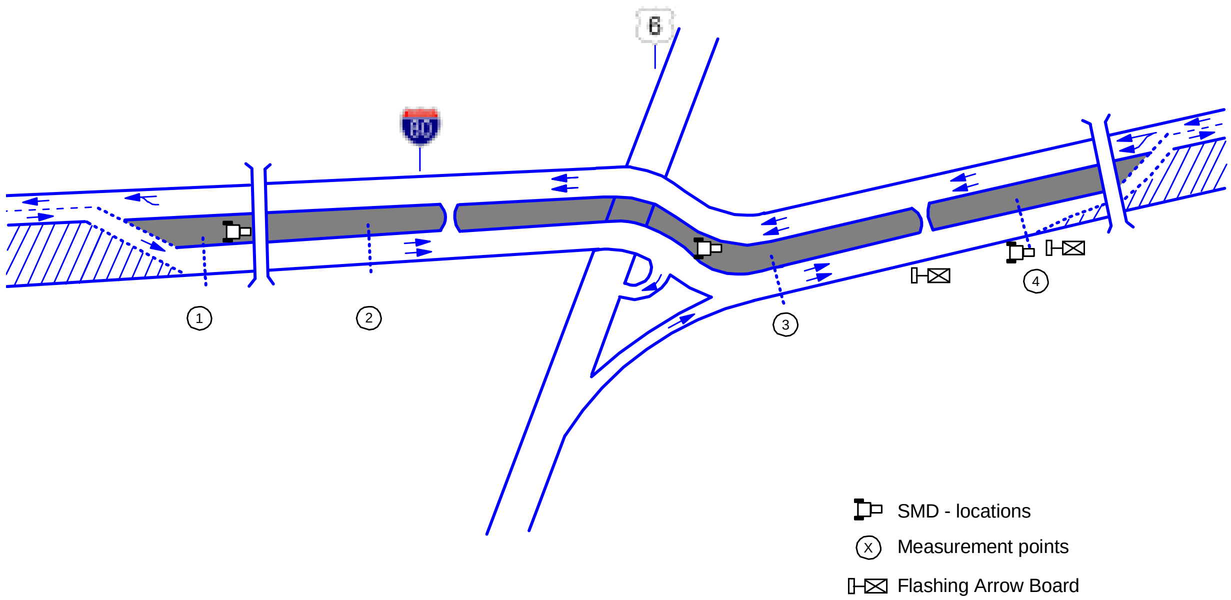

FIGURE 5 Location of Speed Measurements.

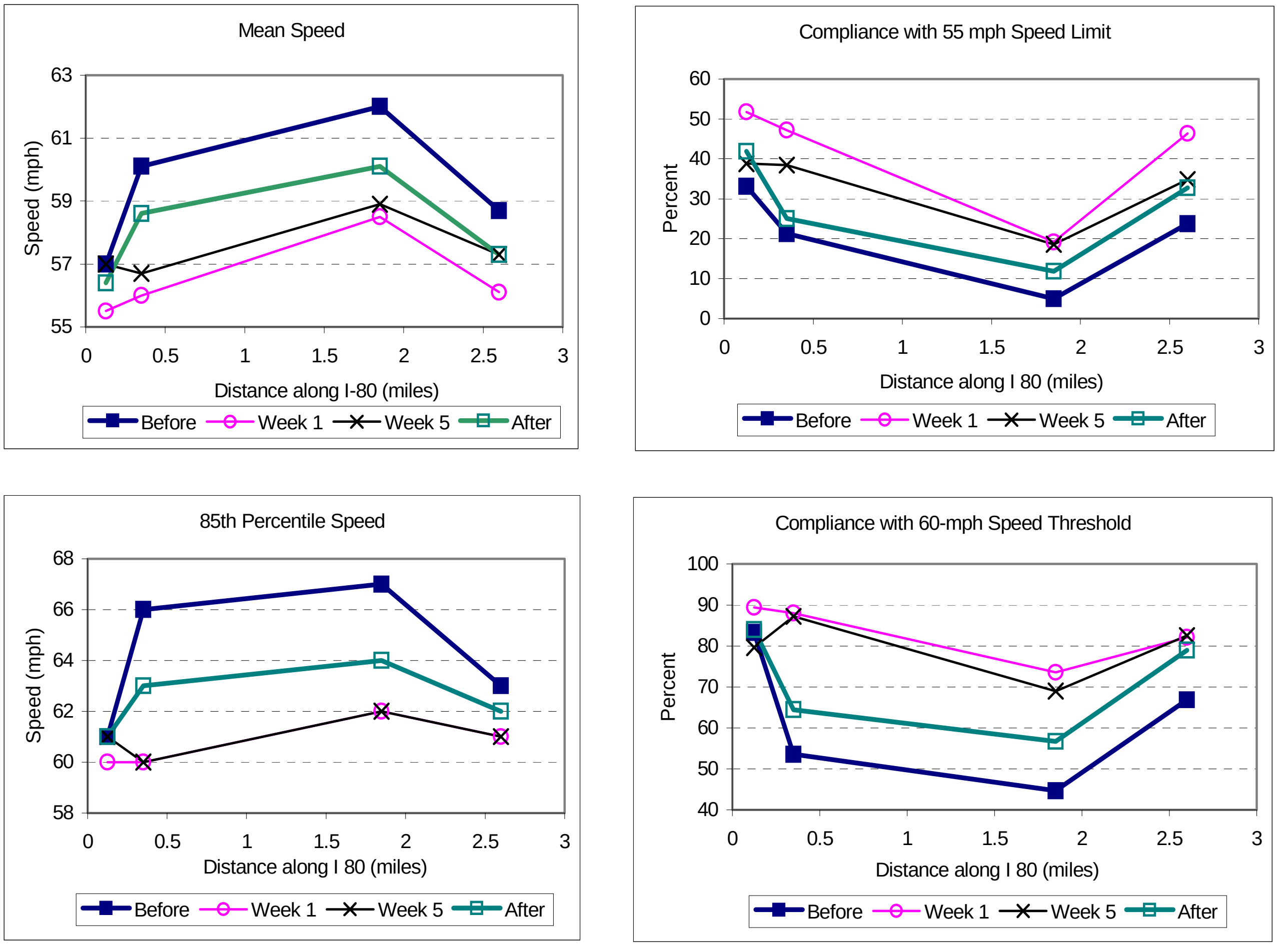

FIGURE 6 Speed Parameter Profiles.

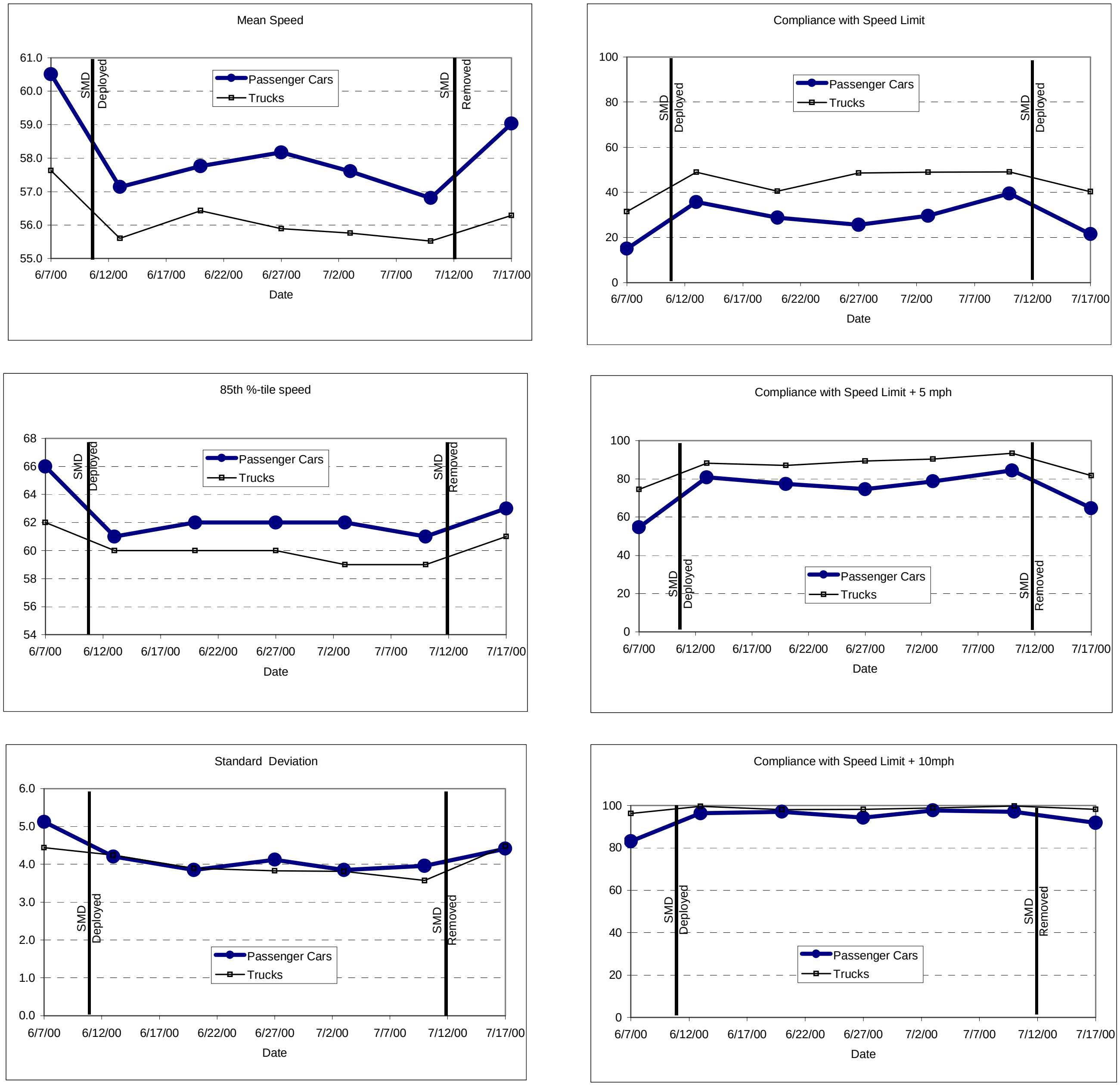

FIGURE 7 Temporal Variation of Speed Parameters.