Effect of Speed Monitoring Displays on Entry Ramp Speeds at Rural Freeway Interchanges

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ABSTRACT
The effectiveness of speed monitoring displays (SMDs) in controlling the speed of on-ramp traffic at rural freeway interchanges 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. SMDs were deployed along two on-ramps of I-80 eastbound near Lincoln, Nebraska. One SMD was operated on each ramp for a two-week period. 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 during the first week of their operation. Greater speed reductions and compliance increases were observed for passenger cars than for other vehicles. However, after two weeks of continuous operation, the SMDs began to loose their effectiveness. It is suspected that the compliance reduction is associated with the relatively high percentage of commuting traffic on the ramps.

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 SMDs (*5,6*) and more sophisticated changeable message sign (CMS) systems (*7,8,9*) have been studied and field-tested. For example, a study conducted at seven locations on two interstate highways in Virginia (*7*) evaluated the speed-reduction effect of radar-equipped CMS units. The results of a statistical analysis of the speed and volume data, collected over 2 to 4 days at each location, indicated that the CMS with radar significantly reduced the speeds of speeding drivers. In addition to these findings, the four messages used in the study were rated according to their level of effectiveness. Another study (*9*) recently conducted on interstate I-80 in Nebraska evaluated the effectiveness of condition-responsive advisory speed messages in advance of a work zone. The messages displayed on three CMSs placed approximately 1, 3, and 8 miles in advance of the work zone, were intended to advise drivers of the speed of slower traffic ahead during congested periods. Speeds measured downstream of the CMS indicated only limited effectiveness of the messages. It was concluded that their effectiveness could have been improved if the distances between the CMSs had been shorter. A driver survey revealed that the speed messages were considered useful by most drivers who recalled seeing them. However, some drivers questioned the reliability of the messages.

The SMD developed in the late 1970s is one of the promising technologies that have been successfully applied both in the United States 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. The use of the SMD technology and the research directed to the evaluation of its effectiveness has grown in recent years.

Most recent studies (*5,6,8,10-13*) have consistently found that vehicle speeds can be reduced by SMDs. A comparative study of photo-radar and SMD conducted in California (*6*) concluded that both devices significantly (i.e., by 4.4-5 mph) reduced speed. They also found that supplementing an SMD with police enforcement can further increase the effectiveness. Another study (*8*) investigated the long-term effect of CMSs with radar on speed reduction at work zones on primary highways in Virginia. They found that the CMS with radar remained an effective speed control technique for a prolonged period of time (up to 7 weeks). In addition to the reduction in the mean and 85th percentile speeds, the speed variances also tended to reduce with the introduction of the CMS in the work zone. A recent study (*10*) evaluating the long-term effectiveness of three SMDs along a 2.5-mile highway section between two work zone on I-80 in Nebraska, found that the mean and 85th-percentile speeds were reduced significantly (" = 0.05) by about 3-5 mph, and the compliance with the posted speed increased by 10 to 20 percent. The SMDs remained effective over a five-week period of continuous operation. However, the validity of the results are limited to conditions with not more than 22 percent commuting traffic. 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 duration and extent of their effectiveness were not evaluated.

OBJECTIVE

The primary objective of the present study is to evaluate the effectiveness of SMDs in controlling the speed on entry ramps of rural freeway interchanges in advance of freeway work zones. To achieve this goal, SMDs were deployed on two on-ramps to eastbound I-80 near Lincoln, Nebraska. One SMD was deployed on each ramp, and the effectiveness of the system was studied over a period of two weeks.

The SpeedGuard™ radar speed reporting system was the SMD used in the 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 as 24-inch numerals on a light-emitted diode (LED) panel. 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 features a "Work Zone Alert", which triggers a sound alarm, and simulates a photo-radar system if approaching speeds are above a preset threshold. However, these features were not activated during the study period.

STUDY SITES

Study Site 1

The first study site was located at the interchange of I-80 and I-180. Both are rural four-lane freeways, but during the study period the two westbound lanes of I-80 were closed for a reconstruction project, and traffic was moving in a two-lane, two-way operation in the two remaining (originally eastbound) lanes. The speed limits are normally 55 mph on I-180 and 65 mph on I-80 at this location. However, because of the road construction, the posted speed on I-80 was limited to 55 mph during the period of the study. Because of the reduced speed and capacity of I-80, vehicles entering from I-180 often had difficulty finding adequate gaps to merge with the eastbound traffic of I-80. Therefore, some vehicles on the entry ramp accelerated intensively, and entered the merge area at speeds higher than the traffic speed on I-80. This erratic maneuver increased the potential for both rear end and side-swipe accidents. To reduce the risk of these types of accidents, a SMD was deployed on the right side of the on-ramp 600 feet in advance of the merge point with I-80, as shown in Figure 2.

Study Site 2

The second study site was located at the interchange of Interstate I-80 and US Highway 77, about 4 miles west of the first study site. The speed limit was 55 mph on both roadways, which operated as four-lane divided highways during the period of the study. Although the construction zone on I-80 did not extend back to this point, its effect could occasionally be observed. It was indicated by increased traffic density and reduced speeds during peak hours or periods of intense work activity in the construction zone. Vehicles entering from Highway 77 to continue their way in the eastbound direction on I-80, often accelerated to more than 55-mph in order to merge the I-80 traffic. To control the speeds of merging vehicles, a SMD was deployed on the right side of the entry ramp 900 ft in advance of the merge point with I-80, as shown in Figure 3. The 900-ft distance was required at this site to ensure that the radar unit of the SMD did not measure the speed of the I-80 traffic.

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 percentages of commuting and local traffic on the two entry ramps were over 60 percent. The commuter and local traffic percentages on I-80 and the entry ramps were estimated by license plate sampling conducted during the study periods. Since the county of residence of a vehicle owner in Nebraska is indicated on the vehicle's license plate, it was possible to identify the vehicles with owners living in the Lincoln and Omaha metropolitan areas.

DATA COLLECTION

Traffic speeds were measured once before and twice after the deployment of the SMDs at both study locations. The before studies were conducted four days prior to the deployment of the SMDs. The SMDs were operated continuously for the next two weeks, and traffic speeds were measured at one-week intervals. 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 similar conditions (i.e., comparable traffic volumes, dry weather and pavement).

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. They were calibrated before and after data collection. As illustrated on Figure 2, vehicle speeds were measured at a point, approximately 100 feet downstream of the SMD on the I-80 eastbound on-ramp at study site 1. However, the availability of a better vantage point at study site 2 made it possible to measure the speed of each vehicle at two points, approximately 200 feet upstream and 200 feet downstream of the SMD, as shown in Figure 3.

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 line of traffic 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 and in front of the vehicles.

Speed data were collected only during uncongested flow conditions. To eliminate the effect of possible vehicle interactions on the ramp (i.e., two or more vehicles in platoon), only the speeds of vehicles with at least 6-second headways were measured. Thus, the collected data include only desired speeds which were unaffected by 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, and after the deployment of the SMDs. The six MOEs were:

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

The statistical significance of the differences in these MOEs corresponding to the periods before and after the deployment 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, 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

Study Site 1

Table 1 summarizes the MOEs calculated for both passenger cars and other vehicles at the measurement point 100 feet downstream of the SMD, approximately 500 feet before the merge with traffic on I-80. The 95 % confidence intervals for the mean speed and the speed-limit compliance are shown in Table 2. For passenger cars, the mean and 85^{th} percentile speeds decreased by 3.3 and 4 mph, and the percent compliance with the 55-mph speed limit and the 60-mph speed threshold increased by 30 and 10 percent one week after the SMD was deployed. For the second week, all MOEs indicated that the SMD was not as effective as it was during the first week, even though their values still showed significant ("=0.05) improvement relative to the before values. The standard deviation of the speed of passenger cars speed and their percent compliance with the 65-mph speed threshold did not change significantly ("=0.05) in response to the SMD messages.

In the case of other vehicles, consisting mostly of trucks, none of the six MOEs were significantly ("=0.05) affected by the SMD messages. However, this is expected considering the low speeds and high speed limit compliance of these vehicle types observed even before the SMDs were deployed at this study site. The 85^{th}-percentile speed was lower than the speed limit, and consequently the speed limit compliance higher than 85 percent did not leave much room for improvement. The low truck speeds at this location may be explained by a combination of factors. One of the main reasons could be the limited visibility of the traffic on I-80 eastbound in the lane where vehicles merged. The drivers' sight on the on-ramp was limited by the two bridges shown in Figure 2, and therefore it was difficult for them, particularly for truck drivers, to estimate the actual available gap and adjust their speed to merge with the traffic in the target lane. Another important factor was the narrow shoulders and steep side slopes along the on-ramp.

The results indicate that the SMD was effective in reducing speeds and increasing speed limit compliance of passenger cars during the first week of SMD-operation, but it began to lose its effectiveness after two weeks.

Study Site 2

At the second study site, it was possible to track each vehicle over a distance of several hundred feet, and measure its speed at two points, approximately 200 feet upstream and 200 feet downstream of the SMD.

Table 3 shows the six MOEs calculated for both passenger cars and other vehicles at the two measurement points, 200 feet upstream and about the same distance downstream of the SMD. The 95 % confidence intervals for the mean speed and the speed-limit compliance are shown in Table 2. It can be seen that the degree of improvement was greater and statistically more significant downstream of the SMD than at the measurement point upstream. One week after the SMD was deployed, the mean and 85th percentile speeds decreased and the speed limit compliance increased significantly ("=0.05) for all vehicle types at both points. For passenger cars the mean and 85th percentile speeds decreased by about 3 mph upstream and 6 mph downstream of the SMD. The reduction for other vehicles was about 5 mph both upstream and downstream of the SMD. The compliance with the 55-mph speed limit and the 60-mph speed threshold significantly ("=0.05) increased for all vehicle types at both measurement points during the first week. The speed limit compliance improved by about 22 percent and the compliance with the 60-mph speed limit increased by 12 percent for both vehicle types upstream of the SMD. Downstream of the SMD, the increase in speed limit compliance was about 37 percent for passenger cars, and only slightly lower, about 35 percent for other vehicles. The compliance with the 60-mph speed threshold was over 30 percent for passenger cars, and about 18 percent for other vehicles at this measurement point during the first week of SMD operation. The standard deviation of speed, and the compliance with the 65-mph speed threshold did not change significantly ("=0.05) upstream of the SMD during this period. However, the compliance with the 65-mph speed threshold improved significantly downstream of the SMD for both vehicle types indicating that even the fastest, most aggressive drivers were positively affected by the SMD during the first week.

By the second week, almost all MOEs became worse at both measurement points. For passenger cars only the 60-mph compliance, and for other vehicles the mean and standard deviation remained statistically different ("=0.05) from the values observed before the SMD was deployed.

In addition to the assessment of the speed parameters and compliance percentages at the two measurement points, the effect of this SMD on the acceleration pattern of vehicles could also be evaluated based on the change in the speed profiles. Figure 4 shows profiles of the mean and 85th-percentile speeds for passenger cars and other vehicles. As the before profiles labeled by letter B indicate, both passenger cars and trucks accelerated over the 400-ft long section. The profiles labeled with A1 show that the situation changed significantly one week after the SMD was installed, particularly in the case of passenger cars which had mean speeds higher than the 55-mph speed limit before deployment. After one week of SMD operation, passenger cars not only reduced their mean speed to at or below the speed limit, but also decelerated as they passed the SMD. The trucks, which had lower than 55-mph mean speed during the before period, further decreased their speeds but their acceleration, on average, did not change (i.e., lines B and A1 remained parallel). However, based on the 85th-percentile profiles, 85 percent of the trucks reduced their speed to at or below the speed limit, and they did not accelerate over the 400-ft ramp section.

Two weeks after the SMDs were deployed, the mean and 85th percentile of both vehicle types increased (see lines A2), and their acceleration followed the pattern of the before period. Although the speeds of passenger cars increased, they did not reach the values measured before SMD deployment. The 85th-percentile speeds of other vehicles returned to the same level, and the mean speed exceeded the values observed during the before period.

The results indicate that, similar to the first study site, the SMD was effective in reducing speeds and increasing speed limit compliance during the first week of operation, but it began to lose its effectiveness in the second week.

CONCLUSIONS

The SMDs were found to be effective in controlling the speeds and increasing the speed limit compliance of the on-ramp vehicles over a period of one week. Statistically significant ("=0.05) improvements in speed parameters (i.e., mean, 85th percentile speed) and speed-limit compliance were observed at both study locations for passenger cars, and at one of the locations for other vehicles consisting mostly of trucks. Trucks at the other site normally travel slower than the posted speed because of sight distance limitations, and therefore, the SMD did not influence them.

Two weeks after the SMDs were deployed, almost all MOEs significantly degraded indicating that the SMDs began to lose their effectiveness. Depending on the measurement location, some of the MOEs approached and others exceeded their initial level observed before the SMDs were installed.

The level of speed enforcement was not changed during the operation of the SMDs at either study sites. Commuters and local motorists, who repeatedly traveled on the ramps, could experience that not-complying with the speed limit did not result in more serious consequences during the SMD operation than before. Therefore, it can not be ruled out that the presence of commuter and local traffic may have an effect on speed-limit compliance.

Another study (10) that evaluated the performance of a series of SMDs in controlling the speed of highway traffic between two work zones, located only a few miles east of the present study locations, found that the SMD messages remained effective over a period of five weeks. It is suspected that the shorter duration of effectiveness found in the current study is associated with the higher percentage of commuting traffic on the two on-ramps compared to the interstate. Another contributing factor might be the driver perception that speed is much more likely to be enforced on the interstate than on entry-ramps. However, these assumptions can only be validated by conducting further studies at sites with various levels of speed enforcement and commuting traffic.

ACKNOWLEDGMENT

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LIST OF TABLES AND FIGURES

TABLE 1 Measures of Effectiveness Downstream of the SMD at the I-180 On-Ramp

MEASURES OF EFFECTIVENESS	BEFORE DEPLOYMENT	DURING OPERATION	
		week 1	week 2
PASSENGER CARS			
Sample Size	279	111	254
Mean Speed (mph)	54.6	51.3	52.1
Standard Deviation (mph)	5.60	4.80	5.00
85^{th}-Percentile Speed (mph)	60.0	56.0	57.0
Compliance with Speed Limit (%)	53.40	82.90	76.80
Compliance with SL + 5 mph (%)	87.80	97.30	96.50
Compliance with SL + 10 mph (%)	97.10	99.10	99.20
OTHER VEHICLES			
Sample Size	27	34	29
Mean Speed (mph)	49.1	49.2	50.8
Standard Deviation (mph)	5.10	5.60	5.10
85^{th}-Percentile Speed (mph)	54.2	56.1	54.8
Compliance with Speed Limit (%)	85.20	82.40	86.20
Compliance with SL + 5 mph (%)	96.30	100.00	96.60
Compliance with SL + 10 mph (%)	100.00	100.00	100.00

Difference from BEFORE value is statistically significant (" = 0.05).

TABLE 2 95 % Confidence Intervals at the I-180 On-Ramp

MEASURES OF EFFECTIVENESS	BEFORE DEPLOYMENT	DURING OPERATION	
		week 1	week 2
PASSENGER CARS			
Mean Speed (mph)	53.9 - 55.3	50.4 - 52.2	51.5 - 52.7
Speed-Limit Compliance (%)	50.5 - 56.3	80.3 - 85.5	74.6 - 79.0
OTHER VEHICLES			
Mean Speed (mph)	47.1 - 51.1	47.3 - 51.2	48.9 - 52.7
Speed-Limit Compliance (%)	80.4 - 90.0	77.5 - 87.3	81.9 - 90.5

TABLE 3 Measures of Effectiveness Up- and Downstream of the SMD at the Hwy 77 On-Ramp

MEASURES OF EFFECTIVENESS	200 FT UPSTREAM OF SMD			200 FT DOWNSTREAM OF SMD		
	BEFORE DEPLOY-MENT	DURING OPERATION		BEFORE DEPLOY-MENT	DURING OPERATION	
		week 1	week 2		week 1	week 2
PASSENGER CARS						
Sample Size	90	91	138	90	91	138
Mean Speed (mph)	57.8	54.9	56.8	59.7	53.8	57.7
Standard Deviation (mph)	5.08	6.15	4.90	4.95	5.50	4.80
85^{th}-Percentile Speed (mph)	64.0	61.5	61.0	65	59	62.0
Compliance with Speed Limit (%)	36.67	54.95	34.80	20.00	57.14	26.80
Compliance with SL + 5 mph (%)	68.89	79.12	83.30	58.89	91.21	76.10
Compliance with SL + 10 mph (%)	93.33	96.70	94.90	88.89	98.90	94.90
OTHER VEHICLES						
Sample Size	66	57	29	66	57	29
Mean Speed (mph)	51.7	46.2	55.3	55.2	49.4	57.3
Standard Deviation (mph)	7.99	8.00	4.10	6.30	5.43	3.80
85^{th}-Percentile Speed (mph)	59.5	55.0	59.0	62	55	60.8
Compliance with Speed Limit (%)	62.12	85.96	51.70	54.55	89.47	34.50
Compliance with SL + 5 mph (%)	84.85	96.49	89.70	80.30	98.25	82.80
Compliance with SL + 10 mph (%)	96.97	100.00	100.00	92.42	100.00	93.10

Difference from BEFORE value is statistically significant (" = 0.05).

TABLE 4 95 % Confidence Intervals at the Hwy 77 On-Ramp

MEASURES OF EFFECTIVENESS	200 FT UPSTREAM OF SMD			200 FT DOWNSTREAM OF SMD		
	BEFORE DEPLOY-MENT	DURING OPERATION		BEFORE DEPLOY-MENT	DURING OPERATION	
		week 1	week 2		week 1	week 2
PASSENGER CARS						
Mean Speed (mph)	56.7 - 58.9	53.6 - 56.2	56.0 - 57.6	58.7 - 60.7	52.7 - 55.0	56.9 - 58.5
Speed-Limit Compliance (%)	31.9 - 41.5	49.9 - 60.0	31.0 - 38.6	16.7 - 23.3	52.1 - 62.2	23.5 - 30.1
OTHER VEHICLES						
Mean Speed (mph)	49.7 - 53.7	44.1 - 48.3	53.7 - 56.9	53.7 - 56.8	48.0 - 50.8	55.9 - 58.8
Speed-Limit Compliance (%)	56.4 - 67.8	82.8 - 89.1	42.6 - 60.8	48.6 - 60.5	87.0 - 91.9	26.3 - 42.7

FIGURE 1 SpeedGuard Speed Monitoring Display

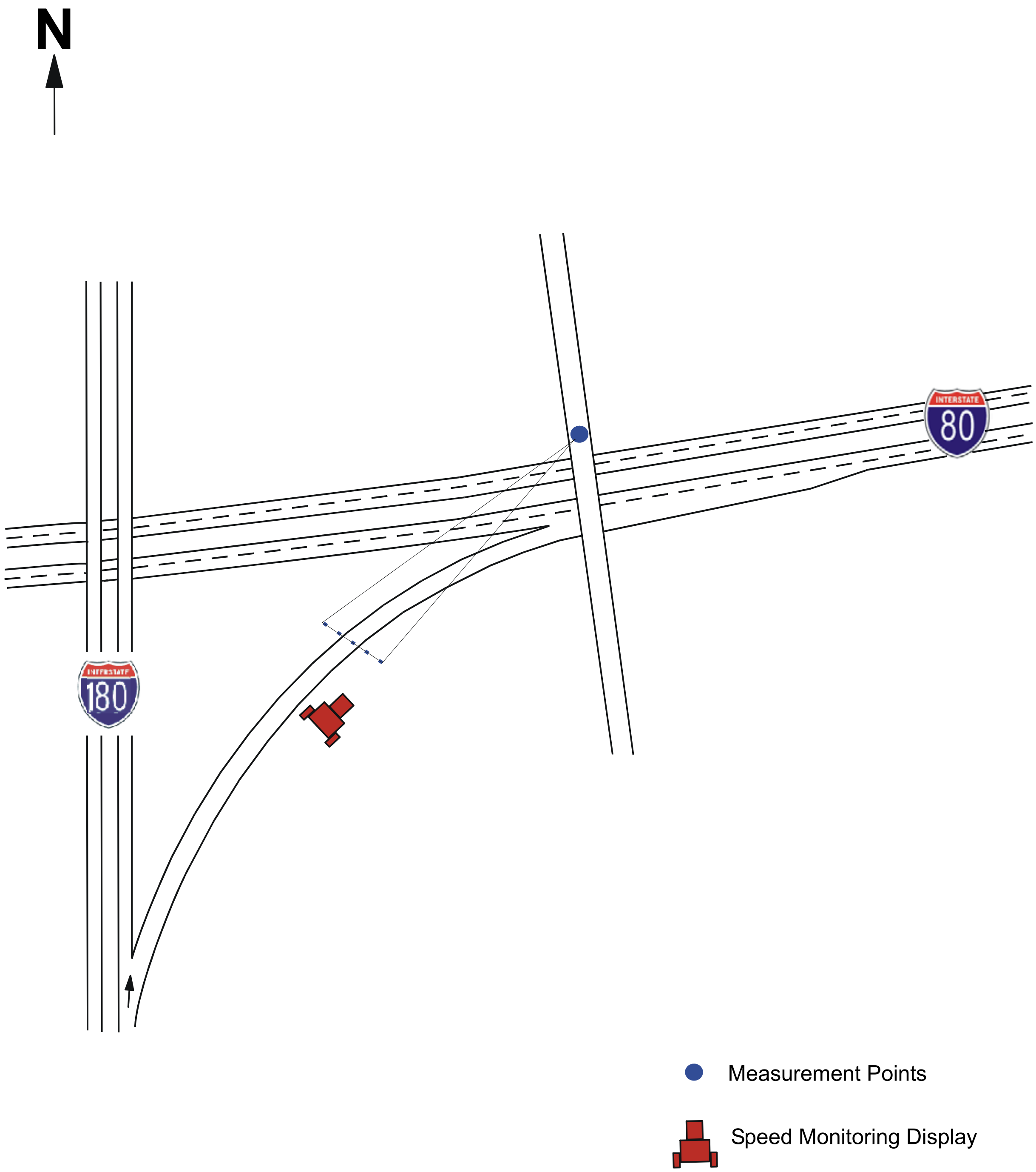

FIGURE 2 Study Site 1

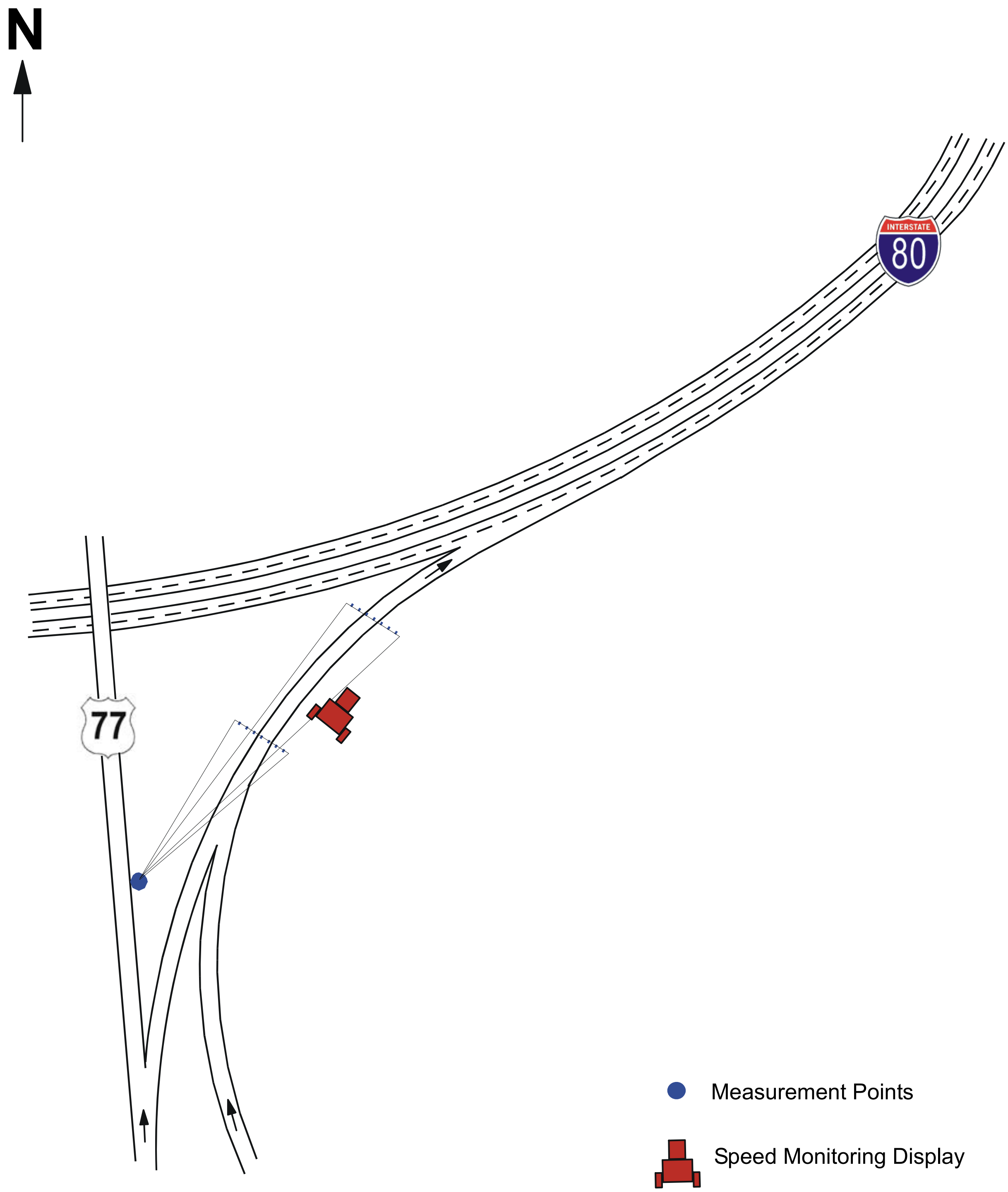

FIGURE 3 Study Site 2

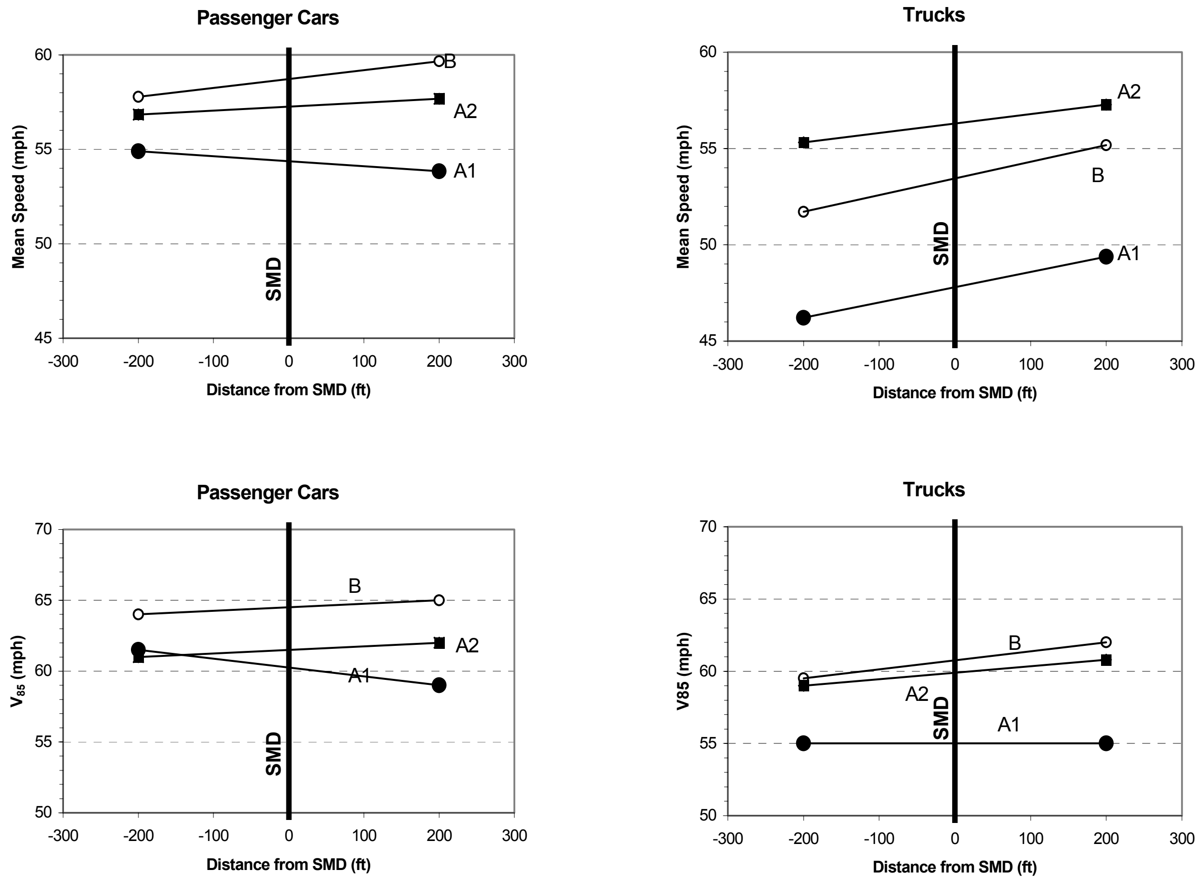

FIGURE 4 Speed Parameter Profiles