Spatial Effectiveness of Speed Feedback Signs

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Speed feedback signs (SFS), also known as dynamic speed displays, provide drivers with feedback about their speed in relationship to the posted speed limit. When appropriately complemented with police enforcement, SFS can be an effective method for reducing speeds at a desired location. However, as reported in the literature, effectiveness of SFS is limited not only in regard to time after the deployment but also for distance. Therefore, a need exists to understand how far upstream and downstream of the SFS speed reductions are maintained. Through a unique data collection methodology, researchers obtained trajectories of free-flowing vehicles that approached an SFS, as well as trajectories of vehicles receding from the SFS. Trajectory data were used by researchers to determine the locations at which drivers willing to reduce their speed when approaching the SFS actually started the reduction. Downstream of the SFS, the distance at which drivers started increasing their speed after complying with the sign was also determined. Results showed the feasibility of determining the spatial effectiveness of SFS. By using the methods as presented, speed enforcement personnel can understand how drivers in an area of interest react to SFS and therefore can determine the best locations for SFS as well as the number of SFS that need to be deployed to achieve a speed reduction over a segment of road.

In 2008, speed-related crashes claimed the lives of 11,674 people in the United States, resulting in more than $40 billion in economic costs. Enforcement is a known and effective method of reducing speeding problems, therefore lowering the crash risk (*1*). Furthermore, safety and speed compliance correlations are well documented. Enforcement has many proven benefits and can provide drivers with the stimulus necessary to change their speed to acceptable levels. However, as resources are limited, deployment of police personnel for speed enforcement tasks at all speeding locations is not possible. Speed feedback signs (SFS), also known as dynamic speed displays, provide feedback to drivers about their current speeds and may prompt better compliance with speed limit, without the need for continuous enforcement.

On the positive side, drivers traveling above the posted limit are reminded about their violations of the rules; however, a negative aspect can be that if signs are installed at a location where speeding is not a concern, drivers are reminded that a speed increase is permissible without any violation of the rules. The use of SFS as a speed enforcement technique is targeted at drivers willing to reduce their speed when provided with information about their speed (*2*). Furthermore, SFS should not be considered a stand-alone solution since their long-term effectiveness is limited (*3*). When no enforcement is provided, and agencies rely on the presence of SFS as a stand-alone solution, drivers will see no consequence when speeding and therefore may not be motivated to reduce speed.

Previous studies have studied the effectiveness of SFS in regard to speed reduction by drivers near the sign. Researchers have studied the speed of vehicles downstream of SFS and concluded the signs have a limited influence on the speed of downstream vehicles (*4, 5*). However, none of the studies have actually quantified the spatial effectiveness of SFS, that is, over what distance upstream and downstream of the SFS installation are reductions in the speed of motorists observed. The objectives of the study presented in this paper are twofold. First, a methodology that can be used to quantify the spatial effectiveness of SFS, that is, the speed profile followed by vehicles when approaching the SFS, needs to be developed. Second, the methodology will be applied at a test site to collect the data and quantify spatial effectiveness of SFS.

Researchers at the Traffic Operations and Safety Laboratory at the University of Wisconsin–Madison recently completed a safety evaluation of the State Highway (STH) 164 corridor in Washington County, Wisconsin (*6*). As part of the evaluation, speeds were monitored at several locations where SFS were installed through an 18-month period. Presented in this paper is an evaluation of one of the locations where a SFS was installed. As part of this evaluation, and using the methodology developed, the research team looked at the speed profile of drivers approaching, as well as receding from, one of the SFS located along the corridor.

LITERATURE REVIEW

Previous research in the area of work zones has confirmed that the effectiveness of SFS reduces with time. Chitturi and Benekohal found that immediately after deploying SFS in Interstate work zones, the average speed of drivers was reduced by 4.4 mph; however, 3 weeks after the installation, speeds were reduced only by 2.3 mph (*7*). Research performed by Lee et al. studied the short- and long-term effects of SFS in school zones and found that shortly after the installation of the SFS, a speed reduction of 5.1 mph was observed; but after a 12-month period, the reduction dropped to 3.6 mph (*8*). The decrease in speed reduction with time is not surprising; especially given that continuous police enforcement for a 6-week period had

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been shown to have a time-halo effect of only 8 weeks, that is, the reductions observed after enforcement last for a period of only 8 weeks (*9*).

Ullman and Rose studied the effect of SFS not only in school zones but also on speed transition zones, high-speed intersection approaches, and horizontal curves (*10*). At school zone sites, speed reductions of 9.0 mph were observed, while at other sites, speed reductions were not as dramatic and averaged 5.0 mph. During the study, drivers who were traveling above the posted speed limit reduced their speed more significantly than did those drivers complying or traveling below the posted speed limit. Researchers found the relationship through the use of least square regression lines.

The spatial effectiveness of enforcement by police was studied by Teed, Lund, and Knoblauch, who studied the percentage of vehicles traveling 10 mph or more over the posted speed limit at the radar exposure location and one mile downstream of the location (*4*). The number dropped from 42%, before radar exposure, to 28% at the exposure location; however, 1 mi downstream, the number increased to 38%. Furthermore, Medina et al. studied the downstream effectiveness of speed feedback trailers with a police car and found that 1.5 mi downstream, there is limited effect on the speeds of vehicles (*5*).

Existing research shows that effectiveness of SFS diminishes with time. Also, in regard to distance, research suggests there is a distance downstream at which reductions in speeds are no longer significant. However, to the authors' knowledge, no research has been performed to quantify the spatial effectiveness of SFS. Quantifying spatial effectiveness can help in determining the location of SFS to maximize the safety benefits at locations such as school zones and short-term lane closures, as well as determine those sites in which more than one SFS might be needed to achieve speed reductions over longer distances.

SITE CHARACTERISTICS

Data were collected on STH 164, a two-lane rural highway with 6-ft paved shoulders, an additional 2 ft of gravel shoulders, and a clear zone wider than 40 ft (see Figure 1). The study section of STH 164 has an average annual daily traffic of 7,000 vehicles, primarily composed of commuter traffic, and a posted speed of 55 mph. The Wisconsin Department of Transportation implemented a comprehensive speed management program to address speeding and safety issues in this corridor. As a part of this plan, SFS were installed at four locations on STH 164 to complement periodic police enforcement in the area. SFS displayed a flashing speed reading when the speed of the vehicle exceeded the speed limit and displayed the speed reading steadily when the speed was below the posted limit. One location was selected for trajectory analysis, shown in Figure 1. Field visits revealed that during the prevailing conditions of the study, a driver approaching the SFS was able to notice the flashing indication up to 2,625 ft upstream of the SFS.

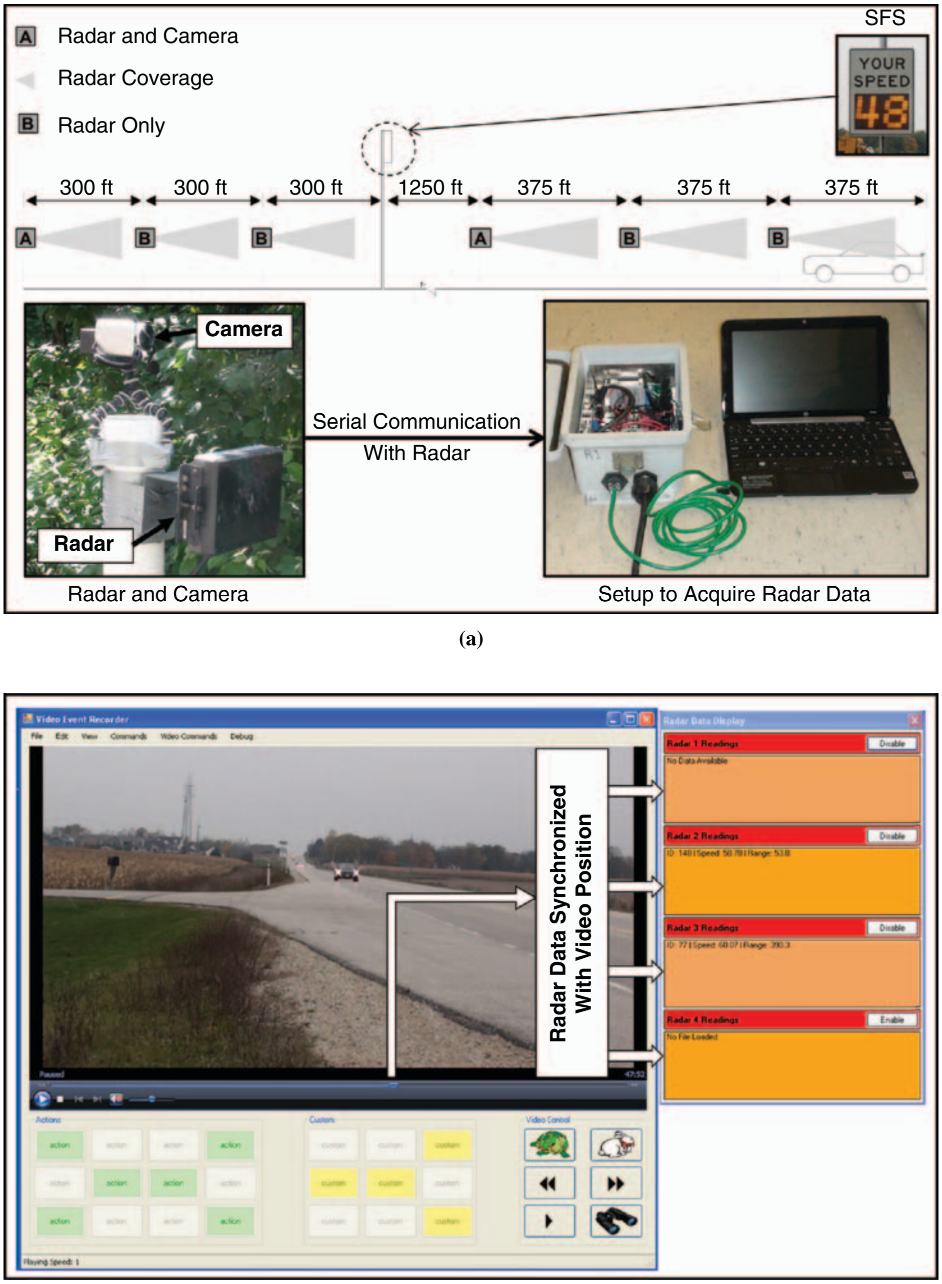
At the study location, approximately 60% of drivers traveled above the posted speed limit. However, approximately only 1.0% of drivers traveled at speeds more than 10 mph over the posted speed limit. Average speed of vehicles was 54 mph, and the 85th percentile speed was 58 mph (*4*). The location shown in Figure 1 was selected as the study location for trajectory data because of the level terrain and the absence of significant development around the road, which limited traffic from entering the study segment from the crossing street. As a result, researchers were able to isolate the effects of the presence of the SFS on vehicle speeds from other variables.

DATA COLLECTION PROCESS

A data collection setup was developed to collect speed trajectories of vehicles as they approached and receded from the SFS. In addition, video data were collected. Trajectories were obtained through a modified vehicle collision avoidance system whose characteristics include the capability of obtaining the position, speed, and azimuth of up to seven vehicles at a frequency of 16 Hz. Video of vehicles as they traveled through the segment of road monitored by the radars was obtained through the use of a digital video camera mounted above one of the radars. Figure 2, *a* and *b*, shows the experimental setup as well as a screenshot of the software used to process the field data, respectively.

As Figure 2*a* shows, a total of 1,125 ft were monitored upstream of the SFS and 900 ft downstream. Trajectories for upstream and downstream were obtained in two data collection sessions. Trajectories upstream of the sign were monitored from 11:00 a.m. to 1:00 p.m., while downstream trajectories were monitored from 2:00 p.m. to 4:00 p.m. on Wednesday, October 28, 2009, therefore avoiding the morning and afternoon peak periods. October 2009 was 1 year after the SFS installation, therefore avoiding the initial SFS novelty effect. Three radar units were used during each session, and the distance between each consecutive unit ranged from 300 to 375 ft. This radar spacing was consistent with the data range of the radar units and

FIGURE 1 Study location site at STH 164.



(a)

(b)

FIGURE 2 Field setup for (*a*) data collection and (*b*) data reduction software.

allowed the total data collection area to be segmented for increased accuracy.

A netbook computer was used with each of the radar units to record the trajectories. A video camera was mounted on top of a radar unit to capture video of approaching (or receding) vehicles. The location of the cameras can be identified by a letter A inscribed in gray squares, as shown in Figure 2*a.* The position of the radars and cameras was selected based on the authors' knowledge about the site and also considering the distance from which the drivers could see the SFS. Radar coverage upstream of the SFS started 1,250 ft upstream of the SFS because during preliminary data collection at the site, it was noticed that reductions started 1,250 ft upstream.

To solve the issues with segmentation of data as well as with time inconsistencies, the software shown in Figure 2*b* was created. By knowing the instance in each of the trajectory files that represents a corresponding instance in the video, the software tool displays the information reported by each of the radars at any time shown in the video.

Times on the netbook computers were recorded by using video during field data collection, enabling synchronization of radar times with video during data reduction. Using the software, the research team was able to determine the different identification numbers that corresponded to each vehicle as the vehicle traveled through segments of the road monitored by each of the radar units, as shown in

Figure 2*a*. Using the information obtained from the software tool, the research team was able to assemble the trajectory of each vehicle and perform the analyses.

Trajectories were obtained only for free-flowing vehicles. A free-flowing vehicle was defined as a vehicle that maintained at least an 8-s gap to the leading vehicle. Through use of the software developed for analysis, the research team was able to identify vehicles whose trajectory changed due to external factors, such as a vehicle parked on the shoulder, conflict with another vehicle or farming equipment, and so forth. During data collection, there was no speed enforcement by the police along the studied corridor. A total of 70 upstream and 47 downstream vehicle trajectories were obtained.

DATA ANALYSIS AND RESULTS

Trajectory data were analyzed on a per vehicle basis upstream and downstream of the SFS. Results for the upstream and downstream locations of the SFS are presented separately. The equipment used for the data collection logged the speed and distance of vehicles 16 times per s. For analysis purposes, speeds were averaged every 100 ft. Averaging the speeds resulted in 13 data points upstream of the SFS and 9 downstream. With consideration of the speed of each vehicle along all the points, the change in vehicle speed was determined, as well as the corresponding speed profile when the vehicle approached the SFS or receded from the SFS. Change in speed upstream of the SFS was defined as the difference between the first speed recorded and the speed at the end of the section. Accordingly, change in speed downstream of the SFS was defined as the difference between the speed at the SFS and the speed at the end of the section.

Using change in speed and vehicle trajectories, the research team obtained profiles showing how each vehicle achieved its speed decrease and increase as a function of distance. From each vehicle profile, the distance upstream of the sign where vehicles start reducing their speed by at least 1.0 mph was determined, as well as the distance downstream where vehicles start increasing their speed accordingly. Three types of speed profiles were observed upstream and downstream of the SFS, as shown in Figure 3. Profile type U_a indicates a speed reduction upstream, U_b indicates no change in speed, and U_c indicates a speed increase upstream of the SFS; downstream profiles are labeled accordingly with the letter *D*. The profile alternative selected by a driver downstream of the SFS is independent of that selected upstream; for example, after reducing the speed upstream of the SFS, a driver could maintain the speed, increase the speed, or even reduce the speed.

The total spatial effectiveness of the SFS was determined by identifying the distance upstream where vehicles with trajectory type U_a accomplish a speed reduction and the location where vehicles with trajectory type D_a accomplish an increase in speed. Only those vehicles with trajectory types U_a or D_a were considered. That is because upstream of the sign, vehicles with trajectory type U_a are the ones on which the presence of the SFS had an impact, and downstream of the SFS, those vehicles with trajectory type D_a are the ones on which the SFS presence had no impact after the downstream spatial effectiveness. Descriptive speed statistics upstream of the SFS during the data collection period were as follows:

- Average speed, 57 mph;
- Median speed, 56 mph;
- 85th percentile speed, 60 mph;
- Percentage of vehicles traveling above the speed limit, 63%; and
- Percentage of vehicles traveling at least 10 mph over the speed limit, 4%.

Upstream of Speed Feedback Sign

Figure 4, *a* and *b*, shows a histogram of change in speeds, if any, upstream of the SFS and a graph showing the cumulative percentage of the change in speeds, respectively. Bins used in the histogram were defined using 1.0 mph intervals; for example, one of the bins is –6.5 to –7.5 mph. Therefore, a vehicle for which a change in speed of –6.89 mph was measured was assigned to the –7.0 mph bin. Figure 4 shows that 50% of the vehicles reduced their speed by at least 1.0 mph.

A binary logistic model was created to predict the probability that a vehicle would reduce speed by at least 1.0 mph depending on how much the vehicle was over the speed limit when approaching the SFS. Vehicles that were not traveling above the speed limit were also included in the model by using the corresponding negative values for the predictor variable. A graphical representation of the binary logistic regression model is shown in Figure 5, and the details of the model are shown in Equation 1, where *X* is the mph over the speed limit.

$$P(\text{speed reduction}) = \frac{1}{1+e^{-(0.63699-0.212735X)}} \tag{1}$$

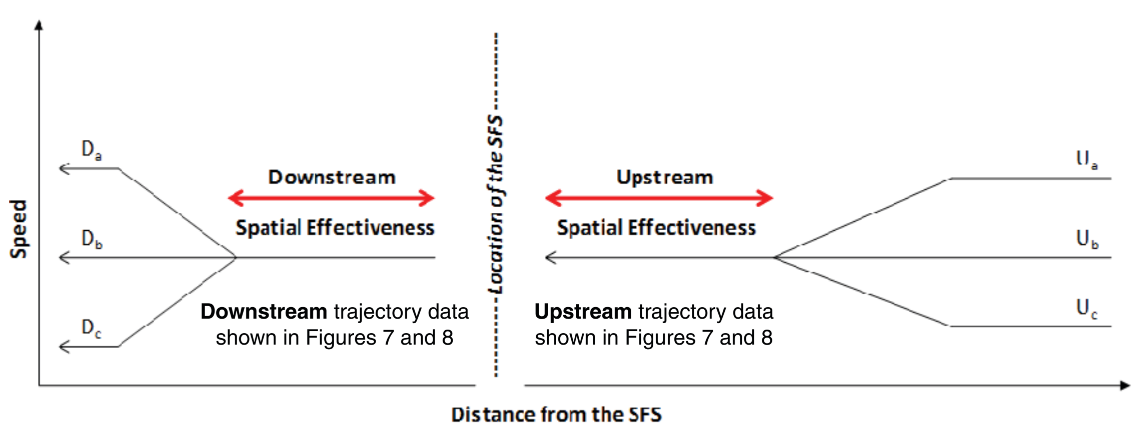


FIGURE 3 Typical trajectories upstream and downstream of SFS.

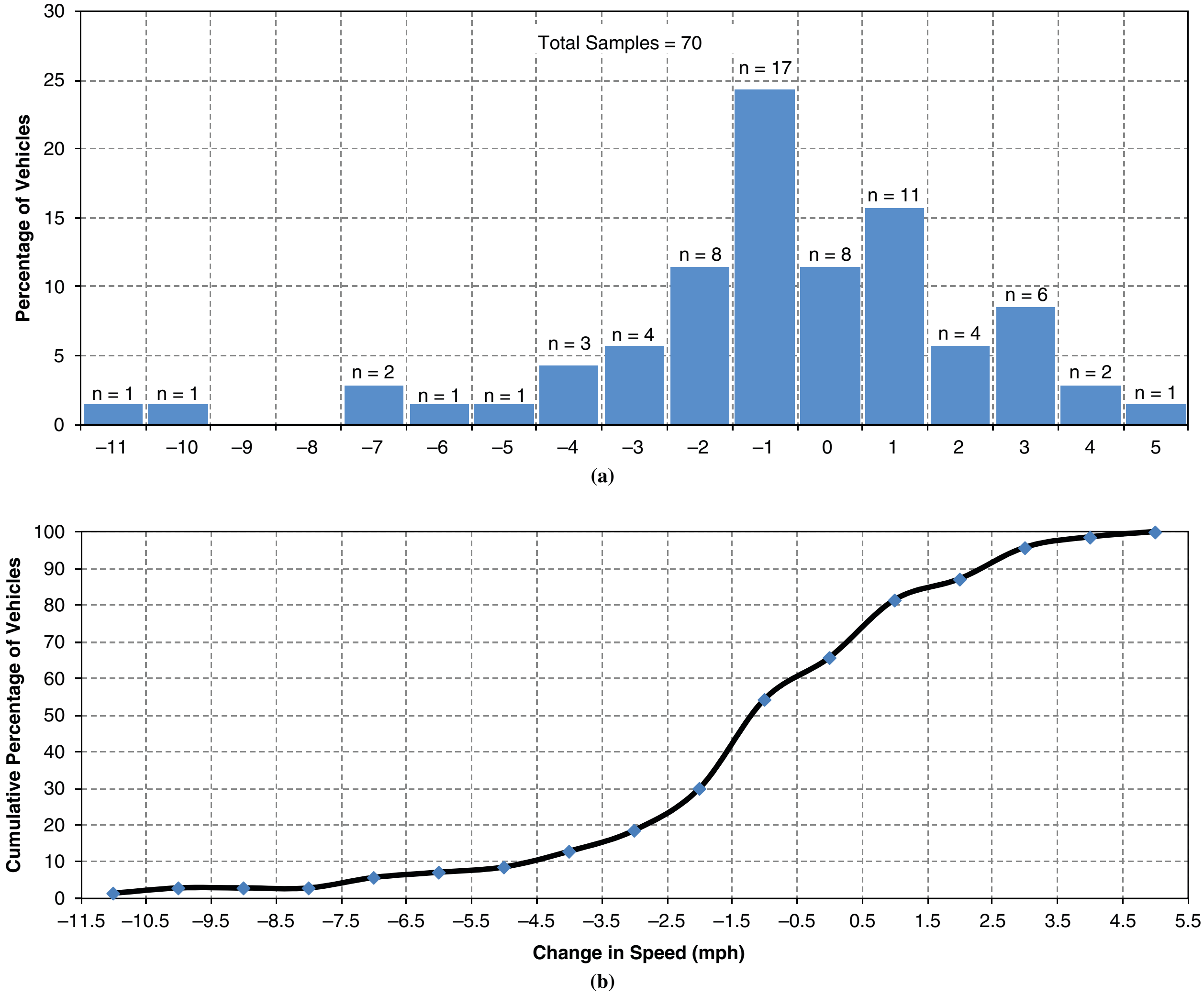


FIGURE 4 Characteristics of speed change upstream of SFS.

As shown, the probability of a vehicle reducing speed was greater than 50% when the vehicle was traveling at least 2.5 mph over the posted speed limit. An important characteristic is that the model assumes a probability of vehicles reducing their speed even when complying with the posted limit. These reductions are consistent with the numbers observed during the data collection, where 20% of nonspeeding vehicles reduced their speed by at least 1.0 mph. A Hosmer–Lemeshow test with a value of 0.886 suggests that the hypothesis of an adequate fit cannot be rejected for the model at a 95% level of confidence. Aside from an adequate fit and the corresponding parameter for the model, an important behavior shown by the model is that as the degree of speeding increases, the probability of a vehicle reducing speed increases. The model confirms what NCHRP Report 500 suggests: that SFS are effective in modifying the speed of only those willing to reduce their speed as shown by the 0.85 probability of reducing the speed by vehicles already traveling more than 10 mph over the posted speed limit (*2*). In other words, 15% of drivers going 10 mph over the speed limit will not reduce their speed.

Figure 5 shows that the mere presence of SFS can produce speed reductions; however, no information is provided on the distance upstream of the signs at which a significant portion of the speed reduction occurs. To understand where the spatial effectiveness of the SFS starts, the research team looked at how each of the vehicles that reduced its speed by at least 1.0 mph achieved the reduction as a function of the distance traveled. The percentage of speed reduction as a function of the distance upstream of the SFS was plotted, and results are shown in Figure 6. A value of 0% indicates that no speed reduction had started at the corresponding distance, while a value of 100% indicates that all the speed reduction measured had been achieved by the corresponding distance.

Figure 6 shows an inflection point in the vehicle trajectories located 1,250 to 1,450 ft upstream of the SFS, that is, the distance at which drivers start reducing their speed by at least 1.0 mph. In Figure 6, some of the vehicles experienced a slow speed reduction before the final one, and in some cases the reduction was of greater magnitude than the final one. Such a behavior suggests that, when provided with feedback about their current speed by SFS, drivers adjust their speed through an oscillatory process until they reach a speed they are comfortable with. While not shown in Figure 6, some of the vehicles, as the histogram in Figure 4 shows, can increase their speed as documented by positive values for change in speed.

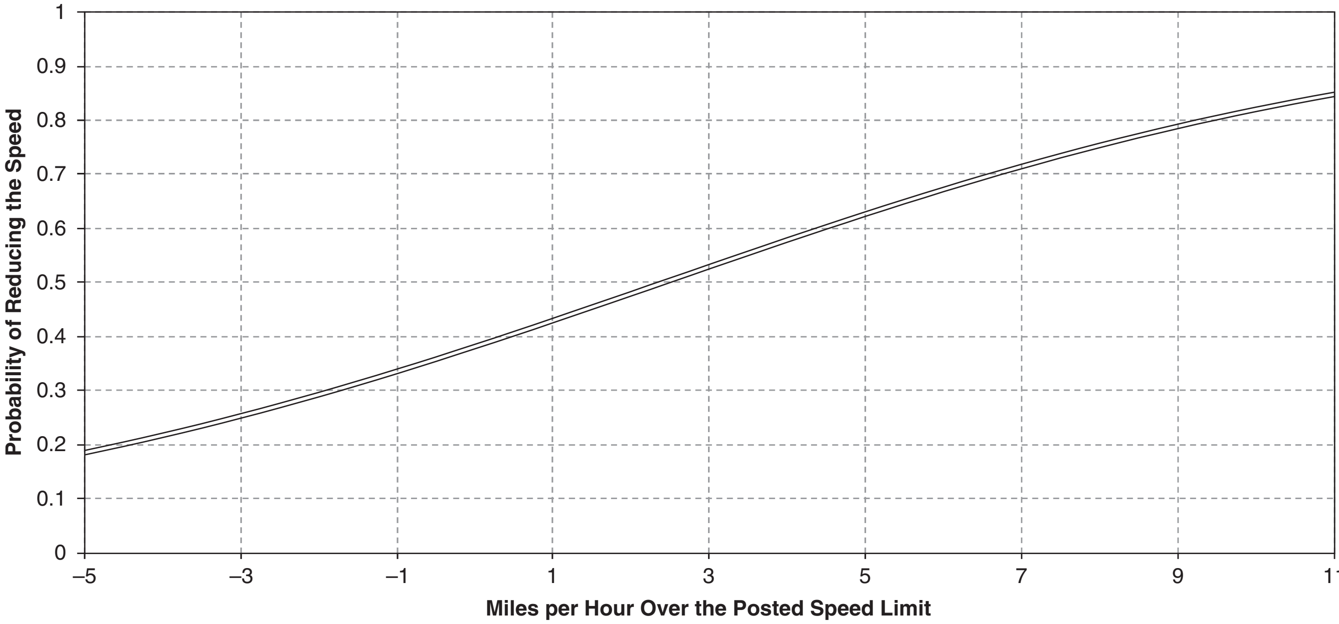


FIGURE 5 Binary logistic regression model to explain probability of speed reduction

Downstream of Speed Feedback Sign

Figure 7, *a* and *b*, shows a histogram of the change in speed by drivers, if any, downstream of the SFS and a graph showing the cumulative percentage of the change in speeds, respectively. The bins used in the histogram are similar to the ones used in Figure 4 to explain the upstream behavior. Results shown in Figure 4 suggest that 50% of the vehicles increase their speed by at least 1.0 mph. Similar to the upstream behavior, downstream of the SFS, approximately 50% (out of 47 vehicles) of the vehicles increased their speed by 1.0 mph. Data shown in Figure 7 suggest that after the initial speed reduction upstream of the SFS, vehicles start increasing their speed again.

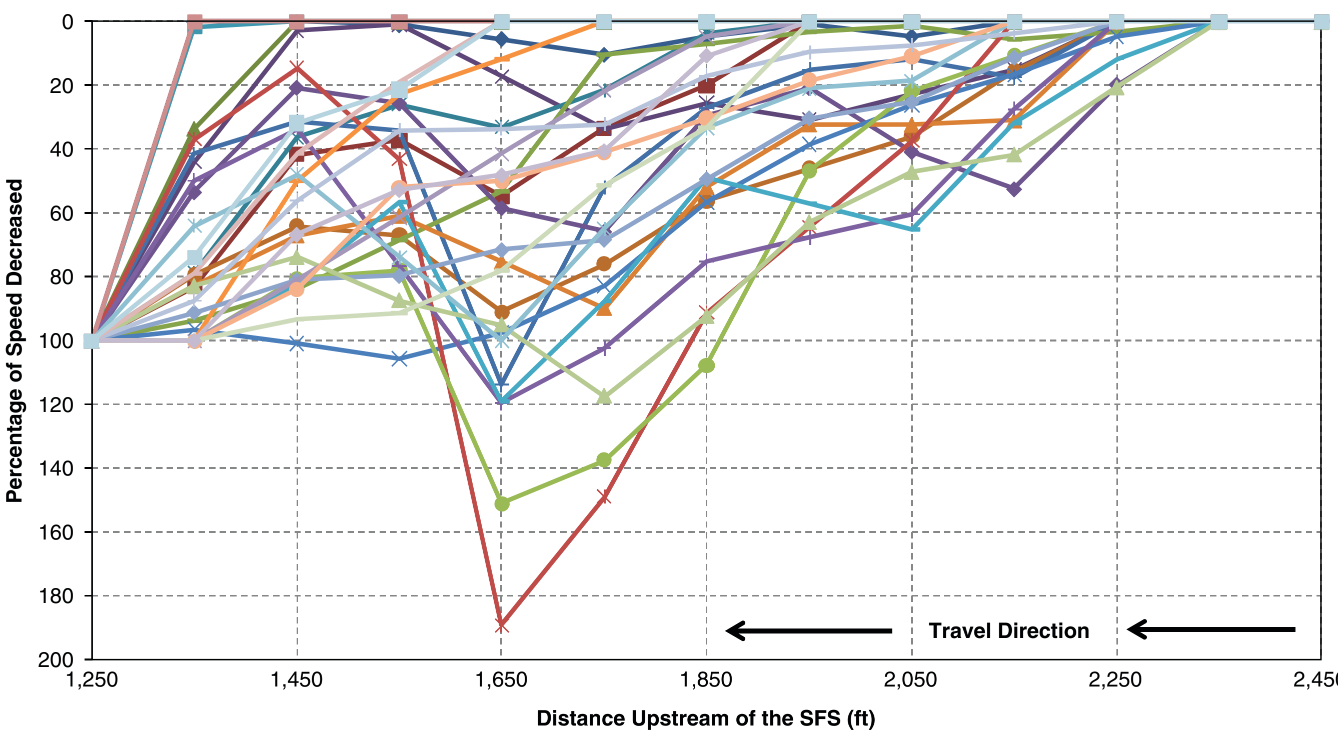


FIGURE 6 Percentage of speed reduction achieved as function of upstream distance.

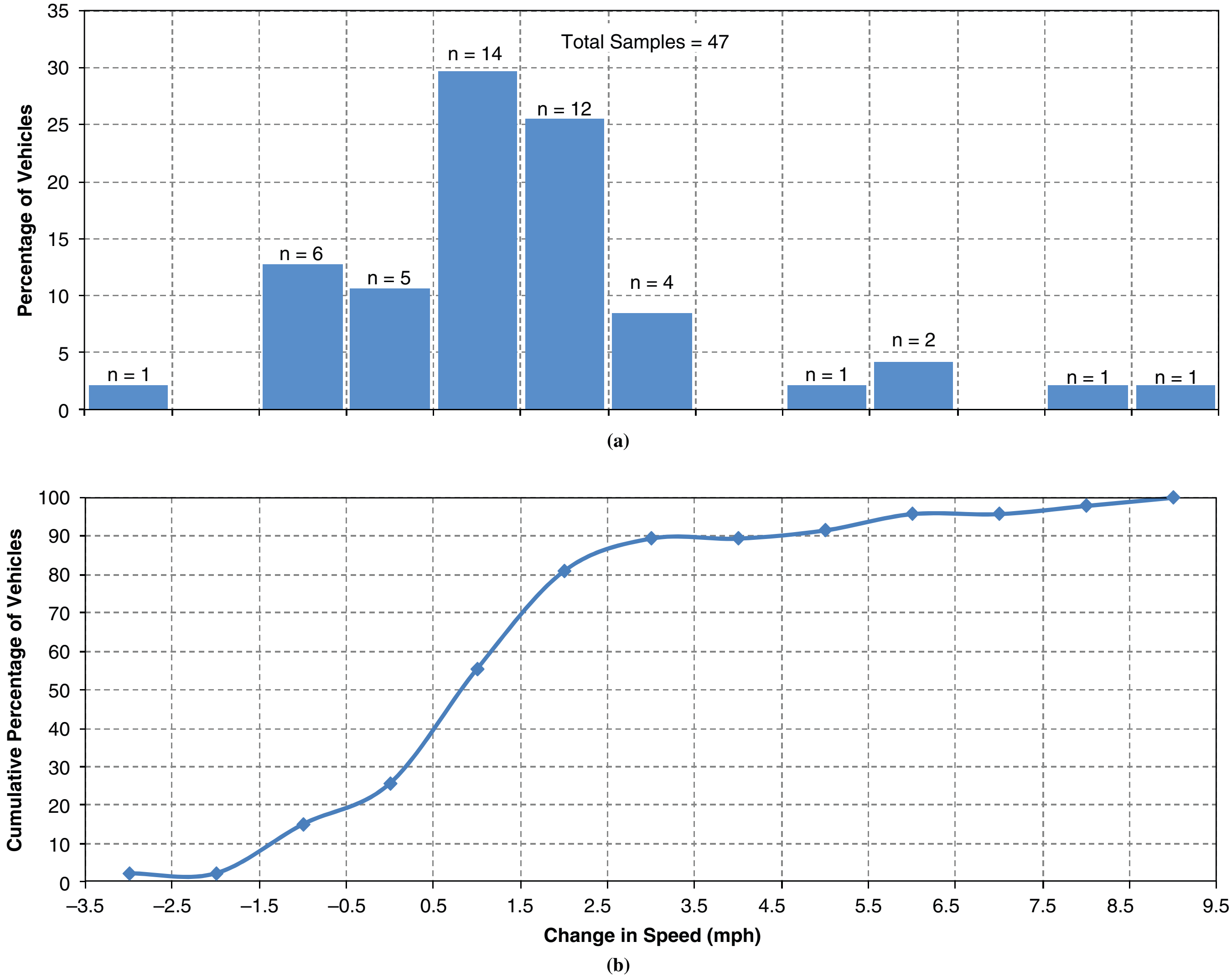


FIGURE 7 Characteristics of speed change downstream of SFS.

Downstream of the SFS, a total of 76% (n = 36) of the vehicles increased their speed, that is, their speed 800 ft after the SFS was higher than their speed at the sign. For analysis purposes, the research team focused their analysis only on those vehicles that increased their speed by at least 1.0 mph, which was equivalent to 49% (n = 23) of the sample.

To understand the end of the spatial effectiveness of the SFS, the research team looked at how each of the vehicles that increased their speed by at least 1.0 mph achieved the increase as a function of the distance traveled. The percentage of the speed increase as a function of the distance downstream of the SFS was plotted, and the results are shown in Figure 8. From those results, the researchers concluded that there is an inflection point in the vehicle trajectories located 300 to 600 ft downstream of the SFS, therefore suggesting that at this distance, the effectiveness of the SFS diminishes. Because the coverage of the radar units used to obtain vehicle trajectories extends to nearly 75 ft upstream of the SFS, not all the vehicles in Figure 8 show 0.0% increase exactly at the SFS, meaning that some of these vehicles started increasing their speed before reaching the SFS.

CONCLUSIONS

SFS are commonly used to provide feedback to drivers about their speed. However, the long-term effectiveness of SFS in slowing drivers is questionable. Also, limited knowledge exists about the distance over which SFS are effective in reducing speeds. By using radar and video recording technologies, vehicle trajectories (speed-distance relationship) near the SFS were monitored. Trajectories were obtained for vehicles approaching the SFS as well as for vehicles receding from the SFS. A binary logistic regression model was developed to understand the behavior of vehicles approaching the SFS. As expected, the model revealed that the greater the speeding, the higher was the probability of a vehicle reducing speed. Even drivers who were not speeding reduced their speed when approaching the SFS, although with a lesser probability.

Through the study of vehicle trajectories upstream of the SFS, the most significant reduction took place 1,200 to 1,400 ft upstream of the SFS. Similarly, downstream of the SFS, speeds started to increase 300 to 500 ft past the SFS. Findings suggest that once drivers pass the SFS, effectiveness is lost significantly. Findings suggest

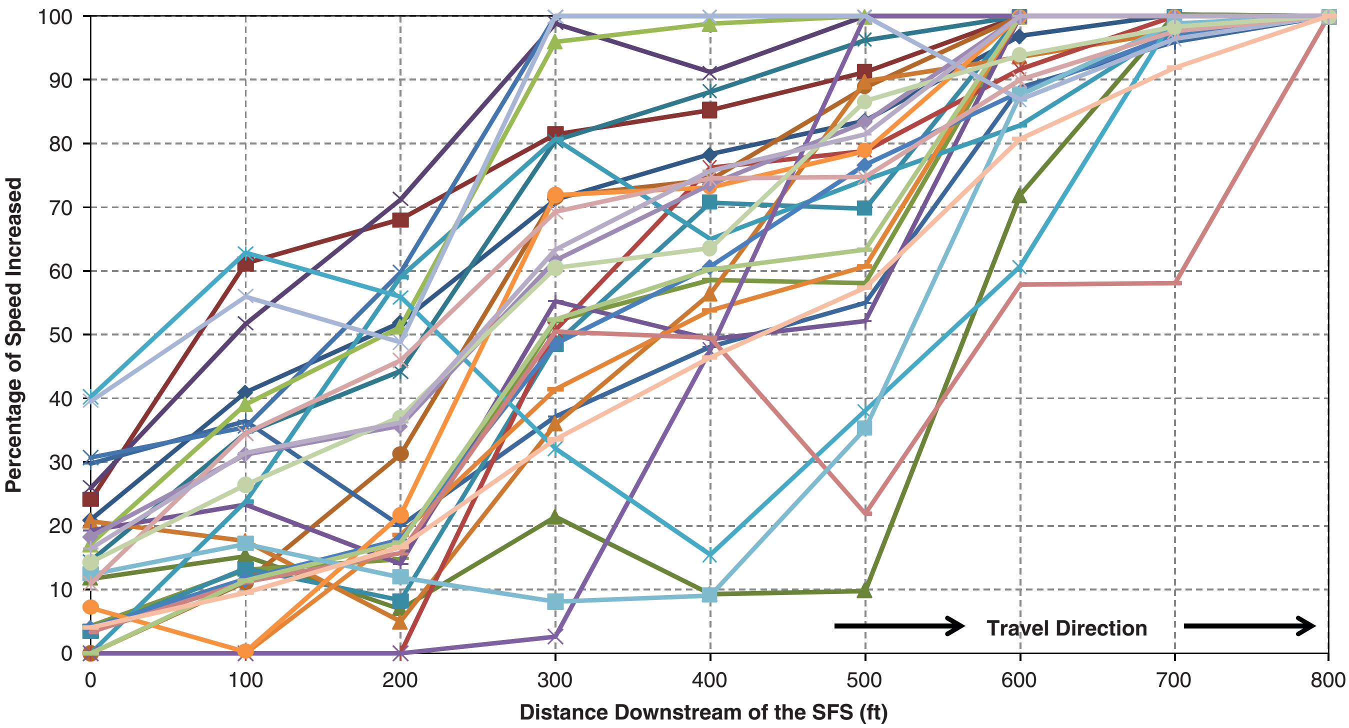


FIGURE 8 Percentage of speed reduction achieved as function of downstream distance.

that SFS should be placed near the location of the intended speed reduction. In addition, speed reductions from SFS are maintained only through short distances and therefore should not be considered a speed enforcement solution at a corridor level.

FUTURE WORK

Through the application of the methodology presented, the research team showed the feasibility of defining spatial effectiveness of an SFS. Further studies are recommended to generalize driver behavior near SFS for different types of sites, such as work zones and school zones.

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