Driver Response to a Dynamic Speed Feedback Sign at Speed Transition Zones Along High-Speed Rural Highways

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ABSTRACT
Research was conducted to assess the effectiveness of a dynamic speed feedback sign (DSFS) as a speed reduction strategy at speed transition zones along five high-speed rural highways in northern Michigan. The DSFS was positioned on the shoulder in advance of the reduced speed limit at each community and was programmed to display speeds of approaching vehicles alternating with the upcoming reduced speed limit. Using handheld LIDAR guns, vehicle speeds were tracked through each speed transition area before and after installation of the DSFS. The DSFS was found to have a significant speed reduction effect throughout each of the five speed transition zones. The speed reductions generally began when the DSFS came into the motorists' view, and the speed reduction effect increased as motorists approached DSFS. The greatest speed reduction effects were observed at the DSFS location itself, where speeds were 3.2 to 7.8 mph lower with the DSFS present, and these reductions were sustained upon entry to the community. Similarly, drivers were 78.8 to 92.4 percent less likely to exceed the reduced speed limit with the DSFS present. Positioning the DSFS further upstream typically resulted in earlier speed reductions, although this effect become negligible once vehicles reached the reduced speed zone entering the community. Based on the study findings, continued use of DSFS for speed management at speed transition zones entering communities on high speed rural roadways is recommended. When used in this context, the DSFS should be positioned 250 to 650 ft upstream of the reduced speed limit.

Keywords: speed transition zones, rural highways, dynamic speed feedback signs

BACKGROUND AND PROBLEM

Speeding is one of the major contributing factors of traffic fatalities in the U.S. According to the National Highway Traffic Safety Administration (NHTSA), speeding was responsible for 26 percent of traffic fatalities in 2019 (*1*). Nearly 86 percent of these speeding-related fatal crashes occurred on non-interstate roadways, and 41 percent (3,848 out of 9299) were on rural highways. In Michigan, speeding was also the cause of 25 percent of fatal crashes, which is similar to the national rate (*1*).

Speeding-related issues on rural highways are particularly critical for the small rural communities located along these highways. Motorists traveling on these highways and passing through rural communities typically expect uninterrupted high speeds, which may not be possible because of the need for lower speed limits through such communities (*2*). To help alert motorists of approaching speed reductions, appropriate speed management strategies must be utilized on the approach to the community. Such areas are typically referred to as speed transition zones, which are defined as "the area in which it is communicated to drivers that the roadway environment is changing (i.e., from rural to built-up) and that their speed should change as well" (*2*).

To reduce speed in advance of and entering a reduced speed limit zone, it is crucial to effectively convey the information pertaining to the pending reduced speed limit to approaching drivers. Various strategies have been implemented to help manage speeds, including median islands, roundabouts, road/lane narrowing, road diets, chicanes, countdown speed signs, transitional speed limits, optical speed bars, pavement markings, speed humps, rumble wave surfaces, gateways, optical lane narrowing, roadside vegetation, and dynamic speed feedback signs (*2*, *3*). Many of these treatments were successful in reducing speeds, particularly in low-speed environments. Unfortunately, their effectiveness on high-speed rural highways is not well established, perhaps due to a reluctance towards the implementation of aggressive speed reduction strategies at speed transition zones on rural highways (3).

A promising treatment strategy that has been implemented both in low- and high-speed environments is the dynamic speed feedback sign (DSFS). This device utilizes radar to detect the speed of the approaching vehicles and display the speed value and/or a speed warning message on a digital display along with targeted messages such as "SLOW DOWN," "TOO FAST," "SPEED LIMIT XX." This targeted messaging strategy can be personalized in nature, and it is particularly effective in reducing excessive speeding (*4–7*). It has been successful and widely used in different settings, including work zones on both freeways and rural highways (*8*, *9*), school zones (*10*), horizontal curves (*10–13*), high-speed arterials (*10*, *12*, *14*, *15*), freeway exit ramps (*5–7*), and also on speed transition zones (*4*, *10*, *16*, *17*). However, the use of speed feedback signs as a speed reduction countermeasure at speed transition zones on rural highways is not well documented, and the effectiveness of these devices in such contexts remains unknown.

Speed management has become an increasingly important topic over the prior decade as speed limits on rural highways have continued to rise across the United States. This includes Michigan, where, in 2017, speed limits were increased from 55 to 65 mph on greater than 900 miles of rural state highways across the northern portions of the state. Recent research found that travel speeds increased by 2.8 to 4.8 mph along with a sample of rural highway segments where the speed limit was raised to 65 mph (*18*). However, this prior research did not consider impacts to travel speeds within speed transition zones along the routes where the speed limit had been increased to 65 mph. These speed transition zones are particularly critical, as the speed limit within the rural community typically remained unchanged, thereby creating a greater speed reduction requirement along these highways. As such, it is imperative to identify treatments that can safely and effectively assist drivers with the transition from a high-speed to low-speed road environment. To that end, research was performed to evaluate the effectiveness of DSFS as a speed reduction strategy on high-speed rural highways transitioning into rural communities. A primary research objective was to assess the effectiveness of the DSFS across various speed limits, considering both the speed limit on the rural highway segment in addition to the reduced speed limit entering the community. The study specifically focused on the changes in driver speed selection at various points while approaching and entering the speed reduction zone before-and-after placement of the DSFS.

LITERATURE SUMMARY

Prior studies have evaluated the effect of DSFS in different settings, including rural highway environments. A comprehensive study on the effectiveness of DSFS on rural highway curves found a speed reduction of approximately two mph for both passenger cars and heavy vehicles, and these effects persisted over the 24 month study period (*4*). Similar effects were also observed from other studies on horizontal curves (*10*, *12*). Additionally, a study on the safety effect of DSFS showed a 5 to 7 percent reduction in crashes during the first three years after the installation on 22 horizontal curves across seven states (*19*).

Several studies have also evaluated the effect of DSFS used at speed transition zones on rural highways. Ullman and Rose (*10*) assessed the impact of DSFS on two transition zones where the transition is from a 55 mph roadway to 45 mph. The average speed dropped by 3.4 mph and 2.6 mph at the two sites after 1-3 weeks of installation and by 1.4 mph after 2-4 months of installation at both sites. A significant reduction in drivers traveling above the posted speed limits was also found. Another study by Sandberg et al. (*17*) found substantial speed reductions in transition zones, where the transition was from 50-55 mph roadways to 30-45 mph roadways. The average speed was reduced by 6 to 7 mph after one week, 3 to 8 mph after two months, 3 to 7 mph after seven months, and 6 to 8 mph after one year of initial deployment. An extended study conducted by Cruzado and Donnell (*16*) in Pennsylvania evaluated 12 transition zones where the vehicle transitions from 45-55 mph roadways to 25-40 mph on two-lane rural highways. The study found free-flowing average speed in the transition zones to reduce by 6.3 mph after the installation of the DSFS. However, the effectiveness of DSFS in reducing the speed only continued when it was activated. Moreover, Hallmark et al. (*4*) evaluated different types of DSFS installed at the transition zones in three small rural communities in Iowa. A simple feedback sign displaying only drivers' speed at a transition site from 55 to 25 mph found a decrease in average speed by 8 mph and reduced speeding five mph over the speed limit by 45 percent after one month of installation. A similar setup, including a static "YOUR SPEED" sign and a separate display showing drivers' speed found a decrease of 5 mph in average speed one month after the installation. Another DSFS, capable of showing alphanumeric messages, was programmed to display vehicle speed when the approach speed was between 26 and 39 mph and display "SLOW DOWN 25" when the approach speed was between 40-75 mph was also tested. The average speed decreased by 5 mph, and vehicles exceeding the speed limit by five mph decreased by 76 percent.

The results of prior research have shown that DSFS are suitable speed reduction countermeasures at speed transition zones. However, no prior studies evaluated the effect of DSFS on speed transitions from speed limits exceeding 55 mph. With the recent increase in speed limits to 65 mph on many rural highways in northern Michigan, further research pertaining to the use of DSFS in speed transition zones on such highway segments was warranted.

METHODOLOGY

A before-and-after field evaluation was performed at five different speed transition zones located along two different two-lane rural highways in northern Michigan. The following subsections detailed the various aspects of this evaluation, including a description of the test sign, speed transition zone sites, speed data collection, and data processing.

Test Sign and Messaging Strategy

The DSFS utilized in this study consisted of a portable changeable message sign (PCMS) with an integrated radar detection system, as shown in Figure 1. This sign complies with the Manual on Uniform Traffic Control Devices (MUTCD) and aligns with the Michigan Department of Transportation (MDOT) Draft Special provision for DSFS. The PCMS LED feedback display measured 138-inch by 75-inch, and was capable of displaying up to three lines of alphanumeric characters, with a maximum of eight 14-inch tall characters per line. The radar unit was embedded at the bottom of the message sign board, and utilized the microwave K-band and has a detection range of 1,000-ft and accuracy of ±1 mph for speed <40 mph and ±2 mph for speeds >40 mph. For this evaluation, the sign was programmed to display the speed of an approaching vehicle using a format of "YOUR SPEED XX" that alternated at one-second intervals with the downstream posted speed limit information in the format of "REDUCED SPEED XX MPH" (Figure 1). The sign was positioned on the shoulder, keeping an adequate lateral buffer from the travel lanes. Two identical signs were utilized during this study.

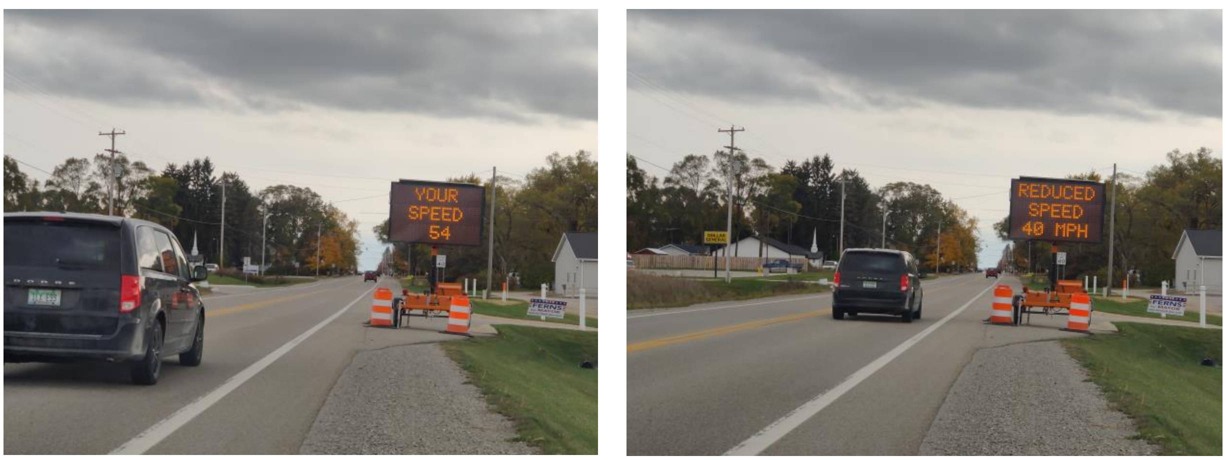


FIGURE 1 Dynamic speed feedback sign for field evaluation

Study Sites

Five speed transition zones on two-lane rural highways entering four small communities in Iosco County, Michigan were selected for this study. The sites were selected based on the recommendations from MDOT considering the reported speeding-related issues. Three of the speed transition zones were located along M-65, which possesses a 65-mph rural speed limit. The remaining two locations were along US-23, which possesses a 55-mph rural speed limit. Table 1 shows the details of each of the five speed transition zone locations.

TABLE 1 Site Characteristics

Site No	Location & Direction	Speed Limit Upstream of Community (mph)	Speed Limit Entering Community (mph)	Distance between Start of Reduced Speed Limit Zone and DSFS (ft)	Distance between Start of Reduced Speed Limit Zone and W3-5 Sign (ft)
1	M-65 Whittemore, NB	65	35	283	1,229
2	M-65 Whittemore, SB	65	40	352	585
3	M-65 Hale, SB	65	45	296	679
4	US-23 Oscoda, NB	55	45	299	628
5	US-23 Tawas, SB	55	45	400 & 625	1,008

MUTCD-compliant W3-5 (Figure 2) advanced warning signs were present at all five sites. However, the location of the advance warning signs with respect to the start of the reduced speed limit zone varied from site-to-site, as shown in Table 1. For example, the W3-5 signs at sites 1 and 5 were positioned at approximately double the distance from the speed limit sign as the W3-5 signs at sites 2, 3, and 4. It should be noted that the nearest 55 or 65 mph posted speed limit sign was more than 2 miles upstream of the speed transition zone at each site.

The DSFS was installed between the W3-5 sign and the posted speed limit sign at each site. For sites, 1 through 4, the DSFS was installed between 283 and 352 ft in advance of the reduced speed limit zone. However, a minor road access point at site 5 required the DSFS to be positioned further upstream, and it was decided to subsequently test the sign at two different upstream locations (400-ft and 625-ft) at this site.

Speed Data Collection

The speed data were collected in two phases at each study site: 1.) under the existing site conditions (without the DSFS), and 2.) after the installation of the DSFS. Note that data were collected with the DSFS present in two different locations on the same day at site 5. Data were collected during weekdays under clear weather conditions in late fall 2020 and late spring 2021. To address any novelty effect associated with the DSFS, the after-period data were collected no earlier than one week after installing the DSFS. The same setups (e.g., the placement of the signs, the positions of data collector vehicles, etc.) were used for both before and after data collection.

Vehicle speeds were continuously tracked for vehicles approaching and entering the speed reduction zone at each location with and without the DSFS in place. The speed data were collected using a sequence of two handheld LIDAR guns (i.e., police laser) operated by technicians from within separate vehicles parked just beyond the shoulder or in a driveway. Data were collected from the same location during each data collection period at a given site. The LIDAR guns were ProLaser III manufactured by Kustom Signals Inc., which can detect vehicular speed and distance three times per second with an accuracy of ±1 mph at a range of 6,000 ft. From a practical sense, each LIDAR gun is typically only utilized over a range of 1,200 feet due to geometry and encroachment of other vehicles.

The upstream LIDAR collector was positioned between 1,810 and 2,280 ft upstream of the speed limit sign, while the downstream collector was positioned between 640 and 1,025 ft upstream of the speed limit sign. These locations were selected to be away from any of the critical traffic control devices of interest (DSFS, W3-5, speed limit sign, etc.) to minimize the influence of the data collection vehicle on driver behavior when passing by these devices. The upstream data collector would track each vehicle at least 100 ft beyond the downstream LIDAR technician, at which point the tracking responsibilities were transferred to the downstream technician, who would track each subject vehicle over the remaining distance to slightly beyond the speed limit sign. The data collectors communicated via cellular communications to ensure a seamless “hand-off” of the LIDAR speed tracking as each subject vehicle proceeded along the speed transition zone. In doing so, the upstream technician would convey the type and color of each subject vehicle to the downstream LIDAR collector. In order to isolate driver response to the traffic control devices, only freely flowing vehicles were included. An example data collection setup including locations of upstream and downstream LIDAR, advance warning sign, DSFS, and posted speed limit sign is presented in Figure 2.

Each LIDAR gun was connected to a laptop using a data transfer cable, which allowed for all measurements to be recorded in real-time using proprietary software. The computer LIDAR recordings included timestamp, distance, and speed for each measurement. After completion of the LIDAR tracking for each subject vehicle, both data collectors added remarks on the type and color of the vehicle, in addition to any other comments, which were later used to combine the two data sets into a continuous speed profile for each subject vehicle. Collecting data using this LIDAR tracking method provides a significant advantage over cameras or pneumatic tubes, as it provides continuous speed measurements over the entire segment of interest, as opposed to spot-speeds at fixed points.

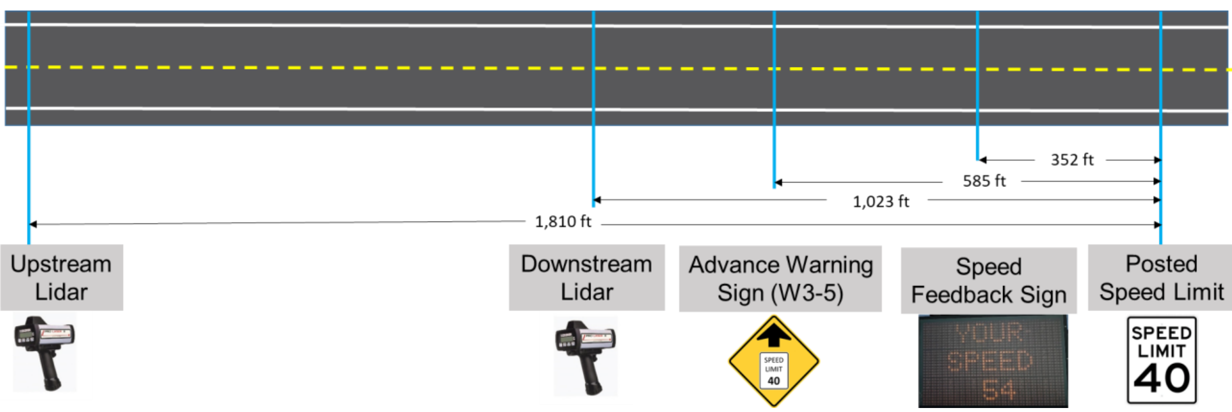


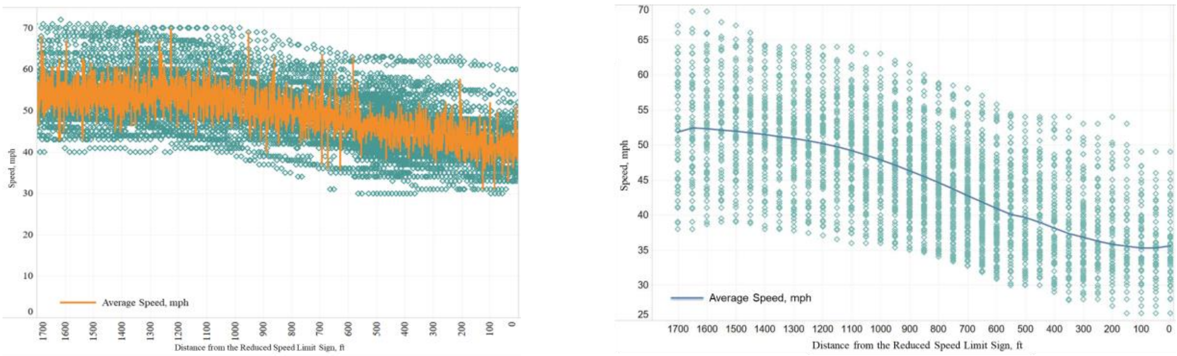
FIGURE 2 Data collection setup for speed tracking (SB Whittemore)

Data Processing

After completion of the LIDAR tracking data collection from the field, both files from the upstream and downstream LIDAR collector were joined using vehicle sequence, type, and color. Vehicles that were not able to be matched between the two data collection files, which occasionally occurred for various reasons (e.g., vehicle entering/exiting a driveway, entire profile not captured due to technical issue, etc.), were removed. A sample of the joined data is shown in Figure 3a.

As the relative distances between the LIDAR collectors and the various traffic control devices were known, all distances were converted to be relative to the start of the speed reduction zone (i.e., the location of the speed limit sign). Because LIDAR speeds cannot be measured at the same locations on the roadway for every vehicle, it was necessary to convert this data to a series of spot speeds using an interpolation technique in order to allow for speeds to be assessed at specific reference points. The combined raw data were linearly interpolated at 1-ft increments using the adjacent speeds. Interpolated speeds were then selected at regular 50 ft intervals starting from the posted reduced speed limit sign at entry to the community (Figure 3b). Compiling the

LIDAR data in this manner provides a robust array of spot speeds and affords a before and after comparison of speed profiles, including change in the speed at various distances from the speed reduction zone for the sample of vehicles traversing through the speed transition zones.



a) Raw LIDAR data b) LIDAR data interpolated at 50-ft increments

FIGURE 3 Raw and interpolated vehicle speed data approaching speed reduction zone

The data collected before and after the installation of the DSFS were combined for each site separately. After processing the data, the descriptive statistics (i.e., mean, standard deviation, etc.) were compared, and simple graphical representations (i.e., scatterplot, line graphs, frequency independently for each site, as the reduced speed limit and the advance warning sign positions were different among the five sites. Passenger cars and heavy vehicles were coded separately. Preliminary models suggested only marginal differences in DSFS effectiveness between passenger cars and heavy vehicles and further analysis of vehicle-specific DSFS effects was not performed.

Analysis

To determine the effectiveness of DSFS in reducing speeds, the entire speed profiles before and after the installation of the DSFS were analyzed. Two primary analyses were conducted using multiple linear regression or binary logistic regression, depending on the nature of the dependent variable. The dependent variables for these analyses included:

- Speeds while traversing through the transition zone, and
- Probability of a vehicle exceeding the posted speed limit at the start of the reduced speed limit zone.

When analyzing the speed data, the speed measurements were binned at 50 feet increments on the approach to the transition zone, beginning with the furthest upstream point (between 1,700 and 1,850 ft depending on the site), and continuing to the posted speed limit sign. The vehicle speed at the furthest upstream point prior to installation of the DSFS at each location was treated as the base condition in the models. The speed data at all other distances (and separated between the before and after the installation of DSFS) were coded with separate binary variables and analyzed against the base condition to determine the effects of the DSFS incrementally on the approach to the speed reduction zone. To streamline the analysis and simplify interpretation of the results, the incremental speed measurements were categorized into different regions, as follows: upstream of the transition zone, at the approximate detection limit of the DSFS radar, at the DSFS itself, and at the speed limit sign posted at the start of the reduced speed limit zone.

Multiple linear regression was used to analyze the vehicular speed data. A general form of the regression model is shown in equation 1:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_k X_{ik} + \varepsilon_i \quad (1)$$

where Y_i is the measured speed at any point for vehicle i, X_{i1} to X_{ik} are the independent variables affecting the target variables, β_0 is the intercept term, β_1 to β_k are the estimated regression coefficients for each independent variable, and ε_i is a normally distributed error term with variance σ^2.

The probability of vehicles exceeding the posted speed limit at the start of the reduced speed limit zone was analyzed using binary logistic regression analysis. The binary logistic regression model has the form:

$$Y_i = logit(P_i) = ln\left(\frac{P_i}{1 - P_i}\right) = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_k X_{ik} \quad (2)$$

where the response variable, Y_i, is the logistic transformation of the probability of speed over the reduced speed limit. This probability is denoted as P_i. Similar to the linear regression model, X_{i1} to X_{ik} are independent variables, β_0 is an intercept, β_1 to β_k are estimated regression coefficients for each independent variable.

RESULTS AND DISCUSSION

Effect of DSFS on Transition Zone Speeds

The results of linear regression models for vehicle speeds traversing each speed transition zone are shown in Table 2, and are reflected graphically in Figure 4. Note, although the DSFS was tested in two positions at Site 5, to provide consistency with the other test sites, only the results from the 400-ft upstream position are included in Table 2. The effects of the DSFS position at this site will be presented and discussed later.

TABLE 2 Linear Regression Results for Transition Zone Speeds, by Site and DSFS Presence

Dependent Variable=Speed, mph											
		Site 1 (65 to 35) (N=9,620)		**Site 2 (65 to 40) (N=9,036)**		**Site 3 (65 to 45) (N=10,728)**		**Site 4 (55 to 45) (N=10,286)**		**Site 5 (55 to 45) (N=17,100)**	
Parameter	**DSFS Present?**	**Est.**	**p-value**	**Est.**	**p-value**	**Est.**	**p-value**	**Est.**	**p-value**	**Est.**	**p-value**
Intercept		55.48	<0.01	55.17	<0.01	59.61	<0.01	56.17	<0.01	56.60	<0.01
Passenger car		*Base Condition*									
Heavy vehicle		-3.82	<0.01	-1.21	<0.01	-1.36	<0.01	1.14	<0.01	-1.55	<0.01
Upstream of transition zone	No	*Base Condition*									
	Yes	-2.16	<0.01	-0.32	0.67	-2.37	<0.01	0.58	0.26	-0.82	0.09
At DSFS radar detection limit	No	-0.55	0.34	-2.20	<0.01	-1.49	0.34	-0.13	0.75	0.44	0.24
	Yes	-3.94	<0.01	-3.03	<0.01	-4.67	<0.01	0.11	0.79	-0.88	0.02
At advance warning sign	No	-0.94	0.20	-5.18	<0.01	-4.82	<0.01	-0.90	0.07	-0.02	0.96
	Yes	-4.75	<0.01	-8.60	<0.01	-9.46	<0.01	-1.78	<0.01	-3.44	<0.01
At DSFS	No	-10.90	<0.01	-6.62	<0.01	-6.58	<0.01	-2.66	<0.01	-1.00	<0.01
	Yes	-18.66	<0.01	-11.27	<0.01	-12.16	<0.01	-5.83	<0.01	-6.34	<0.01
At speed limit sign	No	-13.29	<0.01	-8.91	<0.01	-8.45	<0.01	-3.80	<0.01	-2.41	<0.01
	Yes	-19.53	<0.01	-13.19	<0.01	-13.65	<0.01	-7.40	<0.01	-8.04	<0.01

Note: "Est." refers to the parameter estimates from the linear regression model

The parameter estimates from Table 2 can be directly interpreted as the difference in mean speed compared to the base condition (i.e., speed upstream of the transition zone without the DSFS) at each site. For example, at Site 1, compared to the base condition, mean speeds at the advance warning sign were 0.94 mph lower without the DSFS and 4.75 mph lower with the DSFS. It follows that the magnitude of the DSFS effects can be interpreted by taking the difference between the DSFS parameter estimates (i.e., "Yes" minus "No") at each speed measurement location. So for the aforementioned Site 1 data, the parameter estimates would suggest that the DSFS contributed a 3.81 mph speed reduction when vehicles had reached the advance warning sign.

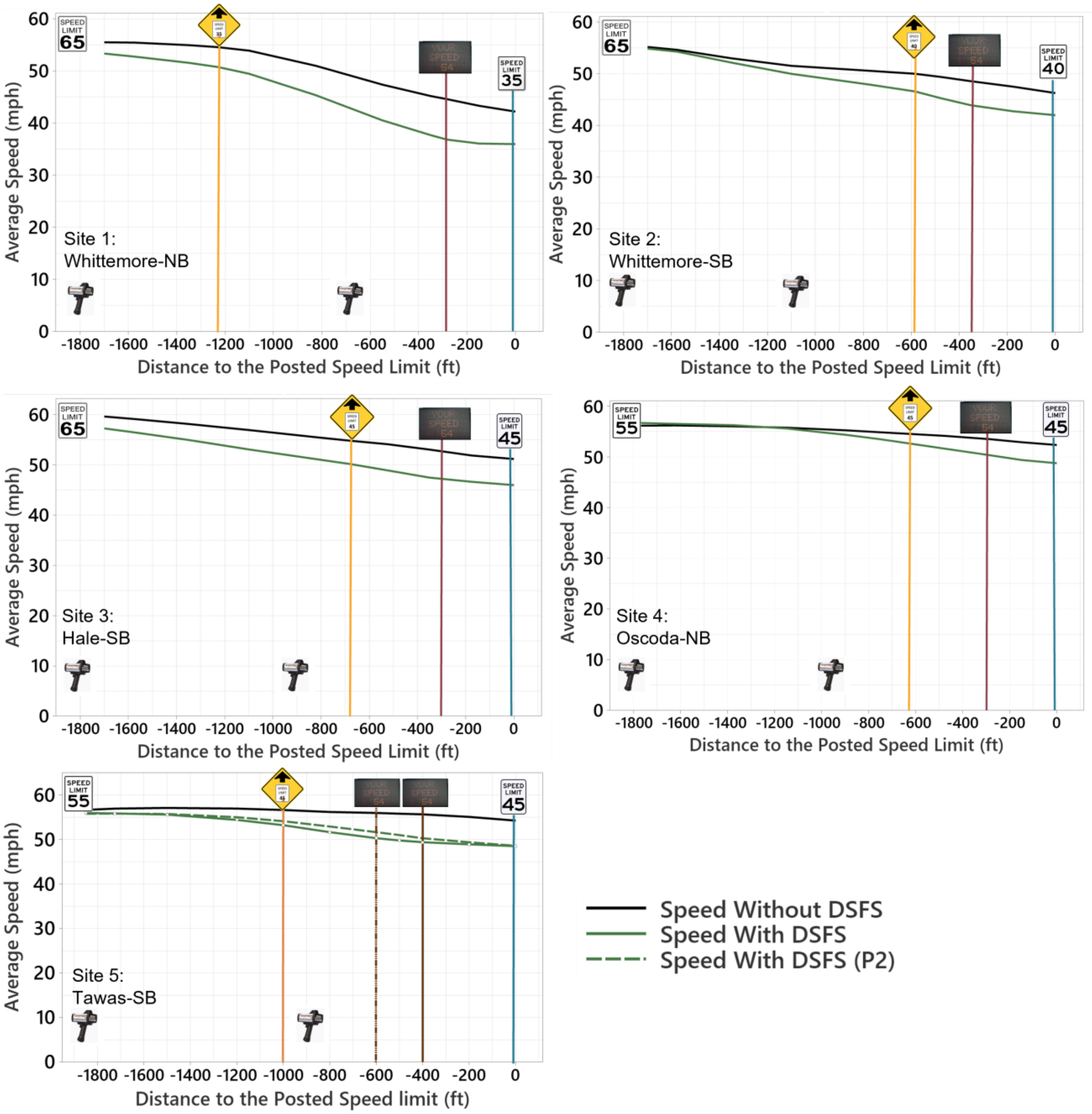


FIGURE 4 Transition zone vehicle speed profiles, by site and DSFS presence

Effect of Speed Measurement Location

The results displayed in Table 2 suggest that the DSFS had a significant effect on vehicle speeds throughout the speed transition zone. At three of the five locations, a measurable speed reduction effect was already present at the furthest upstream data collection point, which was between 1,700 and 1,850 ft upstream of the posted speed limit sign. This was not unexpected, because the DSFS was already visible to motorists at this point. When vehicles entered the typical radar detection range of the DSFS, and where speed feedback messages would subsequently begin to be displayed, average speeds were lower with the DSFS in place at four of the five sites, with DSFS-related speed reductions ranging from 0.8 to 3.4 mph.

Figure 5 presents the speed reduction effects associated with the DSFS at three successive locations on the approach to the speed reduction zone, which included 1.) at the advance warning sign, 2.) at the DSFS, and 3.) at the posted reduced speed limit sign. From Figure 5 it can be observed that the magnitude of the speed reduction effect associated with the DSFS became greater as motorists continued along the approach to the community. The DSFS had the greatest effect on speeds when vehicles reached the DSFS itself, where speeds were 3.2 to 7.8 mph lower, on average, across the five sites when the DSFS was on site. This speed reduction effect was generally sustained through the remainder of the transition zone through to the speed limit sign posted at the start of the reduced speed limit zone, at which point the speed data collection ceased. At this point, vehicular speeds ranged from 3.6 to 6.2 mph lower, on average, across the five sites when the DSFS was present.

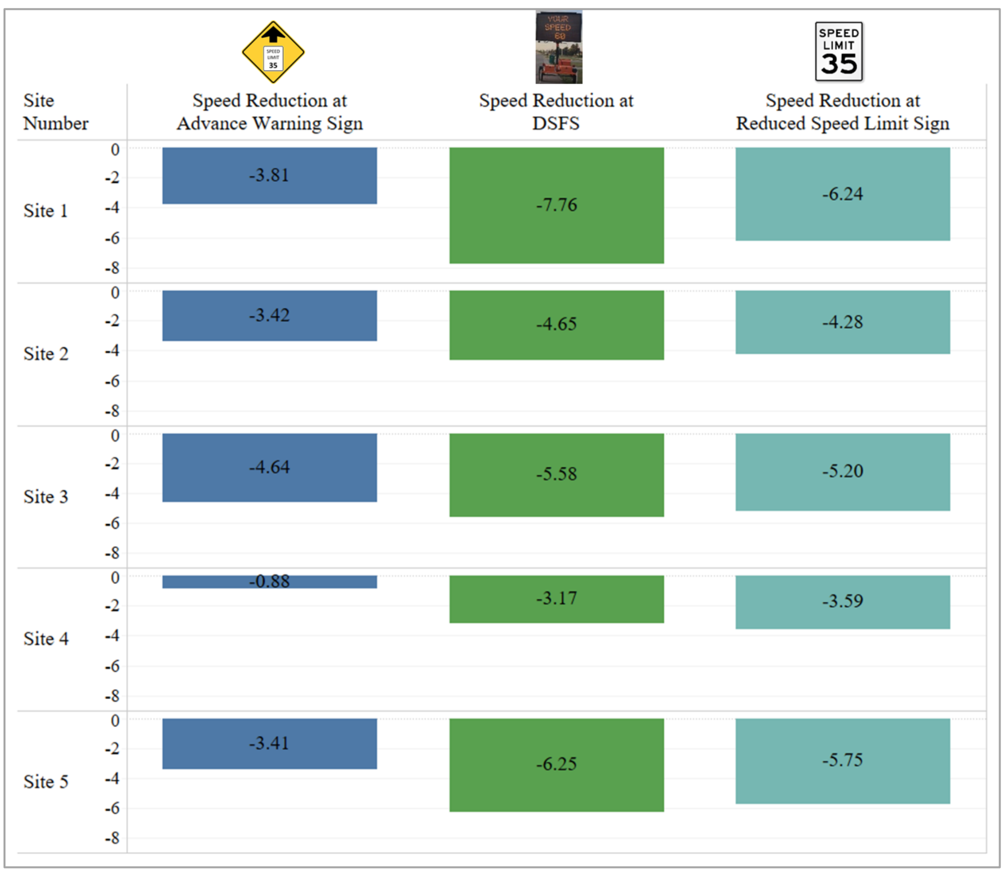


FIGURE 5 Speed reductions with DSFS present at the transition zone, by site and speed measurement location

Effect of Upstream and Downstream Speed Limit

Although the DSFS was shown to reduce speeds at each of the five speed transition zones, the strongest DSFS speed reduction effects were observed at the location with the greatest speed limit reduction (site 1; 65 mph to 35 mph). However, beyond this, there were no apparent trends between the upstream or downstream speed limit and the speed reduction effectiveness of the DSFS. The DSFS consistently showed the weakest effect at Site 4, which was a 55 to 45 mph location. This was perhaps due to the transition zone site being located in a slightly more urbanized environment (e.g., greater density of commercial property and driveways) compared to the other four sites.

Effect of DSFS Location

Site 5 provided the additional opportunity to assess the effect of the position of the DSFS with respect to the speed reduction zone. At this site, the DSFS was tested at 625 ft and 400 ft upstream of the speed limit sign. The results of this analysis are presented in Table 3. Again, the DSFS effects may be directly interpreted by taking the differences between the DSFS parameter estimates at each speed measurement location within the transition zone.

TABLE 3 Linear Regression Results for Transition Zone Speeds with Respect to DSFS Location (Site 5)

Parameter	DSFS Presence and Location	Estimate	p-value
Intercept		56.60	<0.01
Passenger car		*Base Condition*	
Heavy vehicle		-1.55	<0.01
1800-ft upstream of reduced speed limit zone	No DSFS	*Base Condition*	
	DSFS 625 ft upstream	0.69	0.16
	DSFS 400 ft upstream	-0.82	0.09
At DSFS radar detection limit	No DSFS	0.44	0.24
	DSFS 625 ft upstream	-1.05	<0.01
	DSFS 400 ft upstream	-0.88	0.02
At 600 ft upstream of reduced speed limit zone	No DSFS	-0.69	<0.01
	DSFS 625 ft upstream	-6.35	<0.01
	DSFS 400 ft upstream	-4.96	<0.01
At 400 ft upstream of reduced speed limit zone	No DSFS	-1.00	<0.01
	DSFS 625 ft upstream	-7.25	<0.01
	DSFS 400 ft upstream	-6.34	<0.01
At start of reduced speed limit zone	No DSFS	-2.41	<0.01
	DSFS 625 ft upstream	-8.15	<0.01
	DSFS 400 ft upstream	-8.04	<0.01

As expected, the DSFS had a significant effect on vehicle speeds throughout the transition zone for both DSFS installation locations at Site 5. Not surprisingly, the speed reductions began further upstream when the DSFS was positioned further upstream, which is also clearly reflected in the Site 5 graph within Figure 4. At 600-ft upstream of the posted speed limit sign, the DSFS had an approximately 1.4 mph greater effect on motorist speeds when installed at the further upstream location. However, any speed reduction differences between the two sign locations diminished as vehicles approached the speed reduction zone, becoming negligible at the start of the reduced speed limit at entry to the community.

Effect of DSFS on Speed Limit Compliance

Table 4 shows the results of binary logistic regression analysis for vehicles exceeding the speed limit at the speed limit sign posted at the start of the reduced speed limit zone. Figure 6 shows the percentage of vehicles exceeding the speed limit, in addition to exceeding 5 and 10 mph over the speed limit.

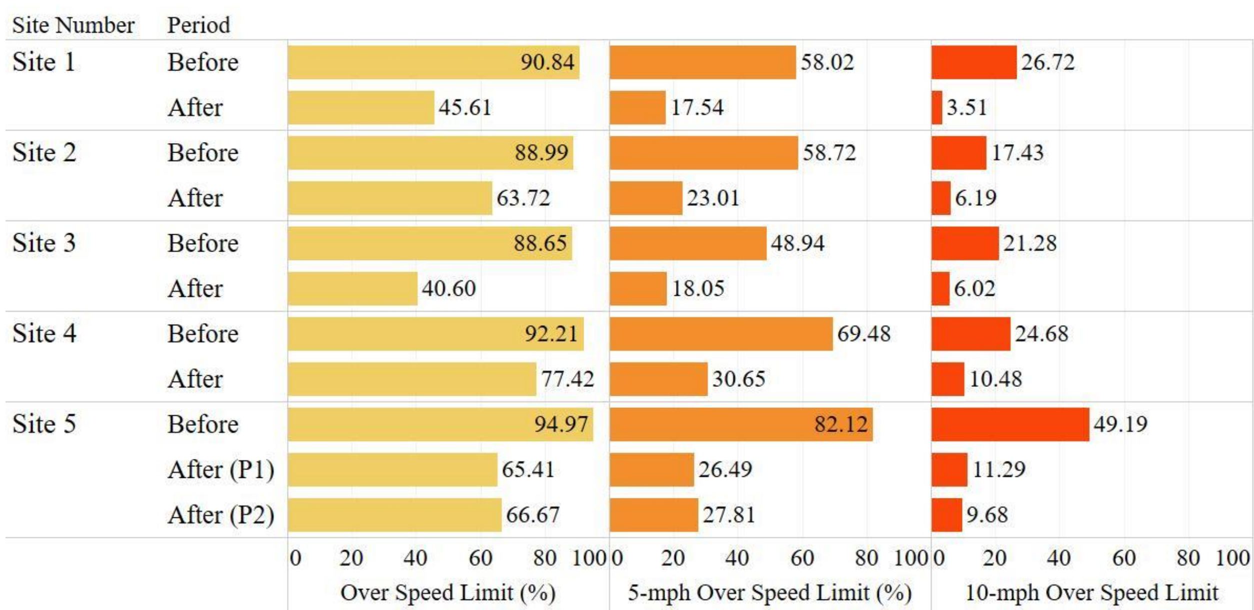


FIGURE 6 Percentage of vehicles exceeding the speed limit, 5-mph over the speed limit, and 10-mph over the speed limit

As expected, drivers were less likely to exceed the speed limit at start of the reduced speed limit zone when the DSFS was present in the speed transition zone. Interpretation of the parameter estimates from the binary logistic regression model suggests that drivers were 78.8 to 92.4 percent less likely to exceed the speed limit at the start of the reduced speed limit zone with the DSFS present on the approach. Similar to the linear regression models for transition zone speeds, the DSFS was found to be most effective where the speed limit reduction was greatest (i.e., Site 1: from 65 mph to 35 mph). Further, the DSFS was also slightly more effective when positioned at the further upstream location (P1: 625 ft upstream) at Site 5. Interestingly, examination of Figure 6 suggests that speed limit compliance was lowest at the two 55 to 45 mph speed reduction zone sites (sites 4 and 5), with and without the DSFS present.

TABLE 4 Binary logistic regression results for exceeding the posted speed limit

Dependent Variable: Exceeding Posted Speed Limit (35 mph) - Site 1				
Parameter	**Estimate**	**Std. Error**	**p-value**	**Elasticity**
Intercept	-4.47	1.58	<0.01	0.01
Upstream Speed	0.13	0.03	<0.01	1.14
Passenger Cars		*Base Condition*		
Heavy Vehicles	0.32	0.66	0.63	1.38
Existing site condition (No DSFS)		*Base Condition*		
DSFS present	-2.57	0.37	<0.01	0.08
Dependent Variable: Exceeding Posted Speed Limit (40 mph) - Site 2				
Parameter	**Estimate**	**Std. Error**	**p-value**	**Elasticity**
Intercept	-7.17	1.66	<0.01	0.0
Upstream Speed	0.17	0.03	<0.01	1.190
Passenger Cars		*Base Condition*		
Heavy Vehicles	-0.99	0.52	0.06	0.370
Existing site condition (No DSFS)		*Base Condition*		
DSFS present	-1.60	0.36	<0.01	0.202
Dependent Variable: Exceeding Posted Speed Limit (45 mph) - Site 3				
Parameter	**Estimate**	**Std. Error**	**p-value**	**Elasticity**
Intercept	-12.185	2.050	<0.001	0.00
Upstream Speed	0.248	0.037	<0.001	1.28
Passenger Cars		*Base Condition*		
Heavy Vehicles	0.536	0.627	0.392	1.71
Existing site condition (No DSFS)		*Base Condition*		
DSFS present	-2.576	0.360	<0.001	0.08
Dependent Variable: Exceeding Posted Speed Limit (45 mph) - Site 4				
Parameter	**Estimate**	**Std. Error**	**p-value**	**Elasticity**
Intercept	-11.25	2.75	<0.01	0.00
Upstream Speed	0.25	0.05	<0.01	1.29
Passenger Cars		*Base Condition*		
Heavy Vehicles	-0.21	0.64	0.74	0.81
Existing site condition (No DSFS)		*Base Condition*		
DSFS present	-1.55	0.41	<0.01	0.21
Dependent Variable: Exceeding Posted Speed Limit (45 mph) - Site 5				
Parameter	**Estimate**	**Std. Error**	**p-value**	**Elasticity**
Intercept	-12.10	2.12	<0.01	0.00
Upstream Speed	0.28	0.04	<0.01	1.32
Passenger Cars		*Base Condition*		
Heavy Vehicles	-0.98	0.45	0.03	0.38
Existing site condition (No DSFS)		*Base Condition*		
DSFS present 625 ft Upstream of the Speed Limit Sign (P1)	-2.33	0.44	<0.01	0.10
DSFS present 400 ft Upstream of the Speed Limit Sign (P2)	-1.98	0.45	<0.01	0.14

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Speed management has become an increasingly important topic over the prior decade as speed limits on rural highways have continued to rise across the United States. This is particularly the case in Michigan, where speed limits were raised from 55 to 65 mph on more than 900 miles of rural two-lane highways in 2017, and research has shown increases in travel speeds along these segments (*18*). In light of this, it is imperative to identify treatments that can safely and effectively assist drivers with the transition from a high-speed to low-speed road environment. While the results of prior research have shown that DSFS are suitable speed reduction countermeasures at speed transition zones, no prior studies had evaluated transitions from speed limits of 65 mph.

To address these issues, research was performed to evaluate the effectiveness of a dynamic speed feedback sign as a speed reduction strategy on high-speed rural highways transitioning into rural communities. A primary research objective was to assess the effectiveness of the DSFS across various speed limits, considering both the speed limit on the rural highway segment along with the reduced speed limit upon entry to the community. A before-and-after observational study was conducted at five speed transition zones on two-lane rural highways in northern Michigan to evaluate the effectiveness of DSFS on motorist speeds while traversing the speed transition zones. Speed limits along the rural highway segments were either 55 or 65 mph, while the speed reduction zones entering the communities ranged from 35 to 45 mph. The DSFS display was mounted on a PCMS and positioned on the shoulder in advance of the reduced speed limit area at each site. The DSFS was programmed to display the approaching vehicle's speed (measured by an auxiliary radar unit attached to the sign) and alternated with information pertaining to the reduced speed limit ahead.

Vehicle speeds were continuously tracked for a sample of vehicles approaching and entering the speed reduction zone at each location before and after installation of the DSFS. The speed data were collected using a sequence of two handheld LIDAR guns operated by technicians from within separate vehicles parked just beyond the shoulder or in a driveway. This LIDAR speed tracking method allowed for the speed reduction effects of the DSFS to be assessed at various points along the speed transition zone.

The results of this evaluation suggest that the DSFS had a significant effect on vehicle speeds throughout the speed transition zone, and this effect was consistent across the five test locations. The speed reductions generally began when the DSFS came into the motorists' view, and the speed reduction effect of the DSFS increased as motorists approached the community. The DSFS had the greatest effect on speeds when vehicles reached the DSFS itself, where speeds were 3.2 to 7.8 mph lower, on average, when the DSFS was present across the five sites. This speed reduction effect was generally sustained through the remainder of the transition zone, continuing to the speed limit sign posted at the start of the reduced speed limit zone entering the community. At this point, vehicular speeds ranged from 3.6 to 6.2 mph lower, on average, across the five sites when the DSFS was present. In terms of speed limit compliance, drivers were 78.8 to 92.4 percent less likely, on average, to exceed the reduced speed limit when the DSFS was present.

There was limited evidence to suggest that the DSFS provided a greater speed reduction benefit as the differential between the upstream and downstream speed limit increased, although this effect was only supported by the results from a single site. Considering the effect of DSFS location with respect to the reduced speed limit zone, not surprisingly, the speed reductions began further upstream when the DSFS was positioned further upstream. However, this effect diminished as vehicles approached the speed reduction zone, becoming negligible at the speed limit sign entering the community.

Collectively, the findings from this research suggest that a DSFS is an effective speed reduction strategy when used in speed transition zones on rural highways, and the continued use of such devices in this context is recommended. To allow motorists with sufficient time to react and adjust speed accordingly, the DSFS should be placed between the advance warning sign (e.g., W3-5) and the posted speed limit sign at the entrance to the speed reduction zone. However, the authors caution against placing the DSFS at too great a distance upstream, as drivers may be more likely to disregard warning message that are delivered prematurely (*5*, *6*). Thus, in this context, installing the DSFS at a range of 250 to 650 ft upstream of the posted reduced speed limit is recommended.

This evaluation was limited to temporary installations of a PCMS-mounted DSFS. Future research should assess the effects of smaller roadside post-mounted DSFS in these contexts, and include a temporal assessment to determine whether the sign loses effectiveness over time. Prior studies have demonstrated the use of the smaller signs (15-inch or 18-inch display) to be effective in speed reduction in other contexts such as interchange ramps and rural highway curves (*5*, *18*). To that end, future evaluations should also assess the amount of time that the portable DSFS, such as those utilized in this study, should be left on site before moving elsewhere.

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CONTRIBUTIONS

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