Effects of Speed Feedback Trailer Positioning and Presence of Law Enforcement on Driver Behavior in Freeway Work Zone Lane Closures

by

Md Shakir Mahmud, M.Sc.
Ph.D. Student
Department of Civil and Environmental Engineering
Michigan State University
East Lansing, MI, 48824
E-mail: mahmudmd@msu.edu

Hisham Jashami, Ph.D., RSP1
Research Associate
Department of Civil and Environmental Engineering
Michigan State University
East Lansing, MI 48824
E-mail: hisham.jashami@oregonstate.edu

Megat Usamah Megat Johari, M.Sc.
Ph.D. Student
Department of Civil and Environmental Engineering
Michigan State University
East Lansing, MI 48824
E-mail: megatjoh@msu.edu

Nischal Gupta, M.Sc.
Ph.D. Student
Department of Civil and Environmental Engineering
Michigan State University
East Lansing, MI 48824
E-mail: guptanis@msu.edu

Anshu Bamney, M.Sc.
Ph.D. Student
Department of Civil and Environmental Engineering
Michigan State University
East Lansing, MI 48824
E-mail: bamneyan@msu.edu

Timothy J. Gates, Ph.D., P.E.
Professor
Department of Civil and Environmental Engineering
Michigan State University
East Lansing, MI 48824
E-mail: gatestim@msu.edu

Peter T. Savolainen, Ph.D., P.E.
MSU Foundation Professor
Department of Civil and Environmental Engineering
Michigan State University
East Lansing, MI 48824
E-mail: pete@msu.edu

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ABSTRACT
Work zone speed limits and management of work zone speeds continue to be critical areas of concern for transportation agencies. This field study sought to evaluate select strategies for improving compliance with work zone speed limits, which included a speed feedback trailer (SFT) and the presence of law enforcement. A SFT was tested at the start and end of the taper within a freeway work zone single-lane closure to determine which position provided the most favorable speed reduction effects. In general, the magnitude of the speed reduction effects was the greatest in the general proximity of the SFT. Accordingly, positioning the SFT near the end of the taper led to lower speeds for a more sustained distance into the work zone compared to when the SFT was positioned near the start of the taper. When SFT was positioned near end of the taper, the average speed was 1.5 mph and 0.8 mph lower at the SFT location and at the end of the measurement area (2,150-ft beyond the start of the taper) compared to no SFT conditions. The second evaluation assessed the effectiveness of a specialized work zone enforcement strategy that included a covert speed measurement vehicle positioned near the end of the work zone along with four police cars positioned just beyond the end of the work zone to stop speeding drivers. The visible presence of law enforcement at this location reduced work zone speed by approximately 5 mph, which increased to 7 mph shortly beyond the end of the work zone as motorists passed by the police cars positioned on the shoulder. These speed reduction effects were only observed when at least one law enforcement vehicle was visibly present at the site.

Keywords: work zones, enforcement presence, speed feedback trailers, speed limit increase, freeways

INTRODUCTION AND BACKGROUND

Speed management continues to be a high priority nationally, both in regards to setting appropriate speed limits and the degree to which drivers comply with the work zone speed limits. One area that remains a particular challenge for speed management is construction work zones, particularly as maximum speed limits continue to increase nationwide. In 2020, there were an estimated 102,000 work zone crashes, resulting in 44,000 injuries and 857 fatalities, including 156 workers (*1*). Many of these crashes can be attributed to excessive speed or speed variance, as speeding has been identified as a contributory factor in approximately 25 percent of all work zone fatal crashes (*2*). Consequently, setting appropriate work zone speed limits and ensuring compliance to it is an important component towards improving work zone safety.

The Manual on Uniform Traffic Control Devices (MUTCD) recommends that reduced speed limits should be used only where conditions or restrictive features are present (*3*). The MUTCD notes that frequent changes in the speed limit should be avoided and that reductions should not exceed 10 mph. Further, where a speed reduction of more than 10 mph is required, additional driver notification should be provided. Recently, with the increase in speed limits, many work zones now require to drop speed above 10 mph, particularly, at the locations near workers' presence. The magnitude of these speed reductions relies on several factors. For example in Michigan, the work zone speed limit policy considers various factors such as the existing speed limit, type of work activity, presence of construction workers, and the presence of channelizing devices or concrete barriers (*4*).

One important concern in establishing work zone speed limits is the degree to which drivers comply with these limits. Several studies have concluded that although certain measures can reduce speeds, motorists generally tend to regulate their speeds as they feel necessary (*5*, *6*). Work zone speeds have also been shown to vary based on free-flow speeds under normal conditions, as well as under various levels of traffic volume, and at different times of day (*7*). The physical characteristic of the work zone and the associated temporary traffic control plan also play an important role. For example, reduced lane widths have been shown to be effective in reducing average speeds, though it decreases the capacity (*8*). The presence of workers and the level of work activity that is ongoing are also important concerns as research has shown that speeds tend to be lower during periods of construction activity. These are also the periods during which the risks to workers are the highest, leading to states such as Michigan introducing lower work zone speed limits where workers are present. However, speeds often remain above these limits regardless of whether the activity is ongoing (*8*). From an agency perspective, additional research is warranted to assess the degree to which drivers comply with work zone speed limits under various conditions.

National Cooperative Highway Research Program (NCHRP) Synthesis 482 (*9*) focused on speed management strategies for work zones on high-speed roads. This review focused on various speed management techniques, including speed management devices, changes in the physical driving environment, and enforcement. Several other studies have also shown enforcement to reduce speeds (*6*, *10–12*) and these reductions tend to be greatest when enforcement activity is highest (*12*). However, these effects dissipate almost immediately after enforcement activities cease (*11*, *12*). The efficacy of enforcement also tends to be influenced by the normal operating speeds of the roadway, as well as details of the temporary traffic control plan (*12*). NCHRP Report 746 details pertinent information about the administration of work zone speed enforcement, along with related issues such as determining how much enforcement is required and where to position police vehicles (*13*).

Given practical difficulties that arise with speed enforcement in work zones, there remains a clear need to examine how other strategies can help to maintain work zone speed limit compliance. Different speed display signs, including speed feedback trailer (SFT) were found to be an effective speed reduction strategy and are being utilized across different states (*14–20*). However, speeding over the work zone speed limits, particularly, at the further reduced speed areas near the workers continue to be a statewide issue.

To this end, a study was designed to find empirical evidence in support of the most effective means of maintaining acceptable levels of compliance with work zone speed limits. This includes consideration of how temporary traffic control devices such as SFT and the presence of law enforcement impact driver speeds while approaching, entering, and exiting the work zone. The objective of this study is to utilize vehicle speed profiles while approaching and traversing through different critical locations in the work zone and this will help to fully understand how and when driver behavior changes in response to different speed reduction strategies. This will ultimately help to provide recommendations for specific traffic control devices and other speeding-related countermeasures of interest.

METHODOLOGY

A series of field evaluations were performed at two freeway work zones to determine the effectiveness of SFT and the presence of law enforcement in reducing drivers' speeds. The following subsections detail various aspects of this evaluation, including study design, study sites, data collection test conditions, speed data collection and processing, and statistical method utilized for this analysis.

Study Design

The study first evaluated the effectiveness of SFT in reducing drivers' speed while approaching and entering a freeway lane closure. The position of the SFT was varied to identify the optimal location for driver speed reduction while entering and traveling through the lane closure. The SFT utilized in this study was a solar-powered trailer-mounted radar speed feedback sign with a high-definition full-matrix display. The sign was capable of displaying real-time speed information (in mph) and feedback messages to the approaching vehicles. The sign assembly, as shown in Figure 1, includes a static 60 mph speed limit sign, which was the work zone speed limit at the freeway lane closure study site when no workers were present, a 35-in by 36-in feedback display capable of displaying 20-inch speed display digits, a smaller black-on-white “YOUR SPEED” panel on top of the display panel, and a solar panel on top of the sign. The sign assembly was mounted on a trailer that allowed the sign to be quickly moved to different areas within the work zone. During the operation, the sign was positioned on the left shoulder behind orange barrels, keeping an adequate lateral buffer from the open travel lane on the right. The sign uses Doppler radar capable of detecting vehicles up to 2,000 ft in advance of its location. For the purpose of this study, the feedback sign was programmed to display the speed of the approaching vehicles alternating with a “SLOW DOWN” feedback message, which is consistent with the Michigan Department of Transportation (MDOT)'s draft special provision for dynamic speed feedback signs. This feedback messaging strategy was found to be very effective in prior evaluations at freeway exit ramps and rural highway curves (*35–37*).

FIGURE 1. Speed feedback trailer positioned at the end of taper at WB I-69 work zone

A second field study was performed to evaluate the effect of law enforcement presence on the behavior of drivers traversing a freeway lane closure. The enforcement and corresponding data collection areas were positioned near the end of the work area. Workers were present during the entire data collection period, and consequently, the 45 mph speed limit was in effect during the enforcement operation. To remain covert, the officer responsible for monitoring work zone travel speeds was seated in an MDOT work truck positioned near the end of the work area, approximately 600 ft upstream of the end of the work zone traffic control, as displayed in Figure 2. A total of four additional Michigan State Police vehicles were parked on the shoulder 150-ft downstream from the end of the work zone and were visible to motorists traversing the work area. The speed monitoring officer, who utilized LIDAR to measure speeds, would relay information on speeding motorists to the downstream officers. The downstream officers would then pursue, stop, and potentially cite the offending vehicles. The cluster of police cars was positioned downstream of the work zone so that motorists could be stopped beyond the end of the work zone to minimize interference with work zone operations.

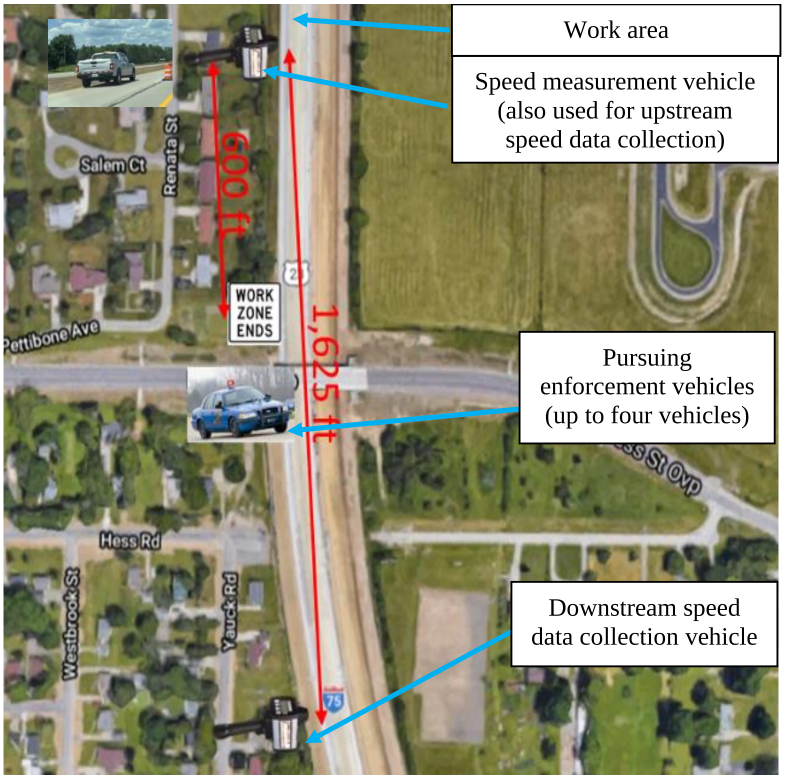


FIGURE 2. SB I-75 work zone data collection setup and law enforcement vehicle locations

Study Sites

Two freeway work zones with lane closures were selected for this evaluation, including one on WB I-69 and the other on the SB I-75. The first work zone on WB I-69 is a two-lane limited-access freeway with a speed limit of 75 mph for passenger cars and 65 mph for heavy vehicles. The left lane was temporarily closed using orange barrels for road maintenance work (Figure 1). The work zone contains all the typical traffic control elements according to the MDOT. In addition to that, three sets of transverse rumble strips were installed prior to entering the single-lane operation segments. The spacing between the individual rumble strip decreased with the proximity to the work zone start, providing drivers with additional alerts to reduce the speed before entering the work zone. The other work zone was on SB I-75, which is a four-lane limited-access freeway in Saginaw County with a non-work zone speed limit of 70 mph for passenger cars and 65 mph for heavy vehicles. The work zone consisted of closure of the rightmost lane for road maintenance work, leaving the three left lanes open. Similar to the WB I-69 site, this work zone also contained all the elements according to the MDOT.

Data Collection Test Conditions

WB I-69 work zone was utilized to evaluate the effectiveness of the SFT and identify the optimal location of the SFT for sustained speed reductions after entering the work zone. To assess the effects of SFT position, the SFT was first installed at the start of the taper and then moved approximately 800 ft downstream to the end of the taper. Data were collected for a total of three test conditions, which included:

- Inactive SFT,
- Active SFT at taper start, and

- Active SFT at taper end.

Data were collected for all three conditions within the same day. This allowed for controlling external factors such as weather and work activity that may otherwise contribute to speed variation. Speed data were collected using a sequence of three handheld LIDAR guns operated by technicians from within separate vehicles parked just beyond the shoulder. This method allowed for continuous measurement of speeds for vehicles approaching and entering the work zone. Vehicles were tracked for over 4,500 ft covering the approach, tapered section, and inside of the work zone. Locations of the data collectors, rumble strips, taper start, taper end, and SFT (both locations) are displayed in Figure 3.

FIGURE 3. WB I-69 work zone and data collection setup

The other work zone, SB I-75, was used to evaluate the effect of law enforcement presence on driver behavior. This evaluation was conducted near the end of the work zone area, with workers present during the entire data collection period. Data were collected before and during the police enforcement. During the enforcement period, at many times, none of the downstream police cars were present at the site due to the frequency of traffic stops for vehicles caught speeding in the work zone. This allowed for the collection of data with no visible police present during the enforcement period. Data were collected for a total of three test conditions, which included:

- Before enforcement
- During enforcement, at least one downstream police car present
- During enforcement, all downstream police cars absent

For this evaluation, data were also collected within a single day for all three enforcement conditions. Vehicle speed data at this site were collected by the research team using a sequence of two handheld LIDAR guns operated by technicians from within separate vehicles parked just beyond the shoulder. Details on the data collection setup are displayed in Figure 2.

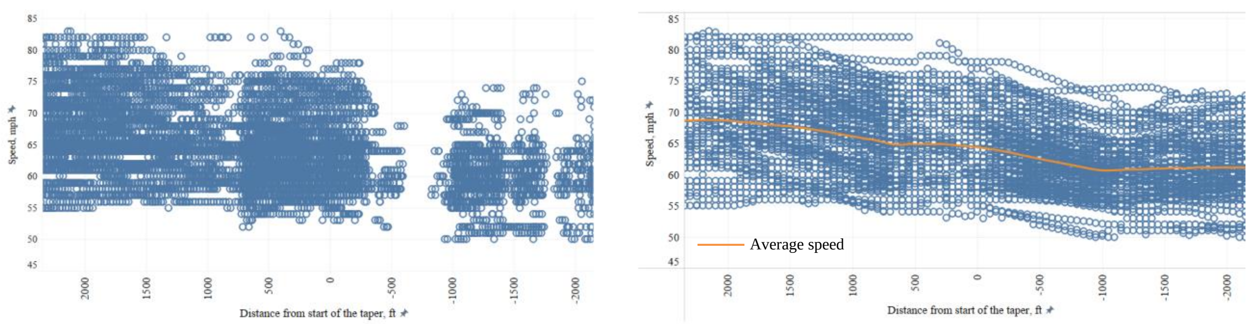
Speed Data Collection and Processing

Speed data were collected using a series of handheld LIDAR guns operated by a team of technicians positioned within unmarked vehicles on the roadside within the work zone. The LIDAR guns were used to continuously track individual vehicle speeds throughout the entire target area at the work zone. The LIDAR guns utilized in this study were ProLaser III manufactured by

Kustom Signals Inc. These devices are able to measure vehicular speed and distance three times per second with an accuracy of ±1 mph at a range of 6,000 ft. The LIDAR data collection vehicles were positioned on the roadside at strategic locations that were away from any critical speed measurement points (e.g., start of taper, end of the taper, work area) to minimize the influence of the data collection vehicle on drivers. The same data collection procedures were utilized across all data collection periods for a given evaluation. Most of the data were collected under dry daylight conditions on weekdays between the hours of 10:00 AM and 4:00 PM.

During the data collection, the upstream data collector would begin to track each subject vehicle and continue tracking at least 100 ft beyond the downstream LIDAR technician. At this point, the tracking responsibilities were then transferred to the downstream technician, who would track each subject vehicle until the next vehicle or over the remaining distance. The data collectors communicated via cellular communications to ensure a seamless “hand-off” of the LIDAR speed tracking as each subject vehicle proceeded through the site. In doing so, the upstream technician would convey the type and color of each subject vehicle to the downstream LIDAR collector. To isolate driver response to the traffic control devices, only freely flowing vehicles (e.g., minimum 3-second headway) were tracked.

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 timestamps, distances, and speeds for each measurement. After completion of the LIDAR tracking for each subject vehicle, all data collectors entered remarks on the type and color of the vehicle, in addition to any other comments. This information was later used to combine the data sets into a continuous speed profile for each subject while traversing through the site.



a) Raw LIDAR data (n=100 vehicles) b) LIDAR data interpolated at 50-ft increments

FIGURE 4. Raw and interpolated vehicle speed data from LIDAR

After completion of the LIDAR tracking data collection from the field, all files from the LIDAR technicians were joined using the vehicle information recorded in the comments. As the relative distances between the LIDAR collectors and the fixed reference points at the sites were known (e.g., start of taper, end of taper/beginning of lane closure), all distances were converted to be relative to the fixed point on the road. An example representation of the output of this process is shown in Figure 4a for vehicles approaching WB I-69 when SFT was at the taper end. 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, thereby allowing 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 calculated at 50 ft intervals using a reference point on the road, as shown in Figure 4b. Compiling the data in this manner provided a robust array of spot speeds throughout each study site.

Statistical Methods

Vehicle speed profiles were analyzed to determine the effects of SFT, law enforcement presence, and the various conditions of their use. First, to determine any obvious trends in the data, sources for potential bias, and data distributions, a preliminary comparison of the descriptive statistics (i.e., mean, standard deviation, percentiles, etc.) and graphical representations (i.e., frequency distribution, box plot, scatterplot) for the vehicular data was performed across the data collection periods. From there, statistical models were developed to estimate the speed at different locations to evaluate the effectiveness of these speed reduction strategies. All the analyses were performed using statistical software RStudio. Speeds were analyzed using multiple linear regression. The general form of the multiple linear regression 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 for vehicle i, X_{i1} to X_{ik} are independent variables affecting the dependent variables (including test condition), β_0 is an intercept, β_1 to β_k are estimated regression coefficients for each independent variable, and ε_i is a normally distributed error term with variance σ^2.

RESULTS AND DISCUSSION

Effect of SFT Positions on Work Zone Speeds

The LIDAR speed data from the WB I-69 work zone were joined, organized, and coded into a single file. The final data set included complete speed profiles for 297 vehicle observations for the three conditions evaluated. The average vehicle speed profiles for all three test conditions are displayed in Figure 5. The figure reveals a few important insights on the effect of SFT location within the work zone, which are summarized as follows:

- SFT Positioned at Start of Taper: When the SFT was positioned at the start of the taper, vehicles began to decelerate more rapidly in advance of the taper compared to the other conditions. By the time vehicles had reached the start of the taper, average speeds were approximately 1 mph lower than the inactive test condition. Vehicles continued to decelerate through the taper, with minimum speeds achieved by the end of the taper. These speeds were generally sustained through the end of the LIDAR tracking range (i.e., more than 1,300-ft beyond the end of the taper).
- SFT Positioned at End of Taper: When the SFT was positioned at the end of the taper, rapid deceleration did not begin to occur until the start of the taper, which was further downstream compared to the start of the taper. However, deceleration was sustained for a longer duration, and by the time vehicles had reached the end of the taper, average speeds were approximately 1 mph lower than the inactive test condition. Additionally, vehicles continued to decelerate beyond the end of the taper, reaching a minimum speed approximately 350-ft beyond the end of the taper. These speeds were generally sustained through the end of the LIDAR tracking range (i.e., more than 1300-ft beyond the end of the taper) but did begin to increase gradually.

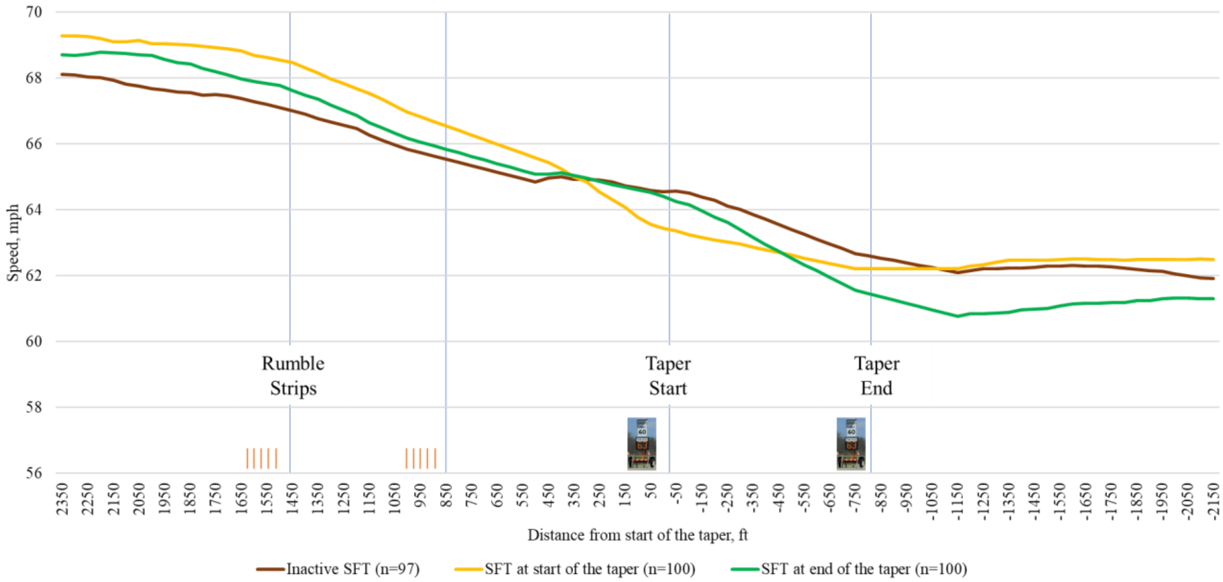


FIGURE 5. Average vehicle speed profile for different locations of speed feedback trailer

In order to confirm the graphical observations presented here, the vehicle speed data were statistically analyzed to determine the effects of SFT operation and installation location on drivers' speed selection while approaching and entering the work zone. Prior to analyzing the data, the speed measurements were binned at 50-ft increments, which covered from 2,350 ft upstream of the start of the work zone taper to 2,150 beyond the start of the work zone taper – for a total tracking distance of 4,500 ft. Binning the data in this manner allowed for the speed-reduction effects of the SFT to be statistically analyzed at various locations of interest throughout the work zone. Separate multiple linear regression models were generated for vehicle speed measured at the following locations of interest within the work zone:

- Speed at the start of taper;
- Speed at the end of taper (800 ft beyond the start of taper);
- Speed 1,300 ft beyond the start of taper;
- Speed 1,800 ft beyond the end of taper; and
- Speed 2,150 ft beyond the end of taper.

The primary independent variables entered into each regression model were as follows:

- SFT operation and location within the work zone:
    - Inactive;
    - Active and positioned at the start of taper;
    - Active and positioned at the end of taper;
- Vehicle type:
    - Passenger vehicle;
    - Heavy vehicle; and
- Speed 2,350 ft upstream of the taper start.

While evaluating the effects of SFT, the vehicle speed at the furthest upstream point (i.e., 2,350 ft upstream of the taper start) was treated as an independent variable (covariate) in the regression models. This allowed for variations in the normal speeding tendencies of drivers between the data collection periods to be controlled for within the models. Controlling for variations in upstream speed between the data collection periods was important, as the upstream speeds were found to be slightly higher during the two active SFT test conditions (see Figure 5), which suggested a slightly faster sample of drivers during the two active SFT test conditions. Analysis of the data in this manner allowed for a direct comparison of the speed reduction effects of each SFT test condition at various locations within the work zone while controlling for vehicle type and speed measured upstream of the work zone. The multiple linear regression results for speeds across the three SFT conditions are presented in Table 1. The parameter estimates from Table 1 can be directly interpreted as the difference in mean speed compared to the base condition (i.e., the inactive SFT). For example, compared to the inactive SFT, mean speeds at the taper start were 1.9 mph lower with the SFT positioned at the start of the taper and 0.5 mph lower for active SFT at the end of the taper.

The results displayed in Table 1 suggest that the SFT operation and location had a statistically significant effect on driver speed selection while traversing the work zone. Speed at the start of the taper was significantly lower when the SFT was positioned at the start of the taper compared to the inactive SFT and SFT at the end of the taper. Similarly, speed at the end of the taper was significantly lower when SFT was positioned at the end of the taper. These findings indicate that the speed reductions were the greatest at or near the SFT itself. This finding has implications on the positioning of the SFT with respect to the work area, which is described in further detail in the paragraphs that follow.

Assessment of driver speed selection beyond the end of the taper found that the SFT positioned at the end of the taper provided a more sustained speed-reduction benefit compared to the SFT positioned at the start of the taper. With the SFT positioned at the end of the taper, speeds continued to decrease beyond the end of the taper, with the lowest overall vehicle speeds in this condition occurring approximately 350 ft beyond the end of the taper. Speeds measured 500-ft beyond the end of the taper were 1.2 mph lower with the SFT positioned at the end of the taper compared to at the start of the taper. Similarly, when vehicles had reached 1000-ft beyond the taper, speeds were 1.0 mph lower with the SPF positioned at the end of the taper versus at the start of the taper.

The results indicate that while the SFT positioned at the start of the taper resulted in an early reduction in speed, the effectiveness of the SFT began to diminish earlier than when the SFT was positioned at the end of the taper. By the time vehicles had reached 500-ft beyond the end of the taper, speeds with the SFT positioned at the start of the taper were not statistically different than those measured with the inactive SFT. On the other hand, the SFT placed at the end of the taper resulted in later driver response, but with speed reductions that were significantly greater by the end of the taper, and sustained a much greater distance into the work zone, continuing to the end of the measurement area (2,150-ft beyond the start of the taper). This finding suggests that the SFT (or series of SFTs) be positioned near the work area so that the speed reduction effect of the SFT is maximized near the workers.

An interesting aspect of this evaluation was the magnitude of speed reduction. While earlier studies have reported a reduction of 2-10 mph in the average work zone speeds with the SFT present (*15, 18, 20, 28, 38*), this study found a decrease of up to 1.5 mph in the average speed. This may be due to the presence of three sets of temporary rumble strips at the site, which follows MDOT standards for long-term freeway lane closures. As the rumble strips were present from the initial implementation of the work zone and associated traffic control, it was not possible to discern the effects of rumble strips across the various SFT test conditions.

TABLE 1. Multiple linear regression results for speeds of vehicles traversing the work zone as a function of SFT location and operation

Parameters	Estimate	Std. Error	t-value	p-value
Speed at Start of Taper				
Intercept	20.395	3.061	6.662	<0.001
Upstream Speed	0.648	0.043	14.994	<0.001
Passenger Cars		*Base Condition*		
Heavy Vehicles	0.120	0.646	0.186	0.852
Inactive Speed Trailer				
Active Speed Trailer at Taper Start	-1.886	0.578	-3.261	0.001
Active Speed Trailer at Taper End	-0.539	0.579	-0.931	0.353
Speed at End of Taper (800-ft Beyond Start of Taper)				
Intercept	28.902	3.103	9.314	<0.001
Upstream Speed	0.494	0.044	11.274	<0.001
Passenger Cars		*Base Condition*		
Heavy Vehicles	-0.019	0.655	-0.030	0.976
Inactive Speed Trailer		*Base Condition*		
Active Speed Trailer at Taper Start	-1.013	0.586	-1.729	0.085
Active Speed Trailer at Taper End	-1.457	0.587	-2.483	0.014
Speed 1,300-ft Beyond Start of Taper				
Intercept	33.804	3.223	10.490	<0.001
Upstream Speed	0.419	0.046	9.208	<0.001
Passenger Cars		*Base Condition*		
Heavy Vehicles	-0.439	0.680	-0.645	0.519
Inactive Speed Trailer		*Base Condition*		
Active Speed Trailer at Taper Start	-0.345	0.609	-0.567	0.571
Active Speed Trailer at Taper End	-1.584	0.610	-2.599	0.010
Speed 1,800-ft Beyond Start of Taper				
Intercept	36.826	3.240	11.366	<0.001
Upstream Speed	0.377	0.046	8.234	<0.001
Passenger Cars		*Base Condition*		
Heavy Vehicles	-0.943	0.684	-1.379	0.169
Inactive Speed Trailer		*Base Condition*		
Active Speed Trailer at Taper Start	-0.276	0.612	-0.452	0.652
Active Speed Trailer at Taper End	-1.233	0.613	-2.012	0.045
Speed 2,150-ft Beyond Start of Taper				
Intercept	38.362	3.374	11.369	<0.001
Upstream Speed	0.349	0.048	7.334	<0.001
Passenger Cars		*Base Condition*		
Heavy Vehicles	-0.927	0.712	-1.300	0.194
Inactive Speed Trailer		*Base Condition*		
Active Speed Trailer at Taper Start	0.092	0.637	0.145	0.885
Active Speed Trailer at Taper End	-0.787	0.638	-1.233	0.219

Effect of Law Enforcement Presence on Work Zone Speeds

A total of 320 vehicle speed profiles were collected between the three different enforcement test conditions during the I-75 work zone evaluation. The average speed profiles for three test conditions are presented in Figure 6. It can be observed from the figure that speeds were approximately 5 mph lower within the work zone when at least one law enforcement vehicle was present, and this reduction was sustained beyond the end of the work zone. Interestingly, when police vehicles were not visibly present at the site during the enforcement period, the average speed profile was very similar to the before enforcement period. Note that the upstream law enforcement car was not readily visible to the drivers. These findings suggest that visible police presence has a substantial speed reduction effect on work zone speeds. Future deployment of this enforcement strategy should consider leaving at least one police vehicle near the work zone site at all times to achieve a sustained speed reduction effect.

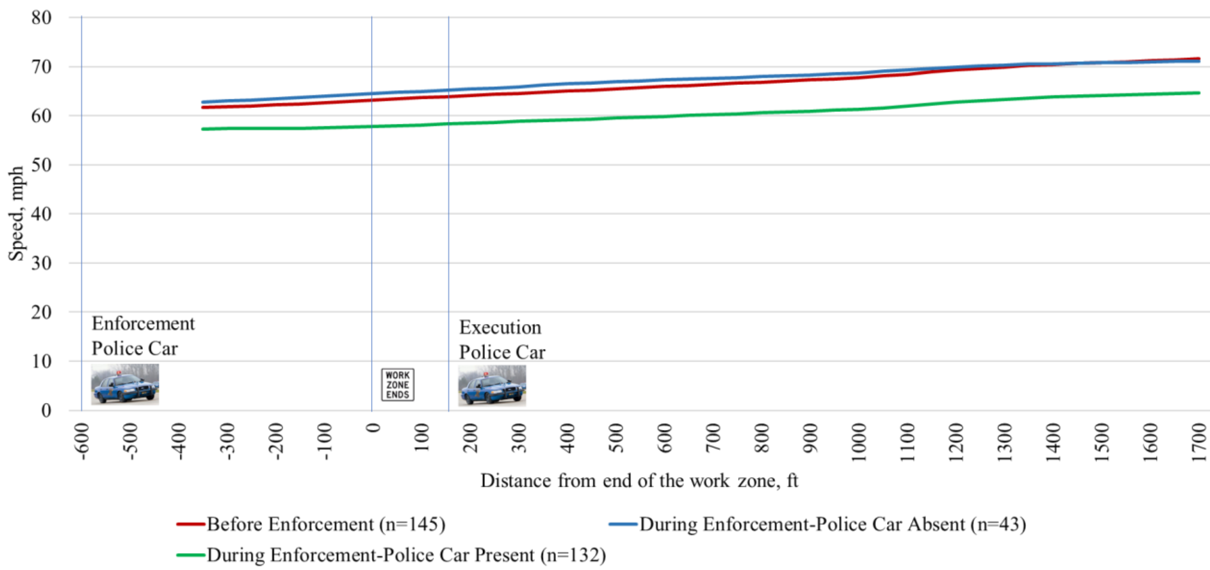


FIGURE 6. Average vehicle speed profiles for police enforcement test conditions

To confirm the graphical observations presented in the prior section, the vehicle speed data were statistically analyzed using linear regression to determine the effects of law enforcement presence on drivers' speed selection while traversing the work zone. Prior to analyzing the data, the speed measurements were similarly binned at 50-ft increments, which covered from 350 ft upstream of the end of the work zone (250 ft beyond the speed measurement vehicle) to 1,700 ft beyond the end of the work zone – for a total tracking distance of 2,050 ft. Similar to the SFT analysis, binning the data in this manner allowed for the speed-reduction effects of the enforcement activity to be statistically analyzed at various locations of interest throughout the work zone and beyond. It should be noted that, unlike the SFT linear regression analysis, this regression model did not control for drivers' normal speed selection tendencies as it was not possible to collect speeds upstream of the work zone. Thus, to simplify the analysis, a single multiple linear regression model was generated with vehicle speed as the dependent variable, along with the following independent variables, each of which was coded in the model as a series of binary indicator variables:

- Speed measurement location:
    - 350-ft prior to the end of the work zone;
    - Speed at the end of the work zone;
    - Speed 150-ft beyond the end of the work zone;
    - Speed 500-ft beyond the end of the work zone;
    - Speed 1,000-ft beyond the end of the work zone;
    - Speed 1,500-ft beyond the end of the work zone;
- Enforcement activity:
    - Before enforcement;
    - During enforcement - no police car present;
    - During enforcement – at least one police car present;
- Vehicle type:
    - Passenger vehicle;
    - Heavy vehicle;
- Lane:
    - Left;
    - Center; and
    - Right.

The multiple linear regression results for speeds across the three enforcement conditions are presented in Table 2. The parameter estimates from Table 2 can be directly interpreted as the difference in mean speed compared to the base condition. For the case of the law enforcement variable, all parameter estimates were computed relative to the speed measured 350-ft prior to the end of the work zone and before the enforcement period. For example, compared to the before enforcement period, mean speeds at this location were 4.3 mph lower during enforcement when at least one police car was present and 0.9 mph higher during enforcement when no police car was present. It follows that the effects of the law enforcement presence are interpreted by taking the difference between the parameter estimates at each speed measurement location. So, for speeds measured at the end of the work zone, the parameter estimates would suggest that the presence of at least one police car at the site during enforcement had a -3.8 – 2.7 mph = -6.5 mph effect on speeds compared to when no police car was present during the enforcement period. These marginal effects on work zone travel speeds associated with the enforcement conditions are displayed graphically in Figure 7.

TABLE 2. Multiple linear regression results for speeds of vehicles traversing the work zone as a function of law enforcement activity

Parameters	Estimate	Std. Error	t-value	p-value
Intercept	60.686	0.412	147.323	<0.001
Passenger Cars		*Base Condition*		
Heavy Vehicles	-3.781	0.283	-13.363	<0.001
Right Lane		*Base Condition*		
Center Lane	1.880	0.248	7.587	<0.001
Left Lane	7.824	0.697	11.224	<0.001
Speed 350-ft Prior to the End of the Work Zone				
Before Enforcement		*Base Condition*		
During Enforcement-No Police Car Present	0.898	0.734	1.224	0.221
During Enforcement-Police Car Present	-4.280	0.511	-8.383	<0.001
Speed at End of the Work Zone				
Before Enforcement	1.467	0.497	2.949	0.003
During Enforcement-No Police Car Present	2.657	0.734	3.620	<0.001
During Enforcement-Police Car Present	-3.819	0.511	-7.481	<0.001
Speed 150-ft Beyond the End of the Work Zone				
Before Enforcement	2.204	0.497	4.431	<0.001
During Enforcement-No Police Car Present	3.315	0.734	4.518	<0.001
During Enforcement-Police Car Present	-3.332	0.511	-6.527	<0.001
Speed 500-ft Beyond the End of the Work Zone				
Before Enforcement	3.803	0.497	7.645	<0.001
During Enforcement-No Police Car Present	5.094	0.734	6.941	<0.001
During Enforcement-Police Car Present	-2.103	0.511	-4.119	<0.001
Speed 1,000-ft Beyond the End of the Work Zone				
Before Enforcement	6.132	0.497	12.327	<0.001
During Enforcement-No Police Car Present	6.891	0.734	9.391	<0.001
During Enforcement-Police Car Present	-0.315	0.511	-0.617	0.537
Speed 1,500-ft Beyond the End of the Work Zone				
Before Enforcement	9.153	0.497	18.401	<0.001
During Enforcement-No Police Car Present	8.940	0.734	12.182	<0.001
During Enforcement-Police Car Present	2.486	0.511	4.868	<0.001

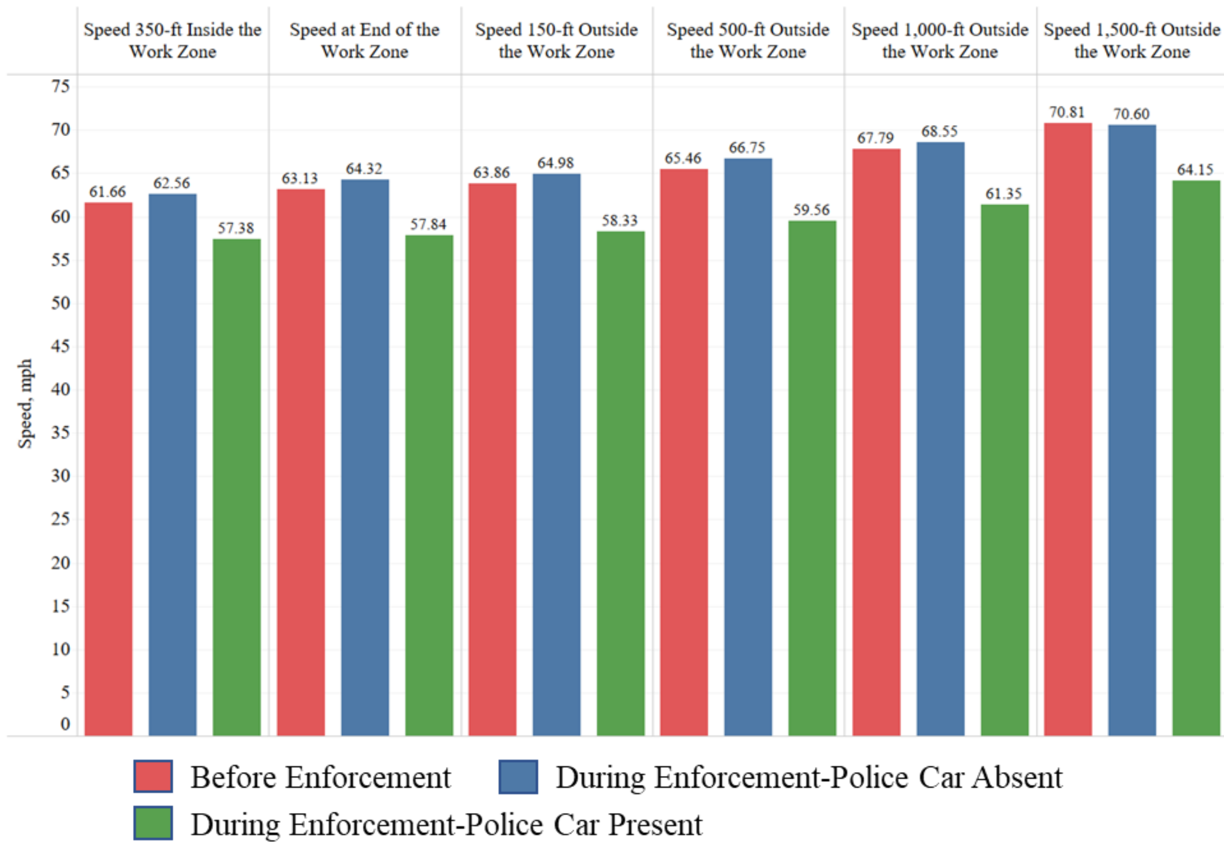


FIGURE 7. Average speeds measured at various locations within and beyond the work zone as a function of law enforcement activity

The results displayed in Table 2 and Figure 7 suggest that the visible presence of at least one law enforcement vehicle has a significant effect on vehicle speeds while exiting the work zone, and this reduction persisted beyond the end of the work zone. Not surprisingly, during the enforcement, when the downstream police car was not present, the speeds at different locations were similar to the conditions prior to the enforcement. As the conditions were most similar during the enforcement period, an assessment of the effects of law enforcement presence was made by comparing the speeds with and without at least one police car present during the enforcement period.

At the initial speed measurement location 350-ft prior to the end of the work zone, the presence of at least one police car resulted in a speed reduction of 5.2 mph, which had increased to 6.5 mph upon reaching the end of the work zone. The law enforcement effects on speeds were maximized between 500-ft and 1000-ft beyond the end of the work zone, where speeds were 7.2 mph lower with at least one police car present on the shoulder. Even 1,500 ft beyond the end of the work zone, where the 70 mph speed limit was in effect, the average speed was 64.2 mph.

CONCLUSIONS AND RECOMMENDATIONS

Work zone speed limits and management of work zone speeds continue to be critical areas of concern for state DOTs. To address these concerns, this study conducted a series of field evaluations to determine the effectiveness of SFT in reducing drivers' speed while approaching and entering a freeway lane closure and identify the optimal installation position for sustained speed reduction effects. Additionally, the study evaluated the effects of law enforcement presence on drivers near the end of the work zone.

The speed feedback trailer was tested at the start and end of the taper within a freeway work zone single-lane closure. Results showed SFT to be an effective speed reduction strategy in the work zone. In general, the magnitude of the speed reduction effects was greatest in the general proximity of the SFT. Accordingly, positioning the SFT near the end of the taper led to lower speeds for a more sustained distance into the work zone compared to when the SFT was positioned near the start of the taper. The SFT positioned near the end of the taper reduced the average speed by approximately 1.5 mph at the SFT location and the reduction at the end of the measurement area (2,150-ft beyond the start of the taper) was 0.8 mph compared to no SFT conditions. It was concluded that the SFT should be positioned near the location of greatest need for speed reductions, such as the work area. Note that, considering inactive SFT as the baseline condition may have resulted in lower magnitude of speed reduction for active SFT conditions as presence of inactive SFT may have some speed reduction affects which could not be captured in this study. Future research in this area should seek to determine the optimal SFT location with respect to the work area, in addition to how worker presence influences the speed reduction effects of the SFT. Furthermore, future research should also include an assessment of the distance that SFT effects are sustained within the work zone in an attempt to determine spacing guidelines for work zone SFTs. Additional evaluations may also consider the use of SFTs in combination with digital speed limit sign, which has recently been approved for use in Michigan and allows for the displayed speed limit to vary in real-time based on worker presence at the site.

Finally, it is likely that the effectiveness of the SFT as a work zone speed-reduction strategy was dampened by the use of rumble strips in advance of the work zone. Future research should evaluate the effects of SFTs at work zone lane closures without rumble strips.

A second evaluation assessed the effectiveness of a specialized work zone enforcement strategy that included a covert speed measurement vehicle positioned near the end of the work zone along with four police cars positioned just beyond the end of the work zone to stop speeding drivers. The visible presence of law enforcement at this location reduced work zone speed by approximately 5 mph, which increased to 7 mph shortly beyond the end of the work zone as motorists passed by the police cars positioned on the shoulder. It must be emphasized that this speed reduction effect was only observed when at least one law enforcement vehicle was visibly present at the site. No speed reduction effects were observed during periods when each of the four patrol cars were pursuing violators downstream of the work zone. These findings suggest that visible police presence has a substantial speed reduction effect on work zone speeds. Future deployment of this enforcement strategy should consider leaving at least one police vehicle in-place near the work area at all times to achieve a sustained speed reduction effect. Further, future work should also assess the effectiveness of law enforcement vehicles positioned at other locations within the work zone, including in advance of the work area, in addition to an assessment of whether the effects of enforcement vary as a function of work zone length and/or duration.

CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study concept and design: Timothy Gates, Peter Savolainen, Md Shakir Mahmud and Hisham Jashami; data collection: Md Shakir Mahmud, Hisham Jashami, Megat Usamah Megat Johari, Anshu Bamney, and Nischal Gupta; analysis and interpretation of results: Md Shakir Mahmud, Timothy Gates, Anshu Bamney, Megat

Usamah Megat Johari, Hisham Jashami, and Peter Savolainen; draft manuscript preparation: Md Shakir Mahmud, Timothy Gates, Anshu Bamney, Megat Usamah Megat Johari, Hisham Jashami, Nischal Gupta, and Peter Savolainen. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. American Road & Transportation Builders Association (ARTBA). Work Zone Data. *Work Zone Safety Information Clearinghouse*. https://workzonesafety.org/work-zone-data/. Accessed Jul. 16, 2022.
2. Federal Highway Administration (FHWA). MUTCDs and Traffic Control Devices Information by State. https://mutcd.fhwa.dot.gov/resources/state_info/index.htm. Accessed Jul. 16, 2022.
3. Federal Highway Administration (FHWA). Manual on Uniform Traffic Control Devices (MUTCD). , 2009.
4. Michigan Department of Transportation. *Guidelines to Establish Speed Limits in Work Zones*. Bureau of Highway Instructional Memorandum 2005-16, Michigan Department of Transportation, Lansing, Michigan, 2005.
5. Brewer, M. A., G. Pesti, and W. Schneider. Improving Compliance with Work Zone Speed Limits: Effectiveness of Selected Devices. *Transportation Research Record*, Vol. 1948, No. 1, 2006, pp. 67–76. https://doi.org/10.1177/0361198106194800108.
6. Finley, M. D. Field Evaluation of Motorist Reactions to Reduced Work Zone Speed Limits and Other Work Zone Conditions. *Transportation Research Record*, Vol. 2258, No. 1, 2011, pp. 40–48. https://doi.org/10.3141/2258-05.
7. Chen, E., and A. P. Tarko. Police Enforcement Strategies and Speed Reduction in Work Zones. Presented at the Transportation Research Board 92nd Annual MeetingTransportation Research Board, 2013.
8. Bham, G. H., M. A. Mohammadi, Mid-America Transportation Center, and Missouri University of Science and Technology. *Evaluation of Work Zone Speed Limits: An Objective and Subjective Analysis of Work Zones in Missouri*. Publication MATC REPORT # 25-1121-0001-119. 2011.
9. Shaw, J. W., M. V. Chitturi, W. Bremer, and D. A. Noyce. *Work Zone Speed Management: A Synthesis of Highway Practice*. National Research Council (U.S.), Transportation Research Board, National Cooperative Highway Research Program, American Association of State Highway and Transportation Officials, United States, 2015.
10. Medina, J. C., R. F. Benekohal, A. Hajbabaie, M.-H. Wang, and M. V. Chitturi. Downstream Effects of Speed Photo–Radar Enforcement and Other Speed Reduction Treatments on Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2107, No. 1, 2009, pp. 24–33. https://doi.org/10.3141/2107-03.
11. Benekohal, R. F., P. T. V. Resende, and R. L. Orloski. EFFECTS OF POLICE PRESENCE ON SPEED IN A HIGHWAY WORK ZONE: CIRCULATING MARKED POLICE CAR EXPERIMENT. PROJECT REPORT. 1992.
12. Wasson, J. S., G. W. Boruff, A. M. Hainen, S. M. Remias, E. A. Hulme, G. D. Farnsworth, and D. M. Bullock. Evaluation of Spatial and Temporal Speed Limit Compliance in Highway Work Zones. *Transportation Research Record*, Vol. 2258, No. 1, 2011, pp. 1–15. https://doi.org/10.3141/2258-01.

13. Ullman, G. L., M. A. Brewer, J. E. Bryden, M. O. Corkran, C. W. Hubbs, A. K. Chandra, K. L. Jeannotte, National Cooperative Highway Research Program, Transportation Research Board, and National Academies of Sciences, Engineering, and Medicine. *Traffic Enforcement Strategies for Work Zones*. Transportation Research Board, Washington, D.C., 2013.
14. Nicholas J. Garber and Surbhi T. Patel. Control of Vehicle Speeds in Temporary Traffic Control Zones (Work Zones) Using Changeable Message Signs with Radar. *TRANSPORTATION RESEARCH RECORD*, Vol. 1509, 1995, pp. 73–81.
15. McCOY, P. T., J. A. Bonneson, and J. A. Kollbaum. Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways. *TRANSPORTATION RESEARCH RECORD*, 1996, p. 8.
16. Mattox III, J. H., W. A. Sarasua, J. H. Ogle, R. T. Eckenrode, and A. Dunning. Development and Evaluation of Speed-Activated Sign to Reduce Speeds in Work Zones. *Transportation research record*, Vol. 2015, No. 1, 2007, pp. 3–11.
17. Pesti, G., and P. T. McCoy. Long-Term Effectiveness of Speed Monitoring Displays in Work Zones on Rural Interstate Highways. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1754, No. 1, 2001, pp. 21–30. https://doi.org/10.3141/1754-03.
18. Wang, C., K. K. Dixon, and D. Jared. Evaluating Speed-Reduction Strategies for Highway Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1824, No. 1, 2003, pp. 44–53. https://doi.org/10.3141/1824-06.
19. Thapa, R., S. Hallmark, O. Smadi, and A. Goswamy. Assessing Driving Behavior Upstream of Work Zones by Detecting Response Points in Speed Profile: A Naturalistic Driving Study. *Traffic Injury Prevention*, Vol. 20, No. 8, 2019, pp. 854–859. https://doi.org/10.1080/15389588.2019.1663348.
20. Anderson, S. M., J. R. Cunningham IV, J. Liang, and E. J. Fitzsimmons. Evaluation of the Effectiveness of Dynamic Speed Feed Back Signs in Work Zones on High-Speed Kansas Roadways. Presented at the 100th Transportation Research Board Annual Meeting, Washington, D.C, 2021.
21. Sommers, N. M., D. S. McAvoy, and Ohio Research Institute for Transportation and the Environment. *Improving Work Zone Safety Through Speed Management*. Publication FHWA/OH-2013/5. 2013.
22. HDR Engineering, Inc. *Work Zone Speed Management Study*. Minnesota Department of Transportation, Saint Paul, Minnesota, 2022, p. 72.
23. Gambatese, J., and A. Jafarnejad. *Evaluation of Radar Speed Display for Mobile Maintenance Operations*. Publication OR-RD-16-09. Oregon Department of Transportation, Oregon, 2015.
24. Gambatese, J. A., F. Zhang, A. M. Vahed, and Oregon State University. School of Civil and Construction Engineering. *Implementing Speed Reductions at Specific Interstate Work Zones from 65 Mph to 35 Mph : Final Report*. Publication SPR 751. 2013.
25. John A. Gambatese and Fan Zhang. *Safe and Effective Speed Reductions for Freeway Work Zones Phase 2*. Publication FHWA-OR-RD-15-04. Oregon Dept. of Transportation, Oregon, 2014.
26. Garber, N. J., and S. T. Patel. *Effectiveness of Changeable Message Signs in Controlling Vehicle Speeds in Work Zones*. Virginia Transportation Research Council, 1994.

27. Thompson, B. *Evaluation of Radar Activated Changeable Message Sign for Work Zone Speed Control.* Maine. Dept. of Transportation, 2002.
28. Sorrell, M. T. Use of Radar-Equipped Portable Changeable Message Sign to Reduce Vehicle Speed in South Carolina Work Zones. 2007, p. 16.
29. Roberts, C. A., and E. J. Smaglik. Driver Feedback on Monetary Penalty and Its Impact on Work Zone Speed. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2272, No. 1, 2012, pp. 27–34. https://doi.org/10.3141/2272-04.
30. Ravani, B., and C. Wang. Speeding in Highway Work Zone: An Evaluation of Methods of Speed Control. *Accident Analysis & Prevention*, Vol. 113, 2018, pp. 202–212. https://doi.org/10.1016/j.aap.2018.01.030.
31. Brian H. Y. Lee, Dale Azaria, and Sean Neely. *Work Zones and Travel Speeds: The Effects of Uniform Traffic Officers & Other Speed Management Measures*. UVM Transportation Research Center, Burlington, VT, 2014.
32. Lodes, M., and R. F. Benekohal. Individual Drivers' Speed Increase in Response to Speed Photo Enforcement and Police Patrol Car. Presented at the Transportation Research Board 92nd Annual MeetingTransportation Research Board, 2013.
33. Benekohal, R. F., A. Hajbabaie, J. C. Medina, M. Wang, and M. V. Chitturi. SPEED PHOTO-RADAR ENFORCEMENT EVALUATION IN ILLINOIS WORK ZONES. p. 165.
34. Joerger, M. Photo Radar Speed Enforcement in a State Highway Work Zone. p. 29.
35. Mahmud, M. S., M. Motz, T. Holpuch, J. Hankin, A. J. Ingle, T. J. Gates, and P. T. Savolainen. Driver Response to a Dynamic Speed Feedback Sign on Freeway Exit Ramps Based on Sign Location, Interchange Type, and Time of Day. *Transportation Research Record: Journal of the Transportation Research Board*, 2021, p. 036119812110152. https://doi.org/10.1177/03611981211015250.
36. Gates, T. J., M. S. Mahmud, A. J. Ingle, M. Motz, T. Holpuch, and P. T. Savolainen. Evaluation of Alternative Messages and Sign Locations on Driver Response to a Dynamic Speed Feedback Sign on a Freeway Interchange Ramp. *Transportation Research Record*, Vol. 2674, No. 12, 2020, pp. 530–541. https://doi.org/10.1177/0361198120959076.
37. Gates, T. J., M. S. Mahmud, P. T. Savolainen, D. Zhao, A. Zockaie, and M. Ghamami. *Evaluation of Dynamic Speed Feedback Signs on Freeway Interchange Ramps*. Publication SPR-1704. Michigan Department of Transportation, Lansing, Michigan, 2022.
38. Huang, Y., and Y. Bai. Driver Responses to Graphic-Aided Portable Changeable Message Signs in Highway Work Zones. *Journal of Transportation Safety & Security*, Vol. 11, No. 6, 2019, pp. 661–682. https://doi.org/10.1080/19439962.2018.1463336.