Texas A&M Transportation Institute

Traffic Control Device Analysis, Testing, and Evaluation Program: FY2021 Activities

Technical Report 0-7096-R1

Cooperative Research Program

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16. Abstract

Traffic control devices are a primary means of communicating highway information to road users. The design, application, and maintenance of traffic control devices are under constant transformation as new technologies, methodologies, and policies are introduced. This project provides the Texas Department of Transportation with a mechanism to conduct high-priority, limited-scope evaluations of traffic control devices. Work conducted and concluded during the 2021 fiscal year included:

- Evaluation of wet-weather pavement markings.
- Assessment of motorist interpretations of centerline buffers on two-lane, two-way roads.
- Review of speed feedback signs in high-speed management approaches.
- Review of direction indicator barricades used in work zones.

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TRAFFIC CONTROL DEVICE ANALYSIS, TESTING, AND EVALUATION PROGRAM: FY2021 ACTIVITIES

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DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of this project was Melisa D. Finley, P.E. #TX-90937.

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CHAPTER 1: INTRODUCTION

Traffic control devices are a primary means of communicating highway information to road users. The design, application, and maintenance of traffic control devices are under constant transformation as new technologies, methodologies, and policies are introduced. This project provides the Texas Department of Transportation (TxDOT) with a mechanism to conduct high-priority, limited-scope evaluations of traffic control devices. Research activities conducted during the 2021 fiscal year (September 2020–August 2021) included:

- Evaluation of wet-weather pavement markings.
- Assessment of motorist interpretations of centerline buffer widths on two-lane, two-way roads.
- Review of speed feedback signs in high-speed management approaches.
- Review of direction indicator barricades used in work zones.
- Review of wait time displays used on portable traffic signals in work zones.
- Review of overhead lane assignment signs for frontage road and ramp approaches to signalized intersections.
- Examination of vehicle speeds and signing needs for gradual curves.
- Examination of operating speed when the posted speed limit changes.
- Guidance on the selection of the appropriate treatment for a particular pedestrian crossing location.
- Evaluation of the design and application of driveway assistance devices in lane closures on two-lane, two-way roads.
- Evaluation of shoulder rumble strip placement on a four-lane, divided road.

Texas A&M Transportation Institute (TTI) researchers completed the first five of these activities during the 2021 fiscal year. Due to the ongoing pandemic, most of the concluded research activities focused on reviewing the state of the practice or developing guidance for select traffic control devices. The findings from the first four activities are documented in this report. Since, the review of wait time displays used on portable traffic signals in work zones was considered internal in nature and pertained to possible future research activities on this project, it is not included herein. The remaining six activities are ongoing and will be documented in future reports, as deemed appropriate.

CHAPTER 2: EVALUATION OF WET-WEATHER PAVEMENT MARKINGS

TTI researchers developed guidance material to aid TxDOT and its contractors with continuous wet retroreflectivity measurements. The guidance covers all aspects of the measurement process, including the equipment, calibration, setup, measurement techniques, and best practices. A summary field guide and a short video were developed to support the guidance material. The field guide can be used as a simple document to reference while in the field taking measurements. The video provides examples of how to calibrate the equipment and how to conduct the measurements. In addition to developing the guidance materials, researchers conducted field investigations to support TxDOT and contractor efforts to evaluate wet-weather pavement markings. A summary of three different field evaluations of wet-weather pavement marking retroreflectivity in Texas is also included herein.

BACKGROUND

Wet-weather pavement markings have been shown to provide a safety benefit compared to traditional markings (*1*, *2*, *3*). Research studies conducted by TTI using Texas data included between 131 and 196 roadway segments and between 730 and 1050 miles of roadway. The data consisted of roadways where wet-weather pavement markings were installed between 2011 and 2017. Researchers incorporated roadway information, crash information, and weather information into the empirical Bayes and full Bayes analyses. Researchers evaluated the crashes by weather (wet and dry) and time of day (day and night) and included subsets of fatal and injury and run-off-the-road crashes. Results indicated statistically significant crash reductions across the wet-weather crash types with up to a 60 percent reduction for wet-night fatal and injury crashes.

Recent research has looked at what continuous wet retroreflectivity levels pavement markings need to achieve to be considered adequate to meet driver needs (*4*). The human factors study conducted by TTI for the Minnesota Department of Transportation and the Minnesota Local Road Research Board had participants evaluate various pavement markings (white and yellow, 4-inch- and 6-inch-wide markings, and various continuous wet retroreflectivity levels) in simulated rain conditions at night. The results of the visibility study and the measured continuous wet retroreflectivity levels of the markings yielded recommendations for the minimum maintained continuous wet retroreflectivity levels of the markings to meet driver needs in nighttime rainy conditions. The research recommended a minimum maintained continuous wet retroreflectivity level of 50 millicandelas per meter squared per lux (mcd/m^2/lux) to provide adequate wet-night visibility to most drivers. The recommendation was not marking width or color dependent.

Wet-weather pavement markings are typically more expensive than standard markings but can provide safety and visibility benefits. To ensure the markings are installed properly and maintained over time, the continuous wet retroreflectivity of the marking should be evaluated. Wet retroreflectivity readings are typically conducted less frequently than dry retroreflectivity readings due to the length of time each measurement takes.

ASTM E2177 (*5*) is the standard test method for evaluating markings in a condition of wetness. This method is also referred to as the bucket method or the recovery method. This method typically uses a bucket to pour water on the marking and then allows it to recover for 45 seconds prior to taking a retroreflectivity measurement. This method best represents marking visibility after rain has stopped.

ASTM E2832 (*6*) is the standard test method for evaluating markings in a continuous wet condition. This method evaluates the marking retroreflectivity while a simulated rain is falling on the marking. This represents the visibility of the marking in a rainy condition. This is the most equitable method to compare marking visibility while it is raining. Continuous wet retroreflectivity measurements are more complicated than dry retroreflectivity measurements. The requirements for the continuous spray application to simulate the rainy condition add another process that needs to be calibrated and conducted properly to achieve accurate and consistent retroreflectivity values.

Dry retroreflectivity readings should be conducted in addition to the wet retroreflectivity readings. Dry marking retroreflectivity is evaluated using ASTM E1710 (*7*). The dry retroreflectivity test method using a portable retroreflectometer is relatively easy to conduct. One of the biggest factors to consider is the sample plan that will be used to conduct the evaluations. ASTM D7585 (*8*) is a standard practice for evaluating marking retroreflectivity using a portable retroreflectometer. TxDOT Item 666 also has a section describing portable measurements of dry retroreflectivity.

Special Specification 6149, All-Weather Thermoplastic Pavement Markings, is the most commonly used wet-weather pavement marking speciation in Texas. This special specification describes the material and performance requirements for the marking. The retroreflectivity requirements cover both dry and wet retroreflectivity values. The wet retroreflectivity values are measured using the ASTM E2832 method. Wet retroreflectivity measurements are to be taken immediately after application and dry measurements 3 to 10 days after application. Table 1 provides the required retroreflectivity values.

Table 1. TxDOT All-Weather Thermoplastic Retroreflectivity Requirements.

Measurement Type	White Markings	Yellow Markings
Dry (ASTM E1710)	400 mcd/m^2/lux	325 mcd/m^2/lux
Wet continuous (ASTM E2832)	150 mcd/m^2/lux	125 mcd/m^2/lux

CONTINUOUS WET RETROREFELCTIVITY MEASUREMENT GUIDANCE

Continuous wet retroreflectivity measurements described in ASTM E2832 (*6*) are more complex than typical dry retroreflectivity measurements. The biggest difference is the requirement of the continuous wetting device to apply the water to the marking in a standardized condition. The setup and calibration of the wetting device is critical to accurate and repeatable measurements. The portable retroreflectometers that are used for dry retroreflectivity measurements can also be used for the continuous wet measurements. However, depending on the specific manufacturer of the equipment, modifications to the instrument may be necessary to allow for the continuous wet measurements. It is critical to perform the device modification, or the measurement will not be accurate. It is also critical to properly maintain and calibrate the retroreflectometer and inspect the lens of the retroreflectometer to make sure it does not get wet or fog.

Researchers developed a guidance presentation, field guide, and guidance video to aid TxDOT and its contractors with continuous wet retroreflectivity measurements. These items are hosted on TTI's programs and guidance webpage at https://visibility.tti.tamu.edu/programs-and-guidance/ under the "Wet Retroreflectivity Measurement Guidance" heading. The items are described in the next several subsections.

Guidance Presentation

The guidance presentation provides detailed step-by-step guidance through the entire process needed to prepare for, conduct, and analyze continuous wet retroreflectivity measurements. The guidance presentation is a PowerPoint presentation with notes on each slide that describe the material presented. The presentation includes a general overview and details on each of the following topics:

- Standards and specifications.
- Equipment.
    - Portable retroreflectometer.
    - Continuous spray wetting device.
    - Calibration equipment.
- Measurement process.
    - Calibration.
    - Setup.
    - Readings.
    - Recording data.
    - TxDOT requirements.
- Data analysis.
- Best practices.
- Additional information.

ASTM E2832 (*6*) should be reviewed and referenced when conducting continuous wet retroreflectivity testing. The ASTM specification details how to build the continuous spray wetting device that is required for the measurements. The presentation covers the information in ASTM E2832 and adds additional information based on knowledge and experience from conducting the measurements in the laboratory and in the field. The calibration spreadsheet that is displayed in the presentation is provided on TTI's programs and guidance webpage at https://visibility.tti.tamu.edu/programs-and-guidance/. Anyone who is planning to conduct continuous wet retroreflectivity measurements should review the guidance presentation and associated materials.

Field Guide

Researchers developed a field guide to supplement the guidance presentation. The guide is a simple document that can be used in the field to provide key reminders and best practices. The field guide contains:

- Bulleted lists of information to serve as reference points during the measurement process.
- Key best practices to help guide proper measurement and address possible issues that may arise.
- Images of the measurement process that can be referenced to ensure proper setup.

Guidance Video

Researchers developed a guidance video that covers two critical areas of the continuous wet retroreflectivity measurements: the calibration process and the measurement process. The video shows the proper way to set up and calibrate portable retroreflectometers, and the proper way to set up and calibrate the continuous wetting spray device. The video shows how to position the retroreflectometer and the spray device, how to check that the system is functioning properly, how to check that the retroreflectometer is flat, and how to take dry and continuous wet retroreflectivity readings. The video is only a few minutes long but provides valuable information for someone who may not be familiar with the calibration and measurement process.

FIELD EVALAUTIONS

In addition to developing the guidance material, researchers assisted TxDOT districts when questions arose about the standards and test methods or issues occurred with continuous wet retroreflectivity measurements. Researchers made several trips to field sites to evaluate roads that had all-weather markings applied. A summary of the evaluations and the lessons learned is provided in the following sections.

Loop 463 Evaluation

The retroreflectivity measurements made by researchers found good dry white retroreflectivity (average 592 mcd/m^2/lux), but the markings failed the yellow dry retroreflectivity evaluation (average 272 mcd/m^2/lux) and failed both the white and yellow continuous wet retroreflectivity evaluation (70 mcd/m^2/lux and 50 mcd/m^2/lux, respectively). The contractor evaluated the dry and wet retroreflectivity of the markings several days prior to TTI. The contractor-supplied data showed all markings passing dry and continuous wet retroreflectivity levels. This difference in data is a significant problem because the contractor data would indicate the markings pass when they do not. Thus, it is necessary to inspect and verify contractor-collected data to ensure contractors are supplying accurate data. Properly training inspectors and making sure the contractors conduct the measurements properly and accurately are critical to producing reliable retroreflectivity data. TxDOT needs to make sure the contractors are conducting the measurements properly, the data provided are reasonable, and the results meet the requirements. TxDOT should also verify a portion of the data through nighttime visual observations or retroreflectivity measurement.

Two notable things were observed during the TTI data collection effort. The first was that the white broken-line continuous wet retroreflectivity data for the first measurement location were about twice the value of the rest of the measurements. This value was likely a false high value. After the measurement was complete and the measurement at the next location was started, researchers noticed that the spray nozzle was not distributing the water properly across the measurement area. It was likely that the nozzle was bumped in transit and was not wetting properly. The nozzle was adjusted, and the spray pattern was checked prior to any additional measurements. This highlights the need to continually check the equipment setup and calibration to make sure the system is properly set up and functioning properly.

The second notable observation was the result of close inspection of the applied markings. Researchers took images to document the marking condition and drainage at the measurement locations. The bead distribution and quantity were good for both the white and yellow markings. However, only standard glass beads were used. A double drop of larger and smaller beads on a flat marking will provide good dry retroreflectivity but will only provide minimal continuous wet retroreflectivity. Therefore, it is not surprising that the continuous wet retroreflectivity values were below the required values. Figure 1 and Figure 2 show that the test locations had adequate drainage as the water spray was running across the lanes. For inspectors, it is important to collect photo documentation of the marking conditions and the measurements. These photos allow the inspector to later check bead distribution, marking characteristics, and drainage of the water among other things.

Figure 1. Yellow Marking after Wet Retroreflectivity Evaluation.

Figure 2. White Marking after Wet Retroreflectivity Evaluation.

US 183 Evaluation

Researchers captured continuous wet retroreflectivity readings on various lines along the length of the job. The yellow marking was applied on the outside edges of a center line milled rumble strip (see Figure 3). Researchers took multiple readings after shifting the wetting device and retroreflectometer to account for the cycle pattern of the milled rumble strip. Figure 4 shows the yellow marking being wetted.

Figure 3. Marking Partially on Milled Rumble Strips.

Both the white and yellow markings had good reflective optics coverage except that one edge of the white marking had fewer wet optics. One issue that occurred with the white marking was that in some measurement locations, the edge line was placed on the pavement joint, which resulted in water pooling more than it should on the marking. The white marking also lacked consistent thickness, especially on the lane line. The white marking tended to have thicker edges with a thinner middle, resulting in water pooling on the center of the marking (see Figure 5). This resulted in low continuous wet values for the broken lane line marking. The resulting values at areas where water was not pooling met the retroreflectivity requirements. Evaluating the markings at representative locations that properly drain is essential to collecting accurate continuous wet retroreflectivity readings. If the markings do not drain properly, the operator must select another area to evaluate; otherwise, the readings may not be representative of the true retroreflectivity of the marking. If large areas of the marking do not drain properly, then it is likely an installation issue and may result in low continuous wet retroreflectivity numbers.

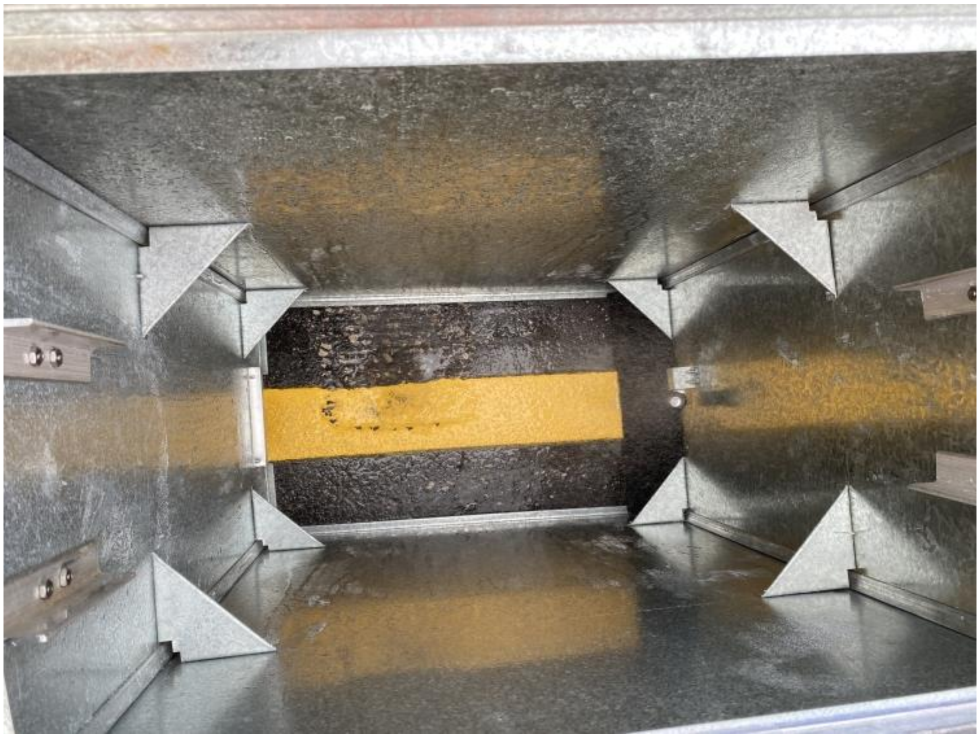


Figure 4. Marking Being Wetted.

Figure 5. Water Pooling on Marking.

US 59 Evaluations

Researchers conducted two separate evaluations on US 59. Prior to the US 59 evaluations, TTI researchers reviewed continuous wet retroreflectivity results provided by the striping contractor. The researchers immediately questioned the data accuracy due to the exceptionally high continuous wet retroreflectivity values (i.e., white and yellow readings above 600 mcd/m^2/lux). When TTI visited the site and took readings, the dry retroreflectivity data were similar in magnitude to the contractor's continuous wet retroreflectivity data. Upon further examination, it was found that the contractor did not place the rails on the retroreflectometer, which are necessary when conducting continuous wet retroreflectivity measurements. Thus, the contractor was measuring dry retroreflectivity instead of continuous wet retroreflectivity because the equipment was not properly set up. Being familiar with the specification, equipment, and how to conduct the measurement is critical to collect accurate data.

The TTI data showed high variability in the yellow dry and yellow continuous wet retroreflectivity values. The yellow marking appeared to have a good quantity and a mostly good distribution of the wet reflective optics except that one outside edge had fewer wet reflective optics. As shown in Figure 6, it also appeared that some of the yellow wet reflective optics were discolored. Further inspection found that there was an issue with some of the wet reflective optics. This caused the high variability along the length of the job. Areas that were not affected had acceptable dry and continuous wet retroreflectivity.

The TTI white dry values were good and consistent, but the white continuous wet retroreflectivity values were low. The white markings had an uneven distribution of the wet reflective optics (see Figure 7). There were a lot in the middle, but the quantity decreased toward the edges. The bead distribution and wear on the broken lane line marking may be possible reasons for the lower than required wet retroreflectivity values.

SUMMARY

All-weather pavement markings have been found to be an effective safety improvement. This safety improvement may not be realized if the markings are not properly installed. Inspection and continuous wet retroreflectivity evaluations are key factors to ensure that markings are properly installed. Being able to correctly conduct the continuous wet measurements and knowing what factors can affect the measurements are critical to achieve good data. TTI researchers have developed guidance material to help TxDOT and its contractors with continuous wet retroreflectivity measurements. The guidance material, ASTM standards and methods, and TxDOT specifications need to be reviewed prior to conducting measurements. These materials will help ensure that continuous wet retroreflectivity measurements are conducted properly and that accurate data are collected.

Figure 6. Yellow All-Weather Marking with Discolored Wet-Weather Optics.

Figure 7. White All-Weather Marking with Poor Distribution of Optics.

CHAPTER 3: MOTORIST INTREPRETATIONS OF CENTERLINE BUFFER WIDTHS

In March 2020, TTI researchers conducted a two-stage survey of practice to assess traffic control device practices and needs in TxDOT districts. As part of this effort, researchers identified 10 districts that have installed a lateral separation greater than 12 inches between opposing travel directions (i.e., centerline buffer) on two-lane and/or four-lane undivided roadways. Researchers documented a wide range of centerline buffer widths (2 to 9 ft) and striping patterns in current use. To aid TxDOT in the development of a standard for centerline buffers, researchers designed and conducted an online survey to assess motorist understanding of various centerline buffer widths on two-lane, two-way roadways.

SURVEY METHODOLOGY

Researchers developed a survey using Qualtrics online survey software. The survey was considered human subjects research by the Texas A&M University Human Research Protection Program. For this reason, the Texas A&M University Institutional Review Board reviewed and approved all participant recruiting materials and survey questions, as well as the study protocol.

Treatments

On the current TxDOT Pavement Marking Standard Sheet PM(1)-20 (*9*), the maximum centerline buffer width is 12 inches (1 ft) on two-lane, two-way roadways (measured between the inside edges of the solid yellow lines). TxDOT wanted to determine at what width motorists begin to interpret the space between the two solid yellow lines as a drivable lane. So, researchers included treatments with centerline buffer widths of approximately 1 ft, 2 ft, 4 ft, 6 ft, and 8 ft. Researchers also included a 16-ft two-way left-turn lane (TWLTL) as a treatment.

During the development of the survey, TxDOT requested that researchers measure the centerline buffer width from the center of one solid yellow line to the center of the other solid yellow line. Thus, this measurement includes 4 inches of the solid yellow line (2 inches of each solid yellow line). Table 2 contains the treatment centerline buffer widths measured per TxDOT's request and as shown in TxDOT Pavement Marking Standard Sheet PM(1)-20.

Treatments 1–5 were created using two solid yellow centerline markings and depicted on a two-lane, two-way roadway with 12-ft lanes and 8-ft paved shoulders. When centerline buffers are installed, typically the shoulder width is reduced to compensate for the added space between opposing travel directions. However, since the main factor of interest was the centerline buffer width, researchers kept the lane and shoulder width constant for each treatment. The striping for the TWLTL (Treatment 6) followed TxDOT Pavement Marking Standard Sheet PM(3)-20 (*10*).

Table 2. Treatment Centerline Buffer Widths.

Treatment Number	Centerline Buffer Width Measured between Centers of Solid Yellow Lines	Centerline Buffer Width Measured between Inside Edges of Solid Yellow Lines
1	1 ft 4 inches	1 ft
2	2 ft	1 ft 8 inches
3	4 ft	3 ft 8 inches
4	6 ft	5 ft 8 inches
5	8 ft	7 ft 8 inches
6	16 ft 4 inches	15 ft 4 inches

Using TTI's driving simulator software, researchers created scene views of the treatments (see Figure 8 through Figure 13). All images included a single vehicle placed ahead of the viewer's lane position to help provide perspective.

Figure 8. Standard 1-ft Centerline Striping Image—Treatment 1.

Figure 9. Experimental 2-ft Centerline Buffer Image—Treatment 2.

Figure 10. Experimental 4-ft Centerline Buffer Image—Treatment 3.

Figure 11. Experimental 6-ft Centerline Buffer Image—Treatment 4.

Figure 12. Experimental 8-ft Centerline Buffer Image—Treatment 5.

Figure 13. TWLTL 16-ft Centerline Striping Image—Treatment 6.

Participant Recruitment, Consent, Demographics, and Qualifications

Researchers advertised the opportunity to participate in the survey using a social media post on TTI's Facebook page and an email distributed to Texas A&M University employees and students via the Texas A&M Bulkmail system. Upon accessing the online survey, participants received information about the study and were asked to provide their consent to participate in the study. Next, the survey asked participants to provide demographic information, including the selection of their age group from the following choices:

- 18–24.
- 25–34.
- 35–44.
- 45–54.
- 55–64.
- 65–74.
- 75–84.
- 85+.

Participants were also asked to select if they were male, female, or preferred not to provide that information. The survey then asked participants three qualification questions:

- If they held a valid Texas driver's license.
- If they could read and understand English.
- If they were completing the survey on a laptop computer, desktop computer, or a full-size electronic tablet.

Researchers determined that surveys requiring the interpretation of roadway images cannot be accurately completed on devices with small screens, such as smartphones. A negative response to any of these questions disqualified the participant from the rest of the study.

Treatment 1 Image and Questions

All participants saw the image of Treatment 1 first with three questions (see Figure 14). The questions were designed to determine if participants thought it was OK to:

- Make a left turn across the solid yellow lines.
- Cross the solid yellow lines to pass another car.
- Drive down the road between the solid yellow lines.

For the question about driving down the road between the stripes, participants were asked to explain their response. The survey programming presented these three questions in a random order for each participant.

Treatments 2–6 Images and Questions

Next, all participants saw one of the five remaining treatments (Treatments 2–6) with the same three questions discussed previously. The survey programming presented the three questions in a random order for each participant. The survey programming also selected the second treatment such that approximately the same number of participants would see each of those treatments.

Question about Differences in Two Images

Finally, the survey asked participants if they recognized any differences between the two images they had seen. Figure 15 shows the response selections provided in randomized order for each participant. Participants were allowed to select more than one answer choice, including entering their own answer. Participants responded based on their own recall of the images because they could not go back and review them.

PARTICIPANT INFORMATION

The online survey was open for responses from May 7 to May 27, and researchers received 298 responses. One participant opted not to participate after reading the study information and consent. Two participants were disqualified because they indicated that they did not have a valid Texas driver's license. Nineteen participants were disqualified after indicating that they were not using a device with a full-size screen. The researchers also eliminated data for 28 participants who did not complete the entire survey. This left 248 completed surveys. Average completion time for these 248 participants was less than 6 minutes. Table 3 shows demographic data for the survey participants, along with demographic data for licensed Texas drivers obtained from a federal data website (*11*). Overall, the various demographic groups are well represented in the study, with no group having more than a 7 percent variation from the licensed driver population in Texas.

The image below shows a two-lane roadway.

If you want to make a left turn into a driveway, is it OK to cross the yellow stripes to do so?

- Yes
- No
- Not sure

Is it OK to drive down the road between the yellow stripes?

- Yes (explain why below)
- No (explain why below)
- Not sure

If you are following another car that you want to pass, is it OK to cross the yellow stripe(s) to do so?

- Yes
- No
- Not sure

Figure 14. Treatment 1 as Displayed to Participants.

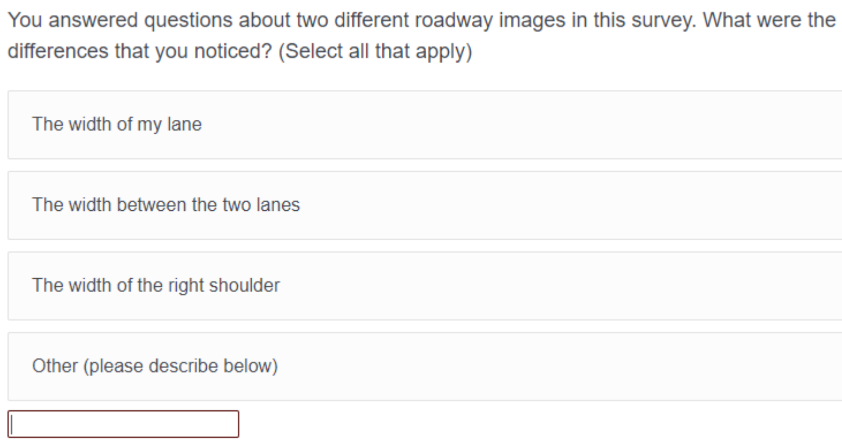


Figure 15. Centerline Width Differences Page Displayed to Participants.

Table 3. Demographic Data (*11*).

Age Group	Study Participants			Licensed Texas Drivers		
	Male (n=108)	**Female (n=137)**	**Total[a] (n=245)**	**Male (n=8,476,274)**	**Female (n=8,665,829)**	**Total (n=17,142,103)**
18–24	5%	8%	13%	6%	5%	11%
25–34	4%	11%	15%	9%	9%	18%
35–44	6%	11%	17%	9%	9%	18%
45–54	11%	9%	20%	9%	9%	18%
55–64	11%	13%	24%	8%	9%	17%
65–74	4%	4%	8%	6%	6%	12%
75–84	2%	1%	3%	2%	3%	5%
85+	0%	0%	0%	0%	1%	1%
Total	43%	57%	100%	49%	51%	100%

[a] Three participants chose not to provide their gender information.

SURVEY RESULTS

When asked if it was OK to cross the yellow stripes to make a left turn into a driveway, the correct answer for all centerline widths was "Yes." According to the Texas Transportation Code (*12*, *13*), drivers can cross the centerline striping in a no-passing zone to make a left turn into or out of an alley, private road, or driveway.

When asked if it was OK to drive down the road between the yellow stripes, the desired answer for all centerline widths was "No." The phrase "down the road" was included in the question to reduce confusion with using the area to make a left-turn approach. According to the *Texas Driver Handbook* (*14*), the only time a vehicle should enter the center turn lane is at a point where the vehicle will have time to slow down or stop to make a safe left-turn maneuver.

When asked if it was OK to cross the yellow stripes to pass another vehicle, the desired answer for all centerline widths was "No." According to the *Texas Driver Handbook* (*14*), a solid yellow line on the motorist's side of the road marks a no-passing zone. In addition, if a center lane is present, it should never be used for passing or as a through traffic lane.

Table 4 shows a summary of the correct answers given by the survey participants. With respect to comprehension, researchers assumed a treatment was understood when at least 85 percent of the survey participants correctly interpreted the meaning (*15*).

Crossing Centerline Striping to Make a Left Turn

Table 4 shows that 70 percent of the participants thought that it was OK to cross the standard centerline buffer width (Treatment 1) to make a left turn into a driveway. This is lower than the 85 percent level researchers use to gauge comprehension of traffic control devices. Similar uncertainty existed with Treatments 2–5, with comprehension levels of 66, 78, 80, and 80 percent, respectively. Without any follow-up questions, a better understanding of these lower comprehension levels is not possible. For Treatment 6, 94 percent comprehension indicates that participants recognized it as a turn lane.

Table 4. Summary of Correct Answers Given by Participants.

Treatment Number	Left Turn	Driving in Lane	Passing	Total
1	173 (70%)	233 (94%)	240 (97%)	248
2	30 (66%)	42 (93%)	44 (98%)	45
3	40 (78%)	46 (90%)	50 (98%)	51
4	40 (80%)	42 (84%)	44 (88%)	50
5	40 (80%)	41 (82%)	37 (74%)	50
6	49 (94%)	35 (67%)	46 (88%)	52

Driving between the Centerline Striping

Most participants recognized that it is not OK to drive down the road between the centerline striping. Table 4 shows comprehension levels of 94, 93, and 90 percent for Treatments 1–3, respectively. When the centerline buffer width reached 6 ft (Treatment 4), comprehension levels began to decline, suggesting that this is the point at which the centerline buffer may appear to be wide enough to be mistaken for a driving lane. Treatment 6 had the lowest comprehension rate (67 percent), meaning that more participants thought they could drive down the road in the TWLTL than for any other treatment. This may reflect a misunderstanding of how to properly use a TWLTL (i.e., the only time a vehicle should enter the center turn lane is at a point where the vehicle will have time to slow down or stop to make a safe left-turn maneuver).

Participants were asked to explain their answers regarding driving down the road between the centerline striping. A few participants did not provide clear answers or did not properly answer the question. The remainder of the responses fell into the following groups:

- Crossing the solid yellow lines was illegal.
- The space between the solid yellow lines was not wide enough to drive between.
- There was a safety issue with oncoming traffic.
- The lane appeared to be a turn lane.

Table 5 summarizes the results. The totals do not add up to 100 percent because some participants provided more than one reason. For a centerline buffer width of 4 ft or less (Treatments 1–3), participants generally understood that it was illegal to use the centerline buffer width as a lane, that their vehicle likely would not fit between the yellow solid lines, and that it would be unsafe to drive in that area due to conflicts with oncoming traffic. For the 6-ft centerline buffer width (Treatment 4), participants still recognized the legal and space issues associated with that centerline buffer. However, researchers observed a lower percentage of responses concerning safety and oncoming traffic, and a higher percentage of responses indicating that the centerline buffer area was a turn lane. For the 8-ft centerline buffer width (Treatment 5), concerns about space and safety related to oncoming traffic appeared to dissipate (with only 12 percent giving these reasons), while the percentage of responses indicating that it was a turn lane continued to increase (37 percent). For Treatment 6 (the TWLTL), 74 percent of respondents who stated that it was not OK to drive down the road in that lane recognized that it was a turn lane.

Table 5. Participant Explanations for Not Driving between Centerline Striping.

Treatment Number	Illegal	Inadequate Space	Unsafe/ Oncoming Traffic	Turn Lane	Other/ Unclear
1	114 (49%)	74 (32%)	71 (30%)	0 (0%)	10 (4%)
2	25 (60%)	8 (19%)	18 (43%)	0 (0%)	2 (5%)
3	16 (35%)	26 (57%)	13 (28%)	2 (5%)	1 (2%)
4	17 (40%)	19 (45%)	2 (5%)	9 (21%)	3 (7%)
5	15 (37%)	5 (12%)	5 (12%)	15 (37%)	8 (20%)
6	6 (17%)	1 (3%)	2 (6%)	26 (74%)	0 (0%)

Crossing Centerline Striping to Pass Another Vehicle

Table 4 shows that most participants recognized that it was not OK to use the centerline buffer area to pass another vehicle. For a centerline buffer width of 4 ft or less (Treatments 1–3), comprehension rates were 97, 98 and 98 percent, respectively. For the 6-ft centerline width (Treatment 4), the percentage of correct answers began to decrease (88 percent), reaching the lowest level (74 percent) for the 8-ft centerline width (Treatment 5). The percentage of correct answers for Treatment 6 was 88 percent because many participants likely recognized it as a turn lane and not a passing lane.

Centerline Width Differences

In the final survey question, participants were asked if they noticed differences in the two images they had previously seen. The correct answer of interest for all treatments was “the width between the lanes.” Participants were allowed to select more than one answer choice, as well as add their own text (under “other”) if they thought something else was different.

Table 6 summarizes the participants’ responses. Overall, the width between the lanes was noticed by 226 of the 248 participants (91 percent). This answer was given by a much lower percentage of participants who saw Treatment 2 than by any other group of participants, mainly because the difference between 1 ft and 2 ft was more difficult to discern. This is further supported by 11 “other” responses (24 percent of the 46 participants who saw Treatment 2) claiming there was no difference between the images they saw. Answers noting differences in the width of the right shoulder and the width of the driving lane were incorrect because these dimensions were the same for all images. Fourteen participants (27 percent) who saw Treatment 6 noted that the striping pattern changed for the TWLTL.

Table 6. Participant Responses to Noticing Image Differences.

Treatment Number	Width between Lanes	Width of Right Shoulder	Width of My Lane	Striping Pattern	No Difference
2	21 (47%)	13 (28%)	4 (9%)	1 (2%)	11 (24%)
3	48 (94%)	3 (6%)	4 (8%)	0 (0%)	1 (2%)
4	47 (94%)	2 (4%)	4 (8%)	1 (2%)	1 (2%)
5	45 (90%)	4 (8%)	1 (2%)	0 (0%)	2 (4%)
6	45 (87%)	2 (4%)	3 (6%)	14 (27%)	0 (0%)

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings, it appears that survey participants were uncertain whether they could cross the centerline to make a left turn into a driveway independent of the centerline buffer width. With respect to driving between the centerline striping and passing, the findings indicated a decline in comprehension of the correct driving behavior when the centerline buffer width was 6 ft or greater. Open-ended responses also indicated that participants thought centerline buffer widths greater or equal to 6 ft could be a turn lane. Therefore, researchers recommend that the allowable centerline buffer width be 1 to 4 ft. Next steps could include a survey to assess motorist understanding of centerline striping patterns used with centerline buffers on two-lane, two-way roads.

CHAPTER 4:
SPEED FEEDBACK SIGNS

Since the early 1990s, speed detection technology and dynamic messages signs (DMSs) have been incorporated into systems designed to monitor motorist speed and provide a warning or feedback message if the driver's speed exceeds a given threshold. Past research indicates that the first applications of radar detection speed monitoring and DMS motorist feedback used in conjunction with one another were to mitigate excessive speed at construction work zones (*16*), while commercially available integrated monitoring and display systems were initially employed in residential speed management programs (*17*). Relatively quickly, such systems were also applied for school zones, curve warning applications, and high-speed approaches to intersections.

Depending on the device implementation purpose, time frame, and technologies involved for both speed sensing and driver feedback messaging, these systems have been variously known as dynamic speed display signs, speed monitoring displays, dynamic curve warning systems, driver feedback signs, speed display signs, and speed feedback signs (SFSs). For this investigation, the general term *SFS* is used because the intent of this research synthesis was to examine the potential for using integrated speed monitoring and driver feedback functionality exclusively for speed management in a permanent application on high-speed highways, and not in proximity to potential downstream hazards.

SFS USE BY APPLICATION

Researchers fully investigated past applications of SFS technologies for community speed management, school zone speed management, curve warning, and other purposes but only because inferences and extrapolations could be made that affect speed management on high-speed facilities. In addition to the role SFSs can play in influencing driver speed choice behavior on approach to specific downstream hazards or controls (e.g., curve speed warning systems and high-speed intersections) or sections of roadway where speed is controlled for focused safety reasons (e.g., school zones and work zones), the focus of this research synthesis was the use of SFSs for overall corridor through-vehicle speed management in support of the posted speed limit on high-speed roadways. The following sections summarize the findings by application: work zones, school zones, curve speed warning, rural speed transition zones, residential speed management, and weather-related speed management.

Work Zones

The Minnesota Department of Transportation was among the first agencies to study SFSs for managing speeds approaching work zones in the 1980s. Motorist speed data were collected with no work zone speed limit, with static work zone speed limit signing, and with SFSs. Static signs proved marginally effective in reducing 85^{th} percentile speed but increased speed variability.

SFSs, however, were shown to create larger reductions in 85th percentile speed, significantly reduced the percentage of highest-speed drivers, and reduced speed variability (*18*).

These findings were confirmed through later research in South Dakota (*19*), Virginia (*20*), Georgia (*21*), and Texas (*22*). The South Dakota research reflected conditions on a high-speed, interstate highway, and the Texas study indicated speed reductions of about 5 mph through a work zone under rural, high-speed conditions. The Virginia research is significant in that it was an extension of previous DMS research (*16*) on work zone speed management and showed that the speed reduction effects of focused radar-monitored speed response messages were effective in interstate highway applications over long durations. The Georgia research reinforced this finding by determining that SFS-related speed reductions on high-speed highways were on the order of 7 to 8 mph and that the speed reduction impacts were not due to "novelty" effects (i.e., the speed reduction impacts were long term in nature).

Work zone SFS research from Nevada (*23*) experimented with the speed feedback display size and flash mode to gauge SFS effectiveness on different classes of vehicles. Overall, the portable work zone SFS application was noted to reduce speeds of all vehicles between 8 and 9 mph. Sign size and flashing mode were not determined to have additional speed influencing/reduction effects.

A very recent study of the speed management impacts of SFSs was performed on high-speed work zones in Kansas (*24*). Findings indicate that speed profiles were reduced 2 mph in work zones where the average speeds typically ranged between 51 and 70 mph.

Overall findings regarding SFS applications for work zones indicate:

- Speed reductions on the order of 5 to 10 mph can typically be expected in high-speed applications.
- Higher-speed drivers were most likely to reduce speed in response to SFSs.
- Even accounting for SFS novelty effects, long-term speed reduction changes in driver behavior will occur.
- SFS size and unique operating characteristics (e.g., flashing mode) do not enhance sign efficacy.

School Zones

In 2003, TxDOT and TTI investigated the long-term efficacy of SFS deployments in school zones and on the approaches to horizontal curves and intersections on high-speed roadways. Previous efforts to evaluate SFS performance were straightforward before-after comparisons, whereas researchers for this study monitored speeds shortly after implementation and again four months after installation to gauge longer-term changes in motorist response to the signs. In relation to school zones, motorist response varied based on their approach speed to the SFS. On average, motorists were driving 10 mph over the regulatory posted speed in the studied school zones. Higher-speed drivers appeared to make the most significant changes in speed, compared to drivers traveling at or below the posted speed. Average speed reductions were on the order of 9 mph at the school zone (i.e., only 1 mph over the posted school zone speed limit) but only 3 mph in speed limit step-down transition zones approaching reduced-speed school zones (*25*).

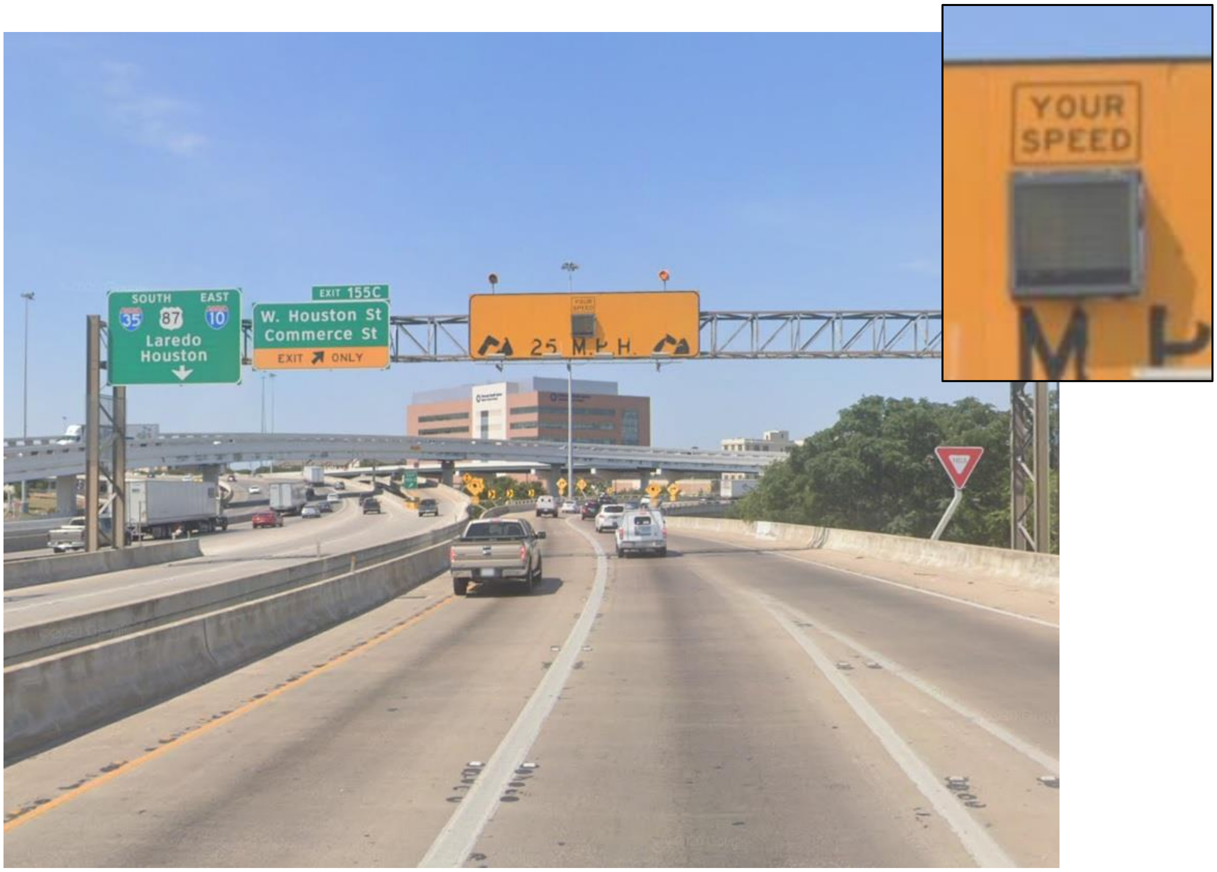
Research into the efficacy of SFSs for school zone speed management was performed for the District of Columbia Department of Transportation following long-standing pedestrian safety concerns with speeding in school zones (*26*). Motorist speeds were monitored before and after field implementation of SFSs at five school zone sites, and the results revealed a statistically significant difference in speed in just over 25 percent of speed comparisons. However, analysts pointed out that speeds were mathematically lower at 69 percent of sites, and the observed before/after speed differential was as large as 7 mph. The authors echoed the findings of the Texas research, indicating that school SFSs were most effective in environments of low visual clutter, on two-lane roadways, and where good sight distance was available.

School zone SFS applications have the following lessons learned that can be translated—to at least some degree—for high-speed SFS applications for speed management:

- Speed reductions on the order of 5 to 10 mph can typically be expected, reinforcing findings associated with work zones.
- Smaller speed reductions (on the order of 3 mph) were associated with transition zones near school zones, suggesting that speed reductions will likely be smaller outside the *immediate area* where a legal speed reduction is required.
- SFSs are most effective in environments with low visual clutter, with fewer lanes, and where good sight distance is available.

Curve Speed Warning

Among the early applications of SFSs for curve speed warning was a permanent, overhead sign bridge installed on the direct connector ramp from IH 35 to IH 10 in northwestern downtown San Antonio, Texas. The curve speed warning application (see Figure 16) has been in operation since early 1994. It provides the curve advisory warning speed, a digital readout displaying radar-monitored motorist approach speeds, and the legend YOUR SPEED.



(Source: © 2021 Google Maps)

Figure 16. IH 35 Curve Warning Sign in San Antonio, Texas.

The curve warning speed itself (25 mph) is rather low to accommodate sharp freeway curve geometry, but the presence of this device on a high-speed freeway is early verification of the radar speed-sensing technology and the viability of a digital speed feedback display on high-speed facilities. The 25+-year service life of this installation also suggests that the radar and digital speed feedback display technologies have been mature technologies for decades and are capable of long-term in-field performance.

Previously mentioned Texas research (*25*) on SFS long-term performance included two advance curve speed warning sites. Results indicated small decreases in speeds for automobiles approaching those curves, but no speed change was observed for large trucks. However, despite these marginal curve warning speed results, the overall study indicated that motorist speed variability did not appear to increase and that the long-term motorist behavior (after novelty effects would have passed) was changed such that drivers most exceeding the posted speed limit were those most likely to be effectively influenced (to reduce speed) by the SFS.

Hallmark, Hawkins, and Smadi (*27*, *28*) performed long-term tests of curve warning SFSs in higher-speed environments (50 to 70 mph) in seven states between 2012 and 2014. Reductions of 2.5 mph in average speed were observed one year after installation and 2 mph after two years.

For 85th percentile speeds, the reductions were 2.4 mph after one year and 2 mph after two years. Reductions in the fraction of vehicles exceeding the speed limit increased as the 5-mph increment above the speed limit increased (e.g., 5 mph, 10 mph, 15 mph, and 20 mph), with up to a 30 to 40 percent reduction in the fraction of vehicles going 15 mph or more over the speed limit. Researchers concluded that SFSs caused moderate reductions in mean and 85th percentile speeds as well as significant reductions—which were sustained over time—in the fraction of vehicles traveling at various increments over the advisory curve speed.

Experience with SFSs for curve warning applications can be summarized as follows:

- SFSs are capable of very long field service life and do not have unusual or frequent maintenance needs.
- Drivers most exceeding the speed limit are those most influenced by SFSs.
- Drivers' long-term behavior is influenced toward speed reductions, reinforcing findings also observed with work zone and school zone SFS applications.

Rural Speed Transition Zones

An extended-duration study of SFS performance in speed transition zones was performed across five higher-speed (45 to 55 mph) sites in Minnesota (*29*). Transition zones effectively act as speed step-down zones along rural highways between undeveloped areas and rural communities, where the posted speed through town is often on the order of 20 mph lower. All signs were 36-inch by 48-inch speed limit signs recommended by the Federal Highway Administration's (FHWA's) *2003 Manual on Uniform Traffic Control Devices* (MUTCD) (*30*) for higher-speed rural highways. The study findings revealed the sustained speed-reducing impact of SFSs in speed transition zones. Speed reductions were applied to mean and 85th percentile speeds as well as the 10-mph pace.

The Pennsylvania Transportation Institute performed similar research into SFS applications in speed transition zones but focused on determining the lasting effects on driver speed once SFSs were removed from 12 study sites (*31*). Aggregated results demonstrated average speed reductions on the order of 6 mph in a rural, higher-speed environment. However, once the SFSs were removed, the residual speed reduction effects were not sustained. Researchers also noted that there was substantial variability in speed reductions across SFS test sites, and that these variations were likely caused by variability in the roadway and roadside features present at each site as well as the different land uses present along each transition zone.

SFSs were among several speed management tools applied in a broad review of rural traffic calming techniques in several small communities in Iowa (*32*). Transverse speed bar and lane narrowing treatments were also applied, and these treatments were used in some cases in combination with SFSs. As a result, it is difficult to draw direct conclusions about SFS performance. However, the authors note that SFSs or the combination of SFSs with another treatment appeared to have a greater influence on driver speed reduction than other treatments alone. The research team emphasized that while even the most effective treatments had a modest influence on mean and 85th percentile speed, their main contribution is "their ability to significantly reduce the number of vehicles traveling over the speed limit" (*32*).

A similar effort to establish the rural community impacts of SFSs was performed in Addison County, Vermont, in 2012 (*33*). SFSs were shown to have speed reduction impacts alone and in combination with pedestrian safety treatments, such as warning signs and sidewalks. However, the study indicated speed reduction impacts were significant without clarifying whether this meant statistically significant or merely substantial in size. Six- to 8-mph speed reductions in 85th percentile speed (4- to 7-mph reductions in average speed) were observed at rural community fringes, while more moderate 3-mph reductions in 85th percentile and average speed were observed closer to the community's center.

In aggregate, findings from rural speed transition area use of SFSs include:

- Five- to 10-mph speed reductions were associated with SFSs in high-speed transition areas between rural and suburban operating environments.
- Speed reduction effects are not maintained if/once SFSs are removed.
- More pronounced speed reduction effects were observed in rural, higher-speed areas compared with speed reduction effects in rural communities (i.e., areas with lower speed limits).

Residential Speed Management

A long-term study of a residential speed management SFS application was conducted in King County, Washington, between 2001 and 2004 (*34*). SFS installation took place in 2002, and an initial study of performance following implementation showed 1- to 2-mph (5 to 10 percent) reductions that were statistically significant. While such speed changes do not practically appear meaningful in terms of motorist response, a subsequent study at the same locations in 2003 and 2004 verified that these changes represented long-term changes in motorist behavior. Further, community feedback reinforced that SFSs were an effective speed management tool.

The City of Bellevue, Washington, has an annually funded program (*35*) to install SFSs for community speed management and to maintain equipment already installed in the field. Most roads were moderately sized local roads and collectors with 25- or 30-mph speed limits and volumes over 3,500 vehicles per day. As of 2009, the city had installed SFSs at 31 sites and had long-term speed reductions at all locations. At most radar sign locations, results show an overall reduction of vehicle speeds between 1 and 6 mph, even up to 8 years after signs were installed.

The Center for Transportation Research and Education at Iowa State University (*36*, *37*) performed rural community speed management experimentation with two types of SFSs: a speed limit sign with border light-emitting diodes (LEDs) that flashed when a vehicle was exceeding the speed limit (posted at 25 mph) and a more traditional SFS with a YOUR SPEED legend that was posted beside a regulatory speed limit sign (also 25 mph). LED sign results showed 85th percentile speed reductions of 1 and 6 mph at separate sites after one year of operation, and SFS results showed a 6-mph reduction after one year. Both LED signs and SFSs showed greater reductions in the proportion of over-speed vehicles as the 5-mph increment over the speed limit increased, with SFSs having greater reductions (up to 71 percent for vehicles going 15 mph over the speed limit) than LED signing.

A 2014 study (*38*) by staff from the City of Calgary, Canada, examined the driver response to temporary SFS implementation using both trailer- and post-mounted units in residential roadway environments. During the deployment of the trailer-mounted SFSs, speeds at all three study sites were significantly reduced, and there was an associated drop in the percentage of drivers exceeding the speed limit. However, after two weeks of removal, speed reduction effects remained at only one of the three study sites. For the post-mounted SFS site, speed reduction and speed variability effects were noticed during the early weeks of a 6-week installation. Both those effects diminished, and average and 85th percentile speeds returned to pre-deployment levels by the fourth week of the test. The authors' experience suggests that SFS deployment in residential speed management applications is most effective in short-term installations, likely on a rotation basis.

Somewhat contradictory results were obtained in a recent, long-term study of 10 SFS sites in Campbell, California (*39*). Sites were a mixture of local and collector roads with 25-mph speed limits, but one arterial had a 35-mph speed limit. Mean speed changes were observed across most sites five years after initial SFS implementation. The roadways with the most significant long-term speed reduction effects were two-lane local streets; speed change effects for multilane roads were mixed. The authors noted that while their findings were statistically significant, in many cases the actual speed reduction was on the order of 1 or 2 mph.

While most community speed management SFS applications tend to be at lower speeds, some of the findings from those applications remain applicable when extending SFS implementation to high-speed roadways. Significant SFS findings for community speed management include:

- Community feedback indicates that SFSs are an effective tool for speed management.
- Speed reduction effects are maintained, even in locations where SFSs have been deployed up to 8 years, but the speed reduction influences decrease over time.
- SFSs are the most effective among several speed management device applications, suggesting they are a preferred device for this purpose. This includes SFSs being favored in comparison to newer technologies, such as LED border-enhanced speed limit signs.
- The greatest SFS effectiveness is likely to be maintained if portable SFSs are used on a rotating schedule/cyclical basis.

- Two-lane roadways demonstrated greater SFS effectiveness than multi-lane arterials, reinforcing SFS school zone findings.

Weather-Related Speed Management

Similar technologies to those used in SFS implementation on high-speed highways are applied to enable variable speed limits (VSLs) on U.S. interstate highways for weather-related speed management. Such systems (see Table 7) are designed to provide road speed management under visibility-limited conditions but also demonstrate the complete viability of condition-monitoring systems (e.g., radar monitored speeds) and (digital) VSL displays that are also fundamental components of SFS implementation on high-speed highways. These systems also demonstrate that the digital speed readouts available in the commercial marketplace are of a size and display technology suitable for high-speed application.

Table 7. U.S. Interstate Weather Variable Speed Limit Systems (*40*).

State	Highway	VSL Range (mph)	Location	Weather Issue(s)
Alabama	IH 10	65–35	Mobile	Fog
Delaware	IH 495	65–45	N/A	Rain, fog, ice
South Carolina	US 25	55–45	Greenville County	Rain, ice
Washington	IH 5, IH 90, SR 520, US 2	65–35	Various	Rain, fog, snow, ice
Wyoming	IH 80	75–35	Laramie to Rawlins	Rain, fog, snow, ice

Among these weather-related VSL systems, the installation on IH 80 between Laramie and Rawlins, Wyoming, is applicable to the current investigation since rural roadway and visibility conditions during non-inclement weather are like the West Texas conditions where SFS implementation is being considered on rural, high-speed highways. Supported by 2008 state legislation that enabled the Wyoming Department of Transportation (WYDOT) to set speed limits based on time of day, vehicle type, weather condition, and other factors, WYDOT equipped the Elk Mountain Corridor with weather sensors and digital VSL signs (see Figure 17) in early 2009 (*40*). Depending on road surface conditions (e.g., dry, wet, or ice) and visibility, the speed limit can be set between 75 and 35 mph by either the Wyoming Highway Patrol (WHP) or WYDOT maintenance foremen. Traffic management center staff can also authorize a speed limit change if neither WHP or WYDOT maintenance foremen are available and use the VSL management system to post the condition-appropriate speed limit value (*40*). At least four additional intracity corridors in Wyoming have been equipped with the technology (*41*).

(Source: © 2021 Google Maps)

Figure 17. WYDOT IH 80 Variable Speed Limit Installation.

In 2010, research by the University of Wyoming (*41*) investigated all aspects of the VSL system deployment and developed several findings pertinent to SFS deployment. First, researchers noted that under clear weather conditions, driver speed variation decreased between 75-mph and 65-mph speed zone data sets (i.e., higher speed limits were associated with greater speed variability). However, for the 65-mph data set, the average and 85th percentile speeds were much higher than the posted speed limit compared with the 75-mph data set. Researchers also noted that drivers adjusted their speed 5.9 to 8.6 mph for every 10-mph speed reduction posted on the signs. This observed speed reduction is in addition to the typical speed reductions due to observed weather conditions.

Weather-related VSL research findings related to SFS implementation include:

- The speed sensing technologies—primarily radar—used in VSL and SFS applications are viable and reliable under even harsh weather conditions and required only nominal maintenance.
- Digital sign technologies available for the speed feedback display integrated with SFSs are of the appropriate size and legibility for very-high-speed applications.

SFS IMPLEMENTATION CONSIDERATIONS

SFS Guidance Warrants

The Western Transportation Institute developed 2010 guidance for effective SFS deployment (*42*). The project team synthesized available SFS research and conducted nationwide surveys to document SFS utilization and engineering practice. Unique elements of the findings include draft descriptions and specifications for SFS equipment depending on application (e.g., work zone, school zone, or curve warning) and the Table 8 general guidance warrants for SFS deployment.

Table 8. General Guidance Warrants for SFS Deployment (Adapted from *42*).

Warrant Basis	Guidance
85th percentile speed	An SFS may be considered when the observed 85th percentile speeds at a site exceed the posted speed limit by 5 mph or more
Mean speed	An SFS may be considered when the observed mean speeds at a site exceed the posted speed limit by 5 mph or more
Average daily traffic (ADT)	An SFS may be considered when ADT exceeds 500 vehicles
Accidents	An SFS may be considered at sites exhibiting a correctable speeding-related crash history within a recent time period
Pedestrians	An SFS may be warranted at sites with a pedestrian-related crash history
Posted speed limit	An SFS may be considered in conjunction with other warrants when the posted speed limit at a site is 25 mph or greater

Effectiveness Prediction

Morgan State University performed a highly detailed investigation (*43*) of drivers and driver behavior in Maryland to develop models of driver responsiveness to SFSs. Researchers developed several interesting conclusions related to SFS effectiveness:

- SFSs are effective speed management devices.
- Drivers' socioeconomic information and attitudes did not have a significant effect on speed compliance.
- SFS effectiveness decreases with time, so they are best positioned as temporary solutions.
- SFSs are effective over a limited distance (drivers increase speed after passing an SFS) and should therefore be used at critical locations (e.g., work zones and school zones).
- SFS effectiveness increases when combined with another speed control device.

The University of Madison–Wisconsin's Traffic Operations and Safety Laboratory conducted a 2012 investigation to determine the spatial effectiveness of SFSs (*44*) using real-world vehicle trajectory data. The most significant speed reductions occurred 1200 to 1400 ft upstream of SFSs, while speeds began to increase 300 to 500 ft after SFSs. Results showed that drivers with the greatest speeding behavior had the greatest likelihood of reducing speed—a finding consistent with previous research. Researchers interpreted their results to suggest that SFSs should be deployed near the locations where speed reductions were intended and should not be considered a speed control solution at a corridor level.

Researchers in Arizona recently completed an investigation of nine sites in Pima County, Arizona, to determine the independent and combined effects of SFSs and law enforcement on motorist speed (*45*). The posted speed limit at study sites ranged from 40 to 50 mph, with most sites having a 45-mph limit. Study of speeds before, at, and downstream of an SFS and/or enforcement showed speed reductions of up to 2.5 mph at the enforcement location and an additional 2.5 to 3.5 mph downstream of the treatment. In other words, the effective influence length of the treatment—especially an SFS combined with enforcement—was approximately one-quarter mile. Also, as with most past studies, the proportion of drivers going over the speed limit and 5 mph above the speed limit was reduced. An SFS combined with enforcement was determined to be the most effective speed management combination, and periodic enforcement was shown to boost SFS effectiveness.

SFS SAFETY EFFECTS

Members of the Norwegian Institute of Transport Economics assembled a catalog of roadway elements and treatments and referenced international studies on the safety impacts of those treatments to present likely safety impacts and ranges of impacts for safety treatments, including SFSs (as a category of variable message signs). The authors' best estimate of change in the number of injury crashes due to SFS implementation was a 41 percent reduction (*46*), though the confidence interval was very large (78 percent reduction to 59 percent increase), and the results were not statistically significant. The authors went on to state that most published results from which they derived their estimates were based on simple before-after comparisons that were subject to regression-to-the-mean effects.

Findings based on more recent U.S. research and published on FHWA's Crash Modification Clearinghouse webpage (*47*) contain SFS results for curve warning applications on two-lane roads in rural conditions. Crash modification factors range from 0.95 to 0.93, indicating a crash reduction for SFSs in rural curve warning applications of 5 to 7 percent. These results were based on a national demonstration project with study sites spread across seven states (*28*).

For the past 10 years, the City of Edmonton, Canada, has been installing SFSs to manage speed and improve safety. As of 2019, over 200 signs have been installed on arterials, collectors, and local streets (*48*). Overall, mid-block crash reductions ranged from 32.5 to 44.9 percent, with the highest reductions observed for severe speed-related crashes. The results were statistically significant and based on analysis of 10 years' worth of data. The evaluation included benefit-cost comparisons, which were strongly favorable for the relatively low-cost SFS treatment.

INSTITUTE OF TRANSPORTATION ENGINEERS MEMBER FORUM QUERY

To find speed management SFS examples—and possible past studies—across the United States, the project team posted an online query through the Institute of Transportation Engineers (ITE) All Member Forum in May 2021. The text of the member request for information is as follows:

> The Texas A&M Transportation Institute (TTI) is currently investigating the use of speed feedback signs (SFS) on high-speed (60+ mph) roads for speed management. All examples of SFS applications on high-speed roads are being investigated (including work zone, curve warning and variable speed limits), but sites and/or studies of the most interest are direct speed management applications—SFS deployments communicating the need to adhere to the speed limit via radar-monitored speed feedback. If you aware of such sites or studies, please share those locations through the forum or by email.

ITE Feedback by State

Florida

Forum feedback from Florida indicated that the Florida Department of Transportation developed a work zone advance warning specification that included SFSs (*49*). The work zone layout was specifically designed for deployment on higher-speed highways (*50*).

Missouri

A unique, high-speed SFS is located along westbound US 50 in Lee's Summit, Missouri (see Figure 18). This SFS installation appears to be solar powered and features only the solar array and SFS two-digit speed display on the sign pole; no posted speed limit sign is present. The SFS location is in a 60-mph zone immediately downstream of a 65-mph zone.

(Source: © 2021 Google Maps)
Figure 18. Missouri US 50 SFS Installation in Lee's Summit, Missouri.

Utah

The ITE community identified US 91/US 89 between Brigham City and Logan, Utah, as a corridor whose speed is managed by a combination of SFS and static speed limit signing. The base speed limit in undeveloped areas is 65 mph, and each SFS displays the motorist's speed as a self-check on speed limit compliance. The mostly rural driving environment and relatively low number of access locations are consistent with West Texas sites being considered for high-speed SFS implementation (see Figure 19). However, these conditions are only present in the more southerly end of the corridor near Brigham City. Farther north, US 91/US 89 operates more as a divided highway and driveway, and side-street access is substantially more frequent.

Wyoming

An ITE member from Colorado recalled sites along US 191 in Grand Teton National Park where SFSs are used along rural highway segments to manage speed. An example (see Figure 20) was found along US 191 northbound near the Gros Ventre River, preceding the approach to a roundabout servicing Gros Ventre Road/Golf Course Road.

(Source: © 2021 Google Maps)
Figure 19. Utah Department of Transportation US 91/US 89 SFS Installation in Brigham City to Logan, Utah.

(Source: © 2021 Google Maps).
Figure 20. WYDOT US 191 SFS Installation in Grand Teton National Park.

ITE Feedback on Proposed MUTCD Changes

During the request for SFS sites conducted through the ITE All Member Forum, researchers received information on a Notice of Proposed Amendments (NPA) for the 11th edition of the MUTCD. The proposed MUTCD revisions include creating a section on SFSs and detailing their use for speed management and curve warning applications. The proposed MUTCD text (*51*) for a new stand-alone section for SFSs is provided below. MUTCD Figure 2C-4, which is referenced in the NPA text, is included in Figure 21.

Section 2C.13 Vehicle Speed Feedback Sign (W13-20, W13-20aP)

Option:

A Vehicle Speed Feedback (W13-20) sign or (W13-20aP) plaque (see Figure 2C-4) that displays the speed of an approaching vehicle back to the vehicle operator may be used to provide warning to drivers of their speed in relation to either a speed limit or horizontal alignment warning advisory speed sign.

Standard:

When used as a warning to motorist of their speed in relation to the posted speed limit, the Vehicle Speed Feedback Plaque (W13-20P) shall be mounted below a Speed Limit (R2-1) sign (see Section 2B.23).

When used to supplement a horizontal alignment warning sign advisory speed, the Vehicle Speed Feedback Sign (W13-20) shall be an independent installation near the point of curvature of a horizontal curve (see Section 2C.06).

The legend YOUR SPEED shall be a black legend on a yellow retroreflective background. The changeable legend displaying the speed of the approaching vehicle shall be a yellow luminous legend on a black opaque background.

The vehicle speed displayed on the changeable portion of the sign shall not flash or change color. The Vehicle Speed Feedback sign and plaque shall not flash, strobe or use other dynamic elements integrated into the changeable legend display. When no vehicles are approaching, the changeable display shall not display a legend.

Guidance:

The changeable portion of the Vehicle Speed Feedback legend should be approximately the same height, width, and stroke of those on the Speed Limit sign it supplements or is mounted below.

When a W13-20P is used with a Speed Limit sign it should be approximately the same width of the Speed Limit sign it is mounted below.

Figure 21. MUTCD Figure 2C-4 Vehicle Speed Feedback Signs (*51*).

PREDICTED SFS PERFORMANCE ON HIGH-SPEED HIGHWAYS

Based on the synthesized review of SFS practice over the last 20 years covering applications for work zones, curve warning, school zones, speed transition areas, community speed management, and weather-related speed management (VSL), researchers projected the performance expectations and implementation issues found in Table 9 for high-speed management use of SFSs. With the extremely limited use of SFSs to date for speed management alone on very-high-speed roadways, some findings are based on extensions of results observed under lower-speed conditions.

Table 9. Predicted SFS Performance on High-Speed Highways.

Issue/Factor	Projected Performance
Sign design	• SFS implementation in high-speed work zones and VSL applications suggests that signs of adequate size (with appropriately sized speed feedback characters) are currently available
Sign durability	• Long-term performance of permanently installed SFSs for curve speed warning and community speed management indicates sign durability will meet department of transportation (DOT) needs with routine maintenance
Effectiveness	• In 65+-mph applications, 3- to 8-mph reductions in both average and 85^{th} percentile speed could be expected on initial implementation. The reductions will be most significant for vehicles exceeding the posted limit by the greatest amount • Reduced-speed effects from SFSs should not be expected for significant distances up- or downstream of the sign (e.g., > 1/4 mile) • SFS speed reduction effects are expected to fade/decrease over time for a permanent installation • Corridor-wide SFS implementation is not recommended; rather, spot implementation is preferred in areas of speed concern • Cyclical use of a portable SFS trailer would provide speed management effects but should be focused on areas with speed concerns; corridor-wide results should not be expected • Long-term effectiveness is more likely with cyclical enforcement
Safety	• Very moderate crash reductions are possible due to reductions in speed variability, based on findings for lower-speed roads • No historical studies are available for SFS performance in very-high-speed management environments, creating large uncertainties in the prediction of crash reduction likelihood
Enforcement	• Enforcement is necessary if long-term SFS effectiveness is expected • At least one example exists of responsible transportation agency staff coordinating with law enforcement in an SFS-related enforcement program

CHAPTER 5: DIRECTION INDICATOR BARRICADES

The U.S. Congress authorized the Strategic Highway Research Program (SHRP)—a five-year, applied research initiative—to develop and evaluate techniques and technologies to combat the deteriorating conditions of the nation's highways and to improve their performance, durability, safety, and efficiency (*52*). One of those initiatives was the study of direction indicator barricades (DIBs) (*53*, *54*, *55*). DIBs were developed, studied, and proven to be a positive guidance device used to delineate the transition of lane closures in a work (construction) zone. DIBs provide directional information to drivers that is not always conveyed with normal barricades.

DIBs are approved in the 2011 Texas MUTCD (*56*) and the TxDOT Barricade and Constructions sheets (*57*) but are rarely used because neither of these documents provides detailed guidance about their application. This chapter summarizes what was discovered through a literature review, a search of state DOT standard sheets (as posted on their websites), and direct contact with 23 state DOTs.

LITERATURE REVIEW

Researchers discovered 23 pieces of literature before 2009 and three pieces of literature after 2009 that contain a discussion of DIBs. Most of the literature describes the development and design of DIBs and/or provides anecdotal findings based on limited testing in the field. Only a few references document studies on the operational impacts of DIBs versus other types of channelizing devices (e.g., barricades or drums). This section summarizes the key literature.

A 1993 SHRP study (*54*) tested two DIB designs and standard barricades on a closed course in left- and right-lane closure applications. Drivers took more time to recognize and interpret the DIBs than standard barricades. However, drivers were more likely to correctly interpret the DIBs than standard barricades. In addition, drivers rated DIBs more favorably than standard barricades. Researchers also did not find any significant differences in lane-change maneuvers or vehicle behavior (i.e., lateral acceleration and speed variance) between the DIBs and standard barricades.

A 1996 TTI study (*58*) noted that DIBs seem to offer additional positive guidance to drivers in work zone tapers and thus are a desirable enhancement for traffic control in a work zone environment. At that time, the safety benefit of DIBs over drums was not known, but the study noted that anecdotal reports had indicated that DIBs were safer to install than drums because DIBs are easier and faster to place. Thus, DIBs may reduce lane closure installation and removal times, and worker exposure to traffic. Overall, the study recommended that TxDOT consider DIBs for implementation.

A 2000 TTI study (*59*) reported that Arkansas, Georgia, Alabama, and Illinois had favorable experiences with DIB applications during the SHRP evaluations. Advantages of DIBs included:

- Ease of handling (i.e., quick to install and easy to store).
- Sturdy and durable.
- Respected by drivers.
- Improved crew safety.
- Improved traffic flow.

Based on these experiences, as well as others (*60*), FHWA included DIBs in the 2000 MUTCD (*61*).

A 2005 study (*62*) reviewed the evaluation of a narrower version of a DIB in Kansas. Since researchers observed no statistically significant changes in speeds or lane distributions, researchers assumed the DIBs were as visible as drums.

In the 2011 Texas MUTCD (*56*), DIBs are referenced in Section 6F.69. The language in this section of the Texas MUTCD (see below and Figure 22) is the same as in the national MUTCD (*63*). DIBs are not the same as Type 1, 2, or 3 barricades.

> **Section 6F.69 Direction Indicator Barricades**
> **Standard:**
> **The Direction Indicator Barricade (see Figure 6F-7) shall consist of a One-Direction Large Arrow (CW1-6) sign mounted above a diagonal striped, horizontally aligned, retroreflective rail.**
> **The One-Direction Large Arrow (CW1-6) sign shall be black on an orange background. The stripes on the bottom rail shall be alternating orange and white retroreflective stripes sloping downward at an angle of 45 degrees in the direction road users are to pass. The stripes shall be 4 inches wide. The One-Direction Large Arrow (CW1-6) sign shall be 24 x 12 inches. The bottom rail shall have a length of 24 inches and a height of 8 inches.**
> Option:
> The Direction Indicator Barricade may be used in tapers, transitions, and other areas where specific directional guidance to drivers is necessary.
> *Guidance:*
> *If used, Direction Indicator Barricades should be used in series to direct the driver through the transition and into the intended travel lane.*

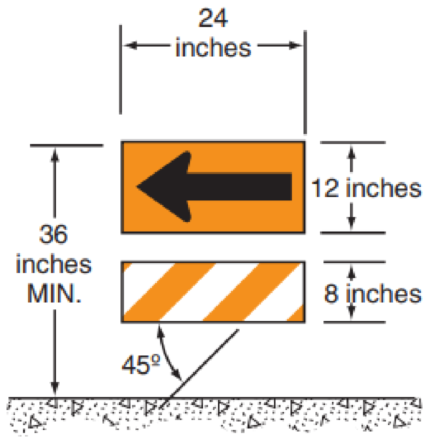
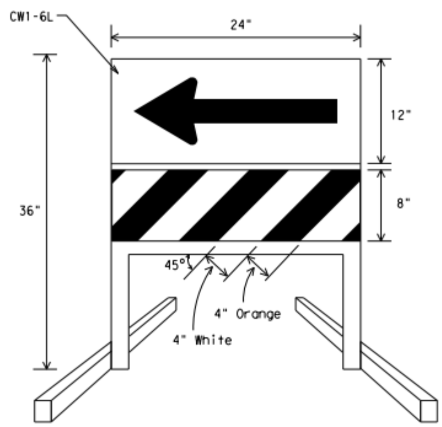


Figure 22. Direction Indicator Barricade from Texas MUTCD Figure 6F-7 (*56*).

DIBs are also referenced in the TxDOT Barricade and Construction Standards (*57*). Figure 23 shows the standard design and general notes for the DBI. Additional details mainly address material specifications. However, double arrows on DIBs are not allowed. So, while both the Texas MUTCD and TxDOT Barricade and Construction Standards indicate that DIBs may be used in tapers, transitions, and other areas where directional guidance is needed, detailed application information is lacking.



DIRECTION INDICATOR BARRICADE

1. The Direction Indicator Barricade may be used in tapers, transitions, and other areas where specific directional guidance to drivers is necessary.
2. If used, the Direction Indicator Barricade should be used in series to direct the driver through the transition and into the intended travel lane.
3. The Direction Indicator Barricade shall consist of One-Direction Large Arrow (CW1-6) sign in the size shown with a black arrow on a background of Type B_{FL} or Type C_{FL} Orange retroreflective sheeting above a rail with Type A retroreflective sheeting in alternating 4" white and orange stripes sloping downward at an angle of 45 degrees in the direction road users are to pass. Sheeting types shall be as per DMS 8300.
4. Double arrows on the Direction Indicator Barricade will not be allowed.
5. Approved manufacturers are shown on the CWZTCD List. Ballast shall be as approved by the manufacturers instructions.

Figure 23. TxDOT Barricade and Construction Channelizing Device BC(8)-14 (*57*).

OTHER STATE DOT USE OF DIBS

Researchers reviewed the other 49 state DOT websites before directly contacting each state DOT to determine if it has standards addressing the use of DIBs. Researchers found that DIBs are included in the MUTCD used by almost every state. The exceptions are Alaska, Hawaii, Michigan, and Washington. Researchers did find DIBs mentioned in other online standards or guidance documents for seven states (i.e., Illinois, Kansas, Minnesota, Missouri, New Mexico, Oklahoma, and Pennsylvania). Yet application information beyond what is included in the MUTCD was limited. No further guidance on DIB use was readily available online for the remaining 38 states.

Researchers then emailed contacts at the 49 state DOTs. Researchers received correspondence from 23 state DOTs (i.e., Alabama, Arizona, Georgia, Idaho, Illinois, Iowa, Kansas, Louisiana, Montana, Maine, Maryland, Minnesota, Missouri, Nebraska, New Hampshire, South Carolina, South Dakota, Utah, Vermont, Virginia, Washington, Wisconsin, and Wyoming). Most of the responses indicated that while DIBs are included in the MUTCD, their use is not specified in that state. While Alabama and Georgia were part of the original SHRP study that tested DIBs, these states never made DIBs part of routine business. The following sections summarize the limited additional guidance found about DIBs.

Illinois DOT

The Illinois Department of Transportation (IDOT) *Standard Specifications for Road and Bridge Construction* (*64*) describes the design of DIBs and states that DIBs are used in lane closure tapers. According to information received from IDOT, DBIs are used to form all lane closure tapers on multilane divided roadways. In some isolated locations, DBIs are used to close lanes on multilane undivided roadways, but it must be ensured that the arrow cannot be seen from the opposite travel direction. The IDOT *Highway Standards* (*65*) includes a standard drawing for lane closures on freeways and expressways (Standard 701401-12) that shows DIBs with steady-burn monodirectional lights spaced every 50 ft to form the lane closure taper. Additional standards that include DIBs include:

- Lane closure freeway/expressway with barrier (Standard 701402-12).
- Lane closure freeway/expressway, day operations only (Standard 701406-12).
- Lane closure freeway/expressway with crossover and barrier (Standard 701416-11).
- Lane closure, multilane, day operations only, for speeds ≥ 45 mph to 55 mph (Standard 701421-08).
- Lane closure, multilane for speeds ≥ 45 mph to 55 mph (Standard 701422-10).
- Lane closure, multilane with barrier for speeds ≥ 45 mph to 55 mph (Standard 701423-10).

- Lane closure, multilane undivided with crossover for speeds ≥ 45 mph to 55 mph (Standard 701431-13).
- Two-lane closure freeway/expressway (Standard 701446-11).

Figure 24 shows an example of DIBs used to close a lane in Illinois.

Source: IDOT
Figure 24. DIBs in Illinois.

Kansas DOT

The Kansas Department of Transportation *Special Provision to the Standard Specification,* Edition 2007, "Section 805 Work Zone Traffic Control and Safety" (*66*) includes DIBs and allows for their use only in tapers (see Figure 25). However, DIBs have only been used once in 32 years for a demonstration project.

	ITEM / LOCATION	CROSS-OVERS	SHOOFLY DIVERSIONS	TANGENTS	TAPERS	RAMPS	HEAD TO HEAD	OBJECT IDENTIFIER	
PORTABLE									
	DRUMS	YES	YES	YES	YES	YES	(1)	YES	
	CONICAL DELINEATORS	YES	YES	YES	YES	YES	(1)	YES	
	VERTICAL PANELS	(2)	(2)	(2)	(2)	(2)	(1,2)	YES	
	DIRECTION INDICATOR BARRICADE	NO	NO	NO	YES	NO	NO	NO	
	TYPE II BARRICADE	(2)	(2)	(2)	(2)	NO	NO	YES	
FIXED									
	TUBULAR MARKERS	(3)	(3)	(3)	NO	(3)	YES	NO	
	VERTICAL PANELS	(3)	(3)	(3)	(3)	(3)	(3)	YES	

(1) Not allowed on centerline delineation along freeways or expressways.

(2) The stripes shall slope downward to the traffic side for channelization.

(3) May be used upon the approval of the Engineer.

Figure 25. Kansas Department of Transportation Guidance for DIB Applications (*66*).

Minnesota DOT

DIBs are listed as Type B channelizers in the 2018 *Minnesota Temporary Traffic Control Field Manual* (*67*). However, no other details or applications are provided.

Missouri DOT

The Missouri Department of Transportation *Engineering Policy Guide* (*68*) contains information about DIBs in Section 616.6.69. The language describing the design of DIBs contained in this guide is like that in the MUTCD. The guide states that for long-term stationary operations, DIBs should be used instead of trim-line channelizers (see Section 616.6.64.2) in merging tapers since DIBs provide direction and have a larger target area for drivers. The guide also states that DIBs may be used in lieu of other channelizers for shorter-duration projects. DIBs cannot be used in shifting tapers. DIBs are not used on two-lane, two-way roadways.

New Mexico DOT

DIBs are included in the list of channelization devices for construction, maintenance, utility, and incident management operations in the New Mexico standards (*69*). However, no other details or applications are provided.

Oklahoma DOT

Similarly, DIBs are included in the 2009 Oklahoma Department of Transportation *Traffic Engineering Standards and Specifications* (*70*). No other details or applications are provided.

Pennsylvania DOT

The Pennsylvania Department of Transportation *Temporary Traffic Control Guidelines* (Publication 213) (*71*) describes the design of DBIs and notes that they may be used for all tapers approaching a temporary traffic control zone. DBIs are recommended on tapers approaching work zones on freeways and expressways.

CONCLUSIONS AND RECOMMENDATIONS

Even though DIBs have been in the MUTCD since 2000, researchers discovered that DIBs are not routinely used by most state DOTs. While DIBs seem to offer additional positive guidance to drivers in work zone tapers, they do not appear to impact driver behavior with respect to lane-change maneuvers and speed. Based on the limited information obtained through a literature review and correspondence with 23 state DOTs, TTI researchers were unable to develop detailed guidance for the application of DIBs. In general, DIBs can be used to form lane closure tapers on multilane divided roadways for long-term stationary operations.

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