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Traffic Control Device Analysis, Testing, and Evaluation Program: FY2019 Activities

Technical Report 0-6969-R2

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
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16. Abstract

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 2019 fiscal year included:

- Review of the application of embedded light-emitting diodes (LEDs) in signs.
- Review of the design and application of lane control signs on frontage roads.
- Assessment of the effectiveness of pedestrian crossing signs with embedded LEDs.
- Assessment of pedestrian crashes on high-speed roads.
- Review of guidance on the selection of appropriate treatment for a particular pedestrian crossing location.
- Field evaluation of pavement marking removal and development of guidelines.

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TRAFFIC CONTROL DEVICE ANALYSIS, TESTING, AND EVALUATION PROGRAM: FY2019 ACTIVITIES

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DISCLAIMER

This research was performed in cooperation with 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 the project was Melisa D. Finley, P.E. (TX-90937).

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CHAPTER 1: INTRODUCTION

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 2019 fiscal year (September 2018–August 2019) included:

- Review of the application of embedded light-emitting diodes (LEDs) in signs.
- Review of the design and application of lane control signs on frontage roads.
- Assessment of the effectiveness of pedestrian crossing signs with embedded LEDs.
- Assessment of pedestrian crashes on high-speed roads.
- Review of guidance on the selection of appropriate treatment for a particular pedestrian crossing location.
- Field evaluation of pavement marking removal and development of guidelines.
- Review of the applicability of traffic signal pole standards.
- Evaluation of wet-weather pavement marking retroreflectivity.
- Evaluation of the design and application of driveway assistance devices in lane closures on two-lane, two-way roads.
- Assessment of the effectiveness of signing and barricades in work zones.
- Evaluation of shoulder rumble strip placement on effectiveness.

The first six of these activities have been completed and are documented herein. The review of the applicability of traffic signal pole standards was completed, but it is considered internal in nature and thus is not included herein. The remaining four activities are ongoing and will be documented in future reports.

CHAPTER 2: REVIEW OF THE APPLICATION OF LEDS IN SIGNS

Embedded LEDs are being used within several types of signs, such as STOP, pedestrian crossing, WRONG WAY, chevron, and school speed limit signs. These flashing lights are used to increase the conspicuity of the sign and in some cases communicate a message via its color (i.e., red for stop and yellow for caution). While LED signs improve sign detectability distance by enhancing the sign conspicuity, previous research has shown that they can decrease legibility distance, especially at nighttime, due to the glare they introduce (*1*, *2*, *3*). Currently, minimum and maximum light levels for LEDs within signs are not specified. As part of this activity, researchers surveyed TxDOT districts to identify the type of signs and applications using embedded LEDs. This information was then used to identify additional research needs.

SURVEY

In July 2018, researchers prepared and distributed an online Qualtrics™ survey to gather information from the 25 TxDOT districts about two activities:

- The use and application of signs with embedded LEDs.
- The use and application of advance intersection lane control signs on frontage roads (R3-8) and turnaround signs (D13-1TL (R)).

The first three survey questions addressed signs with embedded LEDs. The first question asked whether a district had installed any signs with embedded LEDs. If the respondent answered no, he/she was directed to the survey section on advance intersection lane control and turnaround signs. Only districts using signs with embedded LEDs answered the second and third questions.

The second question asked districts about specific uses and applications of signs with embedded LEDs (see Table 1). More specifically, the survey had respondents:

- Select which signs have been installed (i.e., STOP, pedestrian crossing, WRONG WAY, chevron, speed limit, school speed limit, or other).
- Estimate the number of signs installed.
- Select reasons for installing signs from a list of known reasons.

Table 1. Survey Question 2.

Type of sign	District has installed	About how many installed?	Why installed? (*select all that apply*)
STOP  	○	____	____Increase conspicuity of sign ____Crash history at site ____Sunrise/sunset issues ____Due to public request ____Sign clutter ____Nighttime visibility concerns ____Other (please specify on the next page)
Pedestrian Crossing 	○	____	____Increase conspicuity of sign ____Crash history at site ____Sunrise/sunset issues ____Due to public request ____Sign clutter ____Nighttime visibility concerns ____Other (please specify on the next page)
WRONG WAY  	○	____	____Increase conspicuity of sign ____Crash history at site ____Sunrise/sunset issues ____Due to public request ____Sign clutter ____Nighttime visibility concerns ____Other (please specify on the next page)
Chevron 	○	____	____Increase conspicuity of sign ____Crash history at site ____Sunrise/sunset issues ____Due to public request ____Sign clutter ____Nighttime visibility concerns ____Other (please specify on the next page)
Speed Limit  	○	____	____Increase conspicuity of sign ____Crash history at site ____Sunrise/sunset issues ____Due to public request ____Sign clutter ____Nighttime visibility concerns ____Other (please specify on the next page)
School Speed Limit  	○	____	____Increase conspicuity of sign ____Crash history at site ____Sunrise/sunset issues ____Due to public request ____Sign clutter ____Nighttime visibility concerns ____Other (please specify on the next page)
Other (please specify): ______________________	○	____	____Increase conspicuity of sign ____Crash history at site ____Sunrise/sunset issues ____Due to public request ____Sign clutter ____Nighttime visibility concerns ____Other (please specify on the next page)

The third question sought to obtain information on which pedestrian sign assembly, illustrated in Figure 1, was most often installed by districts to increase the conspicuity of pedestrian crossings.

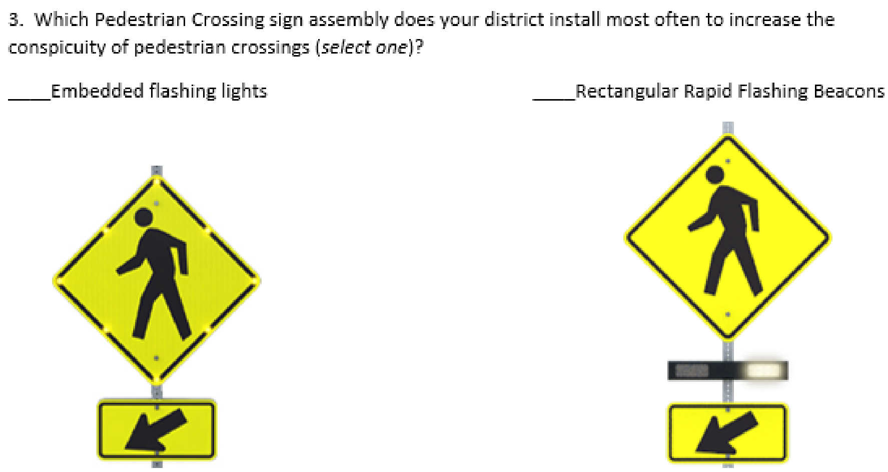


Figure 1. Survey Question 3.

FINDINGS

Twenty-two districts (88 percent) responded to the survey and provided information with respect to the use of signs with embedded LEDs (see Figure 2):

- Seventeen districts have installed signs with embedded LEDs (tan).
- Five districts have not installed any signs with embedded LEDs (maroon).

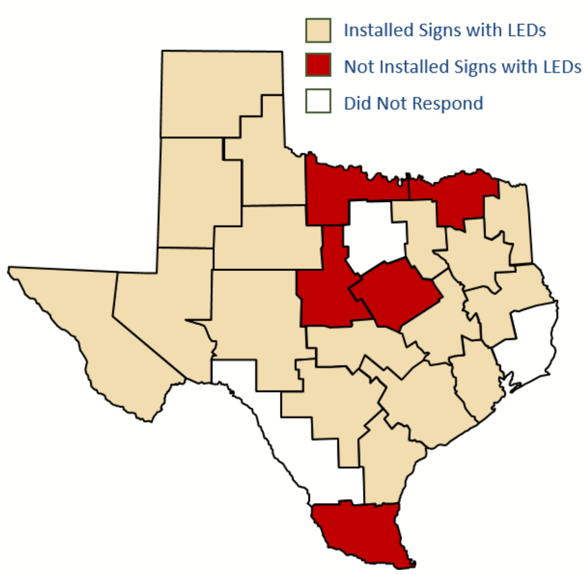


Figure 2. Use of LED Signs in TxDOT Districts.

Table 2 illustrates the results of the survey with respect to the six specific LED-embedded signs shown in Table 1. The main findings include:

- Most of the responding districts (94 percent) have installed STOP signs with embedded LEDs. The responding districts indicated that approximately 179 of these signs have been installed.
- Sixty-five percent of the responding districts have installed chevron signs with embedded LEDs. Even though fewer districts use these signs, there are over 330 of them on TxDOT roadways.
- Pedestrian crossing and WRONG WAY signs with embedded LEDs are used by about one-third of the districts (35 and 29 percent, respectively). Approximately 95 WRONG WAY signs and 25 pedestrian crossing signs with embedded LEDs have been installed.

Table 2. Types of Installed Signs with Embedded LEDs.

	 **R1-1**	 **W11-2**	 **R1-5a**	 **W1-8**	 **R2-1**	 **S4-3P**
Number (percent) of districts where installed (N = 17)[a]	16 (94)	6 (35)	5 (29)	11 (65)	0 (0)	0 (0)
Number of districts reporting number of signs installed	10	6	2	4	NA	NA
Estimate of the number of signs installed	179	25	95	331	NA	NA
Minimum, maximum number of signs installed in a district	2, 50	1, 8	1, 94	10, 221	NA	NA

[a] Total response is more than 100 percent since participants could provide multiple responses.
NA = not applicable.

Districts also reported installing other signs with embedded LEDs (see Figure 3):

- Intersection Warning signs (i.e., Cross Road symbol sign [W2-1] or HIGHWAY INTERSECTION AHEAD text sign [W2-1aT])—three districts.
- Vehicular Traffic Warning signs (i.e., TRUCK CROSSING text sign [W8-6] or Truck Crossing symbol sign [W11-10])—two districts.
- Stop Ahead sign (W3-1)—two districts.
- Horizontal Alignment signs (e.g., curve symbol sign [W1-2])—two districts.
    - Signal Ahead sign (W3-3)—one district.
    - YIELD sign (R1-2)—one district.

Figure 3. Other Signs with Embedded LEDs Installed by Responding Districts.

Table 3 contains the reasons for installing the six LED-embedded signs shown in Table 2. The main findings include:

- Crash history was the primary reason cited by districts for installing STOP signs with embedded LEDs (88 percent of the responding districts) and chevron signs with embedded LEDs (73 percent of the responding districts).
- Increasing sign conspicuity was reported as the primary factor for installing pedestrian crossing signs with embedded LEDs (83 percent of the responding districts) and WRONG WAY signs with embedded LEDs (80 percent of the

responding districts). Increasing sign conspicuity was also a factor in the installation of STOP signs with embedded LEDs (69 percent of the responding districts) and chevron signs with embedded LEDs (45 percent of the responding districts).

- About two-thirds of the districts also reported public requests as a reason for installing pedestrian crossing and WRONG WAY signs with embedded LEDs (67 percent of the responding districts each).

Table 3. Reasons for Installing Signs with Embedded LEDs.[a]

	 **(N = 16)**	 **(N = 6)**	 **(N = 5)**	 **(N = 11)**
Increase conspicuity of sign	69%	83%	80%	45%
Crash history at site	88%	0%	0%	73%
Sunrise/sunset issues	13%	33%	33%	0%
Due to public request	19%	67%	67%	0%
Sign clutter	0%	0%	0%	0%
Nighttime visibility concerns	25%	17%	17%	0%

[a] Total response is more than 100 percent since participants could provide multiple responses.

Other reasons cited by districts for installing signs with embedded LEDs included:

- As the service life of signs with flashing beacons is met, they have been replaced with signs with embedded LEDs.
- Changes to intersection geometry/configuration (pedestrian crossing signs).
- Systematic approach to mitigate wrong-way driving (WRONG WAY signs).

Last, only nine districts responded to the third survey question. Seventy-eight percent of the responding districts have installed the pedestrian sign assembly with embedded flashing lights. Only 22 percent of the responding districts have installed the pedestrian sign assembly with rectangular rapid-flashing beacons (RRFBs).

SUMMARY

The survey results indicate that 77 percent of the 22 districts that responded to the survey have installed at least one sign with embedded LEDs. The majority of the responding districts have installed STOP and/or chevron signs with embedded LEDs, with crash history being the primary reason. Increasing sign conspicuity was also a factor in the installation of STOP and chevron signs with embedded LEDs. Pedestrian crossing and WRONG WAY signs with embedded LEDs are installed in about one-third of the districts, with increasing sign conspicuity being the primary factor. It also appears that the districts prefer to install pedestrian sign assemblies with embedded LEDs over pedestrian sign assemblies with RRFBs.

ADDITIONAL INQUIRY

After reviewing the initial survey results, the TxDOT panel asked researchers to follow-up with districts that have installed signs with embedded LEDs to identify the following:

- How has your district been impacted by the maintenance of these signs?
- What type of power did your district use for these signs: solar, hardwire, or both? Please note any advantages and disadvantages experienced.
- What measures, if any, did your district take to protect these signs?
- Were there significant manufacturer differences in terms of available flash rates, flash duration, or speed of sequential flash progressions?

Out of the 17 districts that have installed signs with embedded LEDs, 10 responded to this additional inquiry.

Seven of the responding districts indicted little to no impact on their maintenance activities as a result of installing signs with embedded LEDs. The remaining districts noted the following maintenance issues with signs that have embedded LEDs:

- More difficult to maintain in rural areas.
- Stolen more often than static signs.
- Public shoots out individual flashing elements. Replacing flashing elements can be difficult and expensive.
- Damaged more easily when struck by a vehicle or by high winds. Sign face may be all right, but flashing elements damaged, so no longer operational. High winds have caused solar panels to turn or break off.
- Entire sign turning due to high winds. This results in the flashing components being less visible.
- Ordering replacement signs is more expensive and difficult.

Eight of the responding districts solely use solar panels to power the signs with embedded LEDs. For the other two responding districts, one uses only hardwire and the other uses both types of power sources. Advantages of solar power include:

- Do not have to install a service pole or underground conduit and wiring.
- Do not incur electrical service charges (initial and recurring).
- Can install quickly.

Disadvantages of solar power include:

- Solar panel often damaged with sign stuck by a vehicle.
- Need to maintain battery charge.
- Need to replace batteries.
- Can be damaged by high winds.

Advantages of hardwire power include:

- No solar panel maintenance/replacement.
- No battery maintenance/replacement.

Disadvantage of hardwire power include:

- Cost to install, especially in rural locations.
- Recurring electrical service charges.

Only two districts have taken measures to protect signs with embedded LEDs. When the public requests these types of signs in a rural location, the district asks that they take an active role in watching the sign to help reduce vandalism. Another district uses different locks on the boxes to prevent theft. The same district also uses anti-theft nuts.

Only one district was aware of differences between manufacturers, but the differences noted focused on the design of the illuminated components. Most manufactures embed LEDs in the border of the sign face. However, one manufacturer is using fiber optics to illuminate a portion of the sign (e.g., STOP) or the entire sign face. Another manufacturer sells flush-mounted flashing LEDs that can be attached to existing static signs. As a result, the district rewrote its specification to remove the word “embedded” and use the word “integrated” instead. This district also noted that flash rates and durations can be customized.

RECOMMENDATIONS

Although TxDOT districts are installing pedestrian crossing signs with embedded LEDs to increase sign conspicuity, the effectiveness of these signs has not been adequately evaluated. To date, there has only been one study that aimed to assess the effectiveness of pedestrian crossing signs with embedded LEDs (*4*), albeit with a small sample size of only two sites. Therefore, researchers recommend a study be conducted in Texas to determine the effectiveness of pedestrian crossing signs with embedded LEDs. Researchers could then compare the findings to results from similar studies conducted for other pedestrian treatments.

Although many districts have installed chevrons with embedded LEDs to reduce crashes, there are many factors that may influence the effectiveness of these signs that have not been evaluated. These factors include flash rate, flash duration, speed of the sequential flash progression through the curve, number of chevrons to flash at a time, and intensity of the flash. Therefore, researchers recommend that a study be conducted to investigate how these factors impact the effectiveness of chevron signs with embedded LEDs.

CHAPTER 3: REVIEW OF THE DESIGN AND APPLICATION OF LANE CONTROL SIGNS ON FRONTAGE ROADS

Advance intersection lane control signs (R3-8 series) are commonly installed upstream of intersections where the number of lanes increases as the driver approaches the intersection (see Figure 4). Sometimes installing advance intersection lane control signs can be challenging due to the number of lanes, right-of-way restrictions, and amount of information on the sign. There was also interest in examining the history and current use of the TURNAROUND sign (D13-1TL(R)) at the intersection of a frontage road and a cross street (see Figure 5).

As part of this activity, researchers reviewed current TxDOT standards and policies as well as previous research regarding the design and application of advance intersection lane control and turnaround signs on frontage roads. Additionally, researchers developed and distributed a survey to TxDOT districts to obtain information about the use of these types of signs and the challenges associated with their design and installation.

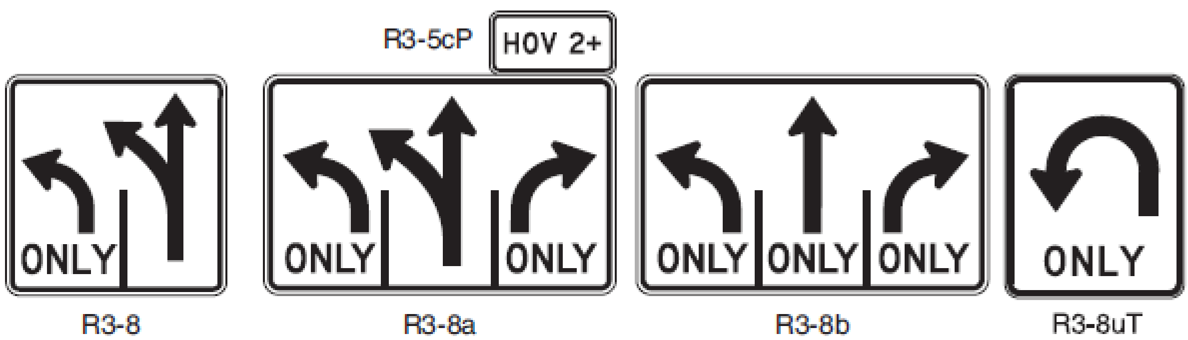


Figure 4. Advance Intersection Lane Control Signs (R3-8 Series) (*5*).

Figure 5. TURNAROUND Sign.

TXDOT STANDARDS AND POLICIES

Researchers reviewed the following documents looking for information about the design and application of advance intersection lane control and turnaround signs:

- 2011 *Texas Manual on Uniform Traffic Control Devices* (Texas MUTCD), Revision 2 (*5*).
- 2008 TxDOT *Freeway Signing Handbook* (*6*).
- 2018 TxDOT *Sign Crew Field Book* (*7*).
- 2017 TxDOT *Sign Guidelines and Applications Manual* (*8*).
- 2012 TxDOT *Standard Highway Sign Designs for Texas*, Revision 2 (*9*).

The findings from the 2011 Texas MUTCD, 2008 TxDOT *Freeway Signing Handbook*, and 2018 TxDOT *Sign Crew Field Book* are discussed below. The 2017 TxDOT *Sign Guidelines and Applications Manual* does not address the design or application of advance intersection lane control signs or turnaround signs. The 2012 TxDOT *Standard Highway Sign Designs for Texas* includes designs for a variety of advance intersection lane control signs and the TURNAROUND sign (D13-1TL(R)).

Texas MUTCD

Sections 2B.18 through 2B.22 of the 2011 Texas MUTCD (*5*) address regulatory signs that control movement, specifically mandatory and optional movement lane control signs, at and near the intersection. Intersection lane control signs (R3-5 through R3-8) are addressed in Section 2B.19. These types of signs require road users to turn from certain lanes, proceed through the intersection from certain lanes, and make permitted turns from other lanes. The signs are applied to three scenarios:

- Mandatory movement lane control (R3-5, R3-5a, and R3-7) signs.
- Optional movement lane control (R3-6) sign.
- Advance intersection lane control (R3-8 series) signs.

According to the 2011 Texas MUTCD (*5*), on signalized approaches where one of the following conditions occurs, overhead lane control signs should be installed at the signalized intersection over the appropriate lanes and in advance of the intersection over the appropriate lanes:

- Through lanes become mandatory turn lanes.
- Multiple-lane turns include shared lanes for through and turning movements.
- Other lane-use regulations that would be unexpected by unfamiliar road users are present.

When intersection lane control signs are mounted overhead, each sign should be placed over the lane to which it applies. The installation of an overhead intersection lane control sign for one approach lane does not require the installation of overhead signs for the other lanes of that approach.

Where overhead mounting of intersection lane control signs in advance of or at the intersection is not practical, one of the following alternatives should be used:

- At locations where through lanes become mandatory left-turn lanes, a mandatory movement lane control sign (R3-7) should be post-mounted on the left-hand side of the roadway where a through lane is becoming a mandatory left-turn lane on a one-way street or where a median of sufficient width is available.
- At locations where through lanes become mandatory right-turn lanes, a mandatory movement lane control sign (R3-7) should be post-mounted on the right-hand side of the roadway.
- At locations where a through lane becomes a mandatory left-turn lane on a two-way street where the median width is not sufficient, an advance intersection lane control sign (R3-8 series) should be post-mounted in a prominent location in advance of the intersection and consideration given to the use of an oversized sign.
- At locations where multiple-lane turns that include shared lanes for through and turning movements are present, an advance intersection lane control sign (R3-8 series) should be post-mounted in a prominent location in advance of the intersection and consideration given to the use of an oversized sign.

Intersection lane control signs may be located overhead or post-mounted when the number of through lanes on an approach is two or fewer. Intersection lane control signs may be omitted where both of the following conditions exist:

- A turn bay is provided through physical construction or pavement markings.
- Only the road users in such turn bays are allowed to make a turn in that direction.

Additional information regarding advance intersection lane control signs is found in Section 2B.22 of the 2011 Texas MUTCD (*5*). The R3-8 series of signs may be used to indicate the configuration of all lanes in advance of the intersection. When used, these signs should be placed at "an adequate distance in advance of the intersection so that road users can select the appropriate lane" (*5*). The 2011 Texas MUTCD (*5*) further states that these signs should be installed in advance of the tapers or at the beginning of the turn lane, and may be repeated closer to the intersection for additional emphasis. On approaches with three or more through lanes, these signs must be post-mounted in advance of the intersection (overhead mounting is not allowed).

Section 2B.22A in the 2011 Texas MUTCD (*5*) addresses the TURNAROUND ONLY sign (R3-8uT). Practitioners use this sign to indicate an exclusive turnaround movement from a specific lane. This sign is commonly used on freeways where a separate traffic lane is provided to connect frontage roads on both sides of the facility without a driver having to go through the intersection. A review of previous editions of the Texas MUTCD revealed that the TURNAROUND ONLY sign was first introduced in the 2006 edition in Section 2B.23 as the R3-8U sign (*10*).

The TURNAROUND sign (D13-1TL(R)) was also first introduced in the 2006 Texas MUTCD; however, the name was D14-1R(L) (*5*). The 2006 Texas MUTCD is the only edition in which this sign is included; earlier and later versions do not include any mention of this sign. Even so, the 2012 TxDOT *Standard Highway Sign Designs for Texas* (*9*) includes the design for the TURNAROUND sign (D13-1TL(R)).

Last, Section 3B.20 of the 2011 Texas MUTCD (*5*) provides standards and guidance for pavement markings, including words and symbols that are used for lane control. Words and symbols should be white and installed in accordance to the *Standard Highway Sign Designs for Texas* book (*9*). Lane-use arrow markings should be used in lanes designated for exclusive turning movements or lanes designated for shared movements (through and turning) that are contrary to the normal rules of the road. When used in turning lanes, two arrows are recommended for use: one of the arrows should be placed upstream of the end of the full-width turn lane and the other at an appropriate distance upstream of the stop line or intersection.

The manual dictates that when through lanes approaching an intersection become mandatory turn lanes, the lane-use arrow symbols shall be used and accompanied by standard signs. For through lanes that change to turn-only lanes, the ONLY word markings (seen in both Figure 6 and Figure 7) should also accompany the lane-use arrow markings and the appropriate signs. The markings and signs should be placed well in advance of the turn and repeated as necessary to avoid being unseen during queues, as demonstrated in Figure 6.

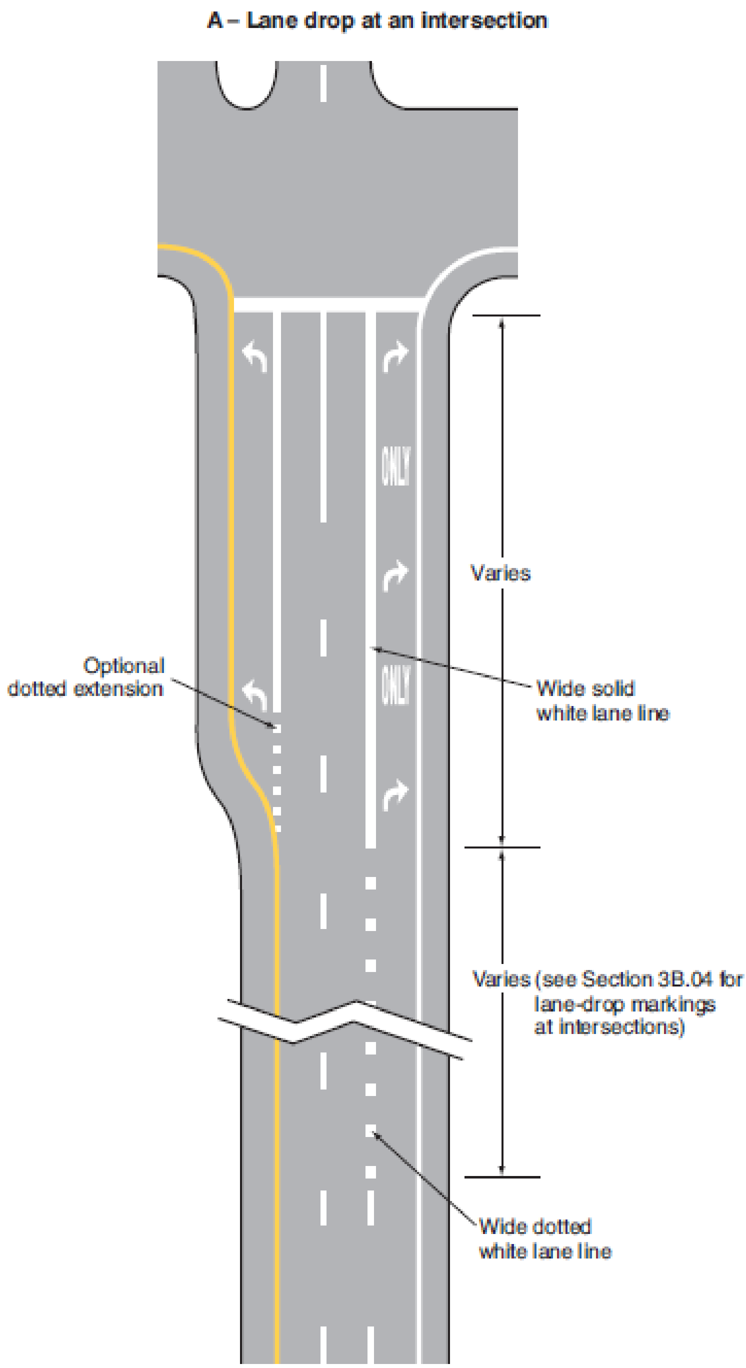


Figure 6. Texas MUTCD Figure 3B-11 Sheet 1 (*5*).

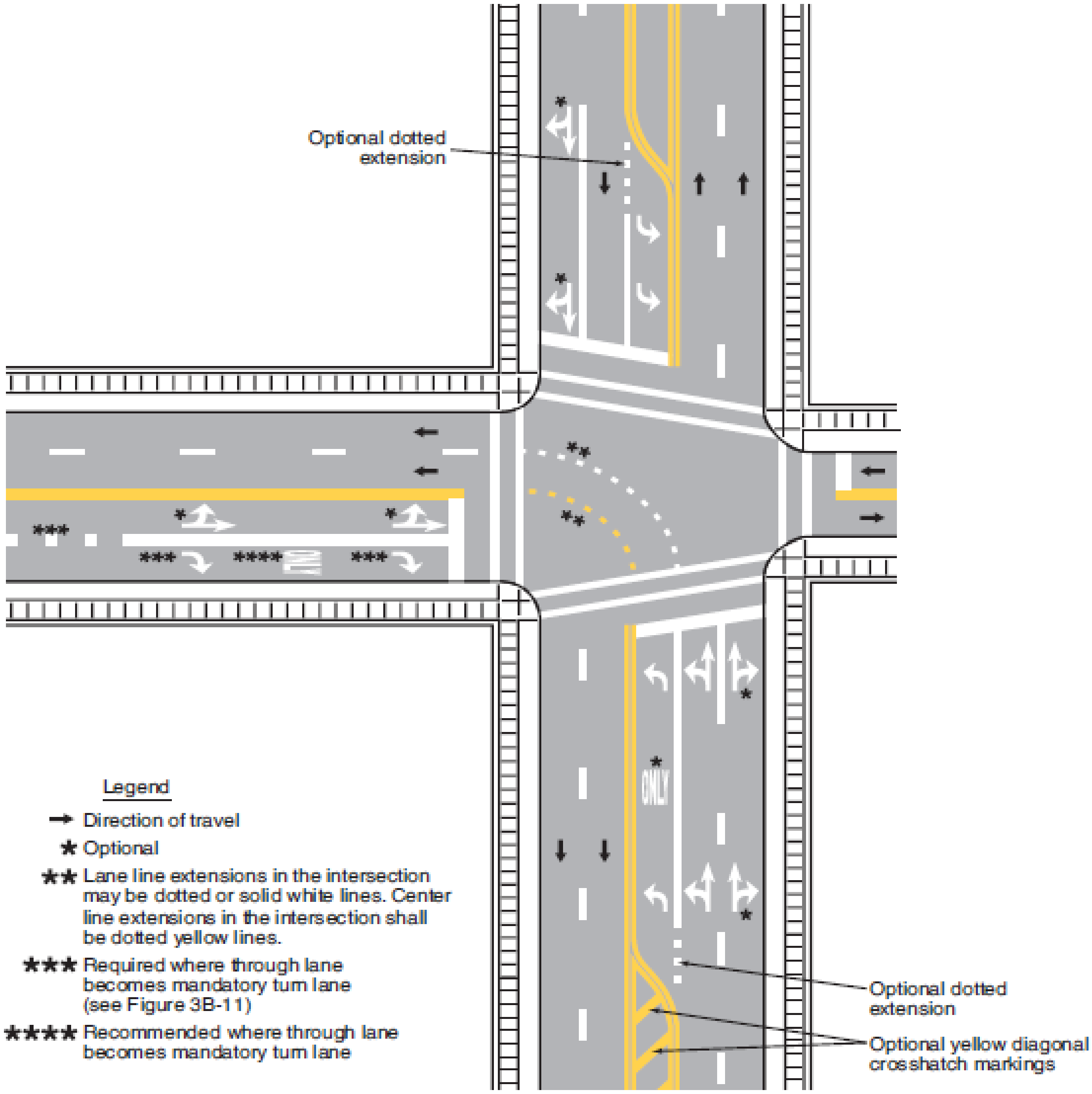


Figure 7. Texas MUTCD Figure 3B-27 (*5*).

TxDOT *Freeway Signing Handbook*

Chapter 6, Section 4, of the 2008 TxDOT *Freeway Signing Handbook* (*6*) focuses on frontage road approach signing. The illustrations begin with simple scenarios of a two-lane frontage road with two lanes at the intersection and evolve into more complex (flared) scenarios incorporating turnaround lanes, left lanes, and/or right lanes with optional turn and turn-only lanes. In several of the illustrations, advance intersection lane control signs (R3-8 series) are located at the beginning of the turn lanes (see Figure 8). As the complexity of the approach increases, a second optional set of advance intersection lane control signs is shown 300 ft upstream of the beginning of the turn lanes (see Figure 8). In some illustrations, flared turn lanes are not provided for designated turn-only lanes (see Figure 9). In these situations, no guidance regarding the specific location of the required and optional sets of advance intersection lane control signs is provided. The figure does note that the desired minimum spacing between signs is 150 ft. In yet other illustrations, an optional split version of advance intersection control signs is shown at the beginning of the turn-lane taper (see Figure 10). Instead of showing the lane assignment for all lanes on both sides of the roadway, each sign depicts only the lane assignments for the left lanes or right lanes, respectively. These signs are reserved for locations where the right of way is limited.

Some of the illustrations in this section of the 2008 TxDOT *Freeway Signing Handbook* also depict an exclusive turnaround lane. A TURNAROUND sign (D13-1TL(R)) is located near where the exclusive lane turns left (see Figure 8 and Figure 10). A TURNAROUND ONLY sign (R3-8uT) is shown in conjunction with other advance intersection lane control signs but not as a separate, stand-alone sign (see Figure 10).

TxDOT *Sign Crew Field Book*

The 2018 TxDOT *Sign Crew Field Book* (*7*) has only two illustrations that include the use of an advance intersection lane control sign:

- Figure 5-9. 3-Leg T, 2 Approach Lanes with Dual Left, Signal Control, Approach Route Goes Right.
- Figure 5-16. 3-Leg Side, 2 Approach Lanes+LT, Signal Control, Approach Route Goes Through.

Both of these figures show the advance intersection lane control sign 325 to 500 ft upstream of the stop bar.

PREVIOUS RESEARCH

In 2003, the Texas A&M Transportation Institute (TTI) completed a research project to evaluate key aspects of freeway signing in Texas and develop guidelines for improving the quality and consistency of freeway signing (*11*). The major tasks included an evaluation of existing freeway signing in Texas, evaluation of driver information needs through focus groups, and development of the TxDOT *Freeway Signing Handbook*.

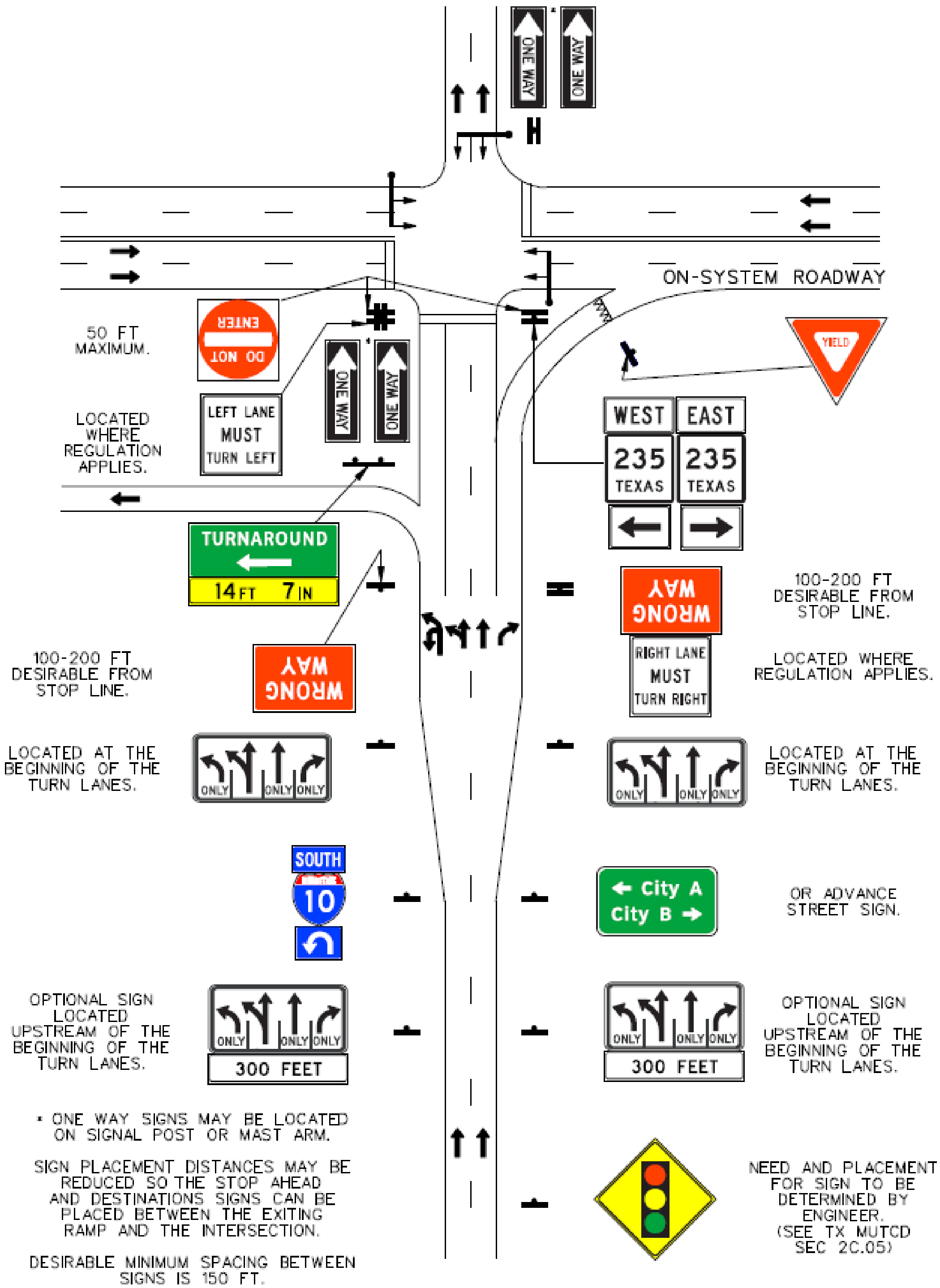


Figure 8. Frontage Road Approach Signing for a Two-Lane Approach with Left-Turn/Turnaround Bay, Right-Turn Bay, and Signal Control (*6*).

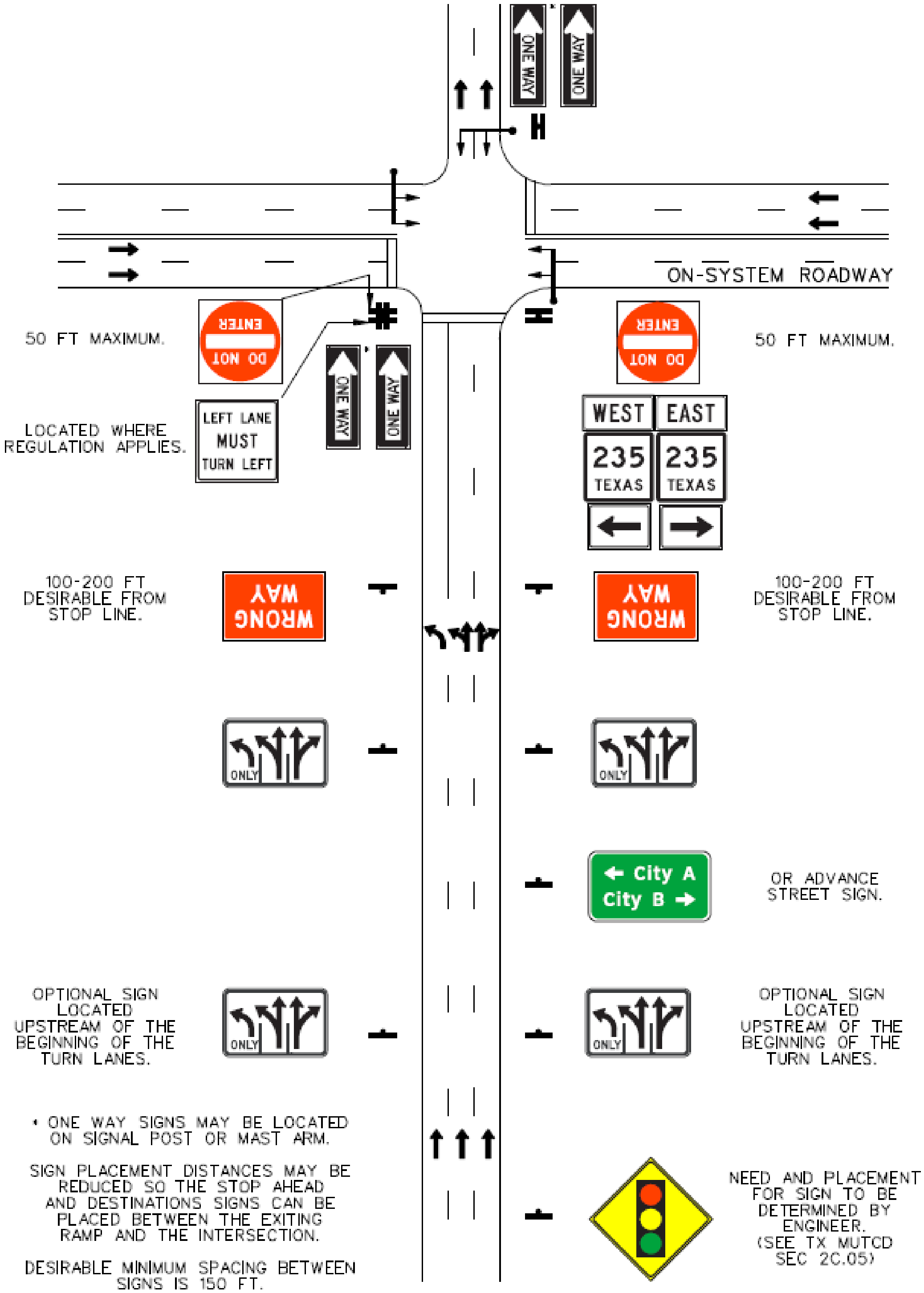


Figure 9. Frontage Road Approach Signing for a Three-Lane Approach with Left-Lane Drop and Signal Control (*6*).

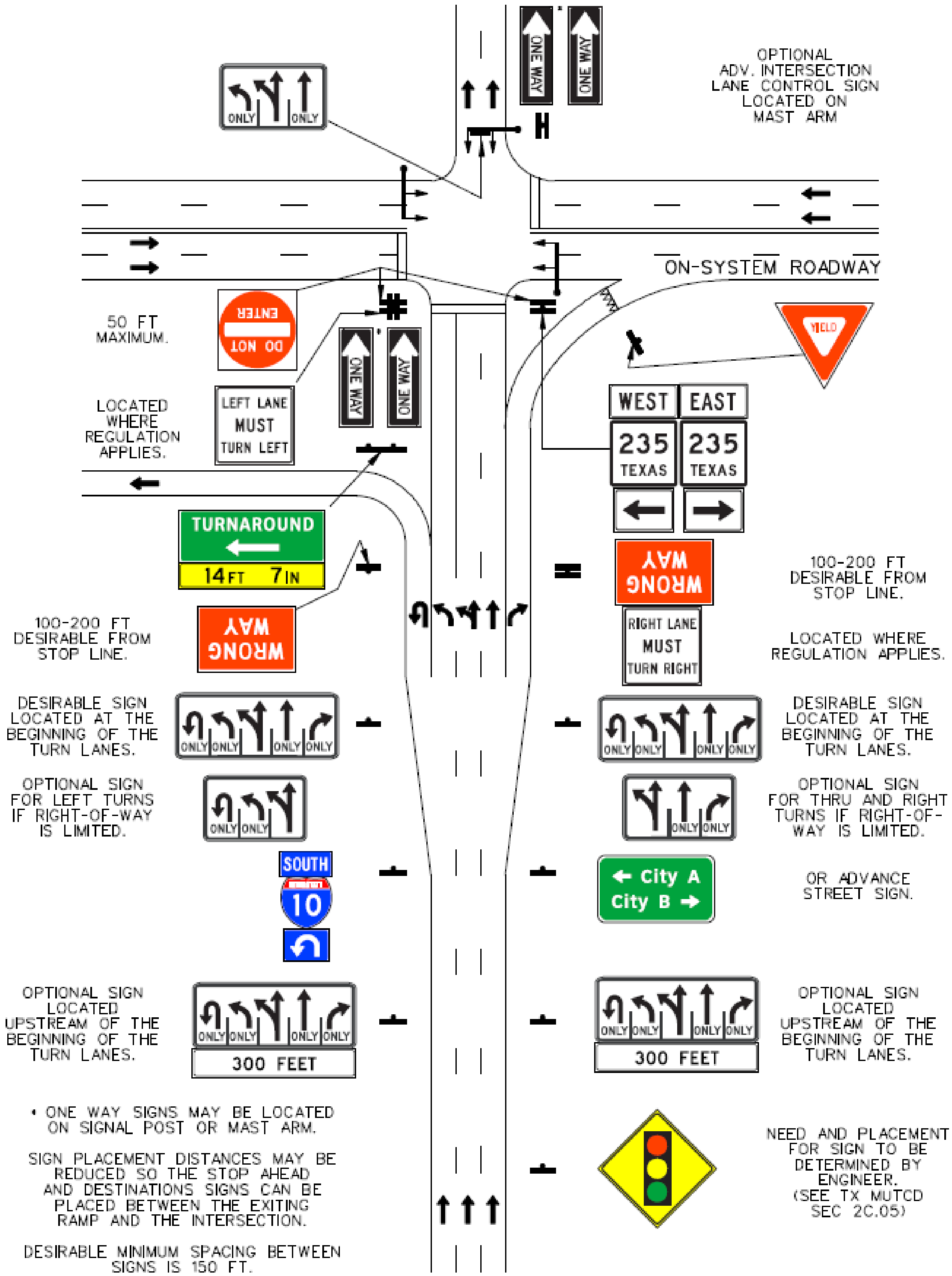
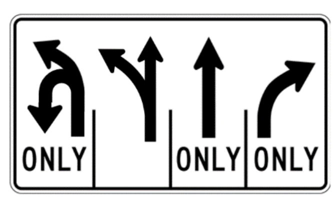


Figure 10. Frontage Road Approach Signing for a Three-Lane Approach with Turnaround Bay, Left-Lane Drop, Right-Turn Bay, and Signal Control (*6*).

As part of the focus groups, researchers examined the signing of frontage road approaches to intersections using still photographs depicting lane-use assignment signs on a two-lane, one-way frontage road. Table 4 shows the same base photo with three different sign scenarios. Participants evaluated each scenario separately, although they did make comparisons between the scenarios.

Table 4. Project 0-4170 Focus Group Lane-Use Assignment Sign Options (*11*).

 Scenario 1	Scenario 1—RIGHT LANES MUST TURN RIGHT sign post-mounted on the right side of the road. 
 Scenario 2	Scenario 2—Symbol (arrow) R3-8 signs with vertical line separators and ONLY post-mounted on both sides of the road. 
 Scenario 3	Scenario 3—Symbol (arrow) R3-8 sign with vertical line separators, ONLY, and supplemental distance plaque post-mounted on the right side of the road and route sign with supplemental U-turn arrow (M5-3T) post-mounted on the left side of the road. 

For Scenario 1, most participants thought there would be two lanes at the intersection. For those that thought more than two lanes would be at the intersection, most assumed a right-turn lane would be added. After more discussion, all of the participants agreed that with the information provided, there was no way of knowing how many lanes were at the intersection.

For Scenario 2, all of the participants thought there would be three lanes at the intersection, although there was some discrepancy about whether the lane would be added to the left or right. Participants preferred signs on both sides of the roadway. Many participants also commented on the benefits of the small vertical separator lines.

For Scenario 3, all of the participants thought there would be four lanes at the intersection because of the sign on the right side of the road. Most participants indicated that a lane would be added on the left and right. Some participants thought the 300 ft distance was measured from the sign to the intersection, while others believed this distance was measured from the sign to the beginning of the additional lanes. Several participants indicated that the U-turn indication on the sign on the right side of the road was not needed if the U-turn sign on the left side of the road was used. Some participants liked the idea of breaking the sign on the right side of the road into two signs (one on each side of the road). Concerns with splitting the information into two signs included the belief that two signs with different information may appear to contradict each other, and if one sign is blocked, the information may be confusing. Other suggestions for improving the signs in this scenario included:

- Use a series of several signs on the intersection approach.
- Use overhead signs.
- Use arrows on the pavement.
- Move the sign on the left side of the road closer to the intersection.

In 2010, TTI completed a research project that investigated how best to sign approaches to diamond interchanges (*12*). Researchers identified international practices of lane assignment with signs and pavement markings from Australia, New Zealand, the United Kingdom, and Germany. Researchers found a common theme among several of the countries of using trap lane signs, which use arrows to illustrate through, shared, and turn-only movements for flared approaches. Figure 11 contains examples of international lane assignment signs.

(a) Australia **(b) United Kingdom** **(c) Germany**

Figure 11. International Lane Assignment Signs for Flared Approaches (*12*).

In the same project, researchers conducted practitioner surveys, focus groups, driver surveys, and field studies to assess the effectiveness of numerous sign concepts intended to assist drivers in the correct selection of a lane on a frontage road approach to an intersection with a cross street. Pertinent findings from the TxDOT practitioner surveys included:

- Flared interchange approaches (those with more lanes at the intersection than upstream) and atypical lane assignments were common in the state of Texas, with 37 percent of the respondents indicating safety and operational issues related to such geometries.
- Advance intersection lane control signs were commonly used on flared approaches that included turn-only lanes and/or trap lanes (i.e., lanes that drop beyond an intersection). Some districts also used advance intersection lane control signs on approaches where long queues formed, blocking the view of mandatory lane control signs near the intersection.
- Most districts used the Texas MUTCD, TxDOT *Freeway Signing Handbook*, and TxDOT *Sign Crew Field Book* to determine the design and placement of lane assignment traffic control devices. District-developed polices, field conditions, and engineering judgement were also used.
- Post-mounted advance intersection lane control signs were typically installed at the taper of the additional lane when only a single set of signs was used. However, when multiple sets of signs were installed, the locations were more varied. Overall, no consistent guidelines were found regarding the placement of the advance intersection lane control signs.

- Advance intersection lane control signs were most commonly post-mounted on both sides of the approaches. The decision to mount these signs overhead was generally based on field conditions, such as high traffic volumes, limited sight distance, other visual obstructions, intersections with dual turn lanes, and proximity to freeway exit ramps. Reasons for not using overhead signs included initial cost, ongoing maintenance requirements, and availability of right of way.
- More districts preferred to use advance intersection lane control signs that show all the lanes at the intersection versus split signs on either side of the roadway. However, six of the 19 districts that provided survey responses reported that they would consider splitting advance lane assignment signs.

Relevant findings from the focus groups and driver surveys included:

- While drivers did not feel advanced lane signing was necessary to mark an upcoming intersection for two-lane frontage road approaches, advance signing was still desired. For more complex approaches, lane assignment pavement markings may be needed.
- For intersection approaches that violate driver expectations or intersections in close proximity, it may be beneficial to use AT SIGNAL plaque for lane assignment signs upstream of the intersection. Furthermore, additional signing further upstream of the intersection may be necessary where driver expectations related to lane use may be violated.
- Split signing should likely be used on approaches with four or more lanes. Signs on each side of the road should represent only the exclusive turn lanes or all-turn-only lanes and shared/optional lanes. The through-only lanes did not appear to impact comprehension.
- On approaches that have an optional turning lane next to a mandatory turn lane, both lane types should be signed to avoid unnecessary lane changes.
- Lane assignment signs that graphically incorporated the taper geometry to show where lane additions occurred were found to be most effective when driver expectations about downstream intersection geometry were violated.
- Drivers responded best to pavement markings that used the word AHEAD in addition to the word ONLY and either the turn symbol or the word TURN.

Based on international practices and the results of the surveys and focus groups, researchers developed an alternative advance intersection lane assignment sign (see Figure 12). This sign was installed and evaluated on a frontage road approach to a signalized intersection where the frontage road flared out to include additional lanes at the intersection (see Figure 13). The alternative advance intersection lane control signs included lane addition tapers (black area on sign in Figure 12). One set of alternative advance intersection lane control signs was installed approximately 635 ft prior to the stop line at the intersection (i.e., point where the three-lane roadway widened to four lanes). A third alternative advance intersection lane control sign was installed on the right side of the roadway approximately 1135 ft prior to the stop line (i.e., in the three-lane roadway section).

Figure 12. Close-Up of Alternative Advance Intersection Lane Control Sign (*12*).

Figure 13. Set of Alternative Advanced Intersection Lane Control Signs at IH-45 Southbound at Cypresswood Drive in Houston (*12*).

Field study findings revealed only a slight reduction in the number of illegal movements at the intersection. In addition, the number of lane changes nearest the intersection remained relatively the same. However, the total number of lane changes in the entire area of interest (from the stop line at the intersection to 1635 ft upstream of the stop line) decreased, leading researchers to assume that drivers were making lane changes farther upstream (outside of the data collection area).

Based on the study findings, researchers developed guidance for enhanced lane assignment signing. The guidance applicable to advance intersection lane control signs is:

- Sign for optional and exclusive turn lanes (not just the exclusive turn lane) to avoid unnecessary maneuvers by drivers.
- Use multiple advance intersection lane control signs when a lane becomes a turn-only lane.
- Place advance intersection lane control signs within 150 ft upstream of the stop line at the intersection. Place additional advance intersection lane control signs within 150 ft upstream of where the roadway widens (i.e., taper of additional lane). When sight distance is limited, advance intersection lane control signs may need to be placed farther upstream.
- Consider adding lane addition tapers to advance intersection lane control signs when geometrics violate driver assumptions. Place advance intersection lane control signs with lane addition tapers where the roadway widens or within 150 ft upstream of where the roadway widens. If queuing is a concern, place additional advance intersection lane control signs with lane addition tapers at least 500 ft upstream of the intersection. “ONLY” legends can be removed to reduce the amount of information on the signs.
- Consider sign splitting when advance intersection lane control signs must depict more than four lanes. The split signs on the left and right sides of the roadway should only include the respective exclusive and optional turn movements.

DISTRICT SURVEY DESIGN

In July 2018, researchers prepared and distributed an online Qualtrics™ survey to gather information from the 25 TxDOT districts about two activities:

- The use and application of signs with embedded LEDs.
- The use and application of advance intersection lane control signs on frontage roads (R3-8) and turnaround signs (D13-1TL(R)).

Questions 4 through 10 addressed the advance intersection lane control signs, and Questions 11 and 13 focused on the turnaround signs. The fourth question asked whether a district used advance intersection lane control signs. If the respondent answered no, he/she was directed to the survey section on turnaround signs. Only districts using advance intersection lane control signs answered the following questions:

- *Question 5—Where does your district use advance intersection lane control signs?* Ten answer choices were provided. Respondents could select all that applied.
- *Question 6—What challenges has your district encountered with designing and/or installing advance intersection lane control signs?* Eleven answer choices were provided. Respondents could select all that applied.
- *Question 7—Does your district ever split the lane assignment information such that only a portion of the information is on the left side of the road and a different portion is on the right side of the road? Why?* Respondents were instructed to look at a figure containing split signs.
- *Question 8—Does your district change the design of advance intersection lane control signs in any other manner to account for a large number of lanes at the intersection (e.g., 5 or more)? If yes, please describe how your district alters the sign design.*
- *Question 9—Does your district alter the installation of advance intersection lane control signs to account for a large number of lanes at the intersection (e.g., 5 or more)? If yes, please describe how your district alters the sign design.*
- *Question 10—Does your district install the optional advance intersection lane control signs located upstream of the beginning of the turn lanes?* Respondents were instructed to look at a figure containing optional advance intersection lane control signs.

All survey respondents were asked the following questions:

- *Question 11—Where does your district use the TURNAROUND ONLY sign (R3-8uT)? NOTE: the TURNAROUND ONLY symbol and text may be used on a sign with other advance intersection lane control symbols or as a stand-alone sign.* Six answer choices were provided. Respondents could select all that applied.
- *Question 12—Where does your district use the TURNAROUND sign (D13-1TL(R))?* Six answer choices were provided. Respondents could select all that applied.
- *Question 13—Describe a condition where your district would use a TURNAROUND ONLY sign (R3-8uT) instead of a TURNAROUND sign (D13-1TL(R)).*

DISTRICT SURVEY FINDINGS

Twenty-two districts (88 percent) responded to the survey. The following sections document the survey findings for the advance intersection lane control signs (R3-8 series) and turnaround signs (R3-8uT and D13-1TL(R)), respectively.

Advance Intersection Lane Control Signs

Figure 14 shows the 21 districts that reported using advanced intersection lane control signs. One district that responded to the survey did not answer the advance intersection lane control sign questions.

Table 5 contains a summary of the locations where advance intersection lane control signs are used. Two-thirds of the responding districts indicated they install R3-8 signs on the approach to intersections that have more lanes at the intersection than upstream (i.e., flared intersections) and approaches that have shared turn lanes. Half of the responding districts indicated having installed R3-8 signs on approaches with turn-only lanes or approaches that have one or more through lane(s) changing into turn-only lane(s). Fewer than half of the responding districts reported installing R3-8 signs on other types of approaches.

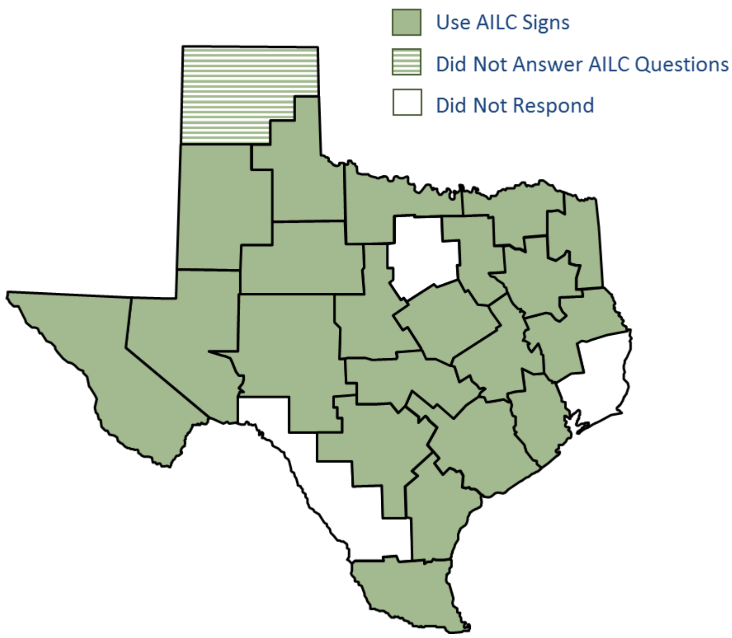


Figure 14. Use of Advance Intersection Lane Control (AILC) Signs in TxDOT Districts.

Table 5. District Use of Advanced Intersection Lane Control (R3-8) Signs.

Where Districts Use R3-8 Signs	Percent of Districts[a]
Approaches that have more lanes at the intersection than upstream	65
Approaches with turn lanes that are shared	65
Approaches with turn-only lanes	50
Approaches that have one or more through lanes changing to turn-only lanes	50
Approaches with a different lane arrangement compared to other approaches in the corridor	45
All approaches	30
Approaches with an alternate intersection design	25
Approaches with a high incidence of illegal turns	25
Approaches with limited sight distance	25

[a] n = 20; total response is more than 100 percent since participants could provide multiple responses.

Table 6 documents the challenges responding districts have encountered with designing and/or installing advance lane control signs. Almost all of the responding districts (90 percent) noted that other signs causing sign clutter was a challenge. Other challenges identified by at least half of the responding districts were limited right of way, driveways, trees/vegetation, too much information for one sign, and large number of lanes at intersections.

Table 6. District Challenges with Advanced Intersection Lane Control (R3-8) Signs.

Challenges with R3-8 Signs	Percent of Districts[a]
Other signs causing sign clutter	90
Limited right of way	75
Driveways	60
Trees and/or vegetation	55
Too much information for one sign	55
Large number of lanes at intersection	50
Upstream geometric features	45
Interference with providing needed intersection sight distance	40
Utilities/utility poles	40

[a] n = 20; total response is more than 100 percent since participants could provide multiple responses.

When there are a large number of lanes at the intersection, it can be difficult to display all the lanes on one sign. One solution is to split the lane assignment information such that only a portion of the information is on the left side of the road and a different portion is on the right side of the road (see Figure 15). Fifty-five percent of the responding districts (n = 20) split R3-8 signs. The main reasons for splitting these signs were:

- Making the sign relevant and easy to read.
- Enhancing the sign's visibility.
- Addressing limited right of way, retaining walls, and other interferences.

Forty percent of responding districts do not split R3-8 signs. Two districts reported using other design/installation options instead of sign splitting. One district eliminates the U-turn arrow/ONLY to reduce the sign size, whereas another district installs the R3-8 signs overhead.

Forty percent of the responding districts (n = 20) install optional R3-8 signs upstream of the beginning of turn lanes, as illustrated in Figure 16. These districts cited the use of the optional sign installation as helpful when long queues compromise the visibility of the signs.

Turnaround Signs

The TURNAROUND ONLY sign (R3-8uT) is used in advance of an intersection to indicate the exclusive turnaround movement from a separate traffic lane to access the frontage road on the other side of the facility without having to go through the intersection. The TURNAROUND sign (D13-1TL(R)) is used at the intersection of a frontage road and a cross street to indicate the direction of the exclusive turnaround movement.

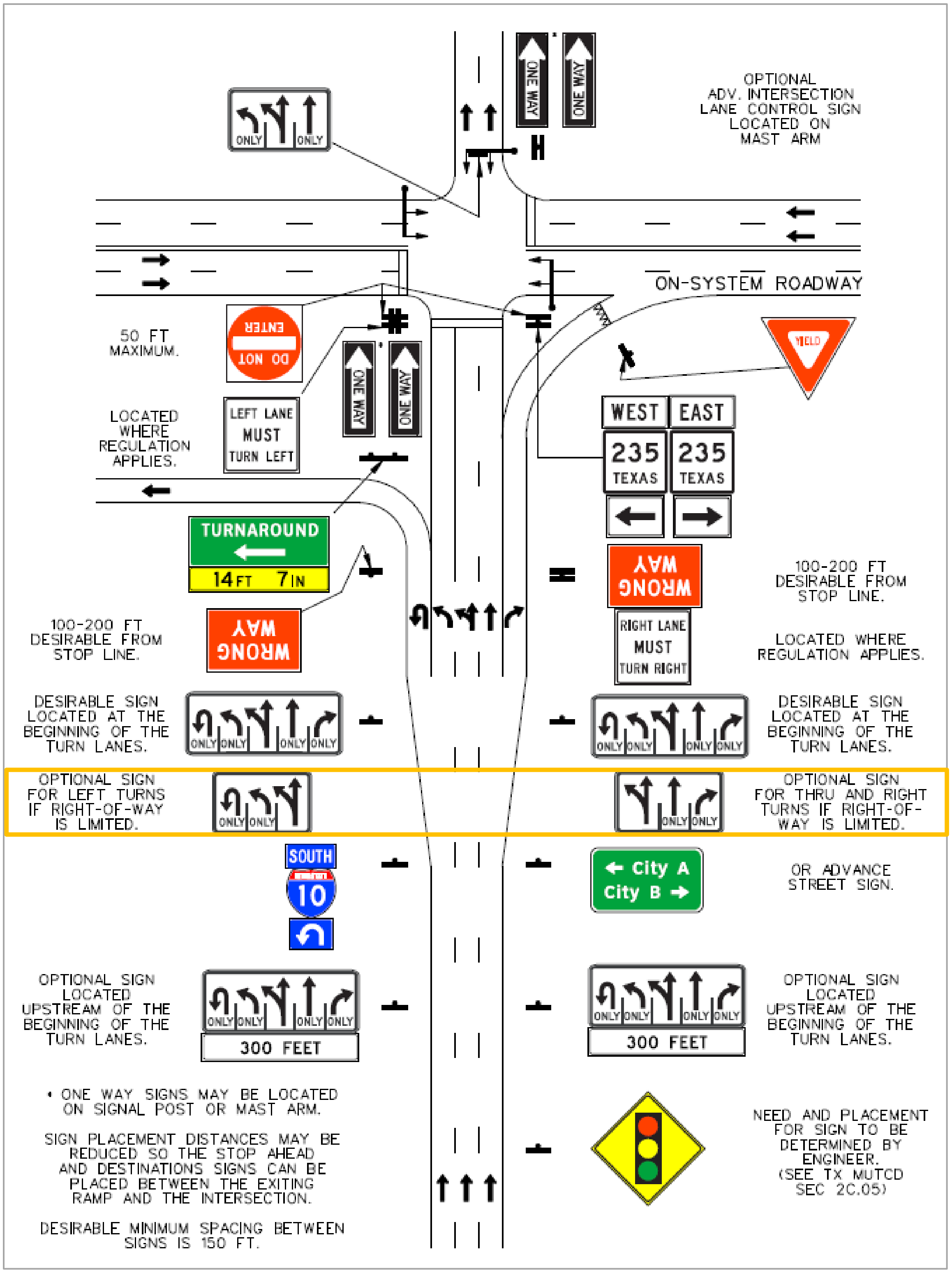


Figure 15. Optional Lane Splitting for a Frontage Road Approach Signing for a Three-Lane Approach with Turnaround Bay, Left-Lane Drop, Right-Turn Bay, and Signal Control (*6*).

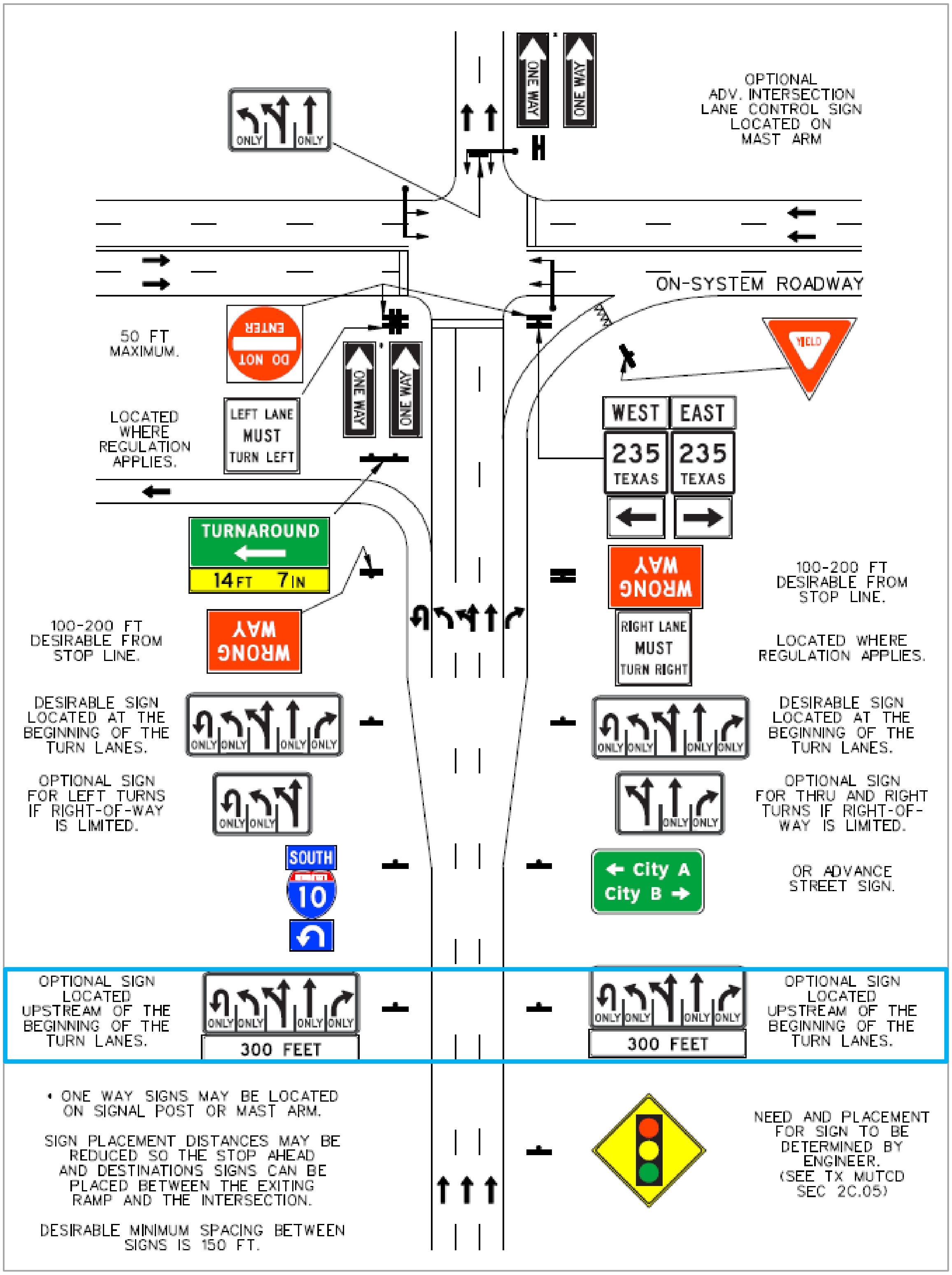


Figure 16. Optional Upstream R3-8 Sign for a Frontage Road Approach Signing for a Three-Lane Approach with Turnaround Bay, Left-Lane Drop, Right-Turn Bay, and Signal Control (*6*).

Twenty districts answered the questions about turnaround signs. The responding districts indicated the following usage of these two signs (see Figure 17):

- Forty percent use only R3-8uT.
- Ten percent use only D13-1TL(R).
- Forty percent use both signs.
- Ten percent chose non-applicable for both signs.

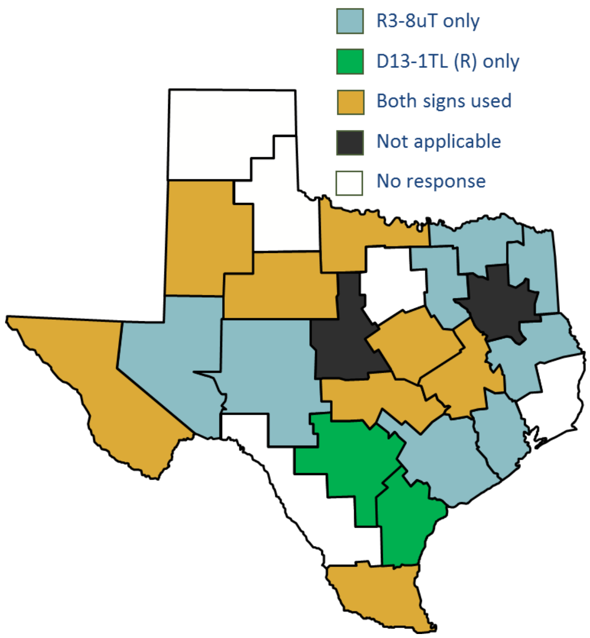


Figure 17. Use of Turnaround Signs (R3-8uT and D13-1TL(R)) in Texas Districts.

Table 7 and Table 8 show the locations where districts use the R3-8uT and D13-1TL(R) signs. Most districts (75 percent) use the R3-8uT sign only on the approach to a U-turn on a frontage road. A few districts also use the R3-8uT sign at other locations, including on the approach to a median opening on a divided highway and on the approach to a U-turn within an alternative intersection design. Most districts (60 percent) use the D13-1Tl(R) sign only at a U-turn on a frontage road. Other locations where the D13-1TL(R) sign is used include at median openings on divided highways and at U-turns within an alternative intersection design. The responding districts provided the following reasons for using an R3-8uT sign instead of a D13-1TL(R) sign:

- Dedicated U-turn lanes.
- Limited right of way.

- Innovative intersections.
- Directional opening where concrete median is used for access management.

Table 7. District Use of R3-8uT Signs on Intersection Approaches.[a]

Where Districts Use R3-8uT Signs	Percent of Districts That Use Only R3-8uT Signs (N = 8)	Percent of Districts That Use Both Signs (N = 8)	Overall Percent of Districts (N = 16)
Approach to U-turn on a frontage road only	100	50	75
Approach to U-turn on a frontage road and in other locations	0	38	19
Approach to median opening on a divided highway	13	13	13
Approach to U-turn within an alternative intersection design	0	13	6

[a] Total response is more than 100 percent since participants could provide multiple responses.

Table 8. District Use of D13-1TL(R) Signs at Turnaround.[a]

Where Districts Use D13-1TL(R) Signs	Percent of Districts That Use Only D13-1TL(R) Signs (N = 2)	Percent of Districts That Use Both Signs (N = 8)	Overall Percent of Districts (N = 10)
At U-turn on a frontage road only	100	38	60
At U-turn on a frontage road and in other locations	0	38	20
At median opening on a divided highway	0	38	30
At U-turn within an alternative intersection design	50	0	10

[a] Total response is more than 100 percent since participants could provide multiple responses.

SUMMARY

As part of this activity, researchers reviewed current TxDOT standards and policies as well as previous research regarding the design and application of advance intersection lane control and turnaround signs on frontage roads. Additionally, researchers developed and distributed a survey to TxDOT districts to gain information on the use of these types of signs and the challenges associated with their design and installation. TxDOT personnel can use this information to determine the need for additional research and changes to the TxDOT *Freeway Signing Handbook* (*6*).

CHAPTER 4: ASSESSMENT OF THE EFFECTIVENESS OF PEDESTRIAN CROSSING SIGNS WITH EMBEDDED LEDS

In recent years, a number of signs have been installed by TxDOT districts and by cities to aid with pedestrian crossing. The light-emitting diode embedded (LED-Em) pedestrian crossing sign is one such traffic control device used at pedestrian crossings. Section 2A.07 of the Texas MUTCD (*5*) lists the standards for retroreflectivity and illumination for the use of LEDs in traffic signs. However, no other standards or guidance exists to help practitioners select these signs as crosswalk treatments. While other pedestrian crossing treatments, such as RRFBs and pedestrian hybrid beacons (PHBs), have been evaluated and compared through various studies, the LED-Em pedestrian crossing signs are novel, and not much is known regarding their effectiveness in terms of driver yield rates for facilities with varying operational and geometry characteristics. For this activity, the researchers sought to evaluate the operational performance of the LED-Em signs and provide a comparison of the operational performance of LED-Em signs, RRFBs, and PHBs.

PREVIOUS RESEARCH

With the emergence of LED incorporation in traffic control devices, there has been a variety of pedestrian crossing treatments being used to enhance signs and emphasize pedestrian presence in a crosswalk with the aim of increasing driver yield rates and reducing pedestrian crashes. To date, two such devices, RRFBs and PHBs, have been studied at length. While there is a lack of in-depth examination of the effectiveness of LED-Em pedestrian crossing signs, the researchers found a few case studies and documented uses of LED-Ems.

LED-Embedded Sign Case Studies

A Des Moines case study (*13*) examined driver and non-staged pedestrian behavior at two sites with LED-Em pedestrian crossing signs. At one of the sites, the LED-Em signs were replaced with RRFBs, and the same data were collected after the installation of the RRFB treatment. The researchers observed non-staged pedestrian crossings in the morning, noon, and afternoon at each of the crossings, for a total of 576 crossings. At one of the LED-Em sign crossings, motorist yielding observed was highest in the morning at 46 percent, followed by lower yielding rates of 40 percent at noon and 30 percent in the afternoon. The researchers also observed a similar declining trend in driver yielding rates from the morning to the afternoon observation times at the second LED-Em sign crossing. However, the rates went from 45 percent in the morning to 33 percent during noon, and zero in the afternoon. The LED-Em sign at this location was later replaced with an RRFB treatment, which researchers found to have higher driver yielding rates (from 41 to 54 percent). The researchers further observed that crossings at which the pedestrians activated the LED-Em signs and RRFBs exhibited higher driver yielding rates by at least 30 percent.

In a Vermont case study (*4*), researchers examined the effectiveness of a pair of LED-Em pedestrian crossing signs at a two-lane road with high vehicular traffic and posted speed limit of 35 mph. The signs were added to an existing warning system with in-pavement crosswalk lighting, which had experienced wear and tear due to weather and vehicle weights. The researchers observed driver yielding behavior for the before installation period, as well as one year and four years after the installation. Vehicle compliance was recorded for staged pedestrian crossings based on the pedestrian only looking both ways, as well as for pedestrian crossings when the pedestrian looked both ways and stepped on the pavement. The results showed the highest increase in yield rate for the period one year after installation, and a slight decrease in yield rate from Year 1 to Year 4 of installation. However, the overall yield rate for observations made four years after installation remained 12 percent higher than the yield rate before installation.

A case study in Maple Grove, Minnesota (*14*) evaluated the replacement of W11-2 fluorescent pedestrian crossing signs with a pair of LED-Em fluorescent pedestrian crossing signs. Researchers observed driver yield rates during both the before (May 2011) and after (July 2011) installation periods. The observations included 54 non-staged pedestrian crossings for the before period and 41 non-staged pedestrian crossings for the after period. The results showed no improvement in driver yield rates and found that less than 20 percent of pedestrians activated the treatment during crossings.

RRFBs

A 2016 TTI report (*15*) that evaluated the effectiveness of RRFBs provides a detailed summary of various studies that investigated the effectiveness of RRFBs utilizing the measure of driver yield rates. The before-and-after studies (*16*, *17*, *18*, *19*, *20*, *21*, *22*, *23*) reported increased yielding rates, although with large variability in the magnitude of the increase, despite most of the studies utilizing a limited sample size for the analysis. Other studies (*3*, *24*, *25*, *26*, *27*, *28*, *29*) examined the yield rate at the treatment sites with either staged or non-staged pedestrian observations and found a wide range of effectiveness, varying also by time of day, treatment activation, beacon location, and shape. The TTI study (*15*) combined previous data from TxDOT and Federal Highway Administration (FHWA) studies, and through a series of statistical models, identified factors associated with driver yielding. For the full data model, these factors included intersection configuration (number of legs), presence of median, crossing distance, crossing direction, and direction of travel (one-way vs. two-way traffic). For a subset of data that included one-minute vehicle counts for each crossing, the statistical model showed a number of significant factors contributing to driver yielding, such as intersection configuration; crossing distance; one-minute traffic count; posted speed limit; location of the beacons (overhead or roadside); sign face; approach side (near or far); and presence of advanced yield or stop line, school, or transit stop.

A 2017 Oregon study (*30*) evaluated the safety effectiveness of four types of pedestrian crossing treatments (i.e., RRFBs, flashing amber, and high-visibility markings) by analyzing pedestrian and rear-end crashes at 191 locations. The researchers observed a decreasing shift in pedestrian crash injury severity, from fatal and incapacitating injuries to non-incapacitating and minor injuries, following the installation of the treatments. However, the shift may have been attributed to the regression-to-the-mean effect, considering the sites were selected to receive the treatments based on their high crash history. The researchers developed crash modification factors (CMFs) for pedestrian and rear-end crashes for the RRFB treatment. The CMFs developed indicated a reduction in pedestrian crashes (CMF = 0.64) and rear-end crashes (CMF = 0.93); however, the performance of RRFBs may have been overestimated due to not accounting for regression to the mean.

PHBs

Several studies (*3, 31, 32, 33*) that have evaluated PHBs have reported high yielding rates varying from 75 to 97 percent for sites with posted speed limits between 30 mph to 45 mph. A more recent study (*34*) utilized 10 locations in Arizona for which operating speeds ranged between 44 mph and 54 mph to evaluate the driver yielding rates for facilities with higher posted speed limits. The researchers found that the average yield rate across the sites was 97 percent, thus concluding that these treatments are equally effective in facilities with higher posted speed limits.

Multiple Treatment Studies

A TxDOT study (*23*) explored the factors associated with driver yielding at pedestrian crossing locations in Texas with traffic control signals (TCSs), PHBs, and RRFBs and posted speed limits between 30 mph and 45 mph. The researchers found that TCS sites had the highest yield rate of 98 percent, followed by yield rates of 89 percent for PHBs and 86 percent for RRFBs. Devices that had been installed for a longer period of time exhibited the higher yield rates. The authors concluded that the results of the statistical analysis support the stance that PHBs can be used on roads with multiple lanes or wider crossing distance, and RRFBs should be used for roads with narrower crossing distance given their lower yield rates in wider facilities.

A 2019 Utah study (*35*) compared the performance of RRFBs against the treatments of high-intensity activated crosswalks (HAWKs—also known as PHBs), overhead flashing beacons (OFBs), and overhead rectangular flashing beacon (ORRFBs) at sites with speed limits between 35 mph to 45 mph. The researchers found that the compliance rate was highest for HAWK treatments at 97 percent, followed by 77 percent for OFBs and 57 percent for either ORRFBs or RRFBs.

Key Findings from Literature

The main findings from the literature review included the following:

- There is a lack of understanding of the effectiveness of LED-Em pedestrian crossing signs. While there have been a few case studies, they have observed and reported on only one or two locations. Additionally, due to small samples, these studies have only reported on the observed yielding rate without examining the factors that affect yielding rate.
- Other pedestrian treatments, specifically RRFBs and PHBs, have been examined, and the following is known regarding these treatments:
    - PHBs have been found to have very high driver yielding rates for a large range of posted speed limits. Additionally, higher yielding rates were observed for sites

with wider crossing distance, making PHBs a preferred treatment for higher-speed/multilane roadways.

- While RRFBs have been shown to be effective treatments, several studies have demonstrated a wide range of effectiveness. The treatment was found to be more effective for crossings with shorter crossing distance, presence of a median, and fewer legs.

These findings suggested that in the examination of LED-Em crossing signs, attention must be paid to obtaining detailed data on site operational and geometric characteristics, including crossing distance, speeds, and volumes. With respect to speed, the study should consider the posted speed limit or the findings from an 85th percentile speed study as surrogates for typical operations. However, it could be a superior study if data were available that reflected actual driver speeds within the same time period as when the driver yielding data were collected. Similarly, having data that reflect the vehicle volume present just prior to the crossings would also provide a more unique picture of the conditions existing during the crossing.

STUDY APPROACH

The following sections describe the site characteristics, data collection methodology, and data reduction processes.

Site Characteristics

The researchers asked TxDOT district engineers, city engineers, and other professional contacts throughout the state of Texas to provide locations where LED-Em pedestrian crossing signs had been installed. From this inquiry, researchers identified a total of 14 locations where the signs were activated with a pedestrian pushbutton. A few additional locations with LED-Em pedestrian crossing signs were suggested; however, they either flashed continuously or researchers could not determine their exact location or characteristics. Researchers collected data at 13 sites (see Table 9). Over half of the signs were installed in school zones; therefore, both the posted speed limit and the school zone speed limit were reported.

The sample of sites exhibited variability in posted speed limit (ranging from 30 mph to 50 mph); cross-section type; crossing distance; and presence of median, shoulders, and sidewalks. Table 10 provides a summary of the key operational and geometrical characteristics for each site.

Table 9. Location and Time of Data Collection.

Site ID	City	Main Street	Nearest Cross Street	Date
CB-01	Cibolo	Cibolo Valley	Silver Wing	5/16/2019
CB-02	Cibolo	Cibolo Valley	Springtree Bluff	5/16/2019
CS-01	College Station	John Kimbrough Blvd	Olsen Blvd	4/23/2019
DF-01	Daingerfield	US 290	Campbell St	5/13/2019
HS-01	Hughes Springs	Hanes Blvd	3rd St	5/13/2019
KT-01	Katy	Katy-Gaston Rd	Summerset Ridge Ln	5/1/2019
MC-01	Missouri City	Waters Lake Blvd	Scanlan Trace E	5/20/2019
NB-01	New Braunfels	Lakeview Blvd	River Rd	5/17/2019
NS-01	Nash	N Kings Hwy	Atkins St	5/14/2019
RW-01	Redwater	Redwater Blvd E	Shields St	5/14/2019
SA-01	San Antonio	Commerce St	S. San Dario	5/17/2019
SA-02	San Antonio	Austin St	Hays St	5/29/2019
YT-01	Yorktown	W Main St	Range Rd	4/26/2019

Table 10. Study Site Operational and Geometric Characteristics.

Site ID	Posted Speed Limit (mph)	School Zone Speed (mph)	Crossing Distance (ft)	Lane Width (ft)	Cross Section[a]	Median Presence[b]	Sidewalk Presence[c]
CB-01	35	20	61	12	5T	2	2
CB-02	35	20	63	12	5T	2	2
CS-01	30	NA	65	11	4D	1	2
DF-01	45	30	63	11	5T	2	0
HS-01	50	NA	30	12	2U	0	1
KT-01	35	20	80	12	4D	1	2
MC-01	30	20	73	12	4D	1	2
NB-01	30	NA	23	11	2U	0	0
NS-01	30	NA	42	10	4U	0	0
RW-01	50	35	48	11	3T	2	0
SA-01	35	NA	69	12	2D	1	2
SA-02	30	NA	38	12	2U	0	2
YT-01	30	20	53	11	2U+S	0	2

NA = not applicable.
[a] 2U = two-lane undivided; 2U+S = two-lane undivided with wide shoulders; 2D = two-lane divided; 3T = two lanes with dual left-turn lane; 4U = four-lane undivided; 4D = four-lane divided; 5T = four lanes with dual left-turn lane.
[b] 0 = no median, 1 = raised median, 2 = two-way left-turn lane.
[c] 0 = no sidewalks, 1 = sidewalk on one side, 2 = sidewalk on both sides.

Data Collection Protocol

The protocol for data collection was developed and refined based on experiences from several previous research projects (*23*, *33*). In general, researchers used the following protocol in the observation studies:

- A minimum of 60 pedestrian crossing events or four hours of data (the smaller of the two) were recorded at each location.
- In order to obtain a sufficient sample of pedestrian crossing observations and to maintain consistency in how the pedestrian conducted a crossing, researchers used a staged pedestrian approach. However, natural pedestrians were also observed, when present. In general, the staged pedestrian is a member of the research team and wears a uniform of gray t-shirt or sweatshirt, blue jeans, and predominantly dark shoes while completing the street crossings. A baseball cap and sunglasses are permitted. The staged pedestrian is trained to approach the crossing in a similar manner for each location to minimize the effects of pedestrian behavior on drivers. The staged pedestrians activated the LED-Em pedestrian crossing sign while vehicular traffic

was approaching and waited until all queued vehicles cleared before beginning another staged crossing so that no drivers observed two consecutive LED-Em sign actuations.

- The observation equipment and the research team members were placed strategically at the site in order to not attract the attention of drivers and natural pedestrians but at the same time have a clear view of the crosswalk, pedestrians, and traffic from both directions.
- Observation times were selected when school was in session. Researchers were interested in collecting observation and video data during times when school zones were not active; however, on three occasions, this condition was not met:
    - At the Yorktown site, the researchers observed that the school zone device was active throughout the duration of the data collection, and it was learned from school employees that the device was kept active during the weekdays when school was in session.
    - A small number of observations at the Cibolo site (CB-01) occurred while the school zone traffic device was active.
- The site in Hughes Springs, while not in a school zone, experienced heavier traffic during the second half of the data collection duration. To account for the different speed and/or traffic pattern of these few sites, the yield rates were reported for both conditions.

The researchers collected the following information during the field observations:

- Crossing number.
- Crossing time.
- Crossing direction (N/S, E/W).
- Whether the crossing was staged or non-staged.
- Whether the pedestrian activated the LED-Em sign (staged pedestrians were trained to always activate the LED-Em sign).
- Count of yielding vehicles and unyielding vehicles for both the near and far side. The near side was the travel direction that was near the pedestrian, and the far side referred to the travel direction farther from the pedestrian.

Within the staged pedestrian protocol, flags are placed on each side of the road for the researcher to use to determine whether a vehicle is far enough from the crosswalk for a driver to reasonably stop. This distance, referred to as driver decision zone, was determined for each site based on the sites' posted speed limit and an assumed 1.5-second perception-reaction time. Once a staged pedestrian activated the LED-Em sign, the observer paid attention to the vehicles upstream and downstream of the flags. Regardless of its initial position (upstream or downstream of the flag when the pedestrian activated the LED-Em sign), a vehicle was classified as a yielder if it yielded to the pedestrian (slowed down significantly or stopped fully). Only the first vehicles in a queue of vehicles slowing or stopping were counted as yielders; the maximum number of yielders was the same as the number of lanes per direction/side. Only vehicles that were upstream of the flags and did not yield to pedestrians were counted as non-yielders. If a vehicle that did not yield to a pedestrian was downstream of the flags when the pedestrian activated the LED-Em sign, that vehicle was not counted as a non-yielder.

Video Footage Collection

The researchers recorded the activity at each pedestrian crossing site utilizing video camcorders and pole-mounting hardware. The cameras were arranged to capture the crosswalk markings, the pedestrian crossings, and the LED-Em signs. Figure 18 shows an example of the camera positioning at a study site. Video data were not available for one of the sites in San Antonio (SA-01).

Figure 18. View from the Camera Position at a Site in Cibolo, Texas.

Video Data Reduction

Researchers manually post-processed the video footage to compute operational speeds (85th percentile and average speeds), as well as identify one-minute vehicular traffic counts associated with each pedestrian crossing. Additionally, researchers counted the number of natural pedestrians. The researchers utilized a video player software with the capability to advance the video footage on a frame-by-frame basis.

Traffic Counts

As previously mentioned, the staged pedestrians activated the LED-Em pedestrian crossing sign while vehicular traffic was approaching. The researchers identified the video frame during which the staged pedestrian pressed the button to activate the LED-Em sign, understood as initiation of a staged crossing. Subsequently, from that time stamp, the researchers rewound the footage either one minute prior or up to the end of the previous crossing, whichever occurred first. During this time period, the researchers counted the vehicles traveling in the near and far side of the crossing, based on the position of the pedestrian. Vehicles that slowly cleared the crosswalk after yielding to a pedestrian were not recorded in these counts. Researchers converted these traffic counts to hourly volumes based on the duration of each count. Similarly, the count of natural pedestrians that were not recorded as non-staged pedestrians was recorded during a non-staged crossing, as well as during the one-minute traffic counts.

Operational Speeds

One of the geometric characteristics that was measured in the field included the width of the crosswalk. This measurement was subsequently used to obtain the operating vehicle speeds. Researchers sampled vehicles traveling through the crosswalk between crossing events, paying attention to sample-only non-yielding vehicles. Vehicles traveling in both directions of the road were included in the sample. The frame-by-frame capability of the software was necessary to record the time stamps when the tires of a sampled vehicle encroached the beginning and end of the crosswalk markings. The researchers divided the crosswalk width by the difference in these time stamps and then converted to a speed in units of miles per hour. From the sampled speeds for each site, the 85th percentile and average speeds were computed. Additionally, researchers reported the number of sampled vehicles. Table 11 summarizes the variables obtained through video data reduction.

Table 11. Operational Characteristics Obtained through Video Data Reduction.

Site ID	Data Collection Date	Average Hourly Traffic (veh/hr)	Non-Staged Pedestrian Count	School Zone Active	Active Speed (mph)[a]	85th-Percentile Speed (mph)	Std. Dev. (mph)	Vehicles Sampled[b]
CB-01	5/16/19	380	0	N	35	38	5.73	34
CB-02	5/16/19	570	1	N	35	42	4.80	75
CS-01	4/23/19	460	54	NA	30	35	5.24	127
DF-01	5/13/19	537	0	N	45	50	5.15	85
HS-01	5/14/19	478	0	NA	50	41	5.08	54
KT-01	5/1/19	417	2	N	35	41	6.25	69
MC-01	5/20/19	401	0	N	30	40	5.04	69
NB-01	5/17/19	190	1	NA	30	33	5.49	28
NS-01	5/14/19	860	7	NA	30	37	4.35	64
RW-01	5/15/19	408	0	N	50	47	6.06	60
SA-01	5/17/19	NA	0	NA	35	NA	NA	NA
SA-02	5/29/19	317	0	NA	30	35	5.17	130
YT-01	4/26/19	520	7	Y	20	24	2.54	102

[a] Governing posted speed limit on the site during the time period of the data collection.
[b] Number of vehicles sampled from video data to obtain operational (85th percentile) speed.

ANALYSIS

Yield Rates

The researchers computed driver yielding rates using the observations of yielder and non-yielder vehicle counts as follows:

$$Yield\ Rate = \frac{NSY + FSY}{NSY + NSN + FSY + FSN}$$

Where:

NSY = Near side count of yielding vehicles.

NSN = Near side count of non-yielding vehicles.

FSY = Far side count of yielding vehicles.

FSN = Far side count of non-yielding vehicles.

Due to procedural requirements for the staged crossings, which make these crossings more uniform than the non-staged crossings, and small sample size of the non-staged crossings, the researchers only used the data for staged crossings.

Yield Rate Contributing Factors

To examine the factors that contribute to driver yielding rate, researchers estimated a statistical model. Researchers used the variables summarized in Table 11 and Table 12 to estimate the statistical model. The model framework chosen was that of a random-intercept logistic regression model, shown in previous research (*36*) to best fit the driver yield data for RRFBs. The random intercept allows the intercept to take on a range of values (and estimates a variance of these intercept values) to account for the correlation among variables of a site, as well as to account for unexplained heterogeneity due to unmeasured or unavailable variables. Like other regression models, logistic regression estimates the relationship between the dependent variable with a set of independent variables. Differently from other regression models, logistic regression estimates the effect of independent variables on the log-odds of the probability of driver yielding, expressed as log(yielding/non-yielding). Thus, the effects of independent variables on the dependent variable are interpreted as the change in log-odds of the probability of yielding. The effects of the independent variables on probability of yielding are not easily understood without some transformation of the equation.

$$\ln\left[\frac{p(yielding)}{p(non-yielding)}\right] = \ln\left[\frac{p(yielding)}{1-p(yielding)}\right] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n$$

In order to compute the probability, each side of the equation needs to be exponentiated and after a few mathematical operations, the probability of yielding results in the following equation.

$$p(yielding) = \frac{\exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n)}{1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n)}$$

This also means that the effects of the independent variables are not linear, and a unit change in an independent variable does not associate with a constant change in yielding probability. Further details are presented in the results section, where the statistical model results are explained.

RESULTS

Simple Yield Rates

Table 12 summarizes the yield rate results from the staged pedestrian field observations. The main finding from the driver yield rates is the wide variability in values for the 13 sites. Yield rates ranged from 5 to 86 percent, with an average yield rate of about 40 percent, which leads to the belief that aside from the sign itself, there are other factors that might contribute to the variability.

Table 12. Driver Yielding Rates by Site for Staged and Non-Staged Crossings.

Site	Count of Crossings	Count of Yielders	Count of Non-Yielders	Count of All Vehicles	Yield Rate (%)
CB-01	51	47	66	113	42
CB-02	60	73	122	195	37
CS-01	62	80	13	93	86
DF-01	60	29	161	190	15
HS-01 (All)	62	28	132	160	18
HS-01 (Light Traffic)	39	17	61	78	22
HS-01 (Heavy Traffic)	23	11	71	82	13
KT-01	60	49	68	117	42
MC-01	60	42	70	112	38
NB-01	61	46	27	73	63
NS-01	61	80	58	138	58
RW-01	61	19	108	127	15
SA-01	60	47	848	895	5
SA-02	60	25	55	80	31
YT-01	61	77	35	112	69

The yield rates for HS-01 were reported for the observations taken during light traffic and heavier traffic conditions caused by a nearby school letting out. The researchers considered it significant to note the difference between the two yield rates (during the light traffic conditions, the yield rate was 8.4 percent higher than during the heavier traffic conditions). This finding could speak to the drivers' impatient behavior during heavier traffic/rush hour. Additionally, some drivers may have tried to avoid being hit by following vehicles if they decided to yield to pedestrians.

Contributing Factors

Based on literature findings on RRFB treatments and the wide variability of yield rates for the LED-Em signs observed, further investigation of the yield rate was warranted for the LED-Em signs. Since the sites observed varied in posted speed limits, active speed limits, and 85th percentile and average speeds measured in the same time period as the staged pedestrian data collection, the researchers explored a visual representation of the yield rate versus the operating speed (see Figure 19). Furthermore, the researchers observed similar downward trends when they examined the relationship between the yield rate and active posted speed limit (see Figure 20).

The graphs illustrate an inverse relationship between the yield rate percentage and speed. The main finding from this exploration is that seemingly, with higher operating speeds, the yield rates for the LED-Em signs decrease. Five of the sites had an active speed limit of 30 mph with a range of driver yielding between 86 and 31 percent, which implies that aside from speed, there are other factors contributing to the yield rate differences among sites.

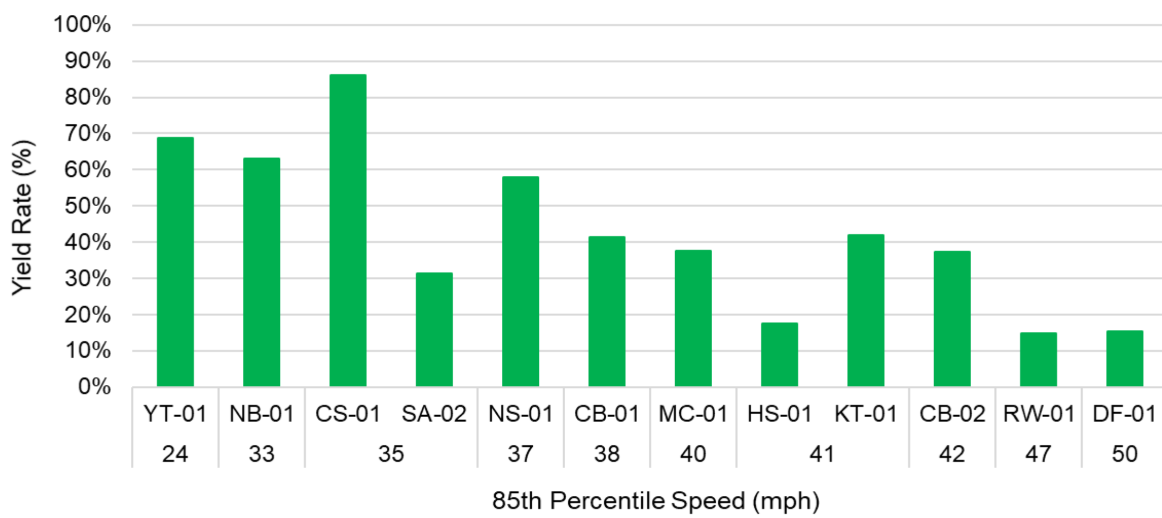


Figure 19. Driver Yield Rates by 85th Percentile Speed for Staged Crossings.

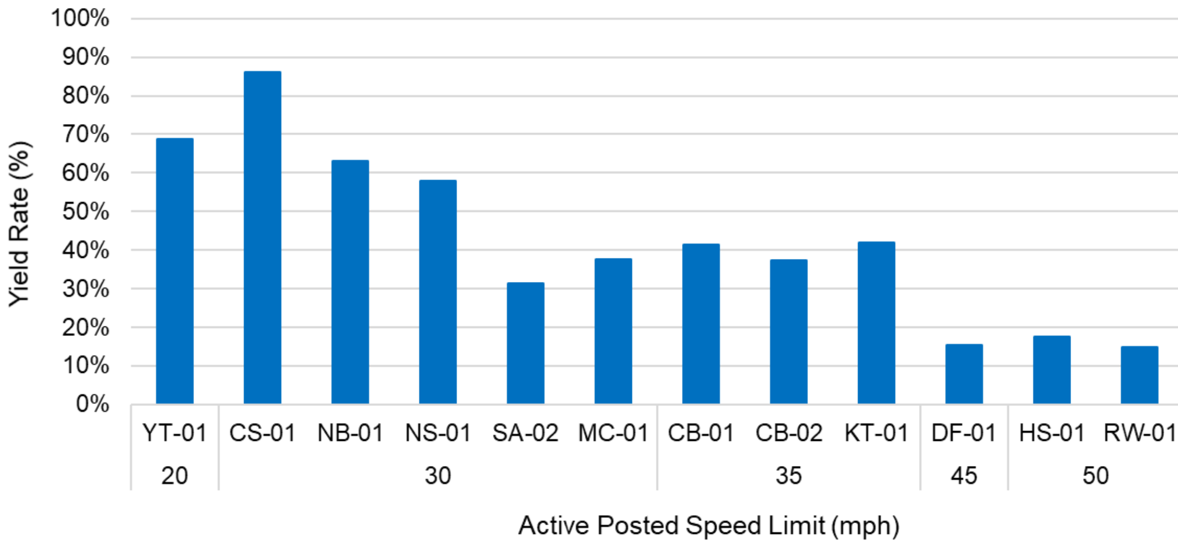


Figure 20. Driver Yield Rates by Active Posted Speed Limit for Staged Crossings

As mentioned previously, based on the variability observed for operating speeds, researchers examined other factor contributions via a statistical framework of a random-intercept logistic regression model. The researchers examined several variables, including hourly volume; operating speed (85th percentile); presence of medians; presence of sidewalks; and crossing distance or other variables correlated to it, such as number of lanes, median width, and lane width (or deviation of lane width from the baseline 12-ft lanes). It should be noted that correlated variables were not simultaneously examined in the model (i.e., a model would not include both median width and median presence). A full model was estimated using hourly volume, 85th percentile speed, lane width deviation from the 12-ft lane baseline, median presence, and sidewalk presence (see Table 13). All the variables were found to be statistically significant at a 95 percent confidence interval, except for median presence, which was ultimately removed. The final model included the natural logarithm of the hourly volume, the operating speed (85th percentile) being less than 45 mph (a binary variable with values of 1 for 85th percentile speeds less than 45 mph and zero for 85th percentile speeds equal to or greater than 45 mph), the difference between the lane width and the baseline of 12-ft lane, and the presence of sidewalk (see Table 14).

Table 13. Results of a Random-Intercept Linear Model for Yield Rate.

	Estimate	Std. Error	p value
(Intercept)	2.4305	0.7554	0.001293*
Natural Logarithm of Estimated Two-Way Hourly Volume	−0.957	0.1202	<0.0001*
Operational (85th percentile) Speed Less than 45 mph (1 = yes, 0 = no)	1.005	0.3726	0.006989*
Baseline Lane Width (12-ft) – Actual Lane Width (ft)	1.7586	0.2567	<0.0001*
Median Presence (1 = yes, 0 = no)	0.4118	0.2499	0.099462
Sidewalk Presence (1 = yes, 0 = no)	1.5377	0.4505	0.000642*

* Statistically significant at the 95 percent confidence interval.

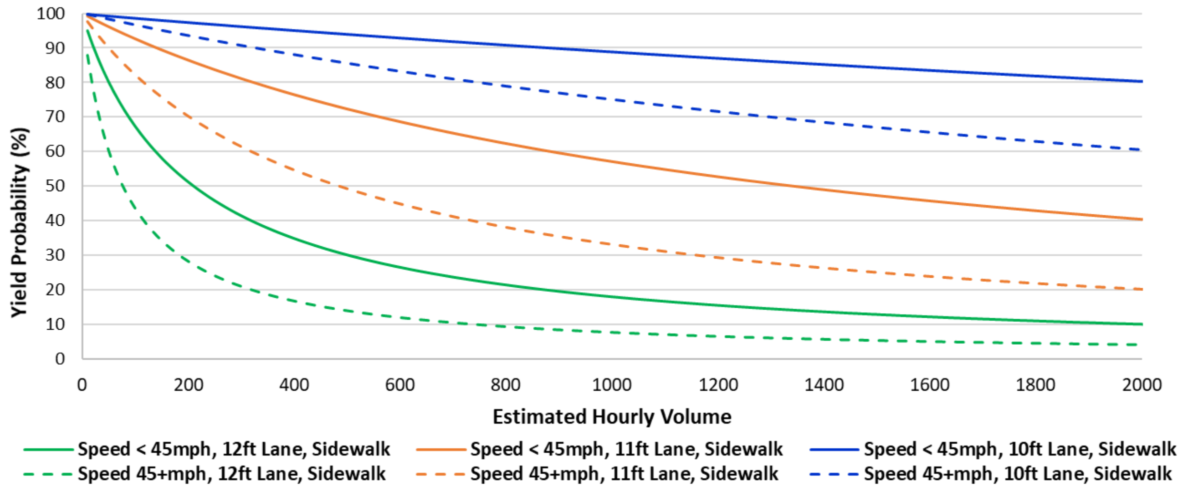
Table 14. Results of the Final Random-Intercept Linear Model for Yield Rate.

	Estimate	Std. Error	p value
(Intercept)	2.482	0.7734	0.00133*
Natural Logarithm of Estimated Two-Way Hourly Volume	−0.9725	0.121	<0.0001*
Operational (85th percentile) Speed Less than 45 mph (1 = yes, 0 = no)	0.9875	0.3997	0.01349*
Baseline Lane Width (12-ft) – Actual Lane Width (ft)	1.7997	0.2737	<0.0001*
Sidewalk Presence (1 = yes, 0 = no)	1.7356	0.465	0.00019*

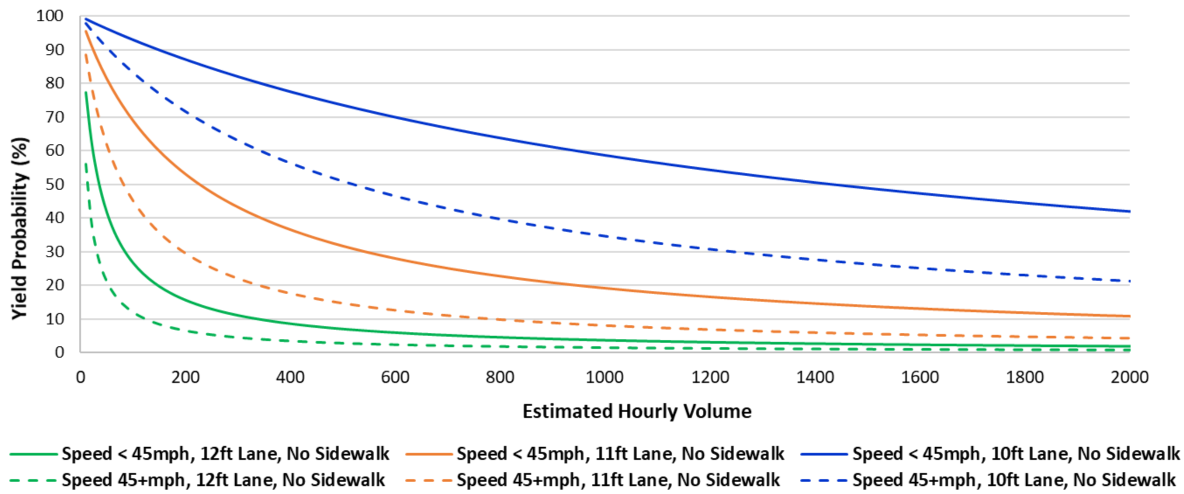
* Statistically significant at the 95 percent confidence interval.

To examine the effects of the independent variables presented in Table 14, the researchers computed the yielding probability for a range of hourly volumes (see Figure 21). The relationship between hourly volume and yielding probability was computed separately for sidewalks present (Figure 21a) and no sidewalks (Figure 21b) for operational speeds of less than or equal to and greater than 45 mph, as well as lane widths of 12 ft, 11 ft, and 10 ft.

A quick visual inspection of Figure 21 shows that yield probability was highest for sites with narrower lanes (shown by the solid blue, orange, and green lines). The dashed lines represent the relationship between yield probability and the dependent variables for operational speeds equal to or greater than 45 mph. These dashed lines show that speeds greater than or equal to 45 mph are associated with lower yield probability, a pattern that is observed for each lane width. The lack of sidewalks is associated with lower yield probabilities, despite the operational speed or lane widths, as evident by the downward shifting of the lines when comparing Figure 21a and Figure 21b. Last, traffic had a crucial effect on yield probability, as shown in the figures. The effect is more emphasized for hourly volumes up to 200 vehicles; it starts to level out for volumes of greater than 600 vehicles per hour, especially in the case of a combination of no sidewalks, 12-ft lanes, and 85th percentile speeds of 45 mph or greater.



(a) Sidewalks



(b) No Sidewalks

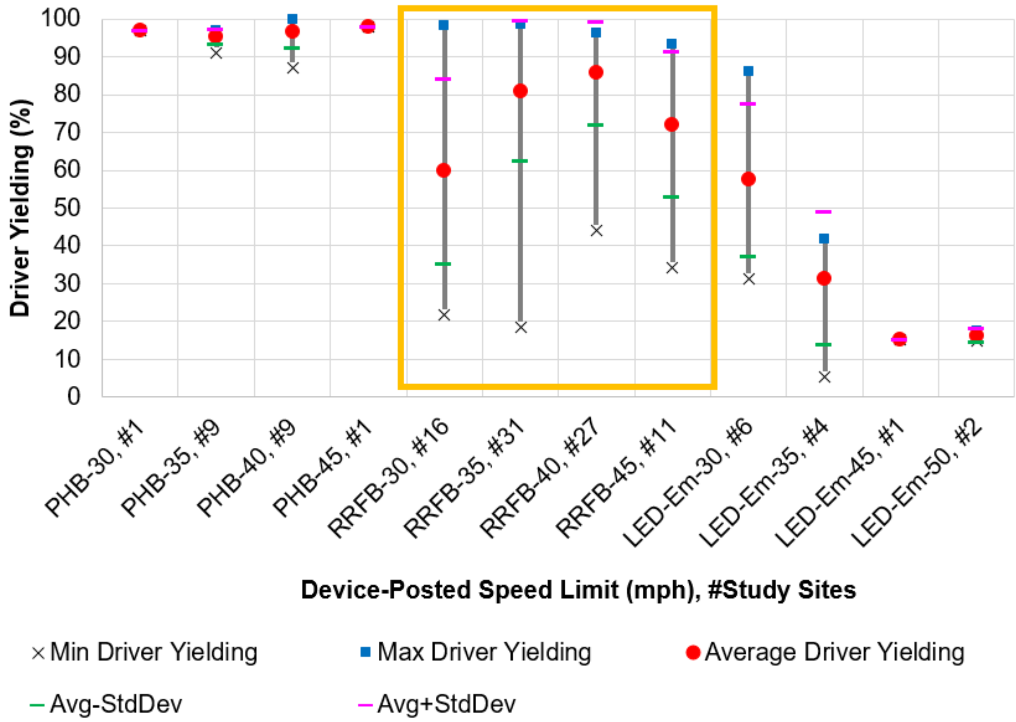
Figure 21. Yield Probability for Driver Yielding Based on Hourly Volume, Operational (85th Percentile) Speed, Lane Width, and Sidewalk Presence.

Comparison of LED-Em Sign, RRFB, and PHB Treatments

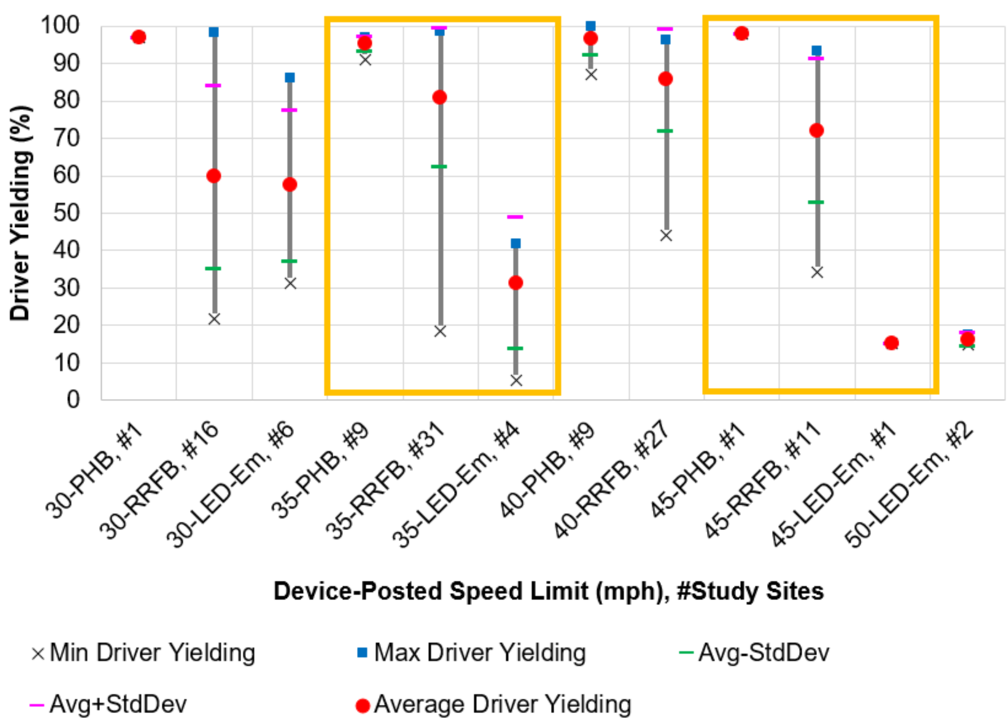
To compare the yield rates across the three pedestrian crossing treatments (i.e., LED-Em signs, RRFBs, and PHBs), researchers utilized data from various studies (*15*, *31*, *32*, *33*, *34*) and graphed driver yielding statistics side by side for ease of visual comparison. Yielding rates for sites with the same posted speed limit were averaged for each treatment, and the results are shown in Figure 22. Figure 22a shows the average yielding rates by posted speed limit grouped by the type of device. Figure 22b shows the average yielding rates for each treatment grouped by posted speed limit for a side-by-side comparison. Both graphs illustrate the following statistics: minimum, maximum, and average driver yielding rates, as well as standard deviations for the average driver yielding rates.

The main results from the comparison of driver yielding rates by posted speed limit were:

- PHBs are highly effective at any posted speed (see Figure 22a).
- LED-Em signs exhibit the lowest driver yield rates (see Figure 22a), and the treatment exhibits a decreasing pattern (i.e., as the posted speed limit increases, the driver yield rates fall below 20 percent).
- RRFB average driver yield rates are variable, ranging from 60 to 86 percent (see Figure 22a); however, even the highest driver yield rates for RRFBs are lower than PHB driver yield rates by approximately 10 percent. Additionally, as posted speed limits increase, RRFB driver yield rates exhibit almost an opposite trend as LED-Em signs, except for a posted speed limit of 45 mph, where RRFB average driver yield rates drop to 72 percent.
- Figure 22b demonstrates that for posted speeds of 35 mph and 45 mph, the highest driver yield rates are those for PHB treatments, followed by a wide range of driver yield rates for RRFBs, and last, very low yield rates for LED-Em signs.
- At a posted speed limit of 30 mph, driver yield rates for RRFBs and LED-Em signs are almost equal, with RRFB yield rates having slightly more variability than the LED-Em sign sites.
- A direct comparison is not possible for posted speed limits of 40 mph and 50 mph due to the lack of LED-Em sign sites with a posted speed limit of 40 mph and the lack of PHB and RRFB sites with a posted speed limit of 50 mph (see Figure 22b).



(a) Driver Yielding Statistics, Grouped by Type of Device



(b) Driver Yielding Statistics, Grouped by Posted Speed Limit

Figure 22. Comparison of the Driver Yielding Statistics for RRFBs, PHBs, and LED-Em Pedestrian Crossing Sign Treatments.

CONCLUSIONS

Due to a lack of studies on the examination of LED-Em pedestrian crossing signs, questions existed on how effective this treatment was and what factors, if any, affected its effectiveness. The researchers collected field observations and video recordings at a total of 13 locations across the state of Texas. The final dataset included 681 staged pedestrian crossings. Sites varied in posted speed limits and cross-section characteristics, with about half of the sites being located in school zones. The researchers utilized driver yielding, a surrogate safety measure, to assess the effectiveness of the LED-Em signs.

Overall, driver yielding for these 13 sites ranged from 5 to 88 percent, averaging to a 40 percent yield rate. The wide range of yield rates implied that factors other than the signs themselves affect driver yielding. The researchers' modeling efforts of the staged crossings showed that the natural logarithm of the estimated two-way hourly volume, operational 85th percentile speed being less than 45 mph (1 = yes, 0 = no), difference between the lane width and the baseline of 12-ft lane, and sidewalk presence were good predictors for log-odds of driver yield probability. The researchers found that driver yielding probability decreased with higher hourly volumes, as well as with speeds equal to or greater than 45 mph, wider lanes (i.e., 12-ft lanes), and lack of sidewalks. These results imply that LED-Em signs are a better candidate treatment for locations with lower operating speeds and lower traffic volumes, narrower lanes, and presence of sidewalks (i.e., characteristics of lower functional class roadways).

The researchers compared the LED-Em pedestrian crossing sign driver yielding rates with the RRFB and PHB driver yielding rates from previous studies. The results showed that LED-Em signs do not perform as well as the other treatments, especially for roadways with higher posted speed limits. This finding was further supported by the results of the statistical model, as explained in the previous paragraph.

During this effort, researchers examined only staged pedestrian crossings for two reasons: (a) to provide a true comparison to the other pedestrian crossing treatments, which were evaluated only through staged pedestrian crossings; and (b) to account for the consistency with which staged crossings occur in terms of LED-Em sign activation and positioning of pedestrians on the crossing. Additionally, only a few pedestrians were observed at some of the sites where data were collected. Consequently, it would be desirable to conduct further research to examine the factors that affect driver yielding behavior for non-staged crossings and compare the various treatments. However, this would require obtaining information on sign installations in more urban/populated areas. Last, further research could examine driver behavior and understanding of the various treatments and compare the results to determine which treatments are more effective at catching driver attention in various roadway environments.

CHAPTER 5: ASSESSMENT OF PEDESTRIAN CRASHES ON HIGH-SPEED ROADS

In the first year of this research project, the research team conducted a review and analysis of pedestrian crashes on high-speed (≥40 mph) roadways in Texas. They developed a methodology to identify clusters of crashes that occurred within 150 ft of each other, using statewide crash data for the period 2012–2017. After performing the cluster analysis, the researchers identified the 31 locations with clusters that had between 7 and 19 crashes in the six-year period, and detailed evaluations were conducted for 26 of the 31 clusters. Clusters were dropped typically due to the narratives indicating crashes occurred farther apart, which would have resulted in the cluster not including enough crashes to make the cutoff point used by the researchers. When investigating the resulting clusters, researchers identified the corresponding locations as either intersections, corridors, or a combination of the two, and they identified potential countermeasures for those locations. Much of the effort for identifying those crashes and clusters was documented in the Year 1 report for the project (*37*). This report also described countermeasures for reducing the number and severity of pedestrian crashes on high-speed roadways and highlighted selected tools and resources for choosing appropriate treatments. In the second year, the researchers finalized their analysis of the findings for each site and met with TxDOT staff in the relevant districts to share their results, discuss the findings, and obtain feedback from the districts on the specific sites and on pedestrian crash treatments in general. This chapter documents those activities.

CHARACTERISTICS OF CRASHES WITHIN THE IDENTIFIED CLUSTERS

A common feature at most of the corridors and intersections containing the 26 clusters was one or more bus stops within the cluster or nearby. This feature suggests a connection between pedestrians who use public transit and pedestrian crashes on high-speed roads. Transit agencies vary from place to place on their criteria for establishing a bus stop; some consider details on the surrounding area (including available pedestrian facilities), while others not as much. Regardless of the process used to establish a bus stop, that process would ideally consider the presence of continuous sidewalks to nearby pedestrian generators and the presence of adjacent crosswalks to provide a common point for crossing pedestrians to use when preparing to cross the street or consider how to have such infrastructure provided. Of course, the location and design of the pedestrian generators (e.g., businesses, etc.) influence pedestrian demand and crossing locations.

All of the sites contained crashes in which a pedestrian was struck by a motor vehicle while crossing the street outside of a crosswalk. In some cases, this occurrence was a result of pedestrians moving between vehicles that were stopped for a red signal when the signal changed to green. The more common instances involved pedestrians who were crossing from one commercial property to another or between residential and commercial areas. In the latter category of crashes, many of the pedestrians were struck while in a two-way left-turn lane, suggesting that a median refuge island could be useful in preventing future crashes of a similar nature.

Also related to commercial properties, researchers reviewed a noticeable number of crashes with pedestrians who were struck while walking on the sidewalk. While some were struck by a vehicle that was out of control and left the roadway (perhaps when a driver was intoxicated), other pedestrians were struck by a vehicle entering or (more commonly) exiting a driveway to a commercial property. A frequent scenario for exiting drivers was that they looked left to check for oncoming vehicles and failed to notice the pedestrian approaching from their right before proceeding through the driveway. Access management measures, such as reducing the number of driveways, can help to reduce pedestrian exposure to these types of crashes. A different kind of access management would apply to a small number of corridor sites that have essentially no defined driveways but rather a mountable curb or no curb adjacent to a series of contiguous commercial properties. These sites also may have no formal sidewalk, though a wide paved surface similar to a shoulder lane might provide additional buffer between a pedestrian and the traffic on the adjoining roadway. Installation of a formal curb with sidewalk and buffer would provide a dedicated pedestrian path at these locations.

A selection of sites had at least half of their crashes occur during nighttime hours, at dawn, or at dusk. This finding indicates that either installation of new roadway lighting or a review of existing lighting would be beneficial for these sites.

Some intersection sites had a high number of pedestrian crashes within the crosswalk, where pedestrians were struck by a left-turning vehicle. A review of street-level images indicates that some of those intersections appear to have protected left-turn phasing, but others have protected/permitted or permitted-only left turns. A formal review of left-turn phasing at these intersections, and introduction of protected-only left turns for some approaches, would reduce the likelihood of pedestrians being struck by drivers who did not see a crossing pedestrian while they concentrated their view on searching for an acceptable left-turn gap. Similarly, a leading pedestrian interval could also give pedestrians a head start on entering the intersection and increasing their visibility before left-turning vehicles begin their turning movements.

The review of crash narratives also revealed a notable number of crashes with vehicles turning right on red or using a free-flow right-turn lane. In the former category, drivers typically did not notice the pedestrian on their right that was preparing to cross the street because they were looking left for oncoming vehicles; outreach/education efforts or supplemental signing at such intersections could be beneficial treatments to help drivers develop a consistent habit to thoroughly check their surroundings. In the latter category, drivers may also be looking to their left as they travel through the right-turn lane to make sure they have a suitable gap in traffic to merge, and speeds in free-flow right-turn lanes can increase the risk of serious injury to pedestrians compared to the right-turn-on-red condition.

Using the compiled information described above, researchers contacted the districts in which one or more clusters were found to meet either in person or by phone/web conference to share the findings and discuss resources and treatments available to address those crashes. The following section summarizes those meetings.

MEETINGS WITH DISTRICT STAFF

Two members of the research team conducted meetings either in person or by phone/web conference to discuss the findings of the analysis, with information and discussion tailored to each individual district and the clusters and crashes found there. The research team met in person with the Houston, Austin, and San Antonio Districts, and by phone with the Lubbock, Ft. Worth, and El Paso Districts. Typically, several district staff members would attend the meeting with the research team. At two of the meetings, representatives of the county or city were also in attendance.

Within each meeting, researchers presented an overview of the project (i.e., a summary of the discussion provided above and in the Year 1 report) and a site-by-site review of each of the sites within the district. After considering the questions and discussion as part of the initial meeting in the Houston District, researchers added a component to the presentation for the remaining meetings to discuss district-wide and statewide trends on pedestrian trips and crashes, as well as existing guidelines and resources on identifying and implementing countermeasures to pedestrian-related crashes.

In their discussions of resources that they use to identify crash locations and select appropriate countermeasures, district staff mentioned the following:

- They would like to have more public education/outreach, either as a broad response to an area-wide problem or more specific to a particular location or treatment, to help reduce crashes that are part of a pattern. An example of an outreach campaign that was implemented in Austin was "Be Safe Be Seen" (*38*), which distributed reflective bags to area residents.
- They would like to more commonly use PHBs and RRFBs at crossing locations. However, while guidance does exist on their use, the requirements of 20 pedestrians per hour and posted speed limits not over 40 mph are limiting the number of installations. Because those locations often do not meet a signal warrant, districts are considering other treatments (e.g., 12-inch circular LED flashing beacons) that may have a lower effectiveness than PHBs and RRFBs but do not have the same restrictions on installation. Districts are curious how those devices' effectiveness compare to other pedestrian treatments.
- Treatments at unsignalized intersections are often installed as part of bigger projects to add sidewalks, signals (with leading pedestrian intervals, pushbuttons, etc.), and/or other treatments.
- Other guidance that is typically used includes Americans with Disabilities Act (ADA) guidelines to ensure that treatments meet those requirements, details on PHB installations when they are used, and coordination with the district design section on intersection upgrades.
- Efforts to identify crashes and crash locations include the district's fatal crash log or fatal crash committee, the heat map from the TxDOT Traffic Safety Division, and coordination with the city.
- Considerations on deciding whether to install a pedestrian treatment include crash numbers, driveways, engineering judgment (used frequently), and pedestrian volume (if available).

- Districts have had success in working with city staff where possible to coordinate certain types of treatment installations, such as accessible pedestrian signals, leading pedestrian interval, and upgrading signals. One specific treatment was the installation of signs (painting "No Peds") on freeway median barriers to discourage pedestrian crossings at a particular location.
- Districts are interested in having a document that discusses best practices. Currently, many treatment requests have to go to the TxDOT Traffic Safety Division for approval. Districts would like to change the PHB speed limit restriction (currently only allowed for roads posted at 40 mph or less) to be able to consider the treatment for more TxDOT roads.

District staff also posed several questions regarding resources that they use to identify crash locations and select appropriate countermeasures:

- One question asked for confirmation on whether the required width of a pedestrian refuge is 5 ft or 6 ft. Researchers identified guidance from three sources:
  - The TxDOT *Roadway Design Manual* (*39*), in Chapter 2, Section 6, states, "Refuge islands enhance pedestrian comfort by reducing effective walking distances and pedestrian exposure to traffic. Islands should be a minimum of 6 ft [1.8 m] wide to afford refuge to people in wheelchairs."
  - The National Association of City Transportation Officials *Urban Street Design Guide* (*40*) in its section on Crosswalks and Crossings under Intersection Design Elements states, "Pedestrian safety islands should be at least 6 feet wide, but have a preferred width of 8–10 feet. Where a 6-foot wide median cannot be attained, a narrower raised median is still preferable to nothing. The minimum protected width is 6 feet, based on the length of a bicycle or a person pushing a stroller. The refuge is ideally 40 feet long."
  - The FHWA Course on Bicycle and Pedestrian Transportation includes a module called Pedestrian Accommodations at Intersections (*41*), which states that design considerations should include the following: "Areas at least 6 feet wide from the face of the curb to the face of the curb. The minimum width should not be less than 4 feet wide from the face of the curb to the face of the curb. The island

should not be less than 12 feet long or the width of the crosswalk, whichever is greater. The minimum island size should be 50 square feet."

- One question asked about the details of the brightness level requirements for beacons. The information would be used to compare to the brightness level planned for 12-inch circular LED flashers. The research team responded that, per Condition 5d of FHWA's Interim Approval IA-21 (*42*), the RRFB "shall meet the minimum specifications for Class 1 yellow peak luminous intensity." Per a discussion with a vendor, the 12-inch circular LED flashers may not have to meet the Class 1 yellow peak luminous intensity.
- One question asked if there is guidance on when a pushbutton is to be included in the pedestrian refuge area, perhaps based on number of lanes or speed on the major road. The research team's review of other state/agency guidance materials on pedestrian crossing treatments revealed that few have discussed this issue. The Florida state manual states that a two-stage pedestrian crossing should be considered for six-lane roads or when crossing distances exceed 80 ft. Arizona also has as a practice the use of two-stage crossings for wider roads.
- One question asked whether accessible pedestrian signals are always used with the RRFB and the PHB. The research team noted that this question was asked during a recent National Committee on Uniform Traffic Control Devices meeting, and the answer was that they are not required but preferred.

Researchers provided the district staff from each meeting with information on two specific resources:

- The Governors Highway Safety Association (GHSA) publishes a series of reports on pedestrian traffic fatalities by state. Researchers used the 2017 (*43*) and 2018 (*44*) GHSA Pedestrian Traffic Fatalities by State reports.
- A recent FHWA project developed a scalable risk assessment method for pedestrians and bicyclists that provides exposure estimates by metropolitan planning organization (MPO), a sample of which was also shared during each meeting. The *Guide for Scalable Risk Assessment Methods for Pedestrians and Bicyclists* (*45*) describes scalable risk assessment methods for pedestrians and bicyclists, wherein risk is a measure of the probability of a crash to occur given exposure to potential crash

events. This guide outlines eight sequential steps to develop risk values at various desired geographic scales and describes the scope and nature of each step, including any guiding principles. The Areawide Exposure Tool (*46*) is supplemental to the *Guide for Scalable Risk Assessment Methods for Pedestrians and Bicyclists* and makes it easy for practitioners to obtain and summarize nationwide travel survey data to estimate pedestrian and bicyclist exposure at statewide and MPO area scales while providing functions for the user to supply local data when available.

In their discussions of the statewide, district-wide, and cluster-specific data on pedestrian exposure and crashes, district staff raised several questions and offered comments and feedback about the study, as follows:

- Multiple districts asked for more information on the distribution of crashes through the study period to better understand whether they were evenly distributed (e.g., one crash each year) or whether there was a trend of increasing or decreasing frequency.
- Requests for crash data used in the project also included information on the number of pedestrian (fatal and all severity) crashes by district, particularly on high-speed roads, and how the districts ranked in those metrics by vehicle miles traveled. The research team provided that information, which can be found below.
- Multiple districts also mentioned that several locations within their respective areas, including a number of study sites, had a challenge with a homeless population, which increased pedestrian activity and perhaps contributed to the crashes in the analysis.
- A raised median (a countermeasure that was mentioned for a number of clusters) was discussed at one particular city council meeting several years ago for a corridor that included a study cluster, but the idea was dismissed due to neighboring business owners' complaints before any work could be done to refine the concept.
- One district mentioned a study it conducted on a separate corridor that was not part of the cluster analysis. After the district described some characteristics of that corridor, researchers explained that the corridor may not have appeared in the list of study clusters because the corridor had a combination of 35-mph and 40-mph segments. The 35-mph segments may have eliminated enough crashes to produce a cluster that was not large enough to be in the analysis, which focused on speed limits of 40 mph and above.

- Another district noted that the identified cluster is already a focus area for the city in an initiative to reduce crashes along the broader corridor. The district will be meeting with the city and will mention the findings from this project in that context to help coordinate efforts and explore additional countermeasures. For example, raised medians are suggested for this area along with traffic signal changes.

In response to the request for more crash information mentioned above, the research team generated a series of three tables and an associated graph. Figure 23 shows the number of pedestrian crashes per year per million vehicle miles traveled (MVMT) for two groups of years to be able to compare changes in crash rates from earlier in the decade to more recent years. Districts are ordered by number of crashes in the entire 2012–2018 period. Unfortunately, in almost every district, the number of pedestrian crashes per MVMT increased in 2016–2018 compared to 2012–2015. Table 15 shows the crash rate and rank of the requested items for the period 2012 to 2018 (seven years). The other two tables are subsets of the first. Table 16 shows the same data for the period 2012–2015 (four years), and Table 17 shows the data for 2016–2018 (three years).

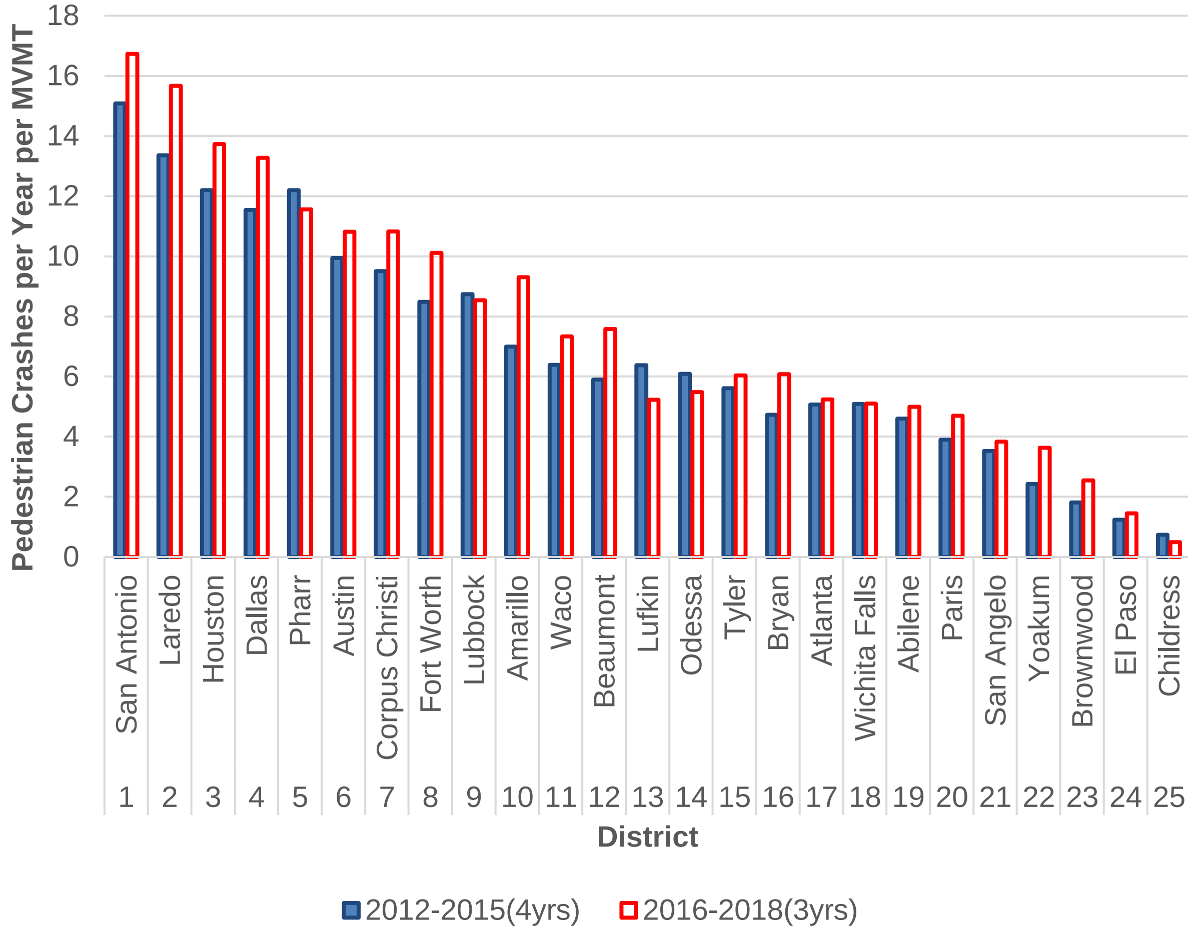


Figure 23. Pedestrian Crashes per Year per MVMT by District and Year Groups.

Table 15. Crash Rate and Rank for 2012 to 2018 (Seven Years).

District	Crash Rate					Rank				
	Ped Crash per Year per MVMT	Fatal Ped Crash per Year per MVMT	High-Speed Ped Crash per Year per MVMT	Fatal High-Speed Ped Crash per Year per MVMT	Hit-and-Run Ped Crash per Year per MVMT	Ped Crash per Year per MVMT	Fatal Ped Crash per Year per MVMT	High-Speed Ped Crash per Year per MVMT	Fatal High-Speed Ped Crash per Year per MVMT	Hit-and-Run Ped Crash per Year per MVMT
Abilene	4.8	0.6	1.8	0.5	0.8	19	17	19	10	19
Amarillo	8.0	0.7	2.3	0.5	2.1	10	14	15	17	10
Atlanta	5.1	0.6	2.7	0.5	1.0	17	18	10	16	18
Austin	10.3	0.7	2.8	0.5	2.6	6	11	9	15	6
Beaumont	6.6	0.9	2.9	0.7	1.5	12	4	8	2	11
Brownwood	2.1	0.3	0.9	0.2	0.2	23	22	23	22	23
Bryan	5.3	0.4	2.0	0.4	1.3	16	21	17	19	14
Childress	0.6	0.2	0.4	0.1	0.1	25	25	25	25	25
Corpus Christi	10.1	0.9	2.5	0.6	2.4	7	5	13	7	7
Dallas	12.3	0.8	3.3	0.6	2.7	4	7	3	9	5
El Paso	1.3	0.2	0.5	0.1	0.2	24	24	24	24	24
Fort Worth	9.2	0.7	3.0	0.5	2.3	8	12	5	13	9
Houston	12.9	0.9	3.1	0.5	3.6	3	6	4	12	2
Laredo	14.3	0.8	2.0	0.4	3.1	2	8	16	20	3
Lubbock	8.7	0.7	3.0	0.5	2.4	9	13	6	14	8
Lufkin	5.9	0.9	3.6	0.9	1.1	13	2	2	1	15
Odessa	5.8	0.7	2.3	0.5	1.5	14	15	14	11	12
Paris	4.2	0.7	1.8	0.6	0.7	20	16	18	6	21
Pharr	11.9	0.9	2.6	0.6	3.0	5	3	11	8	4
San Angelo	3.7	0.3	1.0	0.2	0.7	21	23	22	23	20
San Antonio	15.8	1.1	4.8	0.7	4.1	1	1	1	3	1
Tyler	5.8	0.8	2.9	0.6	1.1	15	9	7	5	16
Waco	6.8	0.8	2.6	0.6	1.3	11	10	12	4	13
Wichita Falls	5.1	0.5	1.7	0.4	1.0	18	19	20	18	17
Yoakum	2.9	0.4	1.2	0.3	0.4	22	20	21	21	22

Table 16. Crash Rate and Rank for 2012 to 2015 (Four Years).

District	Crash Rate					Rank				
	Ped Crash per Year per MVMT	Fatal Ped Crash per Year per MVMT	High-Speed Ped Crash per Year per MVMT	Fatal High-Speed Ped Crash per Year per MVMT	Hit-and-Run Ped Crash per Year per MVMT	Ped Crash per Year per MVMT	Fatal Ped Crash per Year per MVMT	High-Speed Ped Crash per Year per MVMT	Fatal High-Speed Ped Crash per Year per MVMT	Hit-and-Run Ped Crash per Year per MVMT
Abilene	4.6	0.7	1.6	0.6	0.8	19	11	19	6	19
Amarillo	7.0	0.5	2.2	0.4	2.1	10	18	14	19	10
Atlanta	5.1	0.4	2.7	0.4	1.2	17	20	9	17	15
Austin	9.9	0.6	2.7	0.5	2.6	6	12	10	11	6
Beaumont	5.9	0.7	2.4	0.6	1.4	14	5	12	7	12
Brownwood	1.8	0.4	0.8	0.3	0.1	23	21	23	22	24
Bryan	4.7	0.5	1.9	0.4	1.2	18	19	16	16	14
Childress	0.7	0.3	0.4	0.2	0.2	25	24	25	24	23
Corpus Christi	9.5	0.6	2.0	0.4	2.3	7	13	15	15	9
Dallas	11.5	0.7	3.0	0.4	2.7	5	8	4	13	5
El Paso	1.2	0.1	0.4	0.1	0.1	24	25	24	25	25
Fort Worth	8.5	0.6	2.7	0.5	2.4	9	14	8	12	8
Houston	12.2	0.8	2.9	0.5	3.8	4	4	5	10	2
Laredo	13.4	0.7	1.6	0.3	3.3	2	10	18	21	4
Lubbock	8.7	0.6	3.0	0.4	2.6	8	15	3	18	7
Lufkin	6.4	0.9	3.6	0.7	1.1	12	3	2	1	18
Odessa	6.1	0.7	2.3	0.6	1.7	13	6	13	4	11
Paris	3.9	0.6	1.5	0.5	0.5	20	16	20	9	21
Pharr	12.2	0.9	2.7	0.6	3.5	3	2	7	8	3
San Angelo	3.5	0.3	1.2	0.2	0.7	21	23	21	23	20
San Antonio	15.1	1.0	4.4	0.7	4.3	1	1	1	2	1
Tyler	5.6	0.7	2.8	0.6	1.1	15	9	6	5	17
Waco	6.4	0.7	2.5	0.6	1.4	11	7	11	3	13
Wichita Falls	5.1	0.6	1.6	0.4	1.1	16	17	17	14	16
Yoakum	2.4	0.4	1.1	0.3	0.3	22	22	22	20	22

Table 17. Crash Rate and Rank for 2016 to 2018 (Three Years).

District	Crash Rate					Rank				
	Ped Crash per Year per MVMT	Fatal Ped per Year per MVMT	High-Speed Ped Crash per Year per MVMT	Fatal High-Speed Ped Crash per Year per MVMT	Hit-and-Run Ped Crash per Year per MVMT	Ped Crash per Year per MVMT	Fatal Ped per Year per MVMT	High-Speed Ped Crash per Year per MVMT	Fatal High-Speed Ped Crash per Year per MVMT	Hit-and-Run Ped Crash per Year per MVMT
Abilene	5.0	0.6	2.0	0.5	0.8	19	17	18	16	19
Amarillo	9.3	0.9	2.4	0.6	2.0	9	9	15	10	10
Atlanta	5.2	0.7	2.7	0.6	0.8	16	16	12	12	20
Austin	10.8	0.8	3.0	0.5	2.6	7	11	10	15	5
Beaumont	7.6	1.1	3.5	1.0	1.7	11	3	4	2	11
Brownwood	2.5	0.2	1.0	0.1	0.3	23	24	22	24	23
Bryan	6.1	0.4	2.0	0.4	1.4	13	21	19	20	12
Childress	0.5	0.0	0.4	0.0	0.0	25	25	25	25	25
Corpus Christi	10.8	1.2	3.2	0.8	2.5	6	1	7	3	6
Dallas	13.3	1.0	3.7	0.7	2.7	4	5	2	6	4
El Paso	1.5	0.3	0.6	0.2	0.2	24	22	24	22	24
Fort Worth	10.1	0.8	3.4	0.6	2.1	8	12	5	13	8
Houston	13.7	1.0	3.3	0.6	3.3	3	6	6	11	2
Laredo	15.7	1.0	2.4	0.4	2.8	2	7	14	19	3
Lubbock	8.5	0.8	3.0	0.7	2.0	10	15	9	8	9
Lufkin	5.2	1.0	3.6	1.0	1.1	17	4	3	1	14
Odessa	5.5	0.6	2.4	0.5	1.1	15	18	16	17	15
Paris	4.7	0.8	2.1	0.7	0.9	20	14	17	7	17
Pharr	11.6	0.9	2.5	0.6	2.5	5	8	13	14	7
San Angelo	3.8	0.2	0.7	0.2	0.8	21	23	23	23	21
San Antonio	16.7	1.1	5.2	0.8	3.7	1	2	1	4	1
Tyler	6.0	0.9	3.1	0.7	1.0	14	10	8	5	16
Waco	7.3	0.8	2.7	0.7	1.3	12	13	11	9	13
Wichita Falls	5.1	0.5	1.8	0.5	0.9	18	20	20	18	18
Yoakum	3.6	0.5	1.4	0.3	0.6	22	19	21	21	22

CHAPTER 6: REVIEW OF GUIDANCE ON SELECTION OF APPROPRIATE TREATMENT FOR A PARTICULAR PEDESTRIAN CROSSING LOCATION

A 2002 FHWA study (*47*) focused on the safety effects of marked versus unmarked crosswalks. A finding from that study was that there are conditions when a marked crosswalk (without other treatments) is associated with higher vehicle-pedestrian crashes compared to unmarked locations. The authors noted that this finding did not imply that crossings should not be marked but rather that other treatments should be present in addition to the basic pavement markings and signs. Pedestrians are crossing streets because they need to reach the other side, and additional efforts are needed to provide a safer crossing. Since that FHWA publication, several research efforts and agencies have investigated and developed procedures to identify treatments for pedestrian crossings.

As part of this research project, existing documents providing guidance on the selection of pedestrian treatments were identified and reviewed. The following sections summarize those documents. An emphasis was made on the use of RRFBs and PHBs, which are also called HAWKs, since those are the devices specifically addressed in a recent TxDOT memorandum (*48*). A later section provides insights on the potential format for guidelines that could be more acceptable or more used within Texas.

NATIONAL REFERENCE DOCUMENTS

MUTCD

The *Manual on Uniform Traffic Control Devices* (MUTCD) (*49*) specifies the standards by which traffic signs, road surface markings, and signals are designed, installed, and used. The 2009 edition includes several sections that discuss pedestrian crossing treatments, including but not limited to the following:

- Pavement markings, Section 3B.18 Crosswalk Markings.
- Traffic control signal, Section 4C.05 Warrant 4, Pedestrian Volume.
- Pedestrian hybrid beacon, Section 4F Pedestrian Hybrid Beacon, including graphs that are guidelines for the installation of a PHB (see Figure 24).

Figure 4F-1. Guidelines for the Installation of Pedestrian Hybrid Beacons on Low-Speed Roadways

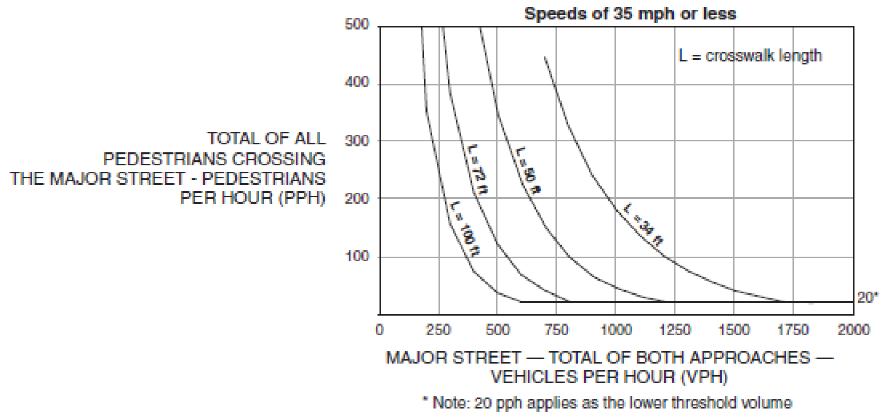


Figure 4F-2. Guidelines for the Installation of Pedestrian Hybrid Beacons on High-Speed Roadways

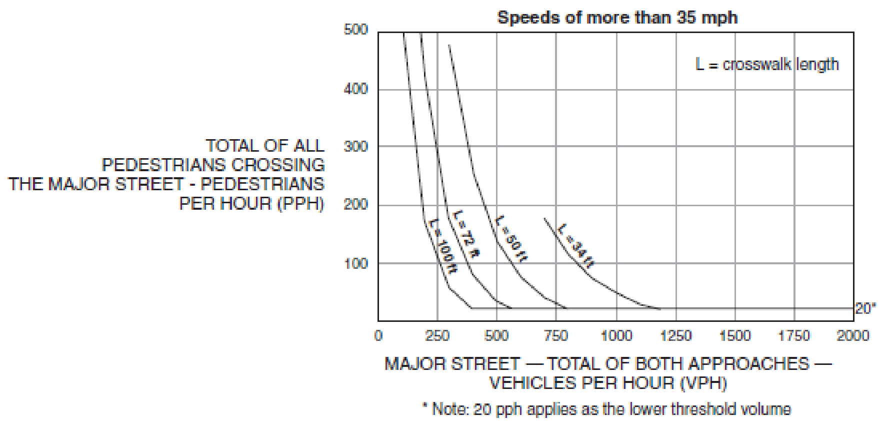


Figure 24. MUTCD Guidelines for the Installation of a PHB (*49*).

The National Committee on Uniform Traffic Control Devices (NCUTCD) recommends to the FHWA proposed revisions and interpretations to the MUTCD. As part of its recent efforts, NCUTCD has recommended changes to the sections on crosswalk pavement markings and PHBs.

Revised Crosswalk Markings

Revisions on crosswalk markings for the next edition of the MUTCD were approved by NCUTCD in June 2011 to provide additional uniformity to the marking patterns (*50*). The revision also expanded discussion on types of high-visibility crosswalk marking patterns and provided guidance regarding the installation of that type of pattern. The specific revisions are available on the NCUTCD website. A new proposed figure provides greater details on crosswalk marking types (see Figure 25).

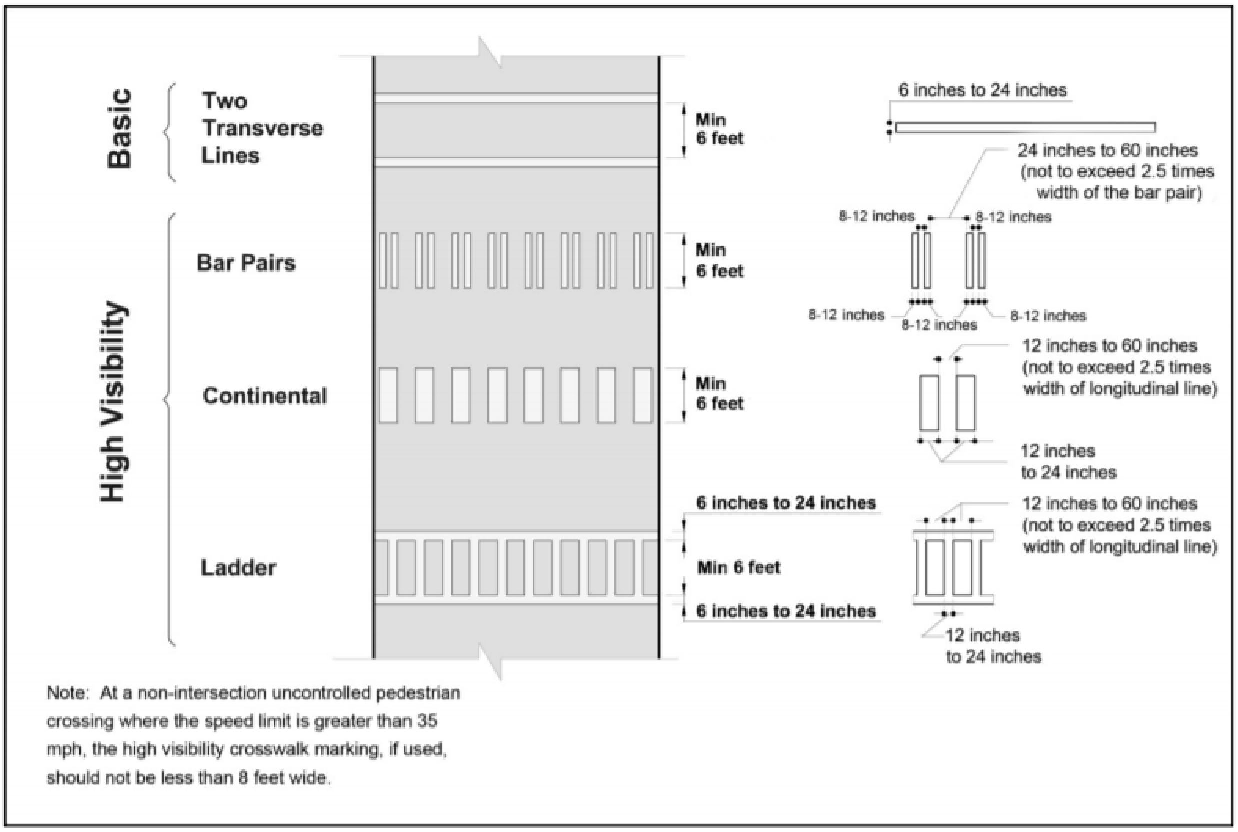


Figure 3B-19. Examples of Crosswalk Markings
[New Figure 3B-19 to replace existing figure]

Figure 25. Proposed Figure for Next Edition of the MUTCD (*50*).

Another related revision was approved by NCUTCD in January 2012 to address a concern that the document, as currently written, provides guidance that adding treatments to a marked crosswalk at an uncontrolled intersection is only recommended when the speed limit is greater than 40 mph. The proposed revision is:

> "New marked crosswalks alone, without other measures designed to reduce traffic speeds, shorten crossing distances, enhance driver awareness of the crossing, and/or provide active warning of pedestrian presence, should not be installed across uncontrolled roadways where any of the following conditions exist ~~the speed limit exceeds 40 mph and either~~:
>
> A. The roadway has four or more lanes of travel without a raised median or pedestrian 55 refuge island and an ADT of 12,000 vehicles per day or greater; or

B. The roadway has four or more lanes of travel with a raised median or pedestrian refuge island and an ADT of 15,000 vehicles per day or greater; or

C. The speed limit exceeds 35 mph." (*51*)

Revised PHBs

Revisions for the next edition of the MUTCD to remove the guidance that a PHB should be installed at least 100 ft from side streets or driveways that are controlled by STOP or YIELD signs were approved by NCUTCD in June 2011 (*52*). The 100-ft guidance was not based on research and was added late in the development of the 2009 MUTCD. In support of the removal of the 100-ft limit, NCUTCD noted that an FHWA study (*53*) that investigated the safety effectiveness of PHBs found a 29 percent reduction in all vehicle crashes and a 69 percent reduction in pedestrian crashes and that all sites included in the FHWA study were located either at a minor intersection (where the minor street was controlled by a STOP sign) or at a major driveway (where the driveway was controlled by a STOP sign).

National Cooperative Highway Research Program 562

National Cooperative Highway Research Program (NCHRP) 562/Transit Cooperative Research Program (TCRP) 112 (*31*) uses pedestrian delay to make the determination of whether to recommend a device with a red indication (e.g., PHB), a yellow indication (i.e., an active device such as an RRFB), or a marked crosswalk (i.e., signs and pavement markings). The method also includes a step to determine whether a traffic control signal is warranted.

Figure 26 shows an illustration of a graph that can be generated from the NCHRP 562/TCRP 112 methodology using an assumed crossing distance and other variables. The user would then consider the major road volume and the pedestrian volume to determine the appropriate type of pedestrian treatment for the site. The graph in Figure 26 may be dated since the research was done prior to the 2009 MUTCD change in the pedestrian signal warrant, but the concept is applicable and has formed the basis of guidance included in other guidelines.

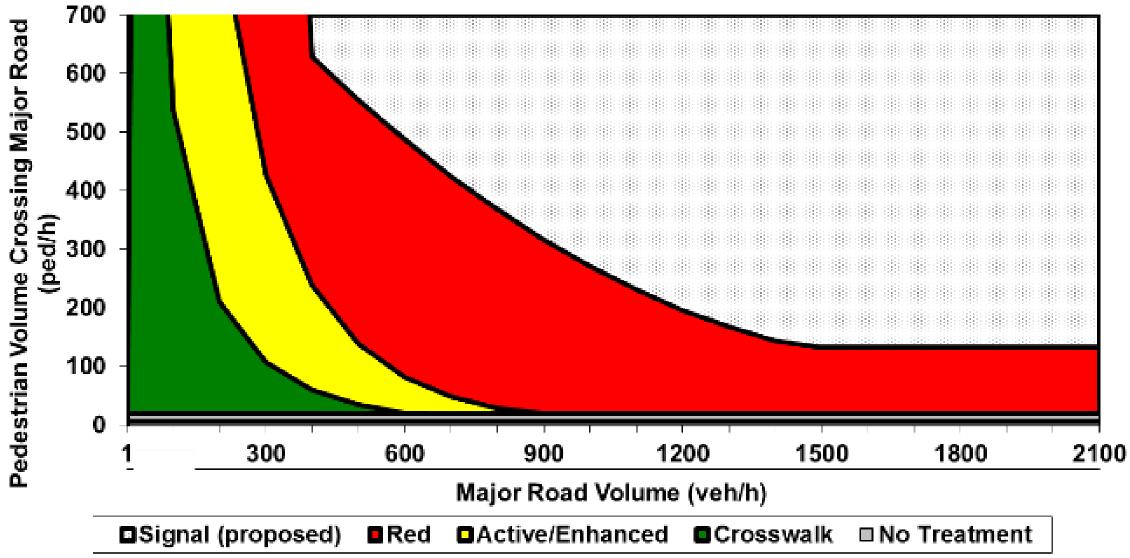


Figure 26. Example of Graph Generated from TCRP 112/NCHRP 562 Methodology (Function of Walking Speed, Crossing Distance, and Other Variables) That Could Be Used to Determine Pedestrian Treatment.

FHWA *Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations*

Recently released is the FHWA *Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations* (*54*) and its companion document, *Field Guide for Selecting Countermeasures of Uncontrolled Pedestrian Crossing Locations* (*55*). The field guide focuses on countermeasure selection tables. It also discusses the following countermeasures: crosswalk visibility enhancements, raised crosswalk, pedestrian refuge island, pedestrian hybrid beacon, and road diet.

Countermeasures are suggested based on roadway configuration, annual average daily traffic (AADT), and posted speed limit. Figure 27 reproduces the suggested countermeasures by roadway feature contained in the FHWA field guide (*55*). Countermeasure numbers are used within the matrix. When the countermeasure number is in a dark circle, that countermeasure should be considered at the location. If the countermeasure number is not present, then it should not be considered for the combination of roadway configuration, AADT, and posted speed limit. If the countermeasure number is present but not in a dark circle, then it is a candidate countermeasure.

Roadway Configuration	Posted Speed Limit and AADT								
	Vehicle AADT <9,000			Vehicle AADT 9,000–15,000			Vehicle AADT >15,000		
	≤30 mph	35 mph	≥40 mph	≤30 mph	35 mph	≥40 mph	≤30 mph	35 mph	≥40 mph
2 lanes (1 lane in each direction)	❶ 2 4 5 6	❶ 5 6 7 9	① 5 6 ❼ ❾	❶ 4 5 6	❶ 5 6 7 9	① 5 6 ❼ ❾	❶ 4 5 6 7 9	① 5 6 7 9	① 5 6 ❾
3 lanes with raised median (1 lane in each direction)	❶ 2 3 4 5	❶ ❸ 5 7 9	① ❸ 5 ❼ ❾	① 3 4 5 7 9	① ❸ 5 ❼ ❾	① ❸ 5 ❼ ❾	① ❸ 4 5 7 9	① ❸ 5 ❼ ❾	① ❸ 5 ❾
3 lanes w/o raised median (1 lane in each direction with a two-way left-turn lane)	❶ 2 3 4 5 6 7 9	❶ ❸ 5 6 7 9	① ❸ 5 6 ❾	① 3 4 5 6 7 9	① ❸ 5 6 ❼ ❾	① ❸ 5 6 ❾	① ❸ 4 5 6 7 9	① ❸ 5 6 ❾	① ❸ 5 6 ❾
4+ lanes with raised median (2 or more lanes in each direction)	❶ ❸ 5 7 8 9	❶ ❸ 5 7 8 9	① ❸ 5 8 ❾	① ❸ 5 7 8 9	① ❸ 5 ❼ 8 ❾	① ❸ 5 8 ❾	① ❸ 5 ❼ 8 ❾	① ❸ 5 8 ❾	① ❸ 5 8 ❾
4+ lanes w/o raised median (2 or more lanes in each direction)	❶ ❸ 5 6 7 8 9	① ❸ 5 ❻ 7 8 9	① ❸ 5 ❻ 8 ❾	① ❸ 5 ❻ 7 8 9	① ❸ 5 ❻ ❼ 8 ❾	① ❸ 5 ❻ 8 ❾	① ❸ 5 ❻ ❼ 8 ❾	① ❸ 5 ❻ 8 ❾	① ❸ 5 ❻ 8 ❾

Given the set of conditions in a cell,

- # Signifies that the countermeasure is a candidate treatment at a marked uncontrolled crossing location.
- ● Signifies that the countermeasure should always be considered, but not mandated or required, based upon engineering judgment at a marked uncontrolled crossing location.
- ○ Signifies that crosswalk visibility enhancements should always occur in conjunction with other identified countermeasures.*

The absence of a number signifies that the countermeasure is generally not an appropriate treatment, but exceptions may be considered following engineering judgment.

1. High-visibility crosswalk markings, parking restrictions on crosswalk approach, adequate nighttime lighting levels, and crossing warning signs
2. Raised crosswalk
3. Advance Yield Here To (Stop Here For) Pedestrians sign and yield (stop) line
4. In-Street Pedestrian Crossing sign
5. Curb extension
6. Pedestrian refuge island
7. Rectangular Rapid-Flashing Beacon (RRFB)**
8. Road Diet
9. Pedestrian Hybrid Beacon (PHB)**

*Refer to Chapter 4, 'Using Table 1 and Table 2 to Select Countermeasures,' for more information about using multiple countermeasures.

**It should be noted that the PHB and RRFB are not both installed at the same crossing location.

This table was developed using information from: Zegeer, C.V., J.R. Stewart, H.H. Huang, P.A. Lagerwey, J. Feaganes, and B.J. Campbell. (2005). Safety effects of marked versus unmarked crosswalks at uncontrolled locations: Final report and recommended guidelines. FHWA, No. FHWA-HRT-04-100, Washington, D.C.; FHWA. Manual on Uniform Traffic Control Devices, 2009 Edition. (revised 2012). Chapter 4F, Pedestrian Hybrid Beacons. FHWA, Washington, D.C.; FHWA. Crash Modification Factors (CMF) Clearinghouse. http://www.cmfclearinghouse.org/; FHWA. Pedestrian Safety Guide and Countermeasure Selection System (PEDSAFE). http://www.pedbikesafe.org/PEDSAFE/; Zegeer, C., R. Srinivasan, B. Lan, D. Carter, S. Smith, C. Sundstrom, N.J. Thirsk, J. Zegeer, C. Lyon, E. Ferguson, and R. Van Houten. (2017). NCHRP Report 841: Development of Crash Modification Factors for Uncontrolled Pedestrian Crossing Treatments. Transportation Research Board, Washington, D.C.; Thomas, Thirsk, and Zegeer. (2016). NCHRP Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways. Transportation Research Board, Washington, D.C.; and personal interviews with selected pedestrian safety practitioners.

Figure 27. FHWA Application of Pedestrian Crash Countermeasures by Roadway Feature (*55*).

TEXAS REFERENCE DOCUMENTS

Texas MUTCD

Texas maintains a state MUTCD called the Texas MUTCD (*5*). It contains guidance that is substantially similar to the federal MUTCD.

TxDOT Memorandum

TxDOT released a memorandum (*48*) on RRFBs and PHBs on September 11, 2018, that provides guidance regarding the use of those devices.

RRFBs

The TxDOT memorandum (*48*) states the following regarding RRFBs:

> "The Federal Highway Administration (FHWA) granted TxDOT interim approval for the use of Rectangular Rapid Flashing Beacons (RRFB) at marked crosswalks where the crossing is not controlled by a traffic control device such as a traffic signal or stop signs.
>
> RRFB are user-actuated amber LEDs that supplement warning signs. A RRFB consist of two rapidly and alternately flashed rectangular yellow indications having LED-array based pulsing light sources.
>
> This device provides an additional tool for improving the safety of crosswalks when traffic signals do not meet warrants. RRFB should be used in conjunction with signs and pavement markings to warn and control traffic at locations where pedestrians enter or cross a street or highway.
>
> All of the following conditions must be met before RRFB can be considered on our highways:
>
> - An established crosswalk with adequate visibility, markings and signs.
> - A posted speed limit of 40 mph or less (does not include school speed zones).
> - 20 pedestrians or more crossing in one hour.
> - Location deemed as a high risk area (e.g. schools, shopping centers, etc.).
> - Crosswalk is more than 300 ft from an existing, traffic controlled pedestrian crossing.
>
> Districts must submit and receive Traffic Safety Division approval for installation of a RRFB for each location."

PHBs

The memorandum (*48*) states the following regarding PHBs:

"The 2011 Texas MUTCD included the Pedestrian Hybrid Beacons (PHB) for use at marked crosswalks which are not managed by a traffic control device such as a traffic signal or stop signs.

A PHB is a pedestrian-activated warning device located on the roadside or on mast arms over midblock pedestrian crossings. The beacon head consists of two red lenses above a single yellow lens. The beacon head is "dark" until the pedestrian wanting to cross the roadway presses the button and activates the beacons.

This device provides an additional tool for improving the safety of crosswalks when traffic signals do not meet warrants. PHB's should be used in conjunction with signs and pavement markings to warn and control traffic at locations where pedestrians enter or cross a street or highway.

All of the following conditions must be met before PHB can be considered on our roadways:

- An engineering study must be performed and meet the guidelines detailed in Chapter 4F of the Texas MUTCD.
- An established crosswalk with adequate visibility, markings and signs.
- A posted speed limit of 40 mph or less (does not include school speed zones).
- 20 pedestrians or more crossing in one hour.
- Location deemed as a high risk area (e.g. schools, shopping centers, etc.).
- Crosswalk is more than 300 ft. from an existing, traffic controlled pedestrian crossing.

Districts must receive Traffic Safety Division approval for installation of a PHB for each location.

You can reference Appendix A of the NCHRP 562 Report for additional information on PHB at the following web address: http://www.trb.org/Publications/Blurbs/157723.aspx.

If the proposed location meets the criteria listed above for a PHB, please submit to the Traffic Safety Division for approval."

OTHER COMMUNITIES' GUIDANCE

Several communities and several state departments of transportation (DOTs) have sponsored or developed guidelines on pedestrian crosswalks. In general, these documents include discussion of different types of pedestrian crossing treatments along with procedures for how to select the treatment. Frequently, the procedures are accompanied by a flowchart that indicates the steps within an evaluation or that illustrates questions to consider depending upon the previous answer. Tables or graphs that can be used to select the treatments are often included and typically consider roadway configuration (number of lanes), vehicle volume, and speed (posted speed limit or operating speed).

Guidelines Reviewed

The guidelines reviewed included the following:

- Arizona Department of Transportation's (ADOT's) 2015 *Traffic Engineering Guidelines and Processes Section 640 Pedestrian Hybrid Beacon* (*56*).
- Boulder, Colorado's 2011 *Pedestrian Crossing Treatment Installation Guidelines* (*57*).
- Champaign-Urbana, Illinois's 2017 *Pedestrian Crossing Enhancement Guidelines* (*58*).
- Clark County, Washington's 2018 Pedestrian Crossing Treatment Policy (*59*).
- Denver, Colorado's 2017 *Uncontrolled Pedestrian Crossing Guidelines* (*60*).
- FHWA's 2018 *Field Guide for Selecting Countermeasures of Uncontrolled Pedestrian Crossing Locations* (*55*).
- FHWA's 2018 *Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations* (*54*).
- Florida's 2018 *Traffic Engineering Manual* (*61*).
- Illinois's 2017 *Establishing Procedures and Guidelines for Pedestrian Treatments at Uncontrolled Locations* (*62*).
- Indiana DOT's 2015 *Selection of Pedestrian Crossing Treatments at Controlled and Uncontrolled Locations* (*63*).
- Longmont, Colorado's 2009 *Pedestrian Crossing Treatment Guidelines* (*64*).
- Minnesota's 2014 *Pedestrian Crossings: Uncontrolled Locations* (*65*).

- North Carolina DOT's 2015 *Pedestrian Crossing Guidance* (*66*).
- Portland, Oregon's 2019 *Crosswalk Guidelines for Portland* (*67*).
- Sacramento, California's 2014 *Pedestrian Crossing Guidelines* (*68*).
- *TCRP Report 175: Guidebook on Pedestrian Crossing of Public Transit Rail Services* (2015), see especially Chapter 6 (*69*).
- Utah DOT's 2013 *Pedestrian Grade Crossing Manual* (*70*).

Following are summaries of the noteworthy documents or documents that contain material that may be of interest to TxDOT.

Boulder, Colorado

Boulder was extremely proactive with respect to developing pedestrian crossing treatment guidelines. The city published *City of Boulder Pedestrian Crossing Treatment Warrants* in 1996. Its recent publication—*Pedestrian Crossing Treatment Installation Guidelines* (*57*)—replaces the 1996 document and was published in 2011. The 2011 document provides:

- Proposed pedestrian crossing criteria and procedures for evaluating the need for crossing treatments, including a flowchart approach.
- Specific pedestrian crossing treatments that may be applicable for a particular set of pedestrian volumes, pedestrian types, vehicular volumes, vehicular speeds, and roadway geometry.

The Boulder document includes a table with criteria for crossing treatments, reproduced as Figure 28. Figure 29 reproduces the graphs included in the Boulder document that can be used for PHBs (HAWKs), signals, or RRFBs. The graphs in Figure 29 are the City of Boulder recommendations for the use of RRFBs overlaid on the MUTCD PHB and pedestrian traffic signal warrant guidelines. The City of Boulder recommendations were developed based on safety and operational evaluations performed by the city over the years at high-volume RRFB locations.

The evaluation of an individual crossing location for potential crossing treatments includes the following four basic steps:

- Step 1: Identify and describe crossing location.
- Step 2: Collect physical data.

- Step 3: Collect traffic data and make operational observations.
- Step 4: Apply data to appropriate figures or tables included in the guidelines to determine appropriate treatments.

Figure 28 and Figure 29 reproduce some of Boulder's guidelines. They also have a flowchart that can be used during the evaluation.

The Boulder guidelines note that while the RRFBs have greatly increased driver yielding to pedestrians at unsignalized crosswalks, there are locations where the use of RRFBs may not be appropriate, such as locations where there is a combination of both high traffic volumes and high pedestrian volumes.

Champaign-Urbana, Illinois

The Champaign-Urbana *Pedestrian Crossing Enhancement Guidelines* (*58*) provides examples of treatments (crossing treatment toolbox) and schematics with dimensions for crosswalk markings. It also contains discussion of several decision-making processes including NCHRP 562 (*31*). As stated in the guidelines (*58*), the preferred procedure is the one adapted from the Boulder document (see Figure 28).

Portland, Oregon

Portland's guidance material is available on a website (*67*). It includes a flowchart to identify crosswalks needing safety enhancement. If the flowchart finds that a location needs enhancement, a suite of options based on roadway configuration (number of lanes and median treatment), vehicle volume, and speed is provided. The suite of options is reproduced in Figure 30.

City of Boulder Pedestrian Crossing Treatment Installation Guidelines

Table 1 - Criteria for Crossing Treatments at Uncontrolled Locations

Roadway Configuration	# of lanes crossed to reach a refuge[1]	# of multiple threat lanes[2] per crossing	Roadway ADT and Posted Speed															
			1,500-9,000 vpd				9,000-12,000 vpd				12,000-15,000 vpd				> 15,000 vpd			
			≤ 30 mph	35 mph	40 mph	≥ 45 mph	≤ 30 mph	35 mph	40 mph	≥ 45 mph	≤ 30 mph	35 mph	40 mph	≥ 45 mph	≤ 30 mph	35 mph	40 mph	≥ 45 mph
2 Lanes (one way street)	2	1	A	B	C	E	A	B	C	E	B	B	C	E	B	C	C	E
2 Lanes (two way street with no median)	2	0	A	B	C	E	A	B	C	E	B	B	C	E	B	C	C	E
3 Lanes w/Raised Median	1 or 2	0 or 1	A	B	D	E	A	C	D	E	B	D	D	E	C	D	D	E
3 Lanes w/Striped Median	3	0 or 1	C	C	D	E	C	C	D	E	C	C	D	E	C	D	D	E
4 Lanes (two way street with no median)	4	2	A	D	D	E	B	D	D	E	B	D	D	E	D	D	D	E
5 Lanes w/Raised Median	2 or 3	2	A	B	D	E	B	C	D	E	B	C	D	E	C	C	D	E
5 Lanes w/Striped Median	5	2	D	D	D	E	D	D	D	E	D	D	D	E	D	D	D	E
6 Lanes (two way street with or without median)	3 to 6	4	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F

Notes:

1. Painted medians can never be considered a refuge for a crossing pedestrian. Similarly, a 4 foot wide raised median next to a left turn lane can only be considered a refuge for pedestrians if the left turning volume is less than 20 vehicles per hour (meaning that in most cases the left turn lane is not occupied while the pedestrian is crossing).
2. A multiple threat lane is defined as a through lane where it is possible for a pedestrian to step out from in front of a stopped vehicle in the adjacent travel lane (either through or turn lane).

Treatment Descriptions:

A ***Install marked crosswalk with enhanced road-side signs***

Specific Guidance : *Install marked crosswalk with "State Law - Yield to Pedestrian" signs mounted on the side of the roadway with standard (W11-2) advance pedestrian warning signs; use S1-1 signs for School Crossing locations.*

B ***Install marked crosswalk with enhanced road-side and in-roadway (bollard mounted) signs***

Specific Guidance : *Install marked crosswalk with "State Law - Yield to Pedestrian" signs mounted on the side of the roadway and on in-roadway bollards; use standard (W11-2) advance pedestrian warning signs; use S1-1 signs for School Crossing locations.*

C ***Install marked crosswalk with enhanced signs and geometric improvements to increase pedestrian visibility and reduce exposure***

Specific Guidance : *For 2 or 3-lane roadways, install marked crosswalk with "State Law - Yield to Pedestrian" signs mounted on the side of the roadway and on in-roadway bollards or median mounted signs; use standard (W11-2) advance pedestrian warning signs; use S1-1 signs for School Crossing locations. Add neckdowns or median refuge islands to shorten the pedestrian crossing distance and increase pedestrian visibility to motorists.*

D ***Install marked crosswalk with enhanced signs, pedestrian activated RRFBs, and geometric improvements to increase pedestrian visibility and reduce exposure***

Specific Guidance : *Install raised median refuge island (unless it is a one-way street or one already exists) to shorten the pedestrian crossing distance and increase pedestrian visibility to motorists. [If a median refuge can not be constructed on a two-way street, Go To Scenario F]. Install marked crosswalk with "State Law - Yield to Pedestrian" signs WITH pedestrian activated RRFBs mounted on the side of the roadway and on median mounted signs; use standard (W11-2) advance pedestrian warning signs; use S1-1 signs for School Crossing locations. Consider adding neckdowns at the crossing if on-street parking exists on the roadway and storm drain considerations will allow. [Note: If pedestrian volume falls above the RRFB limit line on Figure 2, consider Hawk beacon, pedestrian traffic signal, or grade-separated crossing.]*

E ***Do not install marked crosswalk at uncontrolled crossing. Determine if the speed limit can be effectively reduced to 40 mph AND a raised refuge median can be installed. If so, utilize Scenario D criteria above. If this is not possible, or if pedestrian volume falls above the RRFB limit line on Figure 2, consider HAWK beacon, pedestrian traffic signal, or grade-separated crossing.***

Specific Guidance : *Consider HAWK beacon, pedestrian traffic signal or grade-separated crossing; application of these treatments will consider corridor signal progression, existing grades, phyiscal contraints, and other engieering factors*

F ***Do not install marked crosswalk at uncontrolled crossing with 3 or more THROUGH lanes per direction or where the speed limit is ≥ 45 mph and/or there is not a median refuge on a 5-lane crossing. Consider HAWK beacon, pedestrian traffic signal, or grade-separated crossing.***

Specific Guidance : *Consider HAWK beacon, pedestrian traffic signal or grade-separated crossing; application of these treatments will consider corridor signal progression, existing grades, phyiscal contraints, and other engieering factors*

Figure 28. City of Boulder Criteria for Crossing Treatments at Uncontrolled Locations (*57*).

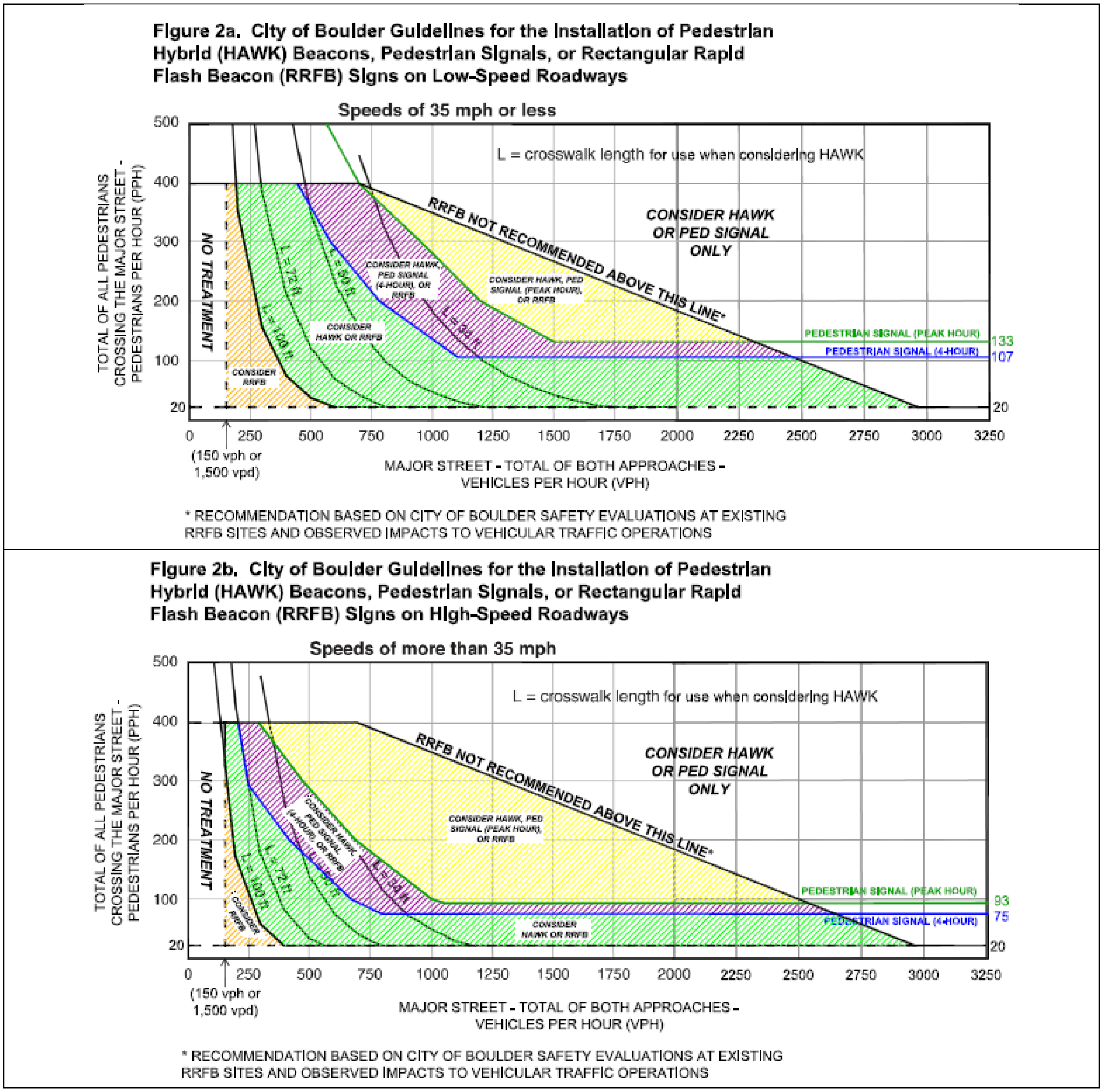


Figure 29. City of Boulder Criteria for Crossing Treatments at Uncontrolled Locations (*57*).

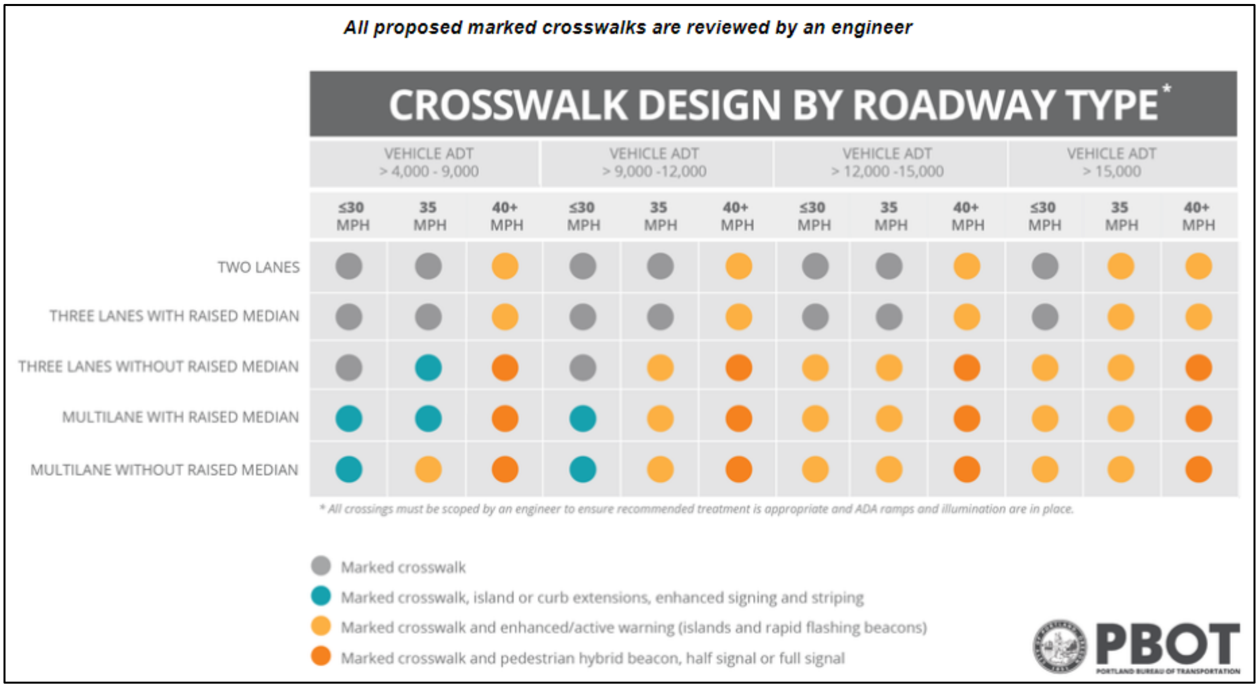


Figure 30. Portland Oregon Suite of Crosswalk Options (*67*).

Utah

The Utah *Pedestrian Grade Crossing Manual* (*70*) discusses treatments for a railroad grade crossing, which has some fundamental differences with the design and appropriate treatments for a pedestrian crossing of a road. A feature of the document that may be of interest is the structure of the flowchart. On one page, the flowchart provides potential treatments along with conditions when those treatments are to be considered. An example is shown in Figure 31. Figure 27, Figure 28, and Figure 29 are other examples of decision tools that show specific potential treatments on a single page.

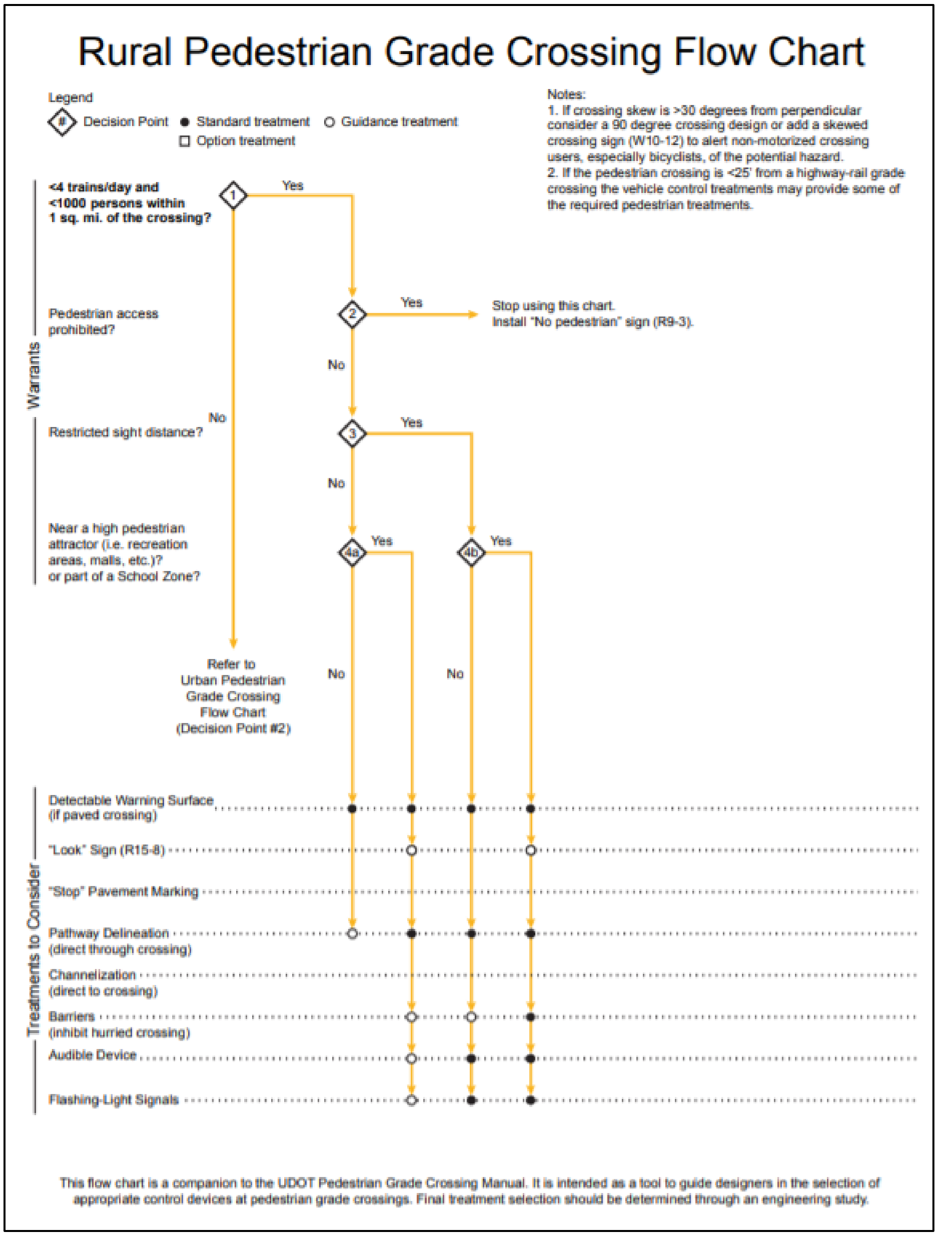


Figure 31. Utah DOT Flowchart for Rural Pedestrian Grade Crossing (*70*).

Clark County, Washington

Clark County, Washington's (*59*) guide starts with decision trees for uncontrolled locations, controlled locations (both signals and stop signs), and near-school locations. The enhanced crossing treatment selection table (see Figure 32) provides appropriate treatment options by roadway type (number of travel lanes), roadway volume, and speed. This table was developed in Clark County using information from peer cities, the results from the 2002 FHWA study (*47*), and delay analysis from the *Highway Capacity Manual* (*71*). Per the Clark County document, "The HCM pedestrian delay was the primary influence on the selection table recommendations…the delay analysis evaluated a set of typical pedestrian crossings to determine delay thresholds to assist in the selection of the appropriate crossing treatment. A delay threshold of 30 seconds was used where only a marked crosswalk at an existing unmarked location would be sufficient" (*59*).

Clark County Pedestrian Crossings

ENHANCED CROSSING TREATMENT SELECTION TABLE - Figure 6

IF THE DECISION TREE OUTCOME WAS | CONSIDER ENHANCED CROSSING TREATMENT | THEN REFER TO THIS SELECTION TABLE

RECOMMENDATIONS FOR MARKED CROSSWALKS AND ENHANCED PEDESTRIAN CROSSING TREATMENTS AT UNCONTROLLED LOCATIONS

ROADWAY TYPE (NUMBER OF TRAVEL LANES)	VEHICLE ADT > 4,000 TO 6,000			VEHICLE ADT > 6,000 TO 9,000			VEHICLE ADT > 9,000 TO 12,000			VEHICLE ADT > 12,000 TO 15,000			VEHICLE ADT >15,000		
	SPEED LIMIT														
	≤ 30 MPH	35 MPH	≥ 40 MPH	≤ 30 MPH	35 MPH	≥ 40 MPH	≤ 30 MPH	35 MPH	≥ 40 MPH	≤ 30 MPH	35 MPH	≥ 40 MPH	≤ 30 MPH	35 MPH	≥ 40 MPH
2 Lanes	A	A	B	B	B	B	B	B	B	B	B	E	B	B	E
3 Lanes	A	A	B	C	C	D	C	D	D	C	D	E	D	D	E
Multi-Lane (4 or more Lanes)	C	C	C	C	C	D	C	D	E	D	D	E	D	D	E

NOTES:

- *Shared-use path crossing locations with ADT less than 4,000 ADT may qualify for marked crosswalks and/or enhanced pedestrian crossing treatments as shown in the column for "Vehicle ADT >4,000 to 6,000."*
- *Installation of marked crosswalk or enhanced crossing treatment, at any location, subject to engineering study and judgement that accounts for factors such as sight distance, traffic safety, traffic operations, other field conditions and pedestrian population. The engineering study must include a site-specific delay analysis, using the HCM.*

LEGEND

- A Marked Crosswalk
- B Marked Crosswalk with Flashing Beacon
- C Marked Crosswalk with Median Island
- D Marked Crosswalk with Flashing Beacon and Median Island
- E Marked Crosswalk with Pedestrian Hybrid Beacon (PHB) or Traffic Signal

REFERENCES:

- *Zegeer, Steward, Huang, "Safety Effects of Marked vs Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines", FHWA, 2002.*
- *Manual on Uniform Traffic Control Devices (MUTCD), 2009 Edition, published by FHWA.*
- *Highway Capacity Manual (HCM), 2016 sixth edition, published by TRB.*

Figure 32. Clark County Enhanced Crossing Treatment Selection Table (*59*).

Florida

Florida DOT (*61*) developed guidelines for installation of pedestrian treatments that specifically show the combination of major street volume, pedestrian crossing volume, crossing distance, and speed where a flashing beacon or RRFB, a PHB, and a traffic signal should be considered. Figure 33 reproduces one of the graphs in the Florida DOT guidelines.

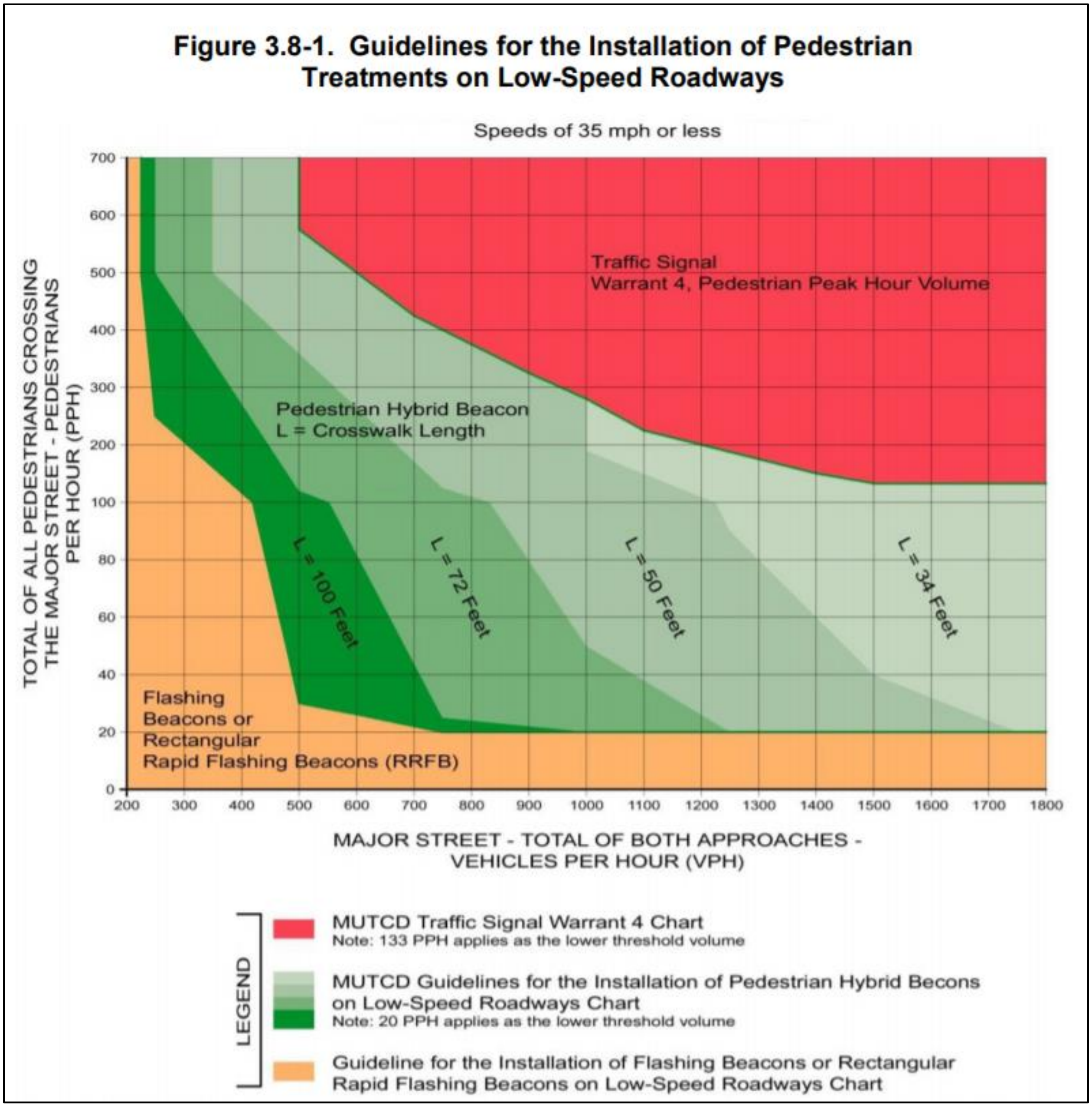


Figure 33. Florida DOT Guidelines (*61*).

SELECT COMPONENTS OF OTHER COMMUNITIES' GUIDELINES

Typical and Minimum Pedestrian Volume Criteria

Several documents discuss minimum pedestrian volumes. For the PHB, the MUTCD (*49*) and TMUTCD (*5*) include a minimum pedestrian volume of 20 pedestrians per hour (PPH) reflecting the total of all pedestrian crossing the major street. The traffic signal warrants based on pedestrians in those documents have a lower threshold volume value of 107 PPH crossing the major street for four hours or 133 PPH crossing the major street for the peak hour.

NCHRP 562 (*31*) has as a minimum pedestrian volume for a peak-hour evaluation of 20 PPH for both directions. If the road speed exceeds 35 mph, then the value of 14 PPH is used. Minnesota's (*65*) flowchart includes similar pedestrian peak-hour volumes (20 when speeds are 35 mph or less and 14 when speeds are greater than 35 mph). Elsewhere in the document, it states, "The above pedestrian volume thresholds can be reduced by 0.33 if more than 50 percent of the pedestrian traffic using the crossing consists of the elderly or children" (*65*).

Denver's (*60*) minimum pedestrian volume for crosswalk installation is 20 PPH. The FHWA guide (*55*) references pedestrian volumes when evaluating for PHBs using the graphs in the MUTCD.

Clark County, Washington (*59*) includes the following for minimum pedestrian volume for an enhanced crossing treatment:

- 20 PPH for any one hour.
- 18 PPH for any two hours.
- 15 PPH for any three hours.

Boulder, Colorado, investigated the relationship between driver yielding and pedestrian and/or bicycle crossing volume and noted the following: "Data collected at Boulder crosswalks where rectangular rapid flash beacon signs (RRFB) or State Law-Yield signs were installed shows that driver compliance typically increases with higher crossing volumes. It is theorized that the primary reason for this relationship is that drivers tend to ignore enhanced crossing treatments over time at locations where they infrequently see pedestrians crossing" (*57*). The city has established the following minimum pedestrian volume thresholds:

- 20 PPH in any one hour. Note young, elderly, and disabled pedestrians count two times toward volume thresholds.
- 18 PPH in any two hours. Note young, elderly, and disabled pedestrians count two times toward volume thresholds.

- 15 PPH in any three hours. Note young, elderly, and disabled pedestrians count two times toward volume thresholds.
- 10 school-aged pedestrians traveling to/from school in any one hour. School crossing is defined as a crossing location where 10 or more student pedestrians per hour are crossing.

Champaign-Urbana (*58*) and Longmont, Colorado (*64*) have the same minimum pedestrian volume thresholds used in Boulder, including the two-times factor for young, elderly, and disabled pedestrians.

Portland, Oregon (*67*) and Champaign-Urbana's (*58*) flowcharts include a minimum pedestrian volume of 20 people walking or biking per hour in any one hour for when an enhanced crosswalk is to be considered. If the crossing is within 300 ft of a protected crossing and has twice the minimum pedestrian volume (i.e., 40 people walking or biking per hour in any one hour), then an enhanced crosswalk can be considered. Note that Portland specifically includes biking in its pedestrian volume.

Sacramento, California's (*68*) flowchart includes a minimum pedestrian volume of 20 pedestrians during the peak hour or 15 elderly or child pedestrians (using a conversion factor of 1.33).

Distance to Nearest Marked Crossing

Portland, Oregon (*67*), Clark County, Washington (*59*), Champaign-Urbana (*58*), and Longmont, Colorado's (*64*) flowcharts include a check for distance to nearest marked or protected crossing of 300 ft.

Champaign-Urbana's (*58*) flowchart has a footnote that states the following: "Distance to the nearest marked or protected crossing may be reduced to 200 ft in urban conditions, subject to engineering judgment, where 1) the crosswalk does cross any auxiliary lanes, and 2) crossing treatments and crossing activity would not create undue restriction to vehicular traffic operations."

ADOT (*56*) awards points toward justifying a PHB based on the distance to nearest existing traffic signal or PHB (−5 points if less than 500 ft and +5 points if over 1000 ft).

Boulder, Colorado's guide (*57*) states that new uncontrolled midblock crossings are to be at least 300 ft from the nearest crossing. However, the flowchart allows this spacing criterion to be waived if the proposed crossing serves a multiuse path, or the pedestrian crossing volume exceeds twice the minimum threshold. The guide also notes that this criterion (as well as all the criteria in the document) is also subject to engineering judgment. Sacramento (*68*) also includes the 300-ft distance with a footnote that exceptions to the 300-ft distance can be considered.

The FHWA guide (*55*) does not discuss distance between crossings.

Minnesota (*65*) states, "If there is a nearby pedestrian crossing facility that can serve the same movements with a shorter travel time—and if this nearby crossing facility can be seen from the crossing location being studied—the crossing location being studied may not be needed."

Limits with Respect to Using RRFBs

Boulder, Colorado's guidelines (*57*) express concerns with using RRFBs on higher-speed, higher-volume, and/or wider crossings.

Florida (*61*) limits the use of RRFBs to roadways with four or fewer though lanes. Florida also states:

> "Any new RRFB on a multilane undivided roadway should be installed overhead unless design constraints or engineering documentation preclude overhead installation. Overhead RRFBs improve visibility for approaching drivers and are consistent with the installation of overhead school zone warning signs on multilane roadways. Consideration should be given to installing advanced warning signs with RRFBs on multilane approaches, especially those with higher traffic volumes and speeds.
>
> When overhead RRFBs are used, they should be combined with ground mounted devices. Overhead RRFBs should feature an internally illuminated pedestrian crossing sign which is continuously lit at night."

The Illinois research report (*62*) suggests the following conditions for when an uncontrolled pedestrian crossing (which would assume to include the RRFB treatment) should not be considered:

- Posted speed limit is greater than 40 mph. When the posted speed limit is greater than 40 mph, the authors suggest traffic control signals.
- Vehicle volume > 35,000 vpd.
- Crossing is undivided four lane or divided with more than six lanes.

- Alternative crossing location is within 300 ft (recommended) or 200 ft (minimum).
- Inadequate vehicle stopping sight distance or pedestrian sight distance exists.

The following documents do not include a maximum speed limit restriction with respect to RRFBs:

- Portland, Oregon (*67*). Per the suite of options, the rapid flash beacon is to be considered for roadway configurations of two lanes or three lanes with a raised median when the speed is 45 mph or greater (see Figure 30).
- FHWA field guide (*55*). As shown in Figure 27, the guidance does not have a maximum speed. The speed ranges are ≤30 mph, 35 mph, and ≥40 mph.
- Clark County (*59*). As shown in Figure 32, there are select vehicle volume ranges where an RRFB could be considered on roads with ≥40 mph speed.

Limits with Respect to Using PHBs

The Champaign-Urbana document (*58*) notes that "there may be a challenge to installing more of these [PHBs] in the Champaign-Urbana area. Section 4F.02 of the Illinois Supplement of the MUTCD states that 'If used, pedestrian hybrid beacons shall be installed at least 100 feet from side streets or driveways and at least 300 feet from traffic signals or railroad grade crossings with active warning devices.' The driveway distance requirement is problematic in the urban environments of the Champaign-Urbana area since there are many entrances on streets, and this requirement elevates all driveways to the same level as side streets." Because of this restriction, planners envisioned that "it is unlikely that many more HAWKs can be installed." The 100-ft restriction in the MUTCD was not based on research and was added late in the process of developing the 2009 MUTCD. NCUTCD has supported a revision to remove the restriction in the next edition of the MUTCD (see Revised Pedestrian Hybrid Beacon section above for more information).

The Florida (*61*) *Traffic Engineering Manual* also includes a similar statement: "This device is not intended for use at intersections or driveways, as MUTCD recommends maintaining a distance of 100 feet from side streets or driveways controlled by Stop or Yield signs."

The ADOT *Traffic Engineering Guidelines and Processes Section 640 Pedestrian Hybrid Beacon* (*56*) currently states, "PHBs should not be installed on roadways with speed limits greater than 45 mph." An ongoing ADOT research project (*34*) is investigating whether that value should be increased or, perhaps, eliminated.

Florida (*61*) notes that for "six-lane roadways or crossing distances exceeding 80 feet, a two-stage pedestrian crossing with a median refuge island should be considered where the proposed marked crossing will be controlled by a warranted pedestrian hybrid beacon. A two-stage pedestrian crossing may have a lesser impact to vehicle delay (compared to a single crossing) since the beacon serves each direction independently while the median island serves as a refuge area for pedestrians to wait prior to completing their crossing."

The following documents do not include a maximum speed limit restriction with respect to PHBs:

- MUTCD (*49*). The warrants are subdivided by 35 mph and less and 40 mph and more.
- Portland, Oregon (*67*). Per the suite of options, a PHB is to be considered for roadway configurations of three lanes without a raised median and multilane with or without raised median when the speed is 45 mph or greater (see Figure 30).
- Boulder, Colorado (*57*). The criteria for crossing treatments at uncontrolled locations identify Treatment Type F (which includes HAWKs or signals, etc.) when six lanes with or without a median are present for all ADT and posted speed limit ranges (see Figure 28).
- FHWA field guide (*55*). As shown in Figure 27, the guidance does not have a maximum speed. The speed ranges are ≤30 mph, 35 mph, and ≥40 mph.

Prioritizing Crossings

The following include guidance on prioritizing crossings using a point system:

- ADOT TGP 640.
- Denver.

Boulder (*57*) notes that staff will prioritize the list of projects and perform crossing treatment installations based on funding availability.

ADOT uses a point system within its PHB evaluation (*56*). Figure 34 reproduces the current version (June 2015) of the point system. An ongoing ADOT research project (*34*) is tasked with recommending updates to this document, so revisions may be forthcoming.

ADOT Traffic Engineering Guidelines and Processes
June 2015
Section 600 – Traffic Signals

Exhibit 640-A. PEDESTRIAN HYBRID BEACON (PHB) EVALUATION

PEDESTRIAN HYBRID BEACON (PHB) EVALUATION

Location: ______________________ Date: ______________

1. Motor vehicle crashes correctable by installation of PHB – Award 5 points for each crash (for the most recent 5 years of data) involving pedestrians, bicyclists, wheel chairs, skateboards, motorized scooters, or golf carts crossing within 500 feet on either side of the proposed PHB locations, or half the distance to the nearest signal (whichever is less): ______

2. Peak hour pedestrian crossing volume – Award points if the average peak hour pedestrian crossing volume within 500 feet on either side of the proposed PHB location, or half the distance to the nearest traffic signal (whichever is less): ______
   - 0 points ➔ 0 – 10 pedestrians per peak hour (average)
   - 2 points ➔ 11 – 20 pedestrians per peak hour (average)
   - 4 points ➔ 21 – 39 pedestrians per peak hour (average)
   - 6 points ➔ 40+ pedestrians per peak hour (average)

3. Location of nearest existing traffic signal or existing PHB – Award points: ______
   - -5 points ➔ Less than 500 feet
   - 0 points ➔ 500 – 1,000 feet
   - 5 points ➔ Over 1,000 feet

4. Posted speed limit – Award points: ______
   - 0 points ➔ Under 30 mph
   - 2 points ➔ 30 – 35 mph
   - 4 points ➔ 40 – 45 mph

5. Roadway traffic volume (AADT) – Award points: ______
   - 0 points ➔ Less than 5,000
   - 2 points ➔ 5,000 – 9,999
   - 4 points ➔ 10,000 – 14,999
   - 6 points ➔ 15,000+

6. Raised median – Award 5 points if the roadway does not have a raised median with a minimum width of 6 feet. ______

7. Shared-use path or walkway – Award 5 points if a designated, maintained, and permitted shared-use path or walkway crosses the road at the proposed PHB location. ______

8. Pedestrian activity generator – Award 5 points if the proposed PHB location is within 500 feet of a senior center, medical facility, community center, school, or other pedestrian activity generator. ______

9. Roadway illumination – Award 5 points if the proposed PHB location does not have roadway illumination. ______

10. Crossing distance – Award 5 points if the crossing distance is greater than 36 feet. (If a raised median with a minimum width of 6 feet is present, the crossing distance is measured to the median). ______

GRAND TOTAL ______

Figure 34. ADOT *Traffic Engineering Guidelines and Processes*, Section 640 (*56*).

Denver considers the following:

- Pedestrian volume. The minimum pedestrian volume for crosswalk installation is 20 PPH. The scoring criteria increases from a score of 2 for 20 to 29 PPH to a score of 18 for more than 100 PPH. Pedestrian count can include a conversion factor of 1.33 for vulnerable populations (children, elderly, persons with disabilities).
- Crash data.

- Distance to crossing. The scoring criteria increase from a score of 2 when the crossing is 300 to 499 ft from a controlled intersection to 12 when the crossing is more than 1300 ft from a controlled intersection.
- Bikeway connectivity.
- Denver Moves: high pedestrian demand index.
- Public input. Can serve as a tiebreaker or method of project escalation where necessary.

INTERVIEWS WITH TEXAS ENGINEERS

Discussions with several Texas engineers led to the following observations:

- Documents being used to address pedestrian crashes include the Texas MUTCD, materials from the Traffic Safety Division, and the FHWA guide (*55*).
- There is very high interest in identifying potential treatments for streets with higher speeds and multiple lanes.
- The districts are working with cities regarding the pedestrian treatments, especially with respect to treatments at signalized intersections.
- Several districts mentioned their fatal crash committee as a means of investigating pedestrian crashes and potential solutions.
- The following have been considered when making pedestrian device decisions: number of crashes, driveway characteristics, and—most frequently—engineering judgment. They may consider pedestrian volume if available.
- Unsignalized intersections may receive a variety of improvements that are often folded into bigger projects that add sidewalks and/or signals (with leading pedestrian intervals, pushbuttons, etc.).
- Being able to influence pedestrian behavior is viewed as an approach to improving pedestrian safety. They asked about effectiveness of education campaigns.
- TxDOT districts are rarely using RRFBs and PHBs. The minimum pedestrian volume and maximum speed criteria were cited as reasons for limiting their use.
- Engineers are exploring other potential devices, such as LED-Em signs and 12-inch circular LED flashers, and are curious about the effectiveness of those devices.

- There is interest in having Texas guidelines. Texas may need to work with cities during the development because cities are installing more of these types of treatments compared to TxDOT districts.
- If a guide is developed, engineers suggest including examples of best practices. Practices suggested for inclusion were:
    - "No Peds" signs painted on the I-35 freeway median barrier near 51st Street.
    - Education campaign of "Be Safe Be Seen" launched in November 2017 in Austin, which included the distribution of reflective bags.

SUMMARY

Guidance on pedestrian treatments is available in state manuals, guides, and research reports, but most frequently as guides. The guides are sometimes a stand-alone document, a website, or part of a research report. The guidance includes materials on:

- Identifying potential treatments for pedestrian crossings using flowcharts, tables, or graphs.
- Information about different treatments such as RRFBs or PHBs.
- Details on crossing designs, such as pavement marking dimensions or distance between signs and the crossing.

Examples of states with manuals that include information on pedestrian crossings are Florida and Arizona. Florida DOT includes information about selecting pedestrian crossing treatments in its traffic engineering manual (*61*), while ADOT provides details about prioritizing locations for PHBs in its traffic engineering guidelines and processes (*56*). Several communities have stand-alone guides that are used in the pedestrian crosswalk treatment selection, such as Boulder, Colorado (*57*) or Champaign-Urbana (*58*). FHWA also has a stand-alone guide (*55*) that was released in 2018 and that is part of the Every Day Counts and Safe Transportation for Every Pedestrian (STEP) initiatives.

Several guidance documents discuss and emphasize the value of providing geometric features, especially a raised median (pedestrian refuge). The need for roadway lighting is also frequently discussed.

Discussions with Texas engineers indicated interest in having Texas guidance material regarding pedestrian treatments, especially with respect to suggestions on potential treatments for higher-speed and wider streets. Because the primary documents currently being used are the Texas MUTCD (*5*) and the recent TxDOT memorandum (*48*), any new material should be included in those sources or referenced by those sources.

POTENTIAL WORK PLAN FOR DEVELOPING GUIDANCE MATERIAL FOR TEXAS

Given the wealth of existing guidance material regarding the selection of treatments for pedestrian crossings, additional efforts within Texas should build upon rather than create new material. The effort should begin with determining the preferences of TxDOT administration with regards to what the guidance should contain. Should it primarily reflect modifications (if needed) to the existing TxDOT memorandum, or should it be a new set of guidelines that could include a flowchart on decisions to be made along with a table or graph to indicate potential treatments? If a new set of guidelines is to be developed, what are other key items to include, such as minimum pedestrian volume (e.g., include bicyclists in the count or have a multiplication factor for older or disabled pedestrians) or distance to nearest marked or protected crosswalk?

Another direction future effort could go is to generate a best practice document to present information on pedestrian treatments that are being used, especially for unusual or difficult situations such as on freeways or arterials with six or more lanes. Education and enforcement are potential additional topics for a best practice document.

CHAPTER 7: PAVEMENT MARKING REMOVAL GUIDANCE

The removal of pavement markings for work zone applications or other reasons can often lead to confusing conditions for drivers and automated driving systems due to improper removal. Incomplete removal, ghost markings, and pavement scarring may all be perceived as delineation that competes with the intended delineation. This chapter presents a follow-up to previous work that looked at past research and made general recommendations to improve TxDOT removal practices (*37*). The work presented herein provides recommendations to update TxDOT *Standard Specification Item 677—Eliminating Existing Pavement Markings and Markers* (*72*), guidance to update the removal section of the TxDOT *Pavement Marking Handbook* (*73*), and general best practices for removal activities. The guidance, recommendations, and best practices are provided to improve the state of marking and marker removal to reduce confusion to drivers and reduce damage to the road surface.

The information presented is based on a literature review, field investigations, and discussions with personnel who conduct or manage pavement marking removal activities. This chapter can be treated as a stand-alone guidance document for pavement marking and marker removal, which is developed in conjunction with recommended updates to *Standard Specification Item 677* and the *Pavement Marking Handbook*.

BACKGROUND

The FHWA MUTCD (*49*) and Texas MUTCD (*5*) both have the same information concerning pavement marking removal. Both documents provide standards and options for pavement marking removal. This information is contained in Sections 3A.02 and 6F.77 in both documents. The information concerning marking removal in each section is provided below.

Section 3A.02 <u>Standardization of Application</u>

Standard:

04 **Markings that are no longer applicable for roadway conditions or restrictions and that might cause confusion for the road user shall be removed or obliterated to be unidentifiable as a marking as soon as practical.**

Option:

05 Until they can be removed or obliterated, markings may be temporarily masked with tape that is approximately the same color as the pavement.

Section 6F.77 <u>Pavement Markings</u>

Support:

01 Pavement markings are installed or existing markings are maintained or enhanced in TTC zones to provide road users with a clearly defined path for travel through the TTC zone in day, night, and twilight periods under both wet and dry pavement conditions.

Guidance:

02 *The work should be planned and staged to provide for the placement and removal of the pavement markings in a way that minimizes the disruption to traffic flow approaching and through the TTC zone during the placement and removal process.*

Standard:

03 **Existing pavement markings shall be maintained in all long-term stationary (see Section 6G.02) TTC zones in accordance with Chapters 3A and 3B, except as otherwise provided for temporary pavement markings in Section 6F.78. Pavement markings shall match the alignment of the markings in place at both ends of the TTC zone. Pavement markings shall be placed along the entire length of any paved detour or temporary roadway prior to the detour or roadway being opened to road users.**

04 **For long-term stationary operations, pavement markings in the temporary traveled way that are no longer applicable shall be removed or obliterated as soon as practical. Pavement marking obliteration shall remove the non-applicable pavement marking material, and the obliteration method shall minimize pavement scarring. Painting over existing pavement markings with black paint or spraying with asphalt shall not be accepted as a substitute for removal or obliteration.**

Option:

05 Removable, non-reflective, preformed tape that is approximately the same color as the pavement surface may be used where markings need to be covered temporarily.

Pavement marking removal is a difficult activity for several reasons, including the need to remove the marking without damaging the pavement surface, pavement marking material being in pores and grooves below the pavement surface, the durable nature of pavement markings making them difficult to remove, and discoloration and texture changes that can occur even when the removal is done as well as possible. Damage to the surface of the roadway from marking removal is an important area of concern. Pavement scarring from marking removal can be confusing to drivers and may also negatively affect the durability of the road surface. Completely removing the pavement marking material is also important because marking material left behind may be mistaken for an actual marking, resulting in confusion to drivers. Finding the optimal removal technique for a given situation that removes all the marking and does not damage the road surface is the goal.

NCHRP Report 759—Effective Removal of Pavement Markings (*74*) is the most comprehensive document in relation to pavement marking removal. NCHRP Report 759 served as the primary document for the information and recommendations provided in the Year 1 report for the project (*37*). The research provided a set of recommendations and best practices to improve pavement marking removal. Information from NCHRP Report 759 has been utilized throughout this chapter to improve guidance and best practices.

RECOMMENDATIONS

TxDOT has two guiding documents that include information on pavement marking removal. The first one is *Standard Specification Item 677* (*72*), and the second is the *Pavement Marking Handbook* (*73*). These two documents can be improved by considering the recommendations and best practices provided in NCHRP Report 759 (*74*) and the information provided in TxDOT Report 6969-R1 (*37*). The recommendations provided could help update these documents to provide engineers with additional information to improve the quality of the work zone and permanent pavement marking removal. The research team considered the information in the mentioned documents (*37*, *74*) and information gathered from field visits and discussions with industry professionals to provide recommended changes for the two TxDOT documents. The research team recommends TxDOT consider the information provided in the following sections to serve as the starting point for updating *Standard Specification Item 677* (*72*) and the *Pavement Marking Handbook* (*73*). Future updates should include a full revision of the *Pavement Marking Handbook.*

Recommended Changes for Item 677

This section describes the recommended updates to TxDOT's *Standard Specification Item 677* (*72*). Several areas in Item 677 should be improved to generate higher-quality pavement marking removal. For example, construction requirement details should be modified to ensure less pavement scarring, and additional information should be provided on the removal techniques. Finally, corrective actions should be mentioned in the document so that engineers can take the necessary steps if removal results in a confusing driving environment. More specifically, the following recommendations have been developed for updating Item 677:

- Include Item 315, "Fog Seal," in the material section as a potential surface treatment. This item will provide another means besides seal coat for correcting areas where scarring or ghost marking occur.

- Reduce the maximum scarring depth from 1/4 in. to 1/8 in. This requirement will hold contractors more accountable for damage caused to the pavement surface, which will result in shallower scars that are not as noticeable.
- Reference the *Pavement Marking Handbook* (*73*) for additional guidance.
- Update the removal methods and descriptions to provide additional descriptive information about the removal techniques.
- Add a dedicated section on corrective actions that could help engineers and contractors if removal results in a confusing driving environment.
- Update Item 677 such that it is not in conflict with itself by indicating a specific removal type on a specific surface (blasting on concrete), and then later indicating that flail milling is acceptable for concrete surfaces.
- Add high-pressure water blasting as a preferred method on concrete.

These recommendations are incorporated into an updated version of Item 677 provided in the Appendix. All changes are highlighted in yellow, and information removed is highlighted in yellow and struck through.

Recommended Changes for the *Pavement Marking Handbook*

This section describes the recommended updates to the Marking Removal Methods section of the TxDOT *Pavement Marking Handbook* (*73*). These recommendations are based on previous research (*37*, *74*) site investigations and discussion that occurred during this portion of the research, as well as the recommended changes for Item 677.

Section 3 of Chapter 2 of the *Pavement Marking Handbook* indicates that existing pavement markings should be removed if they are too thick, losing adhesion to the pavement surface, or made of incompatible material, or if the marking layout requires reconfigurations. TxDOT's *Standard Specification Item 677* is referenced as the guiding standard for the removal. According to the handbook, approved removal methods are flailing, water blasting, and sand blasting. The document notes that those removal techniques do not apply to buttons or tape. The document also states that painting over markings by covering old pavement markings with black paint is not an acceptable removal technique.

The *Pavement Marking Handbook* does not mention the use of burning or the surface treatment method to remove markings. Both techniques are listed in Item 677. The surface treatment is not necessarily a removal technique, but the markings will be covered up and no longer provide delineation. Item 677 also lists numerous other blasting methods that are not mentioned in the *Pavement Marking Handbook.*

It is recommended that the current material be removed from the Marking Removal section of the *Pavement Marking Handbook* and replaced with new material and additional sections to provide improved guidance on marking removal. The improved guidance would cover the following sections: (a) factors to consider when removal is required, (b) reasons for marking removal, (c) removal methods, (d) corrective actions, (e) restriping, and (f) examples of removal results.

Factors to Consider When Removal Is Required

To make the best decision about the method of pavement marking removal to use, how to best determine the chance at successful removal, and how to best plan for delineation after the removal, a selection of factors should be considered. These factors are listed below.

- Types of marking material being removed.
- Type of road surface where the removal will occur.
- Reason for the removal.
- Required speed of removal.
- Availability and cost of removal technique.
- Special environmental conditions.
- Whether a new surface will be installed or markings will be restriped in the future.
- Whether the removed area will be in a location where confusion could lead to an accident.
- Whether other measures can be taken to minimize confusion to the driver.

Each of these factors should play a role in determining what removal method is used. Different removal methods have advantages and disadvantages depending on the type of marking material being removed. Different removal methods may be more likely to remove the marking with minimal damage to the road surface depending on the type of road surface the marking is on. Depending on the reason for the removal, the need to compromise between not removing all of the material or not damaging the pavement surface can be better understood. Speed, cost, and equipment availability need to be considered based on project schedules and the urgency of the removal. Environmental considerations such as the impact of dust from mechanical removal methods or dry blasting removal techniques and freezing temperatures on water blasting techniques need to be considered. Major considerations need to be made concerning what the final delineation will look like after the removal. Is the removal likely to result in confusing scarring, discoloration, surface texture changes, ghost markings, or anything that could result in confusing delineation to drivers at any time of the day?

Reasons for Pavement Marking and Marker Removal

The specific reason for the pavement marking removal is one of the first things to consider when planning marking and marker removal. Several reasons for pavement marking removal are listed below.

- Construction work zone.
- New pavement marking configurations.
- Removal of old marking and markers prior to new installations (too thick, poor adhesion, incompatible materials).
- Correction of pavement marking application errors.

Pavement marking removal should be specified as a percentage of material removed based on the purpose of the removal. The percentage of material removed equates to the percentage of the road surface made visible where the marking was removed. The purpose of the removal should also play a role in the removal method selected and other measures selected to provide a roadway with delineation that is not confusing to drivers. Table 18 provides suggested removal percentages based on the purpose of the removal. Based on current practice, damage to the road surface should be 1⁄8 of an inch or less while changing the road surface texture as little as possible (*74*).

Damage to the surface of the roadway from marking removal is an important area of concern. Pavement scarring from marking removal can be confusing to drivers and may also negatively affect the durability of the road surface. Completely removing the pavement marking material is also important because marking material left behind may be mistaken for an actual marking, resulting in confusion to drivers. Specifying the needed percentage of removal can help optimize the quantity and quality of removal and the inevitable damage to the road surface that may occur if the removal is not properly conducted.

Table 18. Suggested Percentage of Marking Removal Based on Purpose of Removal.

Purpose of Pavement Marking Removal	Suggested Percentage of Material Removed
Change marking patterns	95–100 (High removal percent with minimal pavement damage)
Remove and replace compatible materials	70–90 (Follow new marking material manufacturer guidelines, should not damage pavement)
Remove and replace incompatible materials	80–100 (Follow new marking material manufacturer guidelines, minimal pavement damage)

Pavement Marking and Marker Removal Methods

Marking removal should be conducted in accordance with TxDOT's *Specification Item 677*, which briefly discusses the acceptable removal techniques. The following sections provide further details on the removal methods.

Blasting Methods. Different types of blasting techniques are used for pavement marking removal. The most common are high-pressure water blasting, sand blasting, and shot blasting. Other less common blasting methods include hydro blasting, crushed glass blasting, and soda blasting. The blasting methods are the most likely removal methods to successfully remove marking material below the pavement surface with minimal damage to the pavement.

High-pressure water blasting is used for large-scale pavement marking removal that reaches or exceed 30,000 pounds per square inch (psi). It is a large truck-mounted mobile blasting system with vacuum heads for taking up the water and most of the debris produced during the removal operation. The pavement will be wet after the removal but likely clean enough without any additional need for surface preparation. Water blasting may clean the pavement in the removal area, which may be noticeable compared to the surrounding pavement. Lower-pressure spray heads that cover a larger area can be used to clean the adjacent pavement in areas where the color difference may cause confusion.

Sand blasting utilizes high-pressure air with a nozzle to blast sand or other aggregate on pavement markings to break up the marking surface. A sand blasting system includes a supply vehicle with the sand, a vehicle with the blasting equipment, and a vehicle with an aggregate and debris collection system. This removal technique is more effective at removing thin paint compared to thicker thermoplastic. Cleaning activities will need to occur prior to restriping because sand blasting will generate a lot of debris.

Shot blasting is similar to sand blasting in the use of aggregate, which accelerates with a conveyor at a speed of 175 mph. It is also a truck-mounted mobile system where the blasting aggregate can be recycled. In shot blasting, different types of blast material, such as aluminum oxide, ground glass, or silicon carbide, are used in dry conditions, and typically only on a smooth surface. Similar to sand blasting, shot blasting is more effective at removing non-durable pavement marking compared to durable marking.

Mechanical Methods. TxDOT Item 677 indicates that any mechanical method is acceptable except grinding. Flail milling is acceptable for markings on asphalt and concrete surfaces but may damage the pavement if removal is required for material below the surface. Grinding, milling, flailing, and scarifying are often described interchangeably, though they are not all the same. Mechanical methods may include a drum setup of multiple blades/disks stacked side by side, a drum with teeth, or a drum with a combination of smaller drums with teeth or disks stacked together. Regardless of the type of mechanical method used, this type of removal cannot remove below the pavement surface without damaging the pavement. On porous asphalt and grooved concrete, mechanical methods will damage the pavement if a high percentage of removal is required. If a mechanical method is used, care should be taken to minimize the transition between the removed area and the adjacent pavement so that a hard edge is not visible. Smoothing the edge will result in a more desirable appearance. Hand-operated flailing systems are the most common removal type for short-line markings and symbols. Symbols and text should be removed in a square or rectangular pattern so that the previous shape is not identifiable as a scar or discoloration. Necessary removal or cleaning around the marking will help to blend in the area with the surrounding pavement.

Burn Methods. For thermoplastic pavement markings or prefabricated pavement markings, heat may be applied to remove the bulk of the marking material before blast cleaning. The two main burning methods are hot compressed air and excess oxygen. Both methods typically utilize propane; the difference is the location of the combustion (combustion is internal or external) and if the flame contacts the marking or not based on the combustion location. Burning methods are less common and typically only used for specific temporary tapes (e.g., foil and for thin paint markings). Care needs to be taken, especially on asphalt, to ensure the burning heads are not left in one place too long; otherwise, pavement damage may occur.

Surface Treatment Method and Masking. The surface treatment method of pavement marking removal covers the marking with something else to hide its presence. Covering the markings with a surface treatment can be done across the entire road (desirable in areas where the removal is needed because of lane shifts or changes in the traffic pattern) or a smaller area of surface treatment, minimum of 2 ft wide over the marking itself. The surface treatment material should be like that of the surrounding road surface so that the covered area blends into the surrounding pavement as well as possible to reduce confusion. The types of treatments typically refer to surface treatments, micro-surfacing, or thin asphalt overlay. An advantage when using the surface treatments is that if they are used across the entire roadway or lane width, there will not be any color or texture difference with the surrounding road surface that would be typical of other removal methods, resulting in a less confusing driving environment. The biggest disadvantage of the surface treatment method is that it is the most expensive.

Even when a surface treatment method is used, it may be desirable to remove most of the marking prior to applying the surface treatment. Depending on the type of treatment used, the previous marking material profile may show through the new surface. Another issue is that over time, pavement wear may expose the previous marking or the marking beads may make the marking visible. If most of the marking was quickly removed prior to the application of the surface treatment, the likelihood of the previous marking being visible is reduced.

Similar to how a surface treatment covers markings that are no longer desired, markings can be masked with removable, non-reflective, preformed tape that is approximately the same color as the pavement surface. This method can only be used temporarily to preserve the marking underneath to be reused later. The tape can also be used to cover markings that need removal but have yet to be removed. The MUTCD prohibits masking using other marking materials or for long-term use because of concerns that the marking being covered may become exposed in the future. This means covering markings that are no longer desired with black pavement marking materials is not allowed.

Pavement Marker Removal. Pavement marker removal is a crude process that relies on physical methods to separate the marker from the road surface. The two most common methods are scraping the marker from the surface or hitting the marker to dislodge it from the surface. Markers can be scraped from the road surface with various forms of machinery or, in some cases, with a shovel. Depending on how well the marker is adhered to the road and what type of road surface it is, scraping can be a quick and effective technique. Markers can be dislodged from the roadway by physically being struck with a sledgehammer or pickax. On some asphalt surfaces, the bond of the marker to the surface of the road may be stronger than the bond within the asphalt surface. This occurrence will result in holes in the pavement surface where the marker was dislodged, which could lead to premature pavement failure.

Advantages, Disadvantages, and Effectiveness. There are advantages and disadvantages of each of the pavement marking removal techniques, as shown in Table 19. This table has been modified from NCHRP Report 759 (*74*). The advantages and disadvantages need to be considered when determining which removal method may be best for a particular project. The effectiveness of the removal should be tested and inspected at the start of the project so that another method can be used if the original method was not completing the job as desired.

Table 20 shows the general effectiveness of each removal method with respect to type of pavement marking material being removed. The effectiveness of a removal technique can be evaluated by examining the scarring depth (pavement damage), changes to pavement surface characteristics (color/texture), percentage of marking material removed, and retroreflectivity characteristics of the removed area.

Corrective Actions

Depending on the removal type, road surface type, and road conditions, additional measures may need to be taken to reduce driver confusion with the removed markings. In the case of removing and replacing the markings in the same location, the need for corrective action is minimal. Removal quality needs to be evaluated during the day, at night, and during wet conditions. Surface color changes and scarring will have a greater impact during the day than at night, whereas retroreflectivity from remaining marking material or retroreflectivity differences because of surface texture changes will be more noticeable at night. The direction of travel and the position of the sun also need to be considered. Wet conditions may fill pavement scarring in a way that may look like a wet marking, thus creating confusing delineation in wet conditions. Any pavement surface damaged beyond the requirements specified in Item 677 by the contractor's operations shall be repaired or repaved as determined by the engineer at no additional cost.

Table 19. Advantages and Disadvantages of Common Pavement Marking Removal Methods.

Removal Method	Advantages	Disadvantages
High-Pressure Water Blasting	• Byproduct does not create dust and is contained within the equipment. • Little to no scarring on concrete. • With the exception of drying time, the pavement surface is prepped for pavement marking reinstallation. • Relatively fast for a blasting method. • Large vehicle mobile systems available with additional utility carts for smaller nearby areas.	• Limited to above-freezing conditions. • May polish surface aggregate and/or clean the surrounding pavement, creating a color contrast. • May remove some surface asphalt and fines that could lead to water penetration. • Potential for damage to pavement joints. • Currently not widely available; higher costs. • Proper equipment operation critical to achieve good results.
Sand Blasting	• Minimal pavement degradation. • Little to no scarring. • Hand-operated precision.	• Creates considerable byproduct. • Creates considerable dust. • No current large vehicle mobile system; therefore, slower than mobile methods. • Health hazards depending on blast media.
Shot Blasting	• Minimal byproduct. • Byproduct does not create dust and is contained within the equipment. • Minimal pavement degradation. • Little to no scarring.	• Shot recovery can be problematic, especially on uneven surfaces. • Cannot be used in wet conditions. • Can be slow, especially for thicker markings. • Can cause pavement damage on non-smooth surfaces. • Limited availability of equipment.
Mechanical Method	• Fast and economical. • Depending on the system configuration (effective vacuum system installed to remove dust), dust created by removal can be contained. • High availability.	• Damage to pavement surface. • Scarring with full marking removal; minimizing damage to roadway may leave marking material behind. • Orbital flailing (erasing) may result in less noticeable scarring than drum flailing due to tapered edges. • Non-vacuum systems can create dust clouds and be hazardous.
Surface Treatments and Masking	• No damage to road surface. • Existing markings can be temporarily covered with tape that matches the road surface color and texture, and later reused when the tape is removed. • Removed areas can be masked to help blend in scarring or surface color changes. • Can be used in lane-shift areas to reduce driver confusion due to ghost markings or scarring.	• Can be expensive. • Material may wear away, exposing the markings being covered. • Difficult to match color and texture with tape. • Tape is for temporary purposes only. • Cannot use marking materials other than tape to cover a marking.

Table 20. Removal Effectiveness with Respect to Pavement Marking Material.

Removal Method	Paint	Thermoplastic	Epoxy	Tape
High-Pressure Water Blasting	Good	Good	Good	Marginal
Sand Blasting	Good	Slow	Good	Ineffective
Shot Blasting	Good	—	—	—
Mechanical Method	Good	Good	Good	Marginal

Note: Good = the removal method adequately removes the marking; slow = the removal technique can adequately remove the pavement marking but at a slower speed; marginal = the removal can be completed but is more difficult than with other types of materials. The dash indicates that not enough information was present in the literature to assess effectiveness or that the removal combination was not witnessed by the research team.

In many cases, the quality of the pavement marking removal will be good but may not be great. Appropriate corrective actions can help reduce any confusion that may occur because of the removed markings. If the color change between the removed area and the surrounding asphalt pavement surface is such that it results in possible confusion to drivers, then corrective measures such as a fog seal or slurry seal over the removed area can be used. This can help blend the removed area into the surrounding pavement as well as replace some of the asphalt that was removed to reseal the asphalt surface. The friction of the road surface needs to be considered, but this application will help blend the removed areas with the surrounding pavement. High-pressure water blasting systems can be used on concrete surfaces to clean the surrounding pavement where the marking removal surface color changes may be problematic to blend in the removed areas to reduce confusion. If a mechanical method is used on a grooved concrete and material remains in the grooves, a blasting method can be used to quickly remove the remaining material.

Restriping

The ultimate goal of the removal and, if needed, subsequent corrective actions is to create a driving environment that is not confusing to the driver. This means the new markings (temporary or permanent) applied after the removal need to be considered as well. Other than the case of a full-width surface treatment, the new marking delineation will be competing with the removed area for the driver's attention. Several methods can be used to help reduce confusion as to what delineation should be followed.

Wider and continuous markings in work zone transition areas like lane shifts will provide better guidance to drivers by enhancing the new markings to reduce confusion with the removed markings. Markings with high retroreflectivity levels should be implemented and maintained in work zones and in any areas where marking removal may have remnants of ghost markings that could be confused as the delineation. After construction is complete and the final markings are applied, wider and brighter markings may be necessary so that any prior removal on the final road surface is less likely to be confused with the new markings.

Examples of Removal Results

The research team observed several removal operations and post removal conditions. Images from some of these investigations are provided to identify some key aspects of pavement marking and marker removal that need to be considered to ensure effective removal. Figure 35 through Figure 37 capture the results of flailing removal on a grooved concrete surface in both day and night conditions. This removal was conducted to modify the alignment of the roadway. Figure 35 shows good daytime removal with minimal pavement damage or discoloration. The nighttime image shows some marking material remaining in the grooves. This location had good permanent striping installed, and the remnants of the removed lane line should not cause confusion at night due to the minor change in alignment.

Figure 36 shows removal results near the same area as Figure 35 but focuses on where the original edge line was removed. Figure 36 shows minimal pavement damage but some discoloration and clear remnants of marking showing up at night. Actions could be taken to improve this removal area depending on the perceived confusion caused by the discoloration or visibility of the marking remnants at night. Cleaning of the adjacent concrete pavement with high-pressure water blasting would help alleviate the daytime color issues. The same high-pressure water blasting could be used to remove the marking remnants at the same time to improve the nighttime appearance.

Figure 35. Flailing Removal of Lane Line on Grooved Concrete (Day and Night).

Figure 36. Flailing Removal of Edge Line on Grooved Concrete (Day and Night).

Figure 37 shows an example of the marking remnants that were left in the groove and area below the top surface of the concrete pavement. A blasting technique would effectively remove these remaining pieces of marking with minimal road surface damage if full removal were needed. If the flailing technique were used to completely remove the marking, the pavement surface would have been damaged, and the color difference would have been more noticeable during the day.

Figure 37. Flailing Removal on Grooved Concrete—Marking Remnants in Grooves.

Removal on asphalt is typically more difficult than on concrete due to the variety in types and porosity of asphalt and how asphalt materials change as they age. Figure 38 provides daytime images of high-pressure water blasting results on a new asphalt surface. This removal was conducted to make a minor change in the striping configuration on the newly constructed asphalt. The removal resulted in 100 percent removal of the marking but did cause some removal of the surface asphalt binder and small aggregate. This resulted in a minor color change and texture change that can be seen in the closer photo. Due to the minor change in the striping, the color and texture changes will not result in confusion to the driver in this situation. Corrective actions could be considered if in another situation the pavement marking pattern were more dramatically changed, or if pavement durability concerns were present due to the loss of the surface asphalt binder. These corrective actions could include a fog seal or the like to replenish some of the asphalt and help blend the color back to the darker asphalt color.

Figure 38. High-Pressure Water Blasting on Asphalt.

Figure 39 shows the results of hand-operated flailing removal of a symbol on asphalt. The removal was required due to changes in the intersection lane assignments. The removal resulted in minor changes to the asphalt surface texture and color. The biggest issue with this removal is that the color and texture changes resulted in the removed area looking just like the symbol that was removed even though the white symbol was removed. To reduce driver confusion, the removal could have included making minor color and texture changes outside the areas of the symbol so that the appearance of the removed area did not maintain the symbol’s shape. The removal could have squared off the removed area so that the arrows were not discernable. In addition to reducing confusion by correcting the removal, straight through arrows could be added to the through lane to reinforce the through-only movement in that lane.

Figure 40 shows the results of a marker that had previously been removed. The researchers did not witness the removal or know what removal type was used to remove the marker. The results show that the removal of the marker resulted in loss of some of the asphalt road surface under the marker. It is possible that another removal method would have resulted in less damage to the asphalt road surface. Some asphalt binder could be used to seal or patch the hole if the hole in the asphalt pavement is of concern for water intrusion and possible premature pavement failure.

Figure 39. Hand-Operated Flailing Removal on Asphalt.

Figure 40. Marker Removal on Asphalt.

APPENDIX: UPDATED VERSION OF TXDOT STANDARD SPECIFICATION ITEM 677

The recommendations provided in Chapter 7 have been fully incorporated into an updated version of TxDOT's *Standard Specification Item 677*. All recommended changes are highlighted in yellow, and deletions are struck through in addition to being highlighted in yellow.

Item 677
Eliminating Existing Pavement Markings and Markers

Texas Department of Transportation

1. DESCRIPTION

Eliminate existing pavement markings and raised pavement markers (RPMs).

2. MATERIALS

Furnish surface treatment materials in accordance with the following items:

1. Item 300, "Asphalts, Oils, and Emulsions"
2. Item 302, "Aggregates for Surface Treatments"
3. Item 315, "Fog Seal"
4. Item 316, "Seal Coat"

Use approved patching materials for repairing damaged surfaces.

Use a commercial abrasive blasting medium capable of producing the specified surface cleanliness. Use potable water when water is required.

3. EQUIPMENT

Furnish and maintain equipment in good working condition. Use moisture and oil traps in air compression equipment to remove all contaminants from the blasting air and prevent the deposition of moisture, oil, or other contaminants on the roadway surface.

4. CONSTRUCTION

Eliminate existing pavement markings and markers on both concrete and asphaltic surfaces in such a manner that color and texture contrast of the removed area and surrounding ~~of the~~ pavement surface will be held to a minimum. Remove all markings and markers with minimal damage to the roadway to the satisfaction of the Engineer. Repair damage to asphaltic surfaces, such as spalling, shelling, etc., greater than ~~1/4~~ 1/8 in. deep resulting from the removal of pavement markings and markers. Dispose of markers in accordance with federal, state, and local regulations. Use any of the following methods unless otherwise shown on the plans. The TxDOT *Pavement Marking Handbook* provides additional information on removal types and best practices.

4.1. **Surface Treatment Method**. Apply surface treatment material at rates shown on the plans, or as directed. Place a surface treatment a minimum of 2 ft. wide to cover the existing marking. Place a surface treatment, thin overlay, or micro surfacing a minimum of one lane in width in areas where directional changes of traffic are involved, or other areas as directed. To reduce the chance of the covered marking becoming visible in the future, the marking should be removed with a mechanical method such that it is flush with the pavement surface. This removal prior to the surface treatment should not damage the pavement surface, and 100 percent removal is not required, but removing the majority of the marking will reduce the likelihood of the marking becoming visible in the future during the day or night.

Surface treatment refers to fog seal, slurry seal, micro surfacing, bituminous surface treatment, and other treatments, usually involving asphalt. The main usage is for maintenance or interim roadway surface treatments. An advantage for all the surface treatments is that if they are used across the entire roadway or lane width, there will not be any color difference, and differences in surface characteristics will be minimal. The uniform color and surface texture of a new surface treatment will allow for improved delineation of the roadway and less confusion to drivers.

~~4.3~~4.2. **Blasting Method**. Use a blasting method such as water blasting, abrasive blasting, water abrasive blasting, shot blasting, slurry blasting, water-injected abrasive blasting, or brush blasting as approved. ~~Remove pavement markings on concrete surfaces by a blasting method.~~ High-pressure water blasting is a preferred method for removal on concrete surfaces if the marking pattern is changing. The blasting methods have the highest likelihood of removing marking below the road surface (e.g., grooved concrete, porous asphalt) with minimal damage to the pavement. On asphalt and dirty concrete surfaces, the color of the removed area may differ greatly from the surrounding pavement. On asphalt surfaces, the removal of some surface asphalt and aggregate fines may occur. Older asphalt surfaces are more susceptible to damage by a blasting method. See Section 5 for possible corrective actions.

~~4.4~~4.3. **Mechanical Method**. Use any mechanical method except grinding. Flail milling is acceptable for markings on asphalt and concrete surfaces. Flail milling will damage the pavement surface if 100 percent removal is required, especially if the surface is a grooved concrete or porous asphalt. Pavement repairs may be necessary. See Section 5 for possible corrective actions.

~~4.2~~4.4. **Burn Method**. Use an approved burning method. For thermoplastic pavement markings or prefabricated pavement markings, heat may be applied to remove the bulk of the marking material before blast cleaning. When using heat, avoid spalling pavement surfaces. Care needs to be taken, especially on asphalt, to ensure the burning heads are not left in one place too long; otherwise, pavement damage may occur. Sweeping or light blast cleaning may be used to remove minor residue.

5. Corrective Actions

Depending on the removal type, road surface type, and road conditions, additional measures may need to be taken to reduce driver confusion with the removed markings. Removal quality needs to be evaluated during the day, at night, and during wet conditions. Surface color changes and scarring will have a greater impact during the day than at night, whereas retroreflectivity from remaining marking material or retroreflectivity differences because of surface texture changes will be more noticeable at night. The direction of travel and the position of the sun also need to be considered. Wet conditions may fill pavement scarring in a way that may look like a wet marking, thus creating confusing delineation. Any pavement surface damaged beyond the requirements specified herein by the Contractor's operations shall be repaired or repaved as determined by the Engineer at no additional cost.

If the color change between the removed area and the surrounding asphalt pavement surface is such that it results in possible confusion to drivers, then corrective measures such as a fog seal or slurry over the removed area can be used. This can help blend the removed area into the surrounding pavement as well as replace some of the asphalt that was removed to reseal the asphalt surface. The friction of the road surface needs to be considered, but this application will help blend the removed areas with the surrounding pavement. High-pressure water blasting systems can be used on PCC surfaces to clean the surrounding pavement where the marking removal surface color changes may be problematic to blend in the removed areas to reduce confusion.

The application of wider and continuous markings with high retroreflectivity in transition areas will provide better guidance to drivers by reducing confusion with the removed marking areas during the day and at night.

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6. MEASUREMENT

This Item will be measured by each word, symbol, or shape eliminated; by the foot of marking eliminated; or by any other unit shown on the plans.

This is a plans quantity measurement Item. The quantity to be paid is the quantity shown in the proposal unless modified by Article 9.2., "Plans Quantity Measurement." Additional measurements or calculations will be made if adjustments of quantities are required.

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7. PAYMENT

The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for "Eliminating Existing Pavement Markings and Markers" of the type and width as applicable. This price is full compensation for the elimination method used and materials, equipment, tools, labor, and incidentals. Removal of RPMs will not be paid for directly but will be subsidiary to the pertinent bid items.

REFERENCES

1. Finley, M.D., B.R. Ullman, N.D. Trout, and E.S. Park. *Studies to Determine the Effectiveness of Automated Flagger Assistance Devices and School Crossing Devices*. Research Report FHWA/TX-12/0-6407-1. Texas A&M Transportation Institute, College Station, Texas, January 2012. Available at http://tti.tamu.edu/documents/0-6407-1.pdf. Accessed February 12, 2019.

2. Fitzpatrick, K., S. Chrysler, S. Sunkari, J. Cooper, B.J. Park, and L. Higgins. *Modern Traffic Control Devices to Improve Safety at Rural Intersections*. Research Report FHWA/TX-12/0-6462-1. Texas A&M Transportation Institute, College Station, Texas, September 2011. Available at http://tti.tamu.edu/documents/0-6462-1.pdf. Accessed March 27, 2019.

3. Fitzpatrick, K., R. Avelar, M. Pratt, M. Brewer, J. Robertson, T. Lindheimer, and J. Miles. *Evaluation of Pedestrian Hybrid Beacons and Rapid Flashing Beacons*. Research Report FHWA-HRT-16-040. Texas A&M Transportation Institute, College Station, Texas, July 2016. Available at https://www.fhwa.dot.gov/publications/research/safety/16040/16040.pdf. Accessed March 27, 2019.

4. Ellis, W. and J.P. Tremblay. *Evaluation of BlinkerSign Crosswalk Lighting System*. Research Report 2014-13. Vermont Agency of Transportation, Montpelier, Vermont, December 2014.

5. *Texas Manual on Uniform Traffic Control Devices, 2011 Edition—Revision 2*. Texas Department of Transportation, Austin, Texas, September 2014. Available at https://www.txdot.gov/business/resources/signage/tmutcd.html. Accessed May 29, 2019.

6. *Freeway Signing Handbook*. Texas Department of Transportation, Austin, Texas, October 2008. Available at http://onlinemanuals.txdot.gov/txdotmanuals/fsh/fsh.pdf. Accessed May 29, 2019.

7. *Sign Crew Field Book*. Texas Department of Transportation, Austin, Texas, October 2018. Available at http://onlinemanuals.txdot.gov/txdotmanuals/sfb/sfb.pdf. Accessed May 29, 2019.

8. *Sign Guidelines and Applications Manual*. Texas Department of Transportation, Austin, Texas, May 2017. Available at http://onlinemanuals.txdot.gov/txdotmanuals/smk/smk.pdf. Accessed May 29, 2019.

9. *Standard Highway Sign Designs for Texas*. Texas Department of Transportation, Austin, Texas, 2012 Edition, Revision 2, March 2017. Available at https://www.txdot.gov/inside-txdot/forms-publications/publications/highway-signs.html. Accessed May 29, 2019.

10. *Texas Manual on Uniform Traffic Control Devices, 2006 Edition*. Texas Department of Transportation, Austin, Texas, February 2006.

11. Hawkins, H.G., Jr., S.T. Chrysler, and G.L. Ford. *Urban Freeway Guide Signing: Final Report*. Research Report 0-4170-2. Texas Transportation Institute, College Station, Texas, October 2003. Available at http://tti.tamu.edu/documents/0-4170-2.pdf. Accessed May 29, 2019.

12. Nelson, A.A., J.M. Tydlacka, R.G. Stevens, S.T. Chrysler, and A.P. Voight. *Lane Assignment Traffic Control Devices on Frontage Roads and Conventional Roads at Interchanges: Technical Report*. Research Report 0-6106-1. Texas Transportation Institute, College Station, Texas, November 2011. Available at http://tti.tamu.edu/documents/0-6106-1.pdf. Accessed May 29, 2019.

13. Hawkins, N., and B.A. Bektas. *Evaluating the Effectiveness of the City of Des Moines LED and RRFB Pedestrian Crossing Treatments on Multi-Lane Roadways*. Publication Intrans 10-387, Iowa Department of Transportation, Ames, Iowa, December 2012.
14. Hourdos, J. *Assessing the Impact of Pedestrian-Activated Crossing Systems*. Publication CTS# 2016031, Minnesota Department of Transportation, St. Paul, Minnesota, July 2018.
15. Fitzpatrick, K., M. Brewer, R. Avelar, and T. Lindheimer. *Will You Stop For Me? Roadway Design and Traffic Control Device Influences on Drivers Yielding to Pedestrians in a Crosswalk with a Rectangular Rapid-Flashing Beacon*. Publication TTI-CTS-0010, Texas A&M Transportation Institute, June 2016.
16. Shurbutt, J., and R. Van Houten. *Effects of Yellow Rectangular Rapid-Flashing Beacons on Yielding at Multilane Uncontrolled Crosswalks*. Publication FHWA-HRT-10-043, Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2016.
17. Pécheux, K., J. Bauer, and P. McLeod. *Pedestrian Safety Engineering and ITS-Based Countermeasures Program for Reducing Pedestrian Fatalities, Injury Conflicts, and Other Surrogate Measures Final System Impact Report*. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2009.
18. Hunter, W.W., R. Srinivasan, and C.A. Martell. *Evaluation of the Rectangular Rapid Flash Beacon at a Pinellas Trail Crossing in St. Petersburg, Florida*. Florida Department of Transportation, Tallahassee, Florida, 2009.
19. Brewer, M., K. Fitzpatrick, G.W. Larson, and H. Minter. Before-and-After Study of the Effectiveness of Rectangular Rapid-Flashing Beacons Used with School Sign in Garland, Texas. Technical Memorandum to City of Garland Department of Transportation. Texas A&M Transportation Institute, College Station, Texas, 2011.
20. Ross, J., D. Serpico, and R. Lewis. *Assessment of Driver Yield Rates Pre- and Post-RRFB Installation*. Publication FHWA-OR-RD 12-05, Oregon Department of Transportation, Salem, Oregon, 2011.
21. Domarad, J., P. Grisak, and J. Bolger. Improving Crosswalk Safety: Rectangular Rapid-Flashing Beacons (RRFB) Trial in Calgary. *Canada Institute of Transportation Compendium*, 2013.
22. Bennett, M.K., H. Manal, and R. Van Houten. A Comparison of Gateway In-Street Sign Configuration to Other Driver Prompts to Increase Yielding to Pedestrians at Crosswalks. *Journal of Applied Behavior Analysis*, 2014, Vol. 47, No. 1, pp. 3–15.
23. Fitzpatrick, K., V. Iragavarapu, M. Brewer, D. Lord, J. Hudson, R. Avelar, and J. Robertson. *Characteristics of Texas Pedestrian Crashes and Evaluation of Driver Yielding at Pedestrian Treatments*. Publication FHWA/TX-14/0-6702-1, Texas Department of Transportation, Austin, Texas, 2013.
24. Fitzpatrick, K., R. Avelar, I. Potts, M. Brewer, J. Robertson, C. Fees, J. Hutton, L. Lucas, and K. Bauer. *Investigating Improvements to Pedestrian Crossings with an Emphasis on the Rectangular Rapid-Flashing Beacon.* Publication HRT-15-043. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2015.
25. Morrissey, S. *Circular Rapid Flashing Beacons—Santa Monica, CA*. Publication 4(09)-8(E). Santa Monica, California, 2013. Available at http://www.dot.ca.gov/hq/traffops/engineering/ctcdc/exp/2013-04-24_Final_rpt_4(09)-8.pdf. Accessed July 1, 2019.
26. Fitzpatrick, K., R. Avelar, I. Potts, M. Brewer, J. Robertson, C. Fees, J. Hutton, L. Lucas, and K. Bauer. *TechBrief: Investigating Improvements to Pedestrian Crossings with an*

Emphasis on the Rectangular Rapid-Flashing Beacon. Publication HRT-15-044. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2015. Available at http://www.fhwa.dot.gov/publications/research/safety /15044/15044.pdf. Accessed July 1, 2019.

27. Potts, A., K. Fitzpatrick, K. Bauer, L. Lucas, J. Hutton, and C. Fees. Effect of Beacon Activation and Traffic Volume on Driver Yielding Behavior at Rapid Flashing Beacons. *Transportation Research Record: Journal of the Transportation Research Board*, 2015, No. 2492, pp. 78–83.
28. Fitzpatrick, K., R. Avelar, J. Robertson, and J. Miles. *Comparison of Driver Yielding for Three Rapid-Flashing Patterns Used with Pedestrian Crossing Signs*. Publication HRT-15-041. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2015. Available at http://www.fhwa.dot.gov/publications/research/safety/15041/15041.pdf. Accessed July 1, 2019.
29. Fitzpatrick, K., R. Avelar, M. Brewer, and T. Lindheimer. *Comparison of Driver Yielding for Rectangular Rapid-Flashing Beacons Used Above and Below Pedestrian Crossing Signs*. Publication HRT-16-041. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2015. Available at http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/TTI-2015-12.pdf. Accessed July 1, 2019.
30. Monsere, C., M.A. Figliozzi, S.M. Kothuri, A. Razmpa, and D. Hazel. *Safety Effectiveness of Pedestrian Crossing Enhancements*. Federal Highway Administration and Oregon Department of Transportation, February 2017.
31. Fitzpatrick, K., S. Turner, M. Brewer, P. Carlson, B. Ullman, N. Trout, E.S. Park, J. Whitacre, N. Lalani, and D. Lord. *Improving Pedestrian Safety at Unsignalized Crossings*. TCRP Report 112/NCHRP Report 562. Transportation Research Board, Washington D.C., 2006.
32. Turner, S., K. Fitzpatrick, M. Brewer, and E.S. Park. Motorist Yielding to Pedestrians at Unsignalized Intersections: Findings from a National Study on Improving Pedestrian Safety. *Transportation Research Record: Journal of the Transportation Research Board*, 2006, No. 1982, pp. 1–12.
33. Fitzpatrick, K. and M. Pratt. *Road User Behaviors at Pedestrian Hybrid Beacons*. Publication FHWA-HRT-16-039. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2016.
34. Fitzpatrick, K., M. Cynecki, M. Pratt, E.S. Park, and M. Beckley. *Evaluation of Pedestrian Hybrid Beacons on Arizona Highways*. Arizona Department of Transportation-TBD, 2019 forthcoming.
35. Fayyaz, K., P. Galvez de Leon, and G. Schultz. *Driver Compliance at Enhanced Pedestrian Crossings in Utah*. Publication UT-19.03, Utah Department of Transportation, Salt Lake City, Utah, January 2019.
36. Fitzpatrick, K., M. Brewer, and R. Avelar. Driver Yielding to Traffic Control Signals, Pedestrian Hybrid Beacons, and Rectangular Rapid-Flashing Beacons in Texas. *Transportation Research Record: Journal of the Transportation Research Board*, 2014, No. 2463, pp. 46–54.
37. Finley, M.D., A.M. Pike, E. Park, L. Wu, L. Theiss, M.A. Brewer, K. Fitzpatrick, R. Avelar, and T.P. Barrette. *Traffic Control Device Analysis, Testing, and Evaluation Program:*

FY2018 Activities. Research Report 0-6969-R1. Texas A&M Transportation Institute, College Station, Texas, June 2019. Available at https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6969-R1.pdf. Accessed August 8, 2019.

38. "Saving Lives: TxDOT launches pedestrian safety campaign." Website. Austin Chamber of Commerce, Austin, Texas, November 2017. Available at https://www.austinchamber.com/blog/austin-chamber-partners-with-texas-department-of-transportation-to-improve-pedestrian-safety. Accessed July 31, 2019.
39. *Roadway Design Manual*. Texas Department of Transportation, Austin, Texas, April 2018.
40. *Urban Street Design Guide*. National Association of City Transportation Officials, New York, New York, October 2013.
41. "Pedestrian Accommodations at Intersections." FHWA Course on Bicycle and Pedestrian Transportation. Federal Highway Administration, Washington D.C. Available at https://safety.fhwa.dot.gov/ped_bike/univcourse/pdf/swless15.pdf. Accessed July 31, 2019.
42. "Interim Approval 21—Rectangular Rapid-Flashing Beacons at Crosswalks." Memorandum. Federal Highway Administration, Washington D.C., March 2018. Available at https://mutcd.fhwa.dot.gov/resources/interim_approval/ia21/index.htm. Accessed July 28, 2019.
43. *Pedestrian Traffic Fatalities by State: 2017 Preliminary Data*. Governors Highway Safety Association, Washington D.C., February 2018. Available at https://www.ghsa.org/sites/default/files/2018-03/pedestrians_18.pdf. Accessed July 28, 2019.
44. *Pedestrian Traffic Fatalities by State: 2018 Preliminary Data*. Governors Highway Safety Association, Washington D.C., February 2018. Available at https://www.ghsa.org/sites/default/files/2019-02/FINAL_Pedestrians19.pdf. Accessed July 28, 2019.
45. *Guide for Scalable Risk Assessment Methods for Pedestrians and Bicyclists*. Federal Highway Administration, Washington D.C., July 2018. Available at https://safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa18032/. Accessed May 17, 2019.
46. Areawide Exposure Tool. Spreadsheet. Federal Highway Administration, Washington D.C., July 2018. Available at https://safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa18032/areawide_non-motorized_exposure_tool_v2.xlsm. Accessed May 17, 2019.
47. Zegeer, C.V., R.J. Stewart, H.H. Huang, and P.A. Lagerwey. *Safety Effects of Marked vs. Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines*. FHWA RD-01-075. Federal Highway Administration, Washington D.C., 2002.
48. Chacon, M.A. Rectangular Rapid Flash Beacons (RRFBs) and Pedestrian Hybrid Beacons (PHBs). Internal memorandum from Michael A. Chacon to district engineers. Texas Department of Transportation, Austin, Texas, September 11, 2018.
49. *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 version with Revision Numbers 1 and 2 incorporated. Federal Highway Administration, Washington D.C., May 2012. Available at https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/pdf_index.htm. Accessed August 19, 2019.
50. NCUTCD (June 2011) Crosswalk Markings. Available at https://ncutcd.org/wp-content/uploads/meetings/2011B/Attach-No.-3-Markings-Sec.-3B.18-Apprvd-6-23-11.pdf. Accessed July 17, 2019.

51. NCUTCD (January 2012) Crosswalk Markings Application Criteria. Available at https://ncutcd.org/wp-content/uploads/meetings/2012A/Attach-No.-12-Markings-No.2-Section-3B.18.pdf. Accessed July 17, 2019.
52. NCUTCD (June 2011) Pedestrian Hybrid Beacon (HAWK). Available at https://ncutcd.org/wp-content/uploads/meetings/2011B/Attach-No.-4-Signals-Design-of-Pedestrian-Hybrid-Beacons-Section-4F.02.pdf. Accessed July 17, 2019.
53. Fitzpatrick, K. and E.S. Park. *Safety Effectiveness of the HAWK Pedestrian Crossing Treatment*. FHWA-HRT-10-042. Federal Highway Administration, Washington D.C., 2010. Available at https://www.fhwa.dot.gov/publications/research/safety/10042/10042.pdf. Accessed July 17, 2019.
54. Blackburn, L., C. Zegeer, and K. Broookshire. *Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations*. FHWA-SA-17-072. Federal Highway Administration, Washington, D.C., 2018. Available at https://safety.fhwa.dot.gov/ped_bike/step/docs/STEP_Guide_for_Improving_Ped_Safety_at_Unsig_Loc_3-2018_07_17-508compliant.pdf. Accessed July 17, 2019.
55. Blackburn, L., C. Zegeer, and K. Broookshire. *Field Guide for Selecting Countermeasures of Uncontrolled Pedestrian Crossing Locations*. FHWA-SA-18-018. Federal Highway Administration, Washington D.C., 2018. Available at https://safety.fhwa.dot.gov/ped_bike/step/docs/pocket_version.pdf. Accessed July 17, 2019.
56. ADOT. *Traffic Engineering Guidelines and Processes Section 640 Pedestrian Hybrid Beacon*. 2015. Available at https://azdot.gov/docs/default-source/traffic-library/tgp0640-2015-06.pdf. Accessed July 17, 2019.
57. City of Boulder. *Pedestrian Crossing Treatment Installation Guidelines*. 2011. Available at https://www-static.bouldercolorado.gov/docs/pedestrian-crossing-treamtment-installation-guidelines-1-201307011719.pdf. Accessed July 17, 2019.
58. Champaign-Urbana, Illinois. *Pedestrian Crossing Enhancement Guidelines*. 2017. Available at https://ccrpc.org/wp-content/uploads/2017/06/Draft-Champaign-Urbana-Pedestrian-Crossing-Enhancement-Guidelines-2017-06-22.pdf. Accessed July 17, 2019.
59. Clark County, Washington. *Pedestrian Crossing Treatment Policy*. 2018. Available at https://www.clark.wa.gov/sites/default/files/dept/files/public-works/Traffic/Pedestrian_Crossing_Policy.pdf. Accessed July 17, 2019.
60. Denver, Colorado. *Uncontrolled Pedestrian Crossing Guidelines*. 2017. Available at https://www.denvergov.org/content/dam/denvergov/Portals/705/documents/guidelines/PWES-015.0-Uncontrolled_Pedestrian_Crossing_Guidelines.pdf. Accessed July 17, 2019.
61. Florida DOT. *Traffic Engineering Manual*. 2019. Available at https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/traffic/trafficservices/studies/tem/tem2019/traffic-engineering-manual-may-2019e87d12d98eb449b6857b2630d53cf32b.pdf?sfvrsn=40c95b44_2. Accessed July 17, 2019.
62. Illinois Center for Transportation. *Establishing Procedures and Guidelines for Pedestrian Treatments at Uncontrolled Locations*. 2017. Available at http://www.eng.auburn.edu/files/centers/hrc/siu-fang-establishingprocedures-pedestrian.pdf. Accessed July 17, 2019.
63. Ashur, S. and M. Alhassan. *Selection of Pedestrian Crossing Treatments at Controlled and Uncontrolled Locations*. FHWA/IN/JTRP-2015/03. Indiana Department of Transportation, Indianapolis, 2015. Available at

https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3079&context=jtrp. Accessed July 17, 2019.

64. Longmont, Colorado. *Pedestrian Crossing Treatment Guidelines*. 2009. Available at https://www.longmontcolorado.gov/home/showdocument?id=5788. Accessed July 17, 2019.
65. Minnesota LTAP. *Pedestrian Crossings: Uncontrolled Locations*. 2014. Available at http://www.mnltap.umn.edu/publications/handbooks/pedcrossingguide/documents/ped_guidebook.pdf. Accessed July 17, 2019.
66. Schroeder, B. J., S.W. O'Brien, and D.J. Findley. *Pedestrian Crossing Guidance*. 2015. FHWA/NC/2014-15. Available at https://connect.ncdot.gov/resources/safety/Teppl/TEPPL%20All%20Documents%20Library/Pedestrian_Crossing_Guidance.pdf. Accessed July 17, 2019.
67. Portland Bureau of Transportation. *Crosswalk Guidelines for Portland*. Website. 2019. Available at https://www.portlandoregon.gov/transportation/article/594882. Accessed July 18, 2019.
68. Sacramento, California. *Pedestrian Crossing Guidelines*. 2014. Available at https://www.cityofsacramento.org/-/media/Corporate/Files/Public-Works/Publications/Transportation/Bicycle-Pedestrian/Ped-Safety.pdf?la=en. Accessed July 17, 2019.
69. Fitzpatrick et al. *TCRP Report 175: Guidebook on Pedestrian Crossing of Public Transit Rail Services*. Transportation Research Board, Washington D.C., 2015.
70. Utah DOT. *Pedestrian Grade Crossing Manual*. 2013. Available at https://www.udot.utah.gov/main/uconowner.gf?n=12635319754536158. Accessed July 17, 2019.
71. *Highway Capacity Manual*, 6th Edition. Chapter 20: Two-Way Stop Controlled Intersections: Pedestrian Mode. Transportation Research Board, Washington D.C., 2016.
72. *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges—Item 677: Eliminating Existing Pavement Markings and Markers*. Texas Department of Transportation, Austin, Texas, 2014.
73. *Pavement Marking Handbook*. Texas Department of Transportation, Austin, Texas, August 2004.
74. Pike, A.M., and J.D. Miles. *NCHRP Report 759—Effective Removal of Pavement Markings.* Washington, DC, Transportation Research Board, Washington D.C., 2013.