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Traffic Control Device Analysis, Testing, and Evaluation Program: FY2022 Activities

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Cooperative Research Program

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16. Abstract

Traffic control devices are a primary means of communicating highway information to road users. The design, application, and maintenance of traffic control devices are under constant transformation as new technologies, methodologies, and policies are introduced. This project provides the Texas Department of Transportation with a mechanism to conduct high-priority, limited-scope evaluations of traffic control devices. Research activities conducted and concluded during the 2022 fiscal year included:

- Review of overhead lane control signs for frontage road and ramp approaches to signalized intersections.
- Examination of vehicle speeds and signing needs for gradual curves.
- Investigation of countermeasures for unexpected pedestrians on high-speed roads.
- Evaluation of driveway assistance devices in lane closures on two-lane, two-way roads.

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TRAFFIC CONTROL DEVICE ANALYSIS, TESTING, AND EVALUATION PROGRAM: FY2022 ACTIVITIES

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DISCLAIMER

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

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CHAPTER 1:
INTRODUCTION

Traffic control devices are a primary means of communicating highway information to road users. The design, application, and maintenance of traffic control devices are under constant transformation as new technologies, methodologies, and policies are introduced. This project provides the Texas Department of Transportation (TxDOT) with a mechanism to conduct high-priority, limited-scope evaluations of traffic control devices. Research activities conducted during the 2022 fiscal year (September 2021–August 2022) included:

- Review of overhead lane control signs for frontage road and ramp approaches to signalized intersections.
- Examination of vehicle speeds and signing needs for gradual curves.
- Investigation of countermeasures for unexpected pedestrians on high-speed roads.
- Evaluation of driveway assistance devices in lane closures on two-lane, two-way roads.
- Examination of operating speed when the posted regulatory speed limit is changed.
- Assistance with centerline buffer width, pavement markings, and rumble strip standard development.
- Investigation and evaluation of the use of milled rumble strips on seal coats.

The findings from the first four activities are documented in this report. The examination of operating speed when the posted regulatory speed limit is changed was considered internal in nature, so it is not included herein. The remaining two activities are ongoing and will be documented in future reports, as deemed appropriate.

CHAPTER 2: USE OF OVERHEAD LANE CONTROL SIGNS

INTRODUCTION

The application of overhead lane control signing (OLCS) along frontage road interchange approaches in Texas is relatively rare, despite a preference for overhead compared with roadside lane use signing in the *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) (*1*). Researchers performed a literature review and professional organization query to better identify situations where OLCS should be considered over roadside lane control signing. Included in the review of past research was an effort to identify any state guidelines or state practices that would indicate when OLCS should be deployed and whether any barriers to implementation have been documented.

GENERAL APPLICATION OF OLCS IN TEXAS

The most recent update of the TMUTCD (*1*) provides three categories for Intersection Lane Control Signs per Section 2B.19:

- Mandatory Movement Lane Control (R3-5, R3-5a, and R3-7) signs.
- Optional Movement Lane Control (R3-6) signing.
- Advance Intersection Lane Control (R3-8 series) signs.

Examples of each type of TMUTCD Intersection Lane Control signing can be found in Figure 1. Guidance from Section 2B.19 states that when Intersection Lane Control signs are mounted overhead, each sign should be placed over the lane to which it applies. At signals where through lanes become turn lanes, multi-lane turns that include shared movements, or with other unexpected lane-use regulations, OLCS should be installed over the lanes at the intersection and in advance of the intersection over the appropriate lanes. Only where OLCS are impractical should roadside lane control signing be employed. However, the use of an overhead sign for one approach lane does not require the installation of overhead signs for the other lanes of that approach. For narrower approaches (i.e., two lanes or less), the Intersection Lane Control signs (R3-5, R3-6, or R3-8) may be overhead or (roadside) post-mounted.

TMUTCD Section 2B.20 applies to Mandatory Movement Lane Control signs, which must only indicate the single vehicle movement that is required from the lane. TMUTCD Section 2B.20 also provides some standard requirements about post versus overhead mounting:

> The R3-7 word message shall be for post-mounting only. Where the number of lanes available to through traffic on an approach is three or more, Mandatory Movement Lane Control (R3-5 and R3-5a) symbol signs, if used, shall be

mounted overhead over the specific lanes to which they apply (see Section 2B.19) (*1*).

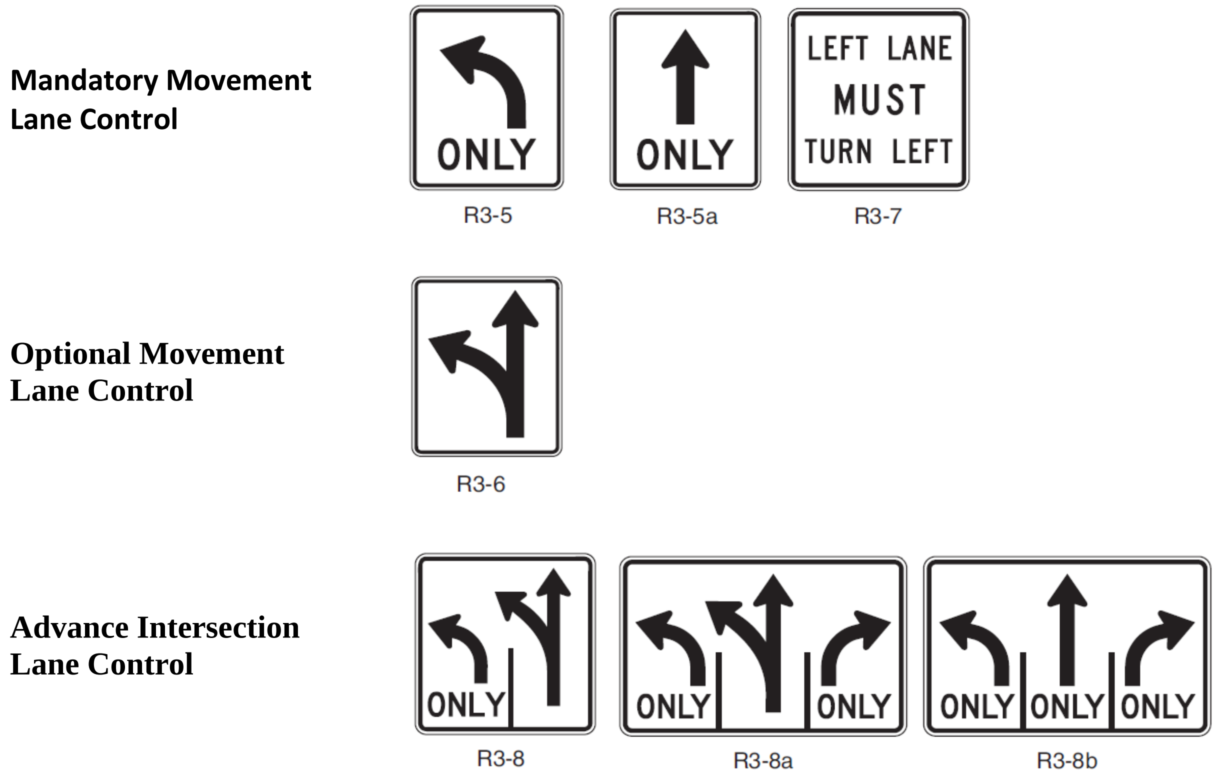


Figure 1. Example TMUTCD Intersection Lane Control Signs (Adapted from *1*).

Placement of Mandatory Movement Lane Control signs indicates that if they are used, they "shall be located in advance of the intersection, such as near the upstream end of the mandatory movement lane, and/or at the intersection where the regulation applies" (*1*). In addition, Guidance for Section 2B.20 indicates that when Mandatory Movement Lane Control signs are used they "should be accompanied by lane-use arrow markings, especially where traffic volumes are high, where there is a high percentage of commercial vehicles, or where other distractions exist." Figure 2shows an example of Mandatory Movement Lane Control signs mounted overhead in advance of the intersection.

TMUTCD Section 2B.21 applies to Optional Movement Lane Control signs, which must be used for two or more movements from a specific lane or to highlight permitted movements. Like the requirements for Mandatory Movement Lane Control signs, this section indicates that:

> Where the number of lanes available to through traffic on an approach is three or more, an Optional Movement Lane Control (R3-6) sign, if used, shall be mounted overhead over the specific lane to which it applies (see Section 2B.19) (*1*).

In addition, placement criteria for Optional Movement Lane Control Signs requires that when they are used they “shall be located in advance of the intersection, such as near the upstream end of an adjacent mandatory movement lane, and/or at the intersection where the regulation applies.”

(Source: © 2021 Google Maps)

Figure 2. Frontage Road OLCS, IH 10 Eastbound at Wurzbach Road, San Antonio, Texas.

Section 2B.22 applies to Advance Intersection Lane Control signs, which may be used to indicate the configuration of all lanes ahead. Advance Intersection Lane Control signs should be placed in advance of the intersection, such as in advance of the tapers or at the beginning of a turn lane, so that drivers can select the appropriate lane. At intersections with three or more approach lanes, Advance Intersection Lane Control signs must be post-mounted. In this situation, Advance Intersection Lane Control signs cannot be mounted overhead since these signs include lane assignment information for multiple lanes (i.e., cannot be mounted directly over the specific lanes to which the sign applies).

LITERATURE REVIEW

Past research regarding the application of OLCS in at-grade roadway environments is relatively rare, but research into driver comprehension of the downstream movements allowed from a lane or lane group based on upstream lane use signing has been ongoing since at least the early 1990s. Research sponsored by TxDOT into driver understanding of urban overhead guide signing (*2*) revealed a number of motorist comprehension shortcomings in the use of lane arrows and diagrammatic guide signing. When the number of overhead arrows on a sign exceeded the number of lanes marked on the roadway, drivers were confused about optional lane usage. Such results are easily applied for advance frontage road OLCS signs approaching interchanges or intersections to limit the number of individual/lane-specific LCSs or lane arrows shown on LCS to the number of striped lanes visible to drivers. Another valuable finding related to the combination of guide signing and lane control signing aggregated into urban guide signs. These (combined) messages were best understood when the signing information was simplified and chances of driver information overload minimized.

Around the same time as the above overhead guide signing research was underway, a research investigation on the use of dynamic OLCSs was underway on a closed course testbed and at a field site in Houston, Texas (*3*). The primary research work related to designing and assessing the effectiveness of a dynamic lane assignment system (DALAS) to match frontage road interchange lane and movement capacity with prevailing demand for each turning movement. In an initial system design, the dynamic OLCSs were located on the same overhead sign bridge (OSB) as the traffic signal heads for the interchange. However, this sign location schema contributed to potential excessive driver information/workload and visual clutter. A visual angle analysis was performed and determined that the OSB for the dynamic OLCSs should be a minimum of 180 ft upstream of the traffic signals (*3*). When implemented at a field test site in Houston, the OSB with OLCSs was ultimately located 200 ft upstream of the stop bar, or about 250 ft upstream of the traffic signal heads.

Further research into DALAS (*4*) indicated that significant delay-saving benefits of dynamic lane assignment on the frontage road approaches to diamond interchanges were possible. Pertinent to the current investigation of OLCS were findings relating to the performance of DALAS systems and driver behavior when extended-length queues were present on the frontage road approach to the signalized interchange. Lane assignment (i.e., lane use) violations greatly increased when queues were of such a length that drivers could not read the lane control sign while on their approach to the intersection. Another applicable result was that the DALAS system deployed in Houston—which used OLCSs—was determined to be more effective than the DALAS deployed in Dallas, which used ground-mounted LCSs. These results were likely due to two factors; the OLCS used in Houston had greater visibility at distance due to its overhead-mounted signs, and this system used fiber-optic (which have higher visibility) rather than electro-mechanical technology with lane use arrow signs to change the lane assignments.

In 2003, the National Cooperative Highway Research Program (NCHRP) released Report 500, which was separated into volumes to provide focused guidance on implementing safety improvement recommendations from the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan. Volume 5 of this series provided guidance on addressing unsignalized intersection collisions (*5*). Among the strategies to improve safety at complex intersections was to provide lane assignment signing since drivers approaching complex intersections can have difficulty determining the appropriate lane from which to perform their desired turning maneuver. Driver indecision can result, contributing to greater crash likelihood for rear-end, sideswipe, and angle crashes when drivers make unexpected maneuvers from an inappropriate lane. The guidance states that overhead signs are preferred to post-mounted signs because they can be placed directly over the lane to which they apply. Also, lane assignment signing should be placed far enough in advance of the intersection so that adequate maneuvering distance is provided.

Around the same time NCHRP issued its Report 500 series, TxDOT-sponsored research produced the first edition of the *Freeway Signing Handbook*, which included a series of frontage road lane assignment signing layouts based on the number of lanes and turn bays on the frontage road approach to a typical interchange. The most recent update (*6*) of this manual retained and improved the graphics for these frontage road lane assignment guidance layouts (Figure 3) and indicated the potential use of lane control signing on the interchange signal mast arm (optional), along the frontage road where the frontage road widens to allow for turn lanes, and a specified distance upstream of the start of the turn lanes (optional). An OLCS would improve the visibly of frontage LCSs and likely remove the need for multiple sets/pairs of roadside LCS signs. Specifically, overhead Mandatory and Optional Movement Lane Control signs could be placed where the roadway widens from three to five lanes.

According to the TMUTCD (*1*), the R3-8 series Advance Intersection Lane Control sign shown in Figure 3 (upper left) on the intersection mast arm is allowed only for narrow approaches with two or less lanes. Instead, individual Mandatory and Optional Movement Lane Control signs should be used for the left turn only, shared left plus through, and through only lanes at the intersection.

A TxDOT-sponsored study (*7*) of driver response to overhead lane assignment signing in advance of freeway interchanges revealed several interesting findings when lane assignment arrows were misaligned with their corresponding travel lanes due to work zone activity. Via a driving simulator, drivers navigated through scenarios where lane assignment arrows did and did not align with the travel lanes. When a misalignment scenario was executed, driver uncertainty led to later lane changes, resulting in lane changes closer to the exit ramp gore area. In complex driving and/or high-volume scenarios, this could lead to erratic maneuvers such as hard braking, last minute lane changes, and vehicle conflicts during merging.

These findings can logically be extended to the frontage road approaches to diamond interchanges, though the lane control signing is often roadside signs rather than overhead signing. Drivers requiring lane use guidance must locate the roadside lane control sign, take adequate time to perceive the lane arrow indications, and associate those symbols and their corresponding lanes with the marked lanes on the roadway surface before they can begin maneuvering into the correct lane for their desired downstream turning movement at the interchange. OLCS effectively limits several of these time elements by providing lane control sign and arrow elements in a location that is visible far in advance of roadside signing and virtually eliminating the time it takes drivers to associate the lane control with the (proper) corresponding lane on the roadway approach to the interchange.

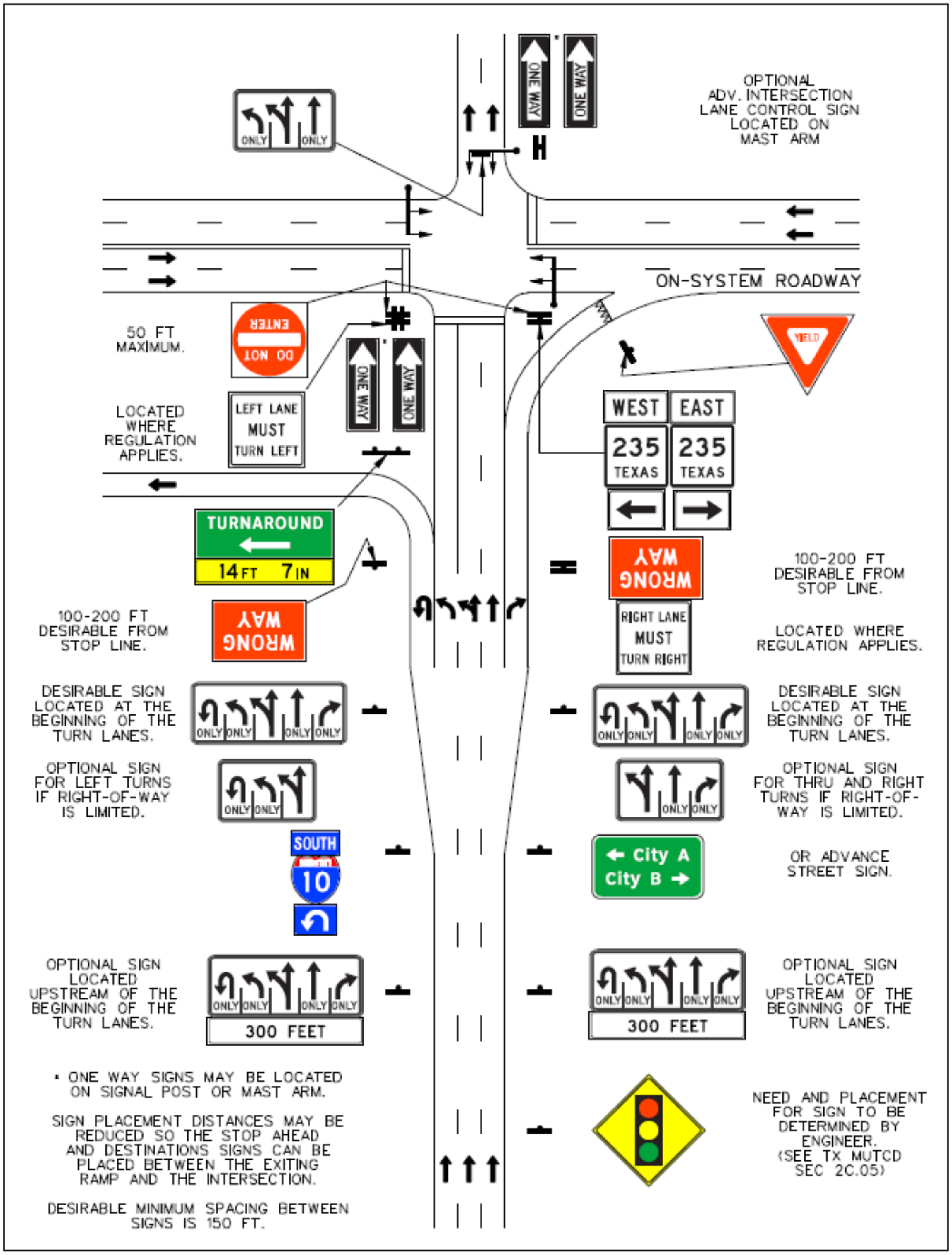


Figure 3. TxDOT Freeway Signing Handbook Frontage Road LCS Guidance (*6*).

TxDOT also sponsored 2011 research on lane assignment devices focused on frontage roads at interchanges (*8*, *9*). One component of the study was a nationwide review of practices, and the results relating to OLCS included:

- Roadside-mounted LCS are (much) more common than OLCS.
- The decision to use OLCS is based on engineering judgment and observed operational issues.
- Reasons for not using OLCS include initial cost, maintenance cost, lack of need for overhead mounting, and availability of right-of-way.

The nationwide survey performed as part of this research also revealed that when OLCS are used they are most commonly located at the beginning of the additional lanes, similar to practices used for locating roadside advance lane control signing. OLCS can also be located immediately upstream of the beginning of additional lanes or on a signal mast arm or span wire. The decision regarding OLCS upstream placement distance is based on field conditions, engineering judgment, and availability of overhead structures; however, standard placement criteria do not exist (*8*).

Two specific suggestions from this 2011 research study apply to the use of OLCS at typical diamond interchanges. The first guidance relates to the arterial approaches to the diamond and indicates that OLCS should be used when drivers are uncertain which lane(s) turn on the other side of the interchange. OLCS are typically placed on the overpass structure, with clarification that placement should not confuse drivers into thinking the turn is before the overpass. The second situation calling for OLCS is when limited sight distance is available to the downstream interchange along the frontage road, and the guidance suggests locating the OLCS after the intersection approach flares out (i.e., widens for turn lanes at the signal). OLCS application is also noted as being more critical when congestion and queues spill back far enough (along the frontage road) where providing an overhead sign could impact lane selection further upstream of the intersection. The human factors study results from this research noted that drivers prefer OLCS for lane guidance and have high comprehension for turn movements when lane assignment arrows are placed directly over the lanes (*8*).

The latest version of the *Handbook for Designing Roadways for the Aging Population* deftly summarizes the issues addressed by lane assignment pavement markings and signing:

> Uncertainty about downstream lane assignment produces hesitancy during the intersection approach; this in turn decreases available maneuver time and diminishes the driver’s attentional resources available for effective response to potential traffic conflicts at and near intersections (*10*).

This handbook advocates that notification of drivers regarding downstream lane use be performed as early as possible because traffic density is lighter, gap opportunities for lane changing are more frequent, and fewer conflicts exist with other vehicles and pedestrians the further away from the intersection any necessary lane changing occurs. This handbook references previous aging driver research (*11*) which indicated that most drivers believed multiple sets of warning signs are necessary in advance of turn-only lanes with the first signing 20 to 30 seconds away from the intersection and the second signing 10 seconds away from the turn location. This previous research (*11*) also stated that OLCS are far more effective than roadside signs for this type of warning.

Recent research into innovative interchange design and management utilized a driving simulator to examine and analyze driver behavior in cases where arterial contraflow lanes were used within a dynamic reversible left-turn (DRLT) diamond interchange and on the approach to a contraflow left-turn (CLT) intersection (*12*). In both cases, versions of OLCS were used to inform drivers of downstream lane control (Figure 4). Despite the unusual interchange approach configuration—where drivers approaching a stop bar could be facing opposing traffic across the intersection—the driver comprehension rate for overhead signing was about 95 percent.

Figure 4. OLCS and Route Signing in Driving Simulator (Adapted from *12*).

In the summary discussion for this research, the authors indicated that OLCS (described by the authors as advance guide signs) used for the reversible-lane interchange:

> … may be helpful to prepare drivers for the potential sight of opposing traffic in their receiving lane, inform them how to identify the operational status of the reversible lane, and provide guidance on how to use the reversible lane. Advanced knowledge may aid in reducing discomfort and hesitation at the intersection itself and reduce improper maneuvers (*12*).

In 2018, the Texas A&M Transportation Institute (TTI) researchers surveyed TxDOT districts regarding their use of advance intersection LCS (*13*). Findings from this investigation revealed that almost all districts use advance intersection LCS and that the locations where they are applied feature the same types of issues/concerns that would be used to justify the installation of OLCS. Table 1 from this research lists the issues motivating advance intersection LCS use.

Table 1. District Use of Advance Intersection LCS (*13*).

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.*

This investigation also asked district staff to identify concerns with implementing advanced intersection LCS; these concerns are listed in Table 2 (also reproduced from the recent TTI research). Note that many of the concerns with applying advance intersection LCS (R3-8 series) signing are eliminated should districts choose to use OLCS.

Table 2. District Challenges with Advance Intersection LCS (*13*).

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.*

OLCS EXAMPLES AROUND TEXAS

To provide a better understanding of how OLCS are used on frontage roads throughout Texas, TTI researchers identified real-world examples in metropolitan areas across the state. Structures for supporting signs vary from poles with mast arms to custom-designed monotube OSB structures. In some cases, route signing is combined with the individual lane control signs to clarify the relationship between lane selection and target route. Figure 2 provides a San Antonio example with a substantial pole and mast arm to provide individual OLCS across five frontage lanes. Figure 5 through Figure 7 contain other samples found in Austin and Dallas. A unique overhead dynamic message sign (DMS) form of lane control signing was found in Houston and is detailed in Figure 8 through Figure 10.

(Source: © 2021 Google Maps)

Figure 5. Frontage Road OLCS, IH 35 Southbound at E. 6th Street, Austin, Texas.

(Source: © 2021 Google Maps)

Figure 6. Frontage Road OLCS, US 75 Southbound at Henderson Avenue, Dallas, Texas.

(Source: © 2021 Google Maps)

Figure 7. Frontage Road OLCS, US 75 Northbound at Caruth Haven Lane, Dallas, Texas.

(Adapted from: © 2021 Google Maps)

Figure 8. Frontage Lane Use, IH 69 Southbound at SH 6, Houston, Texas.

(Adapted from: © 2021 Google Maps)

Figure 9. Lane Use DMS, IH 69 Southbound Frontage at SH 6, Houston, Texas.

(Source: © 2021 Google Maps)

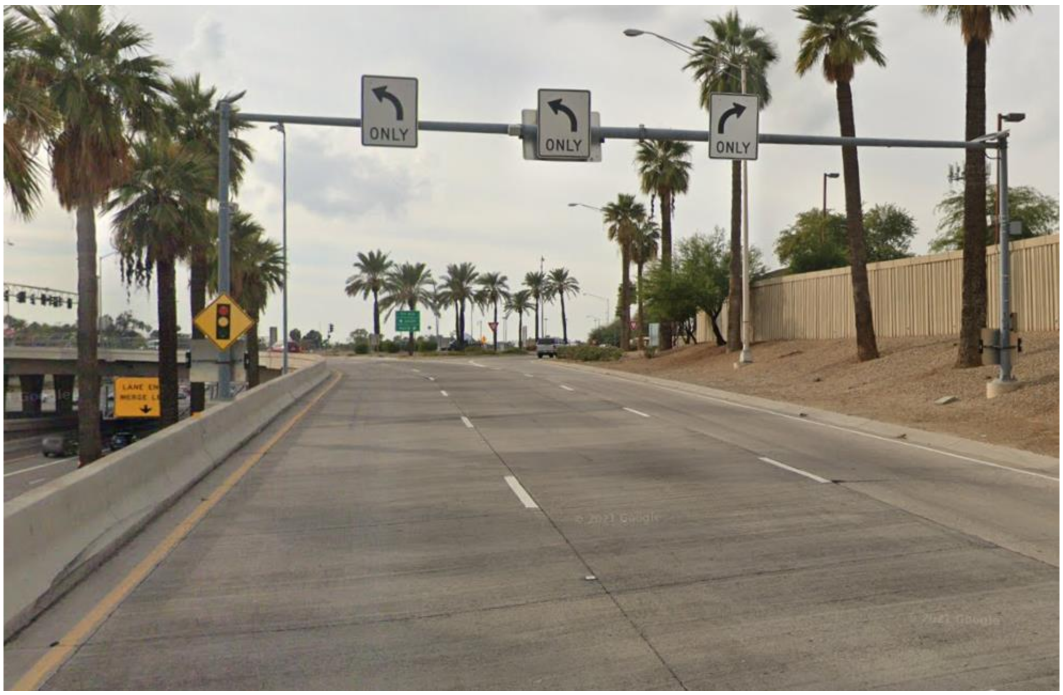
Figure 10. Advance LCS, IH 69 Southbound Frontage at SH 6, Houston, Texas.

A unique lane use situation exists at the large and high-turning-volume interchange at the junction of IH 69 and SH 6 in Sugarland, Texas. The seven-lane approach for the southbound IH 69 frontage road has lane use specified as (U)-turn, (L)eft turn only, (L)eft turn only, (L)eft + (T)hrough, (T)hrough, (R)ight turn only, and (R)ight turn only (see Figure 8). A unique overhead DMS alternates messages between "STAY IN YOUR LANE" and a set of lane allocation and destination messaging (see Figure 9). Advance Intersection Lane Control signs are used in multiple places along the frontage road approach (see Figure 9 and Figure 10), but the use of an Advance Intersection Lane Control sign (TMUTCD R3-8 series sign) on the signal mast arm at the interchange (see Figure 10, circled in yellow in the upper right) is not supported by the TMUTCD since the signing position is overhead-mounted and the frontage approach has more than two lanes. Mast arm mounted overhead lane control signing at the interchange should consist of individual Mandatory and Optional Movement Lane Control signs due to the number of lanes (six at the stop bar) on the approach.

OLCS EXAMPLES ACROSS THE UNITED STATES

TTI researchers expanded their search for real-world frontage road and arterial OLCS examples to other U.S. states using an online query of the Institute of Transportation Engineers (ITE) All Member Forum and an internal query of TTI staff. Examples applied on the freeway corridor ramp or frontage road approaches to interchanges were found in Arizona, New Mexico, and North Carolina. Arterial highway examples were found in Georgia, North Carolina, and Ohio.

Figure 11 through Figure 20 show these OLCS applications and in some cases demonstrate unique support methods or signing combinations not found in Texas. Figure 11 and Figure 12 demonstrate OLCS mounting methods from Arizona showing an example of an overhead “mast arm bridge” and a large pole with a unique mast arm that helps provide a clear zone along the frontage road. In Georgia, TTI researchers found examples of OLCS supported on span wire (see Figure 13 and Figure 14). Unique monotube cantilever and overhead sign bridges were found in Albuquerque, New Mexico (see Figure 15 and Figure 16).

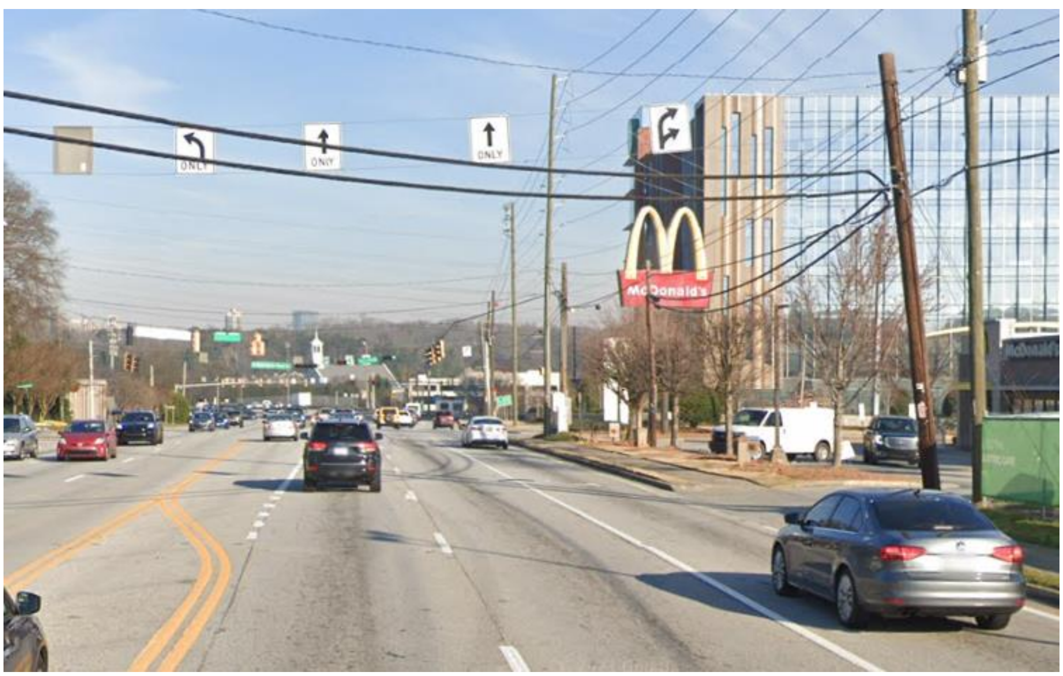


(Source: © 2021 Google Maps)

Figure 11. Ramp OLCS, Westbound IH 10 at N. 7th Avenue, Phoenix, Arizona.

(Source: © 2021 Google Maps)

Figure 12. Frontage OLCS, Northbound El Pastor Freeway at W. Buckeye Road, Phoenix, Arizona.



(Source: © 2021 Google Maps)

Figure 13. Arterial OLCS, Northbound N. Druid Hills Road at Tullie Road, Atlanta, Georgia.

(Source: © 2021 Google Maps)

Figure 14. Arterial OLCS, Westbound Buford Highway NE at N. Druid Hills Road, Atlanta, Georgia.

(Source: © 2021 Google Maps)

Figure 15. Ramp OLCS, Eastbound IH 40 at Carlisle Boulevard, Albuquerque, New Mexico.

(Source: © 2021 Google Maps)

Figure 16. Ramp OLCS, Eastbound IH 40 at Louisiana Boulevard, Albuquerque, New Mexico.

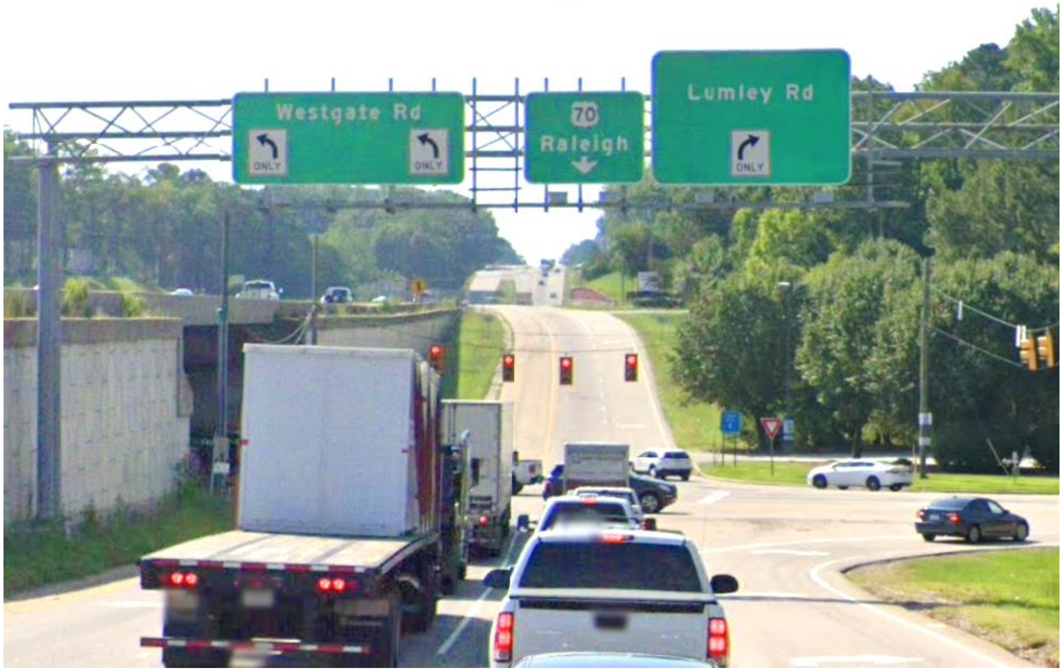
In North Carolina, OLCS examples were supported on truss OSBs (see Figure 17 through Figure 19). One of the North Carolina examples (see Figure 19) also includes route guide signing in combination with OLCS, expediting driver understanding of the route choice implications of lane choice approaching the interchange. An Ohio example (see Figure 20) of OLCS also combines route choice and lane use signing by lane to aid drivers in selecting the correct intersection approach lane to access or remain on their preferred route. The combination of lane control and route guide signing minimizes last-minute lane changing on the approach to a (very) nearby diamond interchange.

(Source: © 2021 Google Maps)

Figure 17. Arterial OLCS, Westbound W. Wendover Ave. at Stanley Road, Greensboro, North Carolina.

(Source: © 2021 Google Maps)

Figure 18. Arterial OLCS, Southbound SH 50 at US 70, Raleigh, North Carolina.



(Source: © 2021 Google Maps)

Figure 19. Ramp OLCS, Eastbound US 70 at Westgate/Lumley Road, Morrisville, North Carolina.

(Source: © 2021 Google Maps).

Figure 20. OLCS on Southbound SH 710 at SH 161 (near IH 71), Columbus, Ohio.

POTENTIAL OLCS APPLICATION GUIDANCE

Based on the synthesized review of OLCS signing standards from the TMUTCD, past research, and applications from around Texas and the United States, the following issues are highlighted as important findings.

At signals where through lanes become turn lanes, multi-lane turns that include shared movements, or other unexpected lane-use regulations, OLCS should be installed over the lanes at the intersection and in advance of the intersection over the appropriate lanes. Only where OLCS are impractical should roadside lane control signing be employed. Overhead Mandatory and Optional Movement Lane Control signs can be used at and in advance of the intersection. However, these signs must be mounted over the specific lane to which they apply and can only indicate the vehicle movements permitted from a specific lane. If used on flared interchange approaches (i.e., those with more lanes at the intersection than upstream), overhead Mandatory and Optional Movement Lane Control signs should be located at the beginning of the left/right turn lanes (i.e., where the road widens). Advance Intersection Lane Control signs should be located an adequate distance in advance of the intersection, not at the intersection. When there are three or more approach lanes, Advance Intersection Lane Control signs cannot be mounted overhead. Instead, they must be post-mounted. If used in conjunction with OLCS on flared interchange approaches, the Advance Intersection Lane Control signs could be placed upstream of the beginning of the additional lanes to provide lane assignment information further upstream, especially where queues are long or sight distance is limited.

OLCS are used at select diamond interchanges—especially in urban areas—in frontage road applications. However, they are typically mounted on the signal mast arm. This gives them limited visibility on the frontage road approach when longer frontage road queues are present. Again, the preference in situations where queues are long or in situations where frontage road sight distance is limited (e.g., on approaches with curved alignments) is for the OLCS to be located at the beginning of the left/right turn lanes servicing the frontage approach.

Past research—especially research into aging drivers—stresses the advantages of OLCS over roadside signing in allowing drivers to rapidly associate each driving lane with its allowed downstream turning movements at a signalized interchange or intersection. OLCS effectively provides lane control sign and arrow elements in a location that is visible far in advance of roadside signing, virtually eliminating the time it takes drivers to associate the lane control with the (proper) corresponding lane on the roadway approach to the interchange. Aging driver research also supports locating OLCS as far as possible upstream from the intersection to allow drivers time to execute safe lane changes into the lane servicing their desired movement. Here again, OLCS are better situated at the beginning of frontage road turn lanes rather than on the signal mast arm at the interchange/intersection.

Cost is cited as one of the reasons that post-mounted Advance Intersection Lane Control signs are used in practice significantly more often than OLCS. The cost of OLCS on both frontage road approaches to a typical diamond interchange would be roughly $45,000 (i.e., two poles and foundations, mast arms, and LCS for multiple lanes each), compared with around $3,000 for advance intersection LCS on either side of each frontage road. Spread over the design life of a typical roadway or interchange project with a multi-million-dollar budget, the signing cost difference for OLCS is minimal.

The typical implementation method for installing frontage road OLCS in Texas is with either a signal pole and (long) mast arm to reach over affected frontage road lanes or a form of OSB structure. However, much more cost-efficient methods are available. For example, an OLCS servicing an entire frontage road approach could be implemented for less than $10,000 with two wooden poles and lane specific OLCS supported on span wire.

OLCS have the potential to reduce rather than increase roadside sign clutter, as with roadside Advance Intersection Lane Control signs. However, one disbenefit for OLCS not cited in the literature is the safety impact of having an additional foundation and pole (in the case of mast arms) or two foundations and vertical supports (in the case of OSBs) in the frontage road driving environment approaching a signalized interchange.

OLCS provide an opportunity to co-locate route signing on a lane-by-lane basis with LCS and provide drivers with a direct understanding of not only the downstream turning movement selection implied by their lane choice but also the route option selected because of lane choice. This potentially reduces roadside sign clutter (since the route signs are also located overhead) and improves driver understanding of the route choice implications of lane selection on the approach to the signalized interchange.

CHAPTER 3:
EXAMINATION OF VEHICLE SPEEDS AND SIGNING NEEDS FOR GRADUAL CURVES

BACKGROUND

Over the past decade, TxDOT has revised state policies on evaluating horizontal curves and setting curve advisory speeds following several research projects conducted by TTI. These research projects included:

- 0-5439: Identifying and Testing Effective Advisory Speed Setting Procedures.
- 5-5439: Workshops on Identifying and Testing Advisory Speed Setting Procedures.
- 0-6960: Enhancing Curve Advisory Speed and Curve Safety Assessment Practices.
- 5-6960: Implementation of Enhancing Curve Advisory Speed and Curve Safety Assessment Practices.

The guidance from these projects has been incorporated into official state documents such as the *Procedures for Establishing Speed Zones* manual (*14*) and documented in various project deliverables, most recently the *Horizontal Curve Evaluation Handbook* (*15*).

In Research Project 0-5439 (*16*), researchers proposed a guidance framework for selecting curve traffic control devices based on side friction and kinetic energy differentials as vehicles decelerate from tangent speed to curve speed. This framework is illustrated in Figure 21 as a contour plot with labeled regions indicating curve severity categories. Curves with a greater severity category would be treated with more devices.

In Implementation Project 5-5439 (*17*), researchers developed a program called Texas Roadway Analysis and Measurement Software (TRAMS) that archives and processes data collected with a GPS receiver, an electronic ball-bank indicator, and a laptop computer to assist practitioners in conducting engineering studies to set curve advisory speeds. They also developed a companion spreadsheet called Texas Curve Advisory Speed (TCAS).

In Research Project 0-6960 (*18*), researchers updated TRAMS and developed a new companion spreadsheet called Texas Curve Evaluation Software (TCES), which incorporates the functions of TCAS and additional features. Both TCAS and TCES provide the analyst with an unrounded advisory speed, which is the average truck speed, and a rounded advisory speed, which is computed by adding 1 mph to the unrounded advisory speed and rounding down to the nearest 5-mph multiple. These programs will not provide a rounded advisory speed if one is not recommended per the guidance for selecting curve traffic control devices.

Following the completion of Implementation Project 5-5439, the federal *Manual on Uniform Traffic Control Devices* (MUTCD) (*19*) was updated to include a guidance framework based on speed differentials between regulatory speed limit and curve advisory speed. This framework is illustrated in Table 3. This table has been incorporated into the TMUTCD (*1*) as Table 2C-5. TxDOT districts are now in the process of evaluating horizontal curves and updating curve traffic control devices based on the new TMUTCD guidance using the tools developed in Research Project 0-6960.

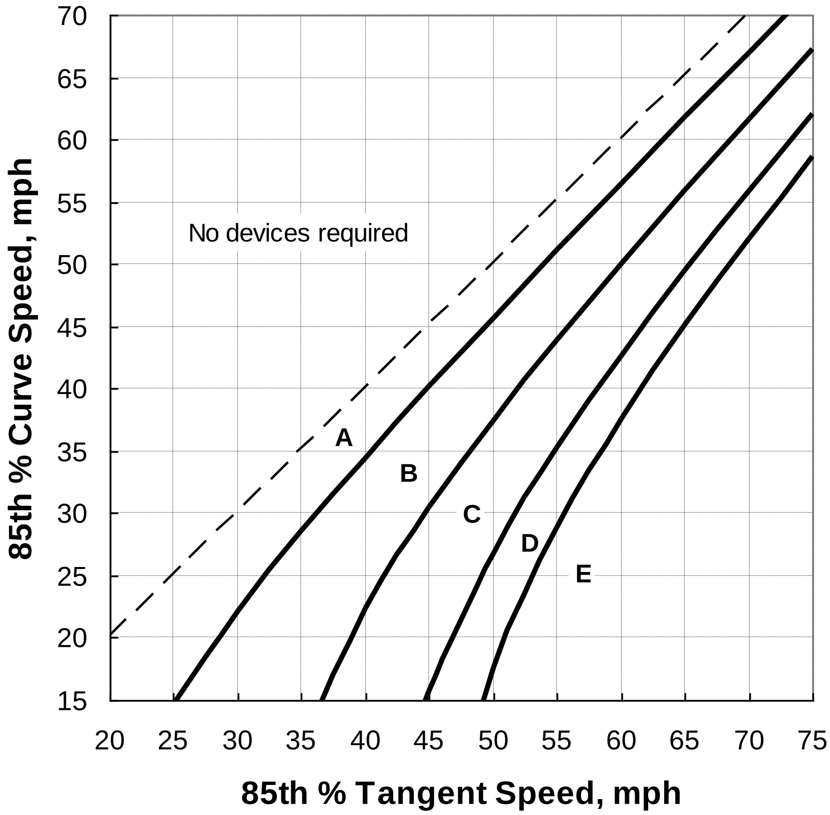


Figure 21. Alternative Guidelines for Choosing Curve Traffic Control Devices (*16*).

Table 3. Horizontal Alignment Sign Selection (*1*, Table 2C-5).

Type of Sign	Difference between Speed Limit and Advisory Speed				
	5	**10**	**15**	**20**	**≥ 25**
Horizontal alignment (W1-1, W1-2, W1-3, W1-4, W1-5), Combination Horizontal Alignment/Intersection (W1-10 series)	Rec.	Req.	Req.	Req.	Req.
Advisory Speed (W13-1P)	Rec.	Req.	Req.	Req.	Req.
Chevron Alignment (W1-8), One-Direction Large Arrow (W1-6)	Opt.	Rec.	Req.	Req.	Req.

Note: Opt. = optional (may be used), Rec. = recommended (should be used), Req. = required (shall be used).

THE ISSUE

The guidance from Research Projects 0-5439 and 0-6960 calls for setting curve advisory speeds based on the average truck speed at the midpoint of the curve (MC). This speed is typically 5–10 mph below the tangent speed even on gradual curves, as shown in Figure 22, for four-lane highways with a 75-mph regulatory speed limit. The graph shows the following trends:

- The "free-flow" speed is computed as the tangent speed on an approach tangent to a curve with a 5730-ft radius (or degree of curve = 1). It is shown as the solid blue line, with two dashed blue lines to indicate speed reductions of 5 mph and 10 mph.
- On four-lane divided highways and freeways (4D+4F), the average truck speed is more than 5 mph below the free-flow speed on all curves with a radius less than about 3000 ft. This speed is shown as the double red data series.
- On 4D+4F roadways, the average truck speed is more than 10 mph below the free-flow speed on all curves with a radius less than about 1700 ft.
- On four-lane undivided highways (4U), the average truck speed is more than 5 mph below the free-flow speed on all curves. This speed is shown as the single red data series.
- On 4U roadways, the average truck speed is more than 10 mph below the free-flow speed on all curves with a radius less than about 2100 ft.

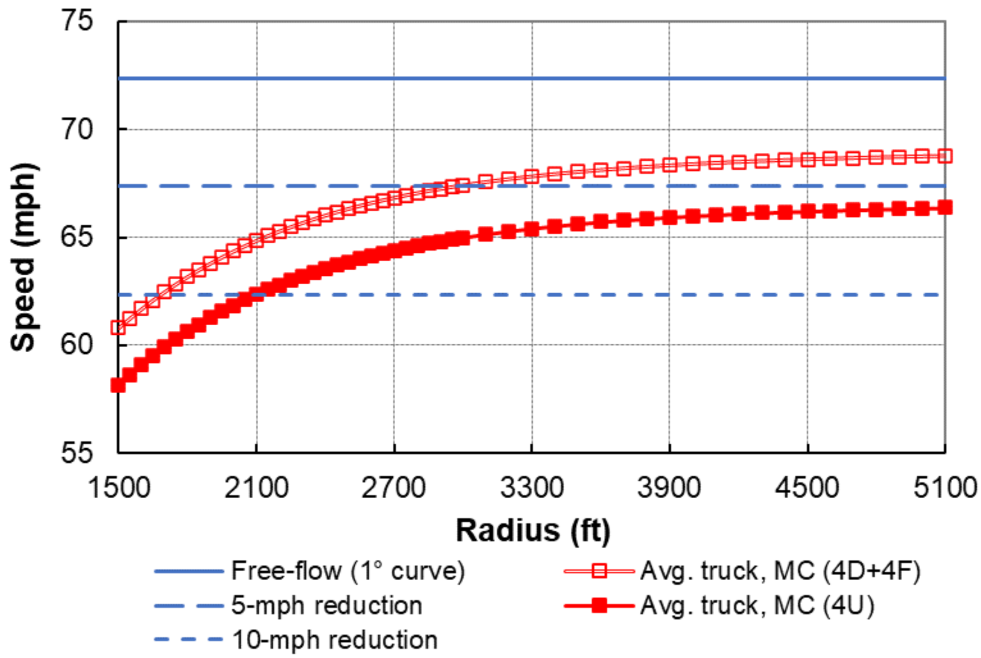


Figure 22. Speed Trends on Four-Lane Rural Highway Curves, 75 mph Speed Limit.

By comparison, see Figure 23, which shows that the average truck speed on a 75-mph two-lane undivided (2U) roadway does not begin to decrease notably until the radius decreases below about 2400 ft. This graph is based on the curve speed models from Research Project 0-6960 (*18*) for curves with a superelevation rate of 2 percent and a range of deflection angles. A superelevation rate of 2 percent is used to represent a curve that is built as a simple alignment change where the crown is reversed but no superelevation is otherwise provided.

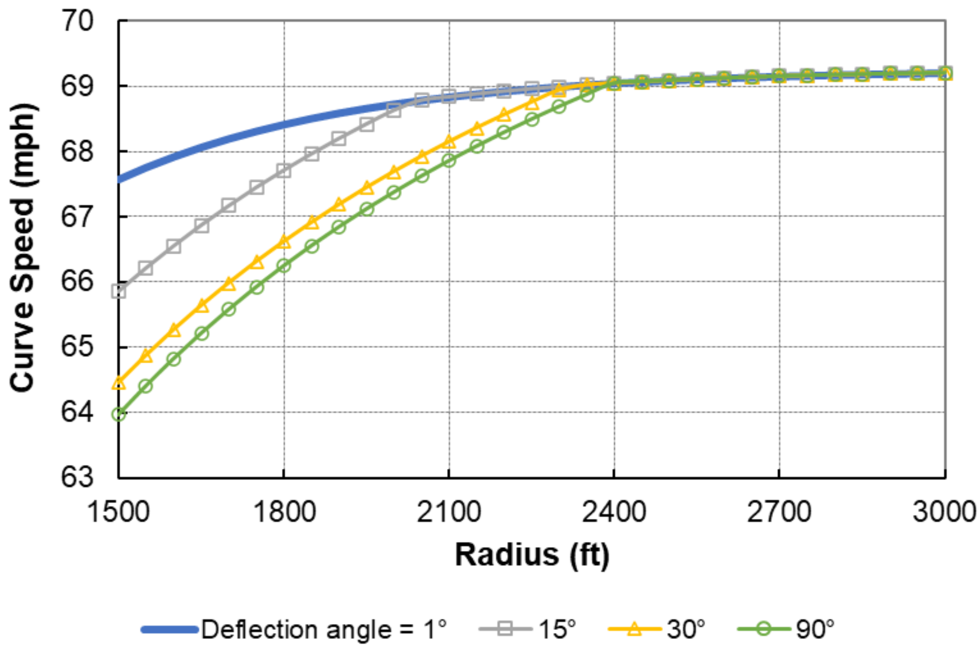


Figure 23. MC Speeds for Average Truck and 2-Percent Superelevation (2U Highway, 75-mph Regulatory Speed Limit).

As shown in Table 3, the TMUTCD recommends an Advisory Speed plaque if the computed advisory speed is 5 mph or more below the regulatory speed limit and requires one if the computed advisory speed is 10 mph or more below the regulatory speed limit. In all cases, the trends in Figure 22 suggest that advisory speeds need to be posted on many curves (e.g., curves with radii of about 2100 ft or less on a 4U roadway or curves with radii of 1700 ft or less on a 4D or 4F roadway) even though the trends in Figure 23 show that these curves would be considered gradual (i.e., would not involve a speed reduction of more than about 2 mph) on 2U roadways. A similar trend occurs for the 15-mph speed differential that corresponds to the posting of Chevron Alignment signs in Table 3.

In effect, district practitioners have found that when they have implemented the guidance from Research Projects 0-5439 and 0-6960 to evaluate curves on four-lane rural highways, a surprising number of seemingly gradual curves are being identified as needing Advisory Speed plaques and even Chevron Alignment signs. This issue was previously observed on 2U roadways with 75-mph regulatory speed limits, so a rule was added to the guidance framework to omit the Advisory Speed plaque if the average truck speed does not decrease between tangent and MC. The application of new curve speed models for four-lane rural highways has necessitated a reexamination of this issue. Should the same rule apply to four-lane roadways, or do vehicle speed trends justify a different rule (e.g., the average truck speed should be allowed to decrease below a certain threshold before the Advisory Speed plaque is needed)?

A related question that has arisen is which curves on the state highway system need to be evaluated—all curves or only those that meet certain criteria? Historically, many of the gradual curves that are being identified for new Advisory Speed plaques may not have been evaluated because they had been deemed too gradual based on engineering judgment or because they had not met the ball-bank indicator threshold of 10 degrees that was used as the threshold for posting advisory speeds before the advisory speed criteria were updated in Research Project 0-5439.

SPEED MODELS AND TRENDS

In Research Project 0-5439, the researchers calibrated models to predict vehicle speeds at the MC and on the approach tangent. These models form the basis for setting curve advisory speeds that are conservative but reasonable, since they allow the analyst to estimate the average truck speed at the MC and the amount of deceleration induced by the curve's geometry. These models take the following functional form:

$$v_c = \sqrt{\frac{15.0R_p\left(b_0 - b_1(1.47v_t) + 0.001b_2(1.47v_t)^2 + b_3I_{tk} + \frac{e}{100}\right)}{1 + 0.0322R_pb_2}} \leq v_t \qquad (1)$$

$$v_t = c_0\sqrt{V_{sl}}\left(1 - e^{c_1(R+100)/5730}\right) \qquad (2)$$

$$R_p = R + \frac{3.0}{1 - \cos\frac{\Delta}{2}} \qquad (3)$$

where:

- v_c = MC speed, mph.
- v_t = approach tangent speed, mph.
- R = curve radius, ft.
- R_p = travel path radius, ft.
- Δ = curve deflection angle, degrees.
- e = superelevation rate, percent.
- I_{tk} = indicator variable for trucks (= 1.0 if predicting truck speed, 0.0 otherwise).
- V_{SL} = regulatory speed limit, mph.
- b_i = calibration coefficients for MC speed model.
- c_i = calibration coefficients for approach tangent speed model.

The path radius term R_p in Equation 3 accounts for drivers' tendency to cut the curve by shifting up to 3 ft in the travel lane while traversing the curve. This curve-cutting behavior is limited by the curve's geometry, particularly its length and deflection angle. Figure 23 shows how drivers can maintain higher curve speeds by cutting the curve for deflection angles of 1 to 5 degrees but are limited in their ability to cut the curve once the deflection angle increases to about 15 degrees. Similarly, once the deflection angle increases to about 30 degrees, drivers run out of lateral space in the lane and can no longer cut the curve enough to maintain higher curve speeds.

In Research Project 0-5439, the researchers calibrated these models for 2U rural highways with regulatory speed limits of 70 mph or lower. In Research Project 0-6960, the researchers re-calibrated these models for 2U rural highways with regulatory speed limits of 75 mph, 4U rural highways with regulatory speed limits of 75 mph or lower, and 4D and 4F rural highways with regulatory speed limits of 80 mph or lower. To extend Equation 1 to four-lane rural highways, the researchers added indicator variables and calibration coefficients to the model to account for travel lane (i.e., left lane or right lane) and undivided highway configuration.

Figure 24 shows curve speed trends for the average truck on a 4D or 4F rural highway with a 75-mph regulatory speed limit and 2-percent superelevation rate. The trends are similar to those shown for 2U highways in Figure 23. Note the following observations:

- Overall, drivers adopt lower speeds on 4D and 4F rural highways than on 2U rural highways, given the same regulatory speed limit (75 mph), radius, and superelevation rate (2 percent). This trend is apparent from the different *y*-axis ranges for the two graphs.
- On 4D and 4F rural highways, drivers appear to decelerate for curves even with more gradual radii (e.g., more than 2850 ft, roughly equating to curves with degree of curve values of 2 or less). However, the magnitude of speed reduction on these gradual curves is small. This trend is apparent by noting that Figure 23 has "knees" where curve speeds do not begin to decrease by more than a nominal amount until the radius decreases to a value in the range of 2000 to 2300 ft (depending on deflection angle), while Figure 24 has no such "knees."

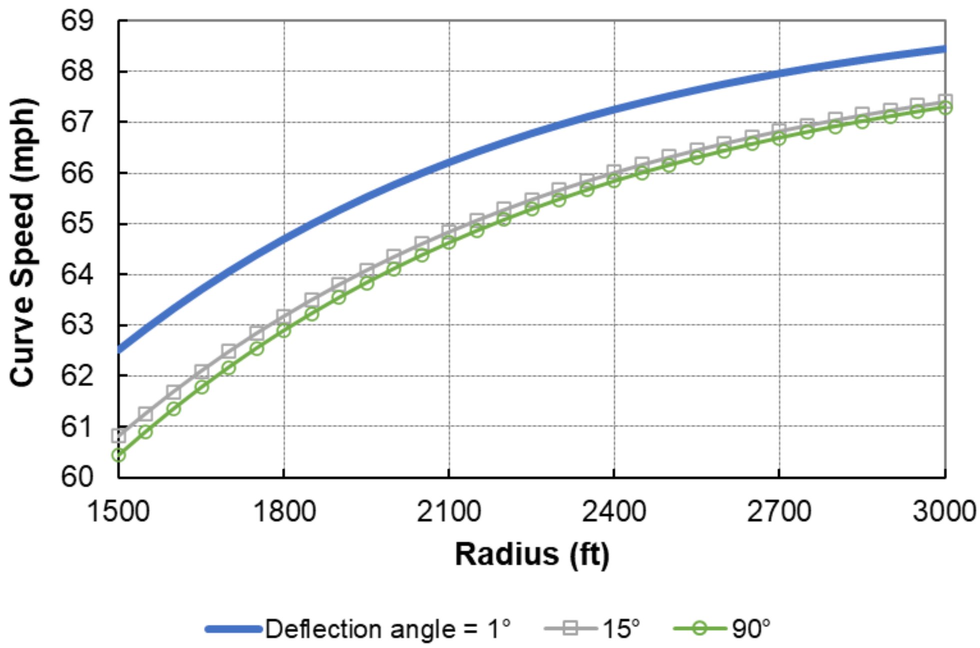


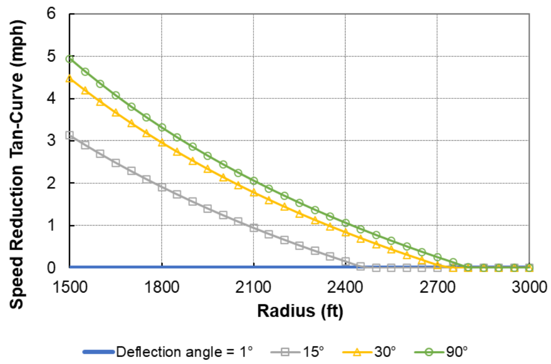
Figure 24. MC Speeds for Average Truck and 2-Percent Superelevation (4D or 4F Rural Highway, 75-mph Regulatory Speed Limit).

Figure 25 shows the magnitude of speed reductions from tangent to MC for four different types of rural highways. These magnitudes are computed by subtracting the predicted MC speed (using Equation 1) from the predicted tangent speed (using Equation 2). The following trends are apparent:

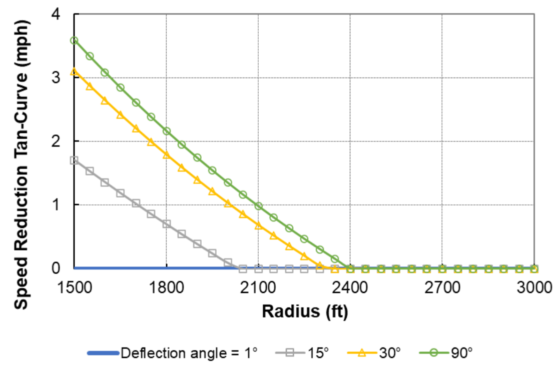
- Drivers decelerate more for the curve if the curve is on a highway with a lower regulatory speed limit (e.g., compare Figure 25a and Figure 25b). This trend has been noted elsewhere (*16*, *18*).
- Drivers decelerate more for curves on 4U rural highways than curves on 4D or 4F rural highways (see Figure 25c and Figure 25d).
- Speed reduction (as measured between approach tangent and MC) increases with decreasing radius on two-lane highways but decreases with decreasing radius on four-lane highways.

The latter observation seems counterintuitive but is explained by the differing coefficients c_0 and c_1 for the tangent speed models (Equation 2) for the different types of highways. These coefficients are provided in Table 4.

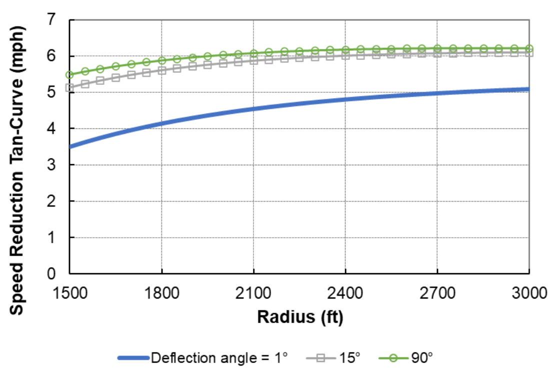
The trends for the radius coefficient (c_1) show that for two-lane highways with higher speed limits and four-lane highways drivers have a greater tendency to reduce their tangent speed in response to an upcoming curve. This trend is illustrated in Figure 26. The free-flow speed is estimated by computing the tangent speed for a curve with a radius of 5730 ft (or degree of curve = 1), and the tangent (Tan) speed is computed for the range of curve radii on the *x*-axis.



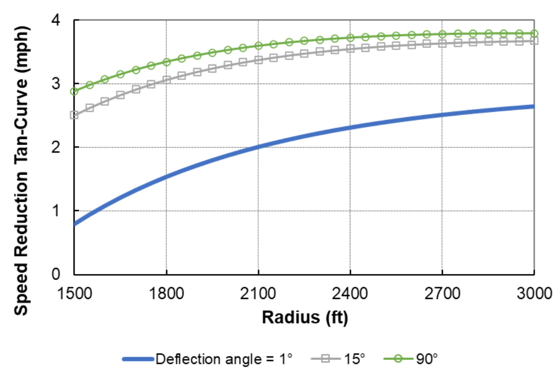
a. 2U, 70-mph Regulatory Speed Limit.



b. 2U, 75-mph Regulatory Speed Limit.



c. 4U, 75-mph Regulatory Speed Limit.



d. 4D or 4F, 75-mph Regulatory Speed Limit.

Figure 25. Speed Reduction Trends (Tangent to MC), 2-Percent Superelevation Rate.

Table 4. Tangent Speed Model Calibration Coefficients.

Highway Type	Speed Limit Coefficient Value (c_0)	Radius Coefficient Value (c_1)
Two-lane undivided, $V_{sl} \leq 70$ mph	8.57	-35.21
Two-lane undivided, $V_{sl} = 75$ mph	9.15	-13.29
Four-lane, $V_{sl} \leq 80$ mph	9.46	-7.44

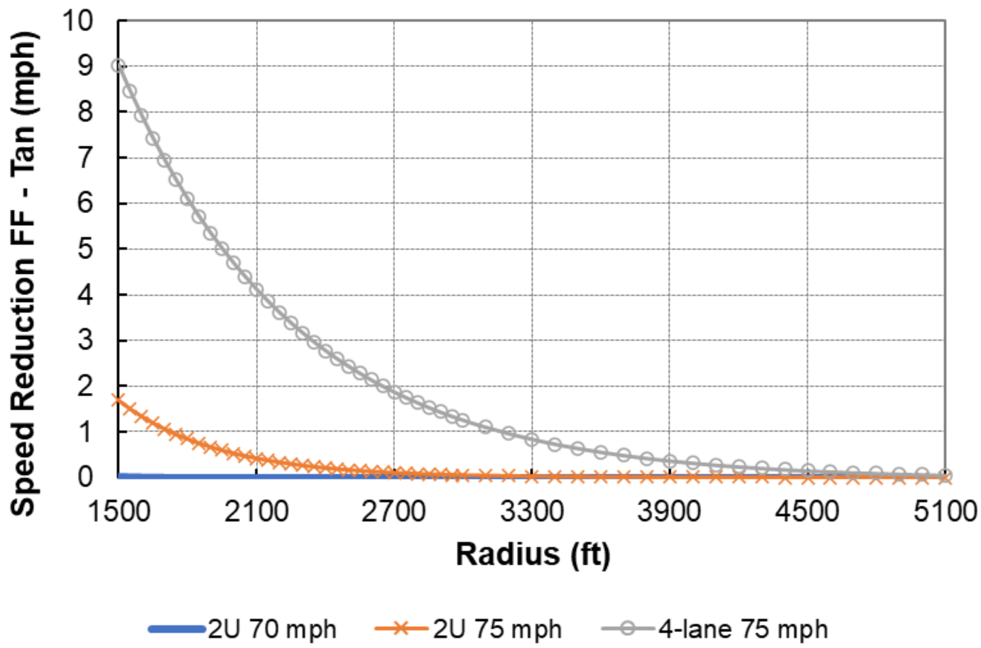


Figure 26. Speed Reduction Trends (Free-Flow—Tangent), 2-Percent Superelevation Rate.

The most notable trend on Figure 26 is the gray data series, which shows significant speed reductions on the approach tangent, reaching values of 5 mph for a curve radius of about 1950 ft. Most of the sites in the dataset used to calibrate this model did not have Advisory Speed plaques, but drivers still saw the curves and reduced their speed notably before arriving at the point of curvature (PC). Table 5 summarizes the key site characteristics; full details are available elsewhere (*18*, Table 5 and Table 6).

Table 5. Four-Lane Highway Curve Site Characteristics.

Characteristic	4U	4D	4F
Number of sites	12	10	10
Range of radii (ft)	865–1891	1793–2848	2821–5316
Range of regulatory speed limits (mph)	55–75	60–75	65–80
Number of sites with an Advisory Speed plaque	2	0	0

CANDIDATE PROCEDURE REVISIONS

In Section 2C.01 of the TMUTCD it states that the purpose of a warning sign is to “call attention to unexpected conditions” and to “alert road users to conditions that might call for a reduction of speed or an action in the interest of safety and efficient traffic operations” (*1*). The purpose of curve traffic control devices, particularly the Advisory Speed plaque, is to alert drivers that a curve is present and is sufficiently sharp that drivers need to reduce speed. Vehicles can slide off the pavement or trucks can roll over, if their drivers do not decelerate adequately, and most of the deceleration should ideally occur on the approach tangent to the curve.

With this rationale in mind, and considering the speed reduction trends that have been observed on the approach tangents to curves on four-lane rural highways (see Figure 26), the researchers suggest the following revisions to curve evaluation procedures *for four-lane rural highways*:

1. If the average truck speed at the MC is 10 mph or more below one of the following three threshold values, then a horizontal alignment sign alone may be posted in advance of the curve. An Advisory Speed plaque may also be posted, but is not required, if a rounded advisory speed is obtained for the curve.
    a. Regulatory speed limit.
    b. Estimated average truck free-flow tangent speed.
    c. Estimated average truck curve speed for a 1-degree curve (i.e., radius = 5730 ft) with the same superelevation rate and deflection angle as the curve of interest.
2. If the average truck speed at the MC is 10 mph or more below two or more of the three thresholds, a horizontal alignment sign and an Advisory Speed plaque shall be posted in advance of the curve. Set the advisory speed equal to the rounded advisory speed obtained from the curve engineering study.

The researchers suggest the following revisions to curve evaluation procedures *for all rural highways*:

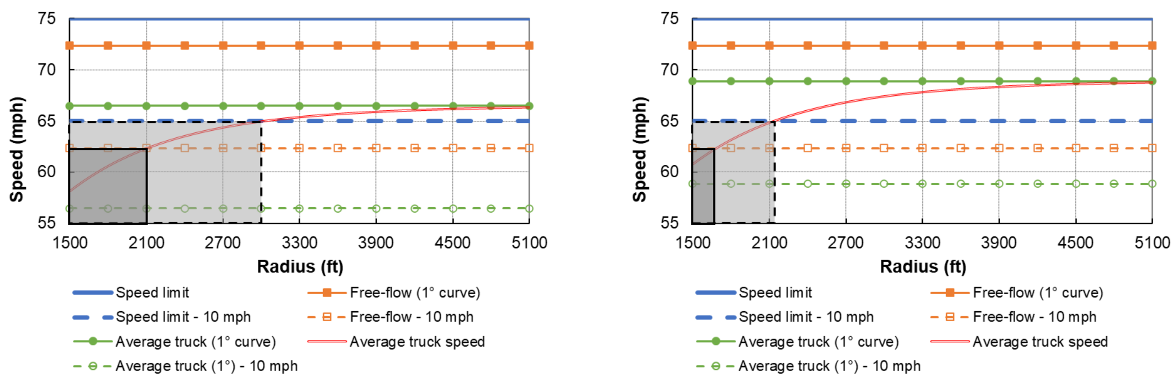
3. If a rounded advisory speed is obtained for a curve with a deflection angle of less than 15 degrees, the Advisory Speed plaque may be omitted, but a horizontal alignment sign alone may be posted in advance of the curve if justified based on engineering judgment.
4. The curve evaluation guidance in the TMUTCD and accompanying documents (e.g., the *Procedures for Establishing Speed Zones* manual and the *Horizontal Curve Evaluation Handbook*) is intended for curves that are built as horizontal alignment changes on continuous highway sections, not for scenarios where a curve is actually a change in routing, such as when a signed highway route turns a corner at an intersection.

Revisions 1 and 2 are applied in tandem and represent a recognition that there are some curves on four-lane rural highways that do not need to be treated with Advisory Speed plaques because most drivers decelerate before arriving at the curve PC. These curves may fall within a lesser category where a small degree of warning (e.g., a horizontal alignment sign alone) may be justified.

Revision 3 is intended to reduce the use of Advisory Speed plaques in situations where a curve may exist but likely does not function as a notable horizontal alignment change. Curves addressed by this revision deflect by a sufficiently small amount that drivers can easily “cut” the curve and traverse it at tangent speed or with minimal speed reduction. Revision 4 is intended to clarify the application scope of horizontal curve evaluation guidance.

Revisions 1 and 3 represent a departure from TxDOT's current position that the TMUTCD does not allow the posting of a horizontal alignment sign without an accompanying Advisory Speed plaque. The researchers suggest a review of this position considering the concerns that the advisory speed guidance is resulting in too many new plaques being required based solely on the speed differential between the regulatory speed limit and rounded advisory speed.

Figure 27 shows the effect of these revisions on the aforementioned example curves with a 2-percent superelevation rate and 15-degree deflection angle. The lighter shaded regions with the dashed lines represent curves where a horizontal alignment sign alone may be posted, and the darker shaded regions with the solid lines represent curves where a horizontal alignment sign and an Advisory Speed plaque shall be posted.



a. 4U, 75-mph Regulatory Speed Limit, 2-Percent Superelevation.

b. 4D or 4F, 75-mph Regulatory Speed Limit, 2-Percent Superelevation.

Figure 27. Illustration of Candidate Procedure Revisions.

The candidate policy revisions would result in no advisory speeds being posted on very gradual curves, such as curves with radii of 2865 ft or greater (or degree of curve = 2 or less). TRAMS is designed to ignore curves in this radius range because (a) speed reductions on these curves are negligible (as shown by the red data curves in Figure 27) and (b) minor steering fluctuations within a lane on a tangent often include short "curves" with these large radius values.

To determine the effect of the candidate policy revisions, the researchers obtained curve data for the districtwide curve engineering study effort from TxDOT's El Paso District. This effort included 2095 curves, 214 of which were on four-lane highways (i.e., 32 on 4U rural highways and 182 on 4D or 4F rural highways). Table 6 shows a count of the four-lane highway curves based on the results of the curve advisory speed calculations (using the TRAMS and TCES tools and the procedures described in the *Horizontal Curve Evaluation Handbook*) and the changes that would occur if the candidate policy revisions were adopted. In the first data row of Table 6, there are 130 curves that do not require Advisory Speed plaques because no rounded advisory speed was obtained from the curve evaluation process (i.e., the TCES program did not provide one). There are another 59 curves in the last data row that have rounded advisory speeds and meet two or more of the thresholds in the candidate policy revisions. For these curves, the candidate policy revisions do not require any changes.

Table 6. Examination of El Paso Curve Guidance (All Four-Lane Curves).

Existing Guidance	Candidate Policy Revision			Results	
Rounded Advisory Speed Obtained?	**One Threshold Met?**	**≥ Two Thresholds Met?**	**Advisory Speed Needed?**	**Number of Curves**	**Comment**
No	Not applicable	Not applicable	No	130	No change
Yes	Yes	No	No	17*	Change in less conservative direction
Yes	Yes	Yes	May post	8*	Change in less conservative direction
Yes	Yes	Yes	Shall post	59	No change

** These curves need Advisory Speed Plaques per existing guidelines, but the candidate policy revisions allow the Advisory Speed Plaques to be omitted.*

In the second and third data rows of Table 6, there are 25 curves that have rounded advisory speeds, and the advisory speeds would be required without the candidate policy revisions but may be omitted if the candidate policy revisions are adopted. These curves are indicated with asterisks in the table. For an advisory speed to be computed in the TCES program, both of the following conditions must be met:

- The average truck speed is 5 mph or more below the regulatory speed limit after the appropriate rounding (i.e., add 1 mph and round down to the nearest 5-mph multiple).
- The average truck speed at the MC is less than the average truck speed on the approach tangent.

The researchers examined these 25 curves to determine the reasons that the curves were not required to have Advisory Speed plaques based on the candidate policy revisions. They found that 17 of the curves had rounded advisory speeds that were only 5 mph below the regulatory speed limit. All 17 of these curves had regulatory speed limits of 60 mph and a rounded advisory speed of 55 mph. Posting these advisory speeds would not be required per TMUTCD guidance. Eight curves had rounded advisory speeds that were 10 mph or more below the regulatory speed limit. Seven of these curves were on highways with a regulatory speed limit of 75 mph and one was on a highway with a regulatory speed limit of 80 mph. All eight curves had deflection angles less than 7 degrees. As shown in Figure 25, curves with such small deflection angles do not entail significant speed reductions, since drivers can shift in the lane to cut the curve and increase the path radius.

TxDOT should review and consider implementing these candidate policy revisions. If some or all the candidate revisions are adopted, they will need to be documented in the following documents:

- *Procedures for Establishing Speed Zones* manual, Chapter 5.
- *Horizontal Curve Evaluation Handbook* (updated version or addendum document).
- TMUTCD, Section 2C.

It should be noted that Chapter 5 of the *Procedures for Establishing Speed Zones* manual contains other material that reflects guidance that was developed in Research Project 0-5439. Specifically, Figure 5-2 (which shows the dotted line and the contour line defining the upper limit of severity category B from Figure 21) and its surrounding discussion reflect the 0-5439 guidance for determining if an Advisory Speed plaque is needed. That guidance is no longer consistent with the TMUTCD. Additionally, the description of the GPS Method procedure in the *Procedures for Establishing Speed Zones* manual reflects the curve analysis programs that have since been updated (i.e., a new version of TRAMS has been distributed and TCES has replaced TCAS). New guidance for using these programs is documented in the *Horizontal Curve Evaluation Handbook*. Hence, Chapter 5 of the *Procedures for Establishing Speed Zones* manual is due for revision in light of these changes. The GPS Method procedure could be removed and replaced with a reference to the *Horizontal Curve Evaluation Handbook* to avoid duplication.

Additionally, the candidate policy revisions would require revisions to be made to the TCES tool, and updated copies of the tool would need to be distributed to district practitioners and others (e.g., consultants) who have been using TCES to evaluate horizontal curves.

Finally, in cases where curve engineering studies have already been conducted and Advisory Speed plaques have already been posted on curves that would no longer require them under the candidate policy revisions, the Advisory Speed plaques could be removed. This action would help TxDOT avoid posting advisory speeds that are too low to be credible from the perspective of most drivers.

CHAPTER 4: INVESTIGATION OF COUNTERMEASURES FOR UNEXPECTED PEDESTRIANS ON HIGH-SPEED ROADS

INTRODUCTION

The TxDOT El Paso and Laredo districts have seen an increase in pedestrian crashes involving undocumented persons crossing high-speed limited access roadways to avoid being apprehended by authorities. The purpose of this activity was to understand if other TxDOT districts and U.S. southern border states have also been experiencing this concern and, if so, to learn what countermeasures have been planned or implemented to address the concern. To gain this information, TxDOT requested that TTI contact all TxDOT districts along the border and in urban areas as well as several other state departments of transportation (DOTs) to interview key individuals. Following a literature review, researchers conducted 12 interviews with TxDOT districts and the border state DOTs. This chapter details the literature review, interview findings, and conclusions.

BACKGROUND

With 3896 fatal traffic collisions in 2020, Texas ranks highest in the total number of traffic fatalities among all states of the United States (*20*). On average, one person is killed on Texas roads by motor vehicles every two hours and 15 minutes (*21*). Although considerable research has been conducted to address pedestrian safety, researchers often neglect one crucial aspect that leads to traffic fatalities—pedestrians on high-speed roadways. In 2020, 214 pedestrians were killed on streets with a speed limit between 50 and 70 mph, 93 percent of which occurred midblock. Another 40 pedestrians were killed on roadways with a speed limit above 70 mph, and none of these crashes occurred at intersections. Together 254 pedestrians were killed on high-speed roadways in 2020, which exceeds the 250 fatalities caused by driver inattention and 141 fatalities caused by driver fatigue and drowsiness.

When pedestrians fail to yield the right of way to motor vehicles, the crashes can result in serious consequences. In 2020, less than 1 percent of all reported crashes in Texas led to fatalities (*22*). However, when collisions involve pedestrians on high-speed roadways, the fatality rate dramatically increases. For roads with a speed limit between 50 and 70 mph, 617 crashes involved pedestrians and 34.8 percent of these crashes resulted in a fatality. For roadways with a speed limit above 70 mph, the fatality rate reaches 59.7 percent. In addition to the safety hazard to pedestrians, the random appearance of pedestrians on high-speed roadways can surprise drivers, leading to sudden braking and changing direction (*23*), which may cause drivers to hit or run over other objects. In 2020, eight vehicle drivers were killed trying to avoid hitting pedestrians that appeared on high-speed roadways.

LITERATURE REVIEW

Undocumented immigrants running across high-speed limited access roadways to avoid being apprehended by authorities is known as a factor that contributes to the higher pedestrian fatality rates of bordering states. Pedestrian crash densities on interstate highways were calculated in a 1997 study (*24*). Authors of the study found that Texas' pedestrian safety ranked the worst in the country. Pedestrian safety in New Mexico and other states bordering Mexico also ranked poorly. Undocumented immigrants crossing highways was believed to have caused these states to rank among the worst in pedestrian safety on interstate highways (*24*).

In 1989, it was estimated that about 2000 to 3000 undocumented immigrants crossed the border near San Ysidro, California, on weekdays, and on weekends the number jumped to 5000 to 10,000 per day. Most of the undocumented immigrants were young adult males from rural areas. During that time, the pedestrian fatality rate on the IH 5 border was 8.515, while the national average was 0.216 (*25*). Between 1987 and 1991, at least 227 pedestrians were struck by vehicles, resulting in 127 fatalities. These crashes mainly occurred between 8:00 p.m. and midnight (*26*).

More recently, studies uncovered the discrepancy of pedestrian behavior between developed nations and developing nations. Case studies based in South Africa (*27*), Bangladesh, and Mexico City (*28*) found that highway pedestrian fatalities accounted for 40 to 50 percent of all pedestrian fatalities in developing nations (*28, 29*), while in the United States the percentage was about 10 percent. Dangerous crossings, which refers to pedestrians crossing the highway at a location without any form of traffic control, inadequate crossing structures, and negative perception of pedestrian safety on the highway, are much more frequent in the developing nations (*28*). In developing countries, motor vehicle traffic is commonly mixed with pedestrian traffic on highways (*23*). In Cape Town, South Africa, crossing the highway is sometimes perceived as the “only viable option” for pedestrians (*27*).

Undocumented immigrants, new to the United States, face a greater risk of being involved in pedestrian crashes (*27*). Some undocumented immigrants may be unaware of the motor vehicle speed on the highway and may mistakenly think that the drivers can see them at night. Some undocumented immigrants wear leather-soled boots, which can be slippery on the highway pavement (*27*).

To complicate matters, vehicle operators in the United States are unprepared for the sudden appearance of pedestrians crossing the highway. An interview of five drivers who struck undocumented immigrants stated that the motorists driving at night are unaware that undocumented immigrants might appear on the road. They said that the undocumented immigrants “appeared from nowhere” (*25*).

Previous research regarding countermeasures is limited. California is the only state that tested a countermeasure specifically focused on reducing undocumented immigrant fatalities when crossing the highway near border regions in and around San Diego. In 1990, to address the increasing fatalities involving undocumented immigrant on highways, the California Department of Transportation (Caltrans) installed a “Caution Watch For People Crossing Road” warning sign (see Figure 28) and later replaced it with a more distinguishable symbol to warn drivers about the potential safety risk. The newer yellow rectangle signs show two adults and a child running (see Figure 29). The image was the source of controversy as some saw it as an offensive caricature of Mexican immigrants (*30*). Around the same time that the signs were erected (1994), California started the Operation Gatekeeper program, which constructed fences and militarized the border areas between San Diego and Mexico. These efforts successfully reduced the number of pedestrian crossing attempts into the San Diego/Chula Vista/San Ysidro region, forcing undocumented immigrant traffic to move eastward to Arizona (*26*). Thus, the effectiveness of the signs could not be examined.

Figure 28. CAUTION WATCH FOR PEOPLE CROSSING ROAD Warning Sign.

Figure 29. Rectangular Symbol Sign.

Other studies investigating general pedestrian safety on high-speed roadways separated highway pedestrians into intentional pedestrians and unintended pedestrians. Unintended pedestrians are typically drivers of vehicles that have been involved in a minor crash or break down who then get out of the vehicle. Bystanders may stop to render aid and exit their vehicle to do so. Once out of the vehicle, they are considered pedestrians. Intentional pedestrians enter the interstate highway on purpose, such as making a shortcut to nearby destinations (*31*). Knowingly crossing the highway, intentional pedestrians are similar to the undocumented immigrants.

Past studies rely on pedestrian collision data to understand the nature of the issue (*25, 32*, *27*). Other data sources include surveys from DOT employees (*31*) and traffic speed/vehicle size data collected at the crash site (*23*). Some studies successfully identified locations that are collision prone (*32*, *23*, *27*). Other studies, particularly those that discuss undocumented immigrants, were not able to identify locations that are of high risk. Due to the nature of the problem, the undocumented pedestrian crossing locations are usually random. For the undocumented immigrants, crossing the highway is likely only one of the challenges that they have to overcome. When crossing, the undocumented immigrants reportedly hide in bushes near the highway, waiting for a break from the highway traffic (*25*).

Although California is the only state that designed safety measures to address undocumented immigrant road safety, other states actively developed countermeasures to increase pedestrian highway safety in general. A 1997 study collected information from the National Association of Governors Highway Safety Representatives (now the Governors Highway Safety Association). The most mentioned countermeasure to keep pedestrians off the highway was either fencing or creating a public education campaign. Other suggestions included providing better signs to warn drivers (*24*); adding lighting, overpass/underpass, barriers, and signs or markings; or increasing law enforcement (*31, 32*). Others mentioned adding dynamic message signs (*31*), increasing the road friction (*29*), and adding a glare screen median pedestrian fence (*33*).

Adding pedestrian and driver warning signs was found to be the most cost-effective countermeasure by some studies. Installing pedestrian warning signs was found to decrease pedestrian collisions by 15 percent (*34*). However, the study was focused on overall pedestrian crashes. Also, some have concerns that pedestrian warning signs induce more pedestrian crossings on the highway (*31*).

The design of the pedestrian warning signs should consider the language and its potentially controversial political and cultural meanings. A 1991 study found that 78 percent of undocumented immigrants could not read; however, they said they could recognize a few Spanish words, such as “eligo,” but not English (*25*). Texas, California, Arizona, and Rhode Island have installed warning signs to reduce pedestrian-related interstate highway collisions (*32*). The design of the sign should consider the graphics and readability as well as high visibility reflectivity to increase effectiveness (*31*).

BORDER CROSSINGS

As of 2016, the U.S. Department of Homeland Security estimated the number of undocumented immigrants in the United States to be 12.3 million. Other agencies' estimates ranged from 8.3 million to 27.5 million using different models and assumptions (*35*). Of these undocumented immigrants, around 42 percent are women and 17 percent are under 18 years old (*36*). In 2010, there were an estimated 1.65 million undocumented immigrants in Texas, representing 6.7 percent of the total population (*37*).

The U.S.-Mexico border has historically been a significant transportation route for undocumented immigrants. Most undocumented immigrants enter the United States from the southern border, mainly from Mexico (*38*). Recent trends indicate that the number of undocumented immigrants entering the United States from the U.S.-Mexico border is rising rapidly.

The U.S. Customs and Border Protection collects and publishes data about border patrol apprehensions and field operation inadmissible subjects encountered along the U.S.-Mexico border (*39*). According to the data, the number of encountered undocumented immigrants crossing the U.S.-Mexico border has increased from 977,509 in fiscal year 2019 to 1,734,686 in 2021, a 77.5 percent increase. The trend has accelerated during the first three months of fiscal year 2022 (i.e., October through December of 2021), in which 518,360 undocumented immigrants were recorded crossing the border, a 137.8 percent increase from the same three-month period in the previous year.

In March of 2021, Texas began Operation Lone Star to focus on border security, combining the efforts of the Texas Department of Public Safety (DPS) and the Texas National Guard (*40*). According to one report, troopers engaged in more than 100 pursuits in counties on or near the border over the course of one month as part of Operation Lone Star (*41*). The increased number of undocumented immigrants crossing combined with the increased efforts to address border security may have had an impact on the number of crashes involving pedestrians who were crossing interstates to evade authorities.

PEDESTRIAN SAFETY ON TEXAS INTERSTATES

The concern of pedestrian safety on interstates has received a fair amount of attention by TxDOT as well as local transportation agencies. Even though pedestrians are not expected on the main lanes of limited access highways, recent studies in Texas show that pedestrians do indeed stand on, walk along, and cross main lanes of limited access highways (see photo in Figure 30). A research study conducted by TTI in 2017 reviewed each of the crash reports for all fatalities involving pedestrians on interstates in Texas. Researchers found that 21 percent of all fatal pedestrian crashes occurred on highways (i.e., main lanes, entrance/exit ramps, and main lane medians/shoulder). Almost one-third of those were found to be related to a stranded vehicle.

Also, the study showed that "most fatal crashes are associated with dark conditions, midblock locations, and high-speed roadways" (*42*).

Figure 30. Pedestrian Crossing the Main Lanes of a Texas Interstate.

In Austin, TTI collected video data for a week in February of 2019 in a section of IH 35 where crossings had been occurring. Results indicated that on average, one pedestrian crossed the main lanes per day over the seven-day period. It appeared that the pedestrians were traveling from the hotels on the west side of the highway to destinations such as fast food and shopping located on the east side of the highway.

In 2018, the Austin District installed No Pedestrian Crossing symbol signs (R9-3) and stenciled no pedestrian crossing symbols on the concrete median barrier along this section of the highway. (see Figure 31 and Figure 32, respectively). In 2020, the district installed an additional barrier on top of the existing concrete median barrier to reduce pedestrian crossings (see Figure 33).

Other evidence of pedestrian activity has been documented by people who call 9-1-1 to report a pedestrian on a high-speed roadway. The call code was established by the Austin Police Department (APD) to understand pedestrian safety concern locations. Over 3600 9-1-1 calls were made to APD about pedestrians on IH 35 between April 2017 (when the call code was established) and December 2019. This equated to about 180 calls per month within the Austin city limits. Figure 34 shows a density map of the 9-1-1 call data.

At a broader level, TxDOT implemented the Texas Strategic Highway Safety Plan (SHSP) in 2016 to address motor vehicle fatalities on Texas roads. Since its implementation, Texas saw decreasing motor fatalities and fatality rates from 2016 to 2019. The plan has seven emphasis areas, which includes pedestrian safety. The report pointed out that 79 percent of pedestrian fatalities occurred at nighttime and impaired pedestrians caused 67 percent of the fatalities.

Figure 31. No Pedestrian Crossing Sign on IH 35 in Austin.

Figure 32. No Pedestrian Crossing Stencil and Signs on IH 35 in Austin.

Figure 33. Stencil and Barrier on Top of Center Median on IH 35 in Austin.

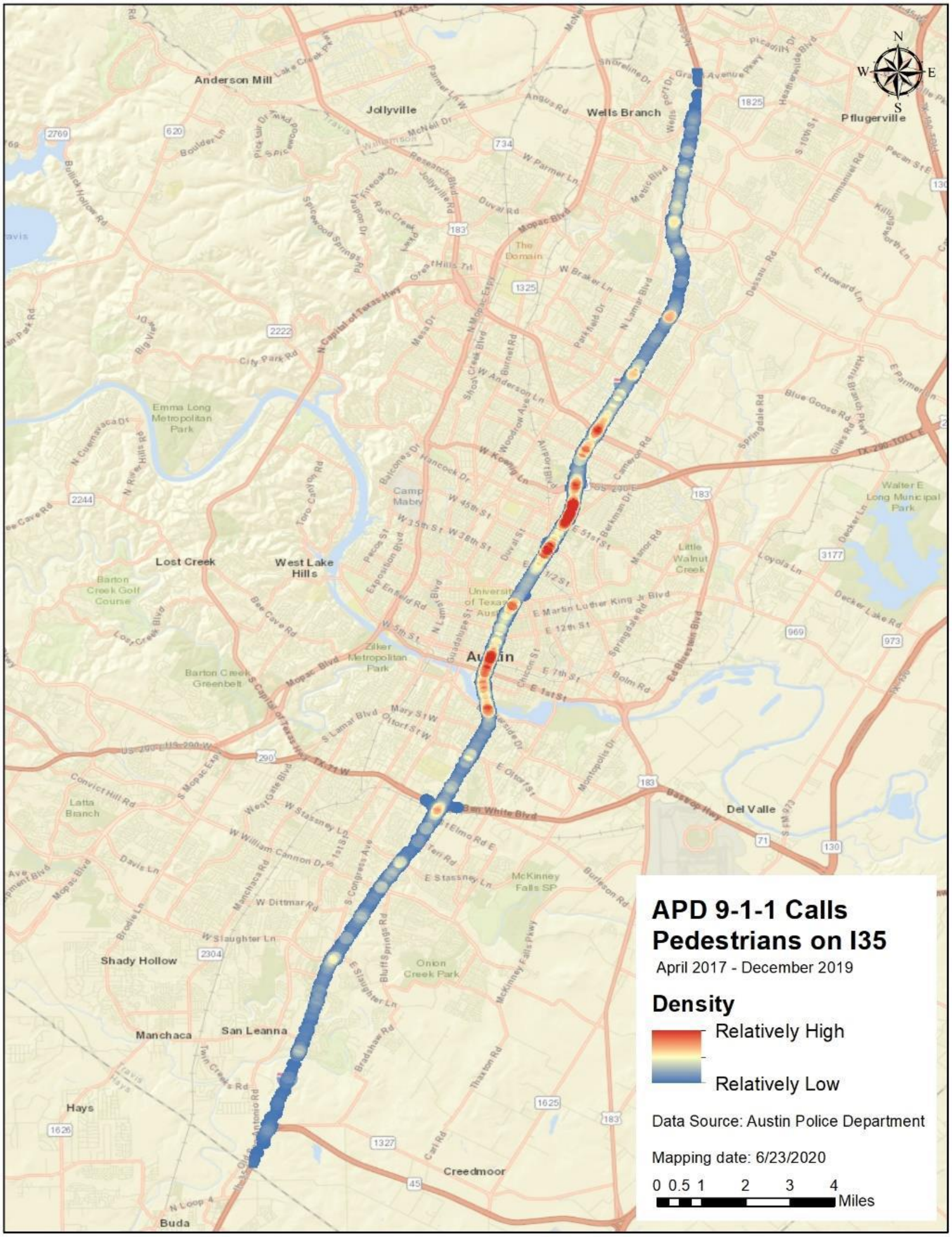


Figure 34. 9-1-1 Call Data Heat Map on IH 35 in the City of Austin Limits.

The plan recommended strategies and countermeasures for unintended pedestrians, impaired pedestrians, and frequent crossings in high-demand areas. These countermeasures included building a public service announcement campaign, expanding courtesy patrol programs, providing high-visibility enforcement of targeted behaviors, and adapting the impaired driving message to impaired walking and biking. Other recommendations included improving nighttime visibility and controlling vehicle speed as countermeasures to address pedestrian fatalities.

SHSP created 77 programs and projects related to pedestrian safety issues, including Highway Safety Improvement Program, Vision Zero, and driver feedback signs. However, no project specifically addresses undocumented immigrants crossing border areas.

INTERVIEW FINDINGS

Researchers sent emails and made phone calls to 16 TxDOT and U.S. state district offices. Researchers contacted TxDOT districts along the Texas/Mexico border (i.e., El Paso, Laredo, Pharr, and Odessa) and urban districts (i.e., Austin, Dallas, Fort Worth, Houston, and San Antonio) for interview (see Figure 35). Figure 36 shows the other state DOTs that were contacted. Overall, researchers conducted 12 interviews. The questions centered on experiences and countermeasures considered, planned, and implemented. The final questions were about the potential of signs alerting drivers to the increased likelihood of pedestrians as an effective and low-cost option. This section describes the findings in three categories: border districts, urban districts, and border state DOTs.

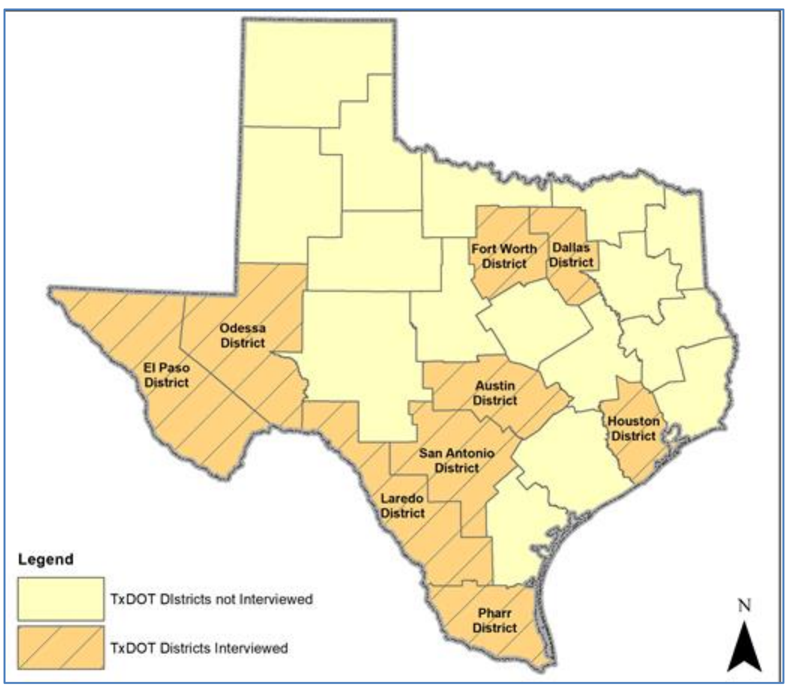
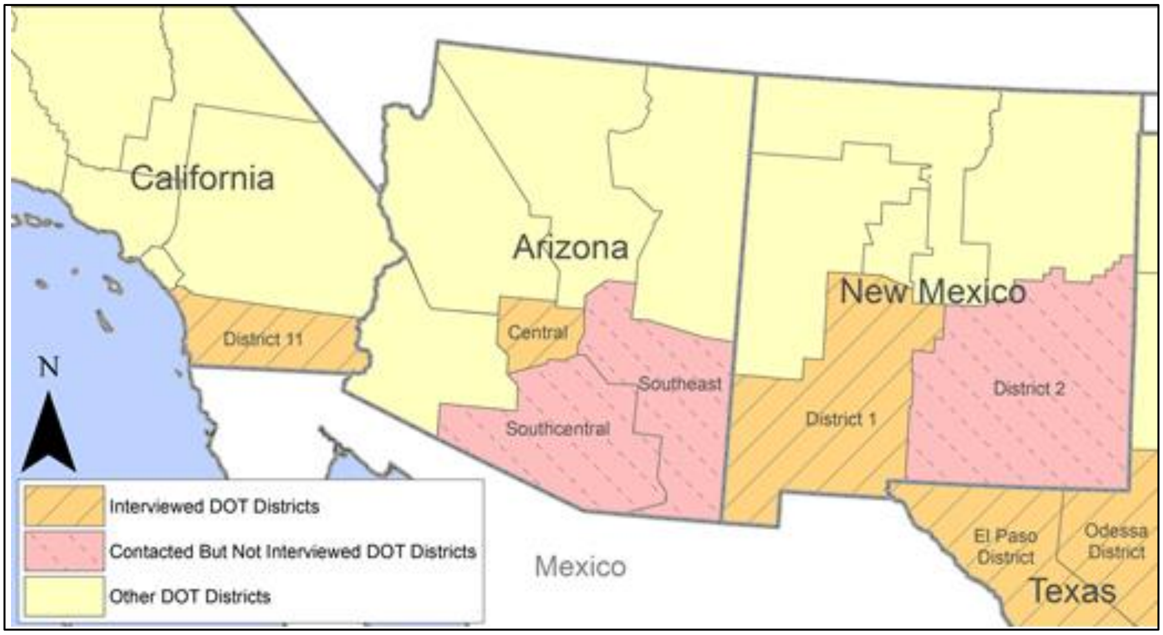


Figure 35. TxDOT Districts Contacted for Interview.



Data source: Texas Department of Transportation (43) and U.S. Census Bureau (44).

Figure 36. State DOT Districts Contacted for Interview.

TxDOT Border Districts

Researchers contacted staff from all four border districts (i.e., El Paso, Laredo, Odessa, and Pharr) to learn about experiences with pedestrians on limited access highways, specifically about undocumented persons being struck. The main takeaways from the discussions include the following:

- Laredo and El Paso districts have had an increase in pedestrians involved in crashes on interstates in recent months; these pedestrians turned out to be undocumented immigrants crossing to evade border patrol officers. The Pharr District experienced a recent pedestrian fatality involving a pedestrian crossing an interstate roadway as well.
- Unintended pedestrians (i.e., stranded motorist or good Samaritan who exits vehicle) have also been in crashes in the Laredo District.
- Some crashes follow a high-speed chase that ends in people exiting the vehicle while others involve drivers stopping on the shoulder to let undocumented people out of the vehicle.
- Intentional pedestrians are also involved in crashes. Loop 250 in Midland was mentioned where minors cross to get to the store or movie theater. Other intentional pedestrians could be hitchhiking or just walking on the shoulder.
- Pedestrian crashes are mainly happening:
  - At night.
  - In urban areas.

    - Where the interstate cross section is flat with open access.
    - On frontage roads (though this is not a focus of this study).
- There is a lack of coordination between border patrol and DOTs, which is a barrier to addressing pedestrian safety issues on limited access highways. It was suggested that coordinating with border patrol is critical in identifying locations to implement countermeasures.
- Countermeasures implemented/considered:
    - Lighting along the interstates.
    - Overpasses/underpasses.
    - Median barriers (similar to Austin District).
    - Barrier stencil markings (similar to Austin District).
    - Safety corridor signs.
    - Enforcement.
    - Public engagement.
- Crash data from TxDOT Crash Records Information System (CRIS) are used to help make decisions.

TxDOT Urban Districts

Researchers interviewed five urban districts (i.e., Austin, Dallas, Fort Worth, Houston, and San Antonio) to learn about experiences with pedestrians on limited access highways. Although the type of pedestrian may be different, the ways to address the concern may be similar. The following bullets highlight the interview findings:

- Clusters of pedestrian crashes have been identified in most of the urban districts.
- Persons experiencing homelessness were mentioned as those involved in the pedestrian crashes.
- Intentional and unintended pedestrian crashes have been occurring.
- All of the urban districts have motorist assistance programs. The San Antonio District saw a reduction in unintended pedestrian crashes related to good Samaritans after implementing its safety service patrol.
- Crash data from TxDOT CRIS are used.
- Data needs include impairment data, whether the person is undocumented or unsheltered, and pedestrian count data for before/after studies. There is also a need for camera surveillance or other technology to detect pedestrians. One district was interested in 9-1-1 call data, while another mentioned that 9-1-1 call data require too much processing to make them helpful.
- All urban districts mentioned the use of a fatality review team/process. The Fort Worth District mentioned that staff reviews each pedestrian incident.

- Pedestrian crashes are mainly happening:
  - At night.
  - In densely populated urban areas.
  - Where shopping, food, and other destinations are on one side of the roadway and apartments, hotels, and bus depots are on the other side of the roadway.
  - In low-income areas.
  - Where there is a clear line of sight to the other side of the roadway. Most mentioned that the main lanes are flat.
  - Crash clusters were identified by most; others said that the crashes appear to be random.
- Countermeasures implemented/considered:
  - Fencing/barriers along the concrete median barrier or in the median. Glare fencing was used in the Fort Worth and Dallas districts. Fencing along the frontage road was considered but decided it was not appropriate. Pedestrians continued to cut down and break fences to make shortcuts in both the Austin and San Antonio districts.
  - Austin District staff are working with the city staff to address pedestrian safety on interstates.
  - The Austin District is the only district to paint no pedestrian crossing symbols on the concrete median barrier. The Austin District also installed No Pedestrian Crossing symbol signs (R9-3). The San Antonio District is currently installing No Pedestrian Crossing symbol signs.
  - Traffic safety specialists in the districts are assisting in increasing awareness of the issue.
  - Lighting added. However, the San Antonio District suggested that one of their past studies showed that illumination projects caused highway pedestrian collisions to increase.
  - Grade separated crossings.
  - Outreach/education in general about pedestrian safety concerns.

Other State DOTs

Researchers contacted staff from all three border state DOTs (i.e., New Mexico, Arizona, and California) to discover their experiences with pedestrian safety on limited access highways. The following bullets highlight the feedback received:

- Caltrans had issues many years ago with undocumented immigrants crossing interstates, but that issue was resolved when the border crossing was moved to a different location.
- Both New Mexico and Arizona DOTs have developed studies to address pedestrian safety. Arizona has a State Pedestrian Safety Action Plan where pedestrians crossing interstates are specifically mentioned.

- People experiencing homelessness crossing interstates was specifically mentioned by both New Mexico DOT and Caltrans.
- Pedestrian safety of persons living in tribal communities was mentioned as a concern for both Arizona DOT and New Mexico DOT. Interstates are a concern in New Mexico, while state highways were mentioned in Arizona.
- Street lighting, barriers, and fencing are countermeasures being considered by the Arizona DOT and New Mexico DOT in their safety plans.
- Several pedestrian overpasses have been installed in Albuquerque, New Mexico, over IH 40.
- Unintended pedestrians (i.e., stranded motorists) were mentioned as a concern by all three state DOTs. The random occurrence of these crashes and the challenge in knowing if this is the reason the pedestrian is on the interstate (have to get the police report to know this detail) present difficulties when developing possible solutions. New Mexico DOT has a program to educate stranded motorists under their Look For Me campaign. The New Mexico Department of Health field offices help distribute outreach materials.
- Motorist assistance programs exist in each of these border states. In the border districts of California, the Freeway Service Patrol is funded jointly by Caltrans, the California Highway Patrol, and the local transportation agency. New Mexico has a 3-1-1 system that operates in Albuquerque on IH 40 and IH 25 as well as other highways. Among other things, the system helps stranded motorists get to safe locations.
- When asked about signs, there were mixed responses. Arizona DOT was concerned that signs might not be effective due to sign clutter and driver workload. Caltrans would only install signs after careful review of a documented problem. No pedestrian crossing symbols on the concrete median barrier were mentioned as a countermeasure being considered by New Mexico DOT.
- Adding fences effectively reduced pedestrian crossings in Caltrans District 11.

SUMMARY AND CONCLUSIONS

During the interviews researchers found that most TxDOT border districts and urban districts have experienced issues with pedestrians being involved in crashes on the main lanes of limited access highways. The majority of the urban districts have installed countermeasures, such as a median barrier at problem locations, additional lighting, and pedestrian accommodations on overpasses and underpasses crossing limited access highways. Border districts are considering the installation of these countermeasures as well. In addition, all of the urban districts have a motor vehicle assistance program that removes the disabled vehicle and its occupants off of the high-speed roadway thereby reducing the likelihood of an unintended pedestrian crash.

The feedback from the U.S. border states was similar to that in Texas where people have been seen crossing, walking along, and involved in crashes on interstate limited access highway main lanes. Caltrans District 11 (southern border) worked to address the specific issue of undocumented immigrants crossing interstates to avoid being apprehended by authorities in the 1980s through early 2000s. While the demographics of the pedestrians and the reasons they are on interstate main lanes may be different, countermeasures implemented and considered are often the same or similar in each scenario. In New Mexico and Arizona, the DOTs have recently conducted safety studies and are working to implement solutions to improve the safety of pedestrians.

Potential countermeasures were identified from the literature review and DOT interviews. The countermeasures included adding fences, median barriers, driver warning signs, pedestrian warning signs, lighting, pedestrian under/overcrossings, law enforcement efforts, and education programs. Adding warning signs is one of the more cost-effective countermeasures suggested by multiple pieces of literature. Although Caltrans District 11 is the only agency interviewed that has installed warning signs on limited access highways to warn motorists of potential pedestrian activity, other agencies interviewed expressed interest in this approach.

As for signs and markings directed toward pedestrians, the Austin District installed No Pedestrian Crossing symbol signs and stenciled no pedestrian crossing symbols on the concrete median barrier to discourage pedestrians from crossing a limited access highway. Several interviewees mentioned the countermeasure used in Austin as something they are considering.

Although installing signs is relatively low cost and can be effective, some literature and interviewees suggested its limitations. The pedestrian warning signs indicate popular pedestrian crossing locations, which may incite more illegal pedestrian crossing by people who knowingly break the law. In urban districts, the density of signs is relatively high. The interviewed urban district staff expressed concerns that too many signs will confuse drivers and become “sign pollution.” In the more rural border districts, pedestrian crossings are typically dispersed and random. Therefore, it is challenging to select locations to install warning signs.

CHAPTER 5:
EVALUATION OF DRIVEWAY ASSISTANCE DEVICES

INTRODUCTION

When a lane is closed on a two-lane, two-way road for construction or maintenance activities, provisions must be made to alternate one-way movement of the two original travel lanes through the work area. Quite often, there are minor approaches, such as residential driveways, within the one-lane road section. While these minor approaches should be monitored, existing methods (e.g., flaggers and portable traffic signals) are not always feasible based on conditions such as work duration, traffic volume, time of day, and cost of the method.

In 2012, TxDOT and TTI developed driveway assistance devices (DADs) to control traffic entering the one-lane road section from low-volume driveways (*45*). DADs are neither a portable traffic signal (PTS) nor an automated flagger assistance device. Instead, DADs are a new device designed to work in synchronization with PTSs placed at each end of the lane closure on the main road. Since DADs were not included in the MUTCD (*19*), TxDOT submitted a request to experiment with DADs to the Federal Highway Administration (FHWA). The request was approved by FHWA on June 27, 2013. Since that time, TxDOT has continued to use and evaluate DADs. This chapter documents the findings from recent field studies.

BACKGROUND

In 2012, TTI researchers conducted a series of motorist surveys at the DPS Driver License Offices in Bryan, San Angelo, and Tyler, Texas, to assess motorist expectations and comprehension of several DAD designs (*45*). In the first survey, researchers investigated what indications motorists thought would be displayed during the stop and proceed phases on the device in Figure 37. Key findings from this survey include:

- Ninety-one percent of respondents stated that the top indication would be illuminated to show when a driver must stop and remain stopped. All participants thought the top indication would be red, 91 percent thought the top indication would be a circular indication, and 84 percent thought the top indication would be steady.
- Ninety-seven percent of the respondents replied that the bottom indications would be illuminated to show which direction drivers on the minor approach could turn. Sixty-six percent thought the bottom indications would be yellow (the remainder thought it would be green), 88 percent thought the bottom indications would be a symbol (all but one wanted an arrow), and 53 percent thought the bottom indications would be flashing (the remainder thought it would be steady).

Figure 37. Mock Prototype DAD.

Based on these findings, researchers designed the three-section doghouse DAD in Figure 38. This device uses a 12-inch steady circular red indication and 12-inch flashing yellow arrows to control traffic. The steady circular red indication is shown when the minor approach traffic must stop and remain stopped. Since drivers facing a steady circular red indication may turn right after stopping when no other traffic control device is in place prohibiting a turn on red, a NO TURN ON RED sign (R10-11) was also displayed. The flashing yellow arrows indicate that the minor approach traffic is permitted to cautiously enter the roadway only in the direction of the arrow.

a. Steady Stop Indication.

b. Flashing Proceed Indication.

Figure 38. Prototype Three-section Doghouse DAD.

In the second and third motorist surveys, researchers evaluated motorist comprehension and the need for the R10-11 sign. Key findings from these surveys include:

- Without the R10-11 sign, 32 percent of the respondents indicated they could turn onto the main road when the steady circular red indication was displayed. In addition, 56 percent stated they would stop and then turn onto the main road (like at a STOP sign) without the R10-11 sign.
- With the R10-11 sign, 96 percent of respondents indicated they could not turn onto the main road when the steady circular red indication was displayed.
- Ninety-five percent of the respondents correctly understood which direction they could turn when a flashing yellow arrow indication was displayed. In addition, 98 percent stated they needed to yield to vehicles on the main road.

Based on these findings, researchers recommended the R10-11 sign be used in the field evaluations.

In 2013, researchers conducted daytime controlled and non-controlled field studies at a lane closure on a two-lane, two-way road in Cleburne, Texas. For the studies, researchers installed a three-section doghouse DAD at a stop-controlled intersection with a county road. Since the DAD informed drivers when to stop and when to proceed, researchers and TxDOT personnel decided to cover the STOP sign located at the intersection to remove any conflict between the two devices. Based on TxDOT recommendations, the DAD was placed at the intersection across the main road in front of oncoming motorists to ensure that drivers could view the full device.

Eight participants from the local area were recruited for the controlled field study. Each participant began the study by driving a state-owned vehicle through the work zone site. A researcher documented the actions and comments of the participants as they approached and reacted to the DAD. Each participant was then directed back to the minor approach, directed to park in a predetermined location where the participant could view the DAD (while not impeding other traffic) and asked a series of questions while viewing the DAD cycle through its various phases.

Drivers not involved in the controlled field study (i.e., encountering the DAD on their own) were also observed at the minor approach. For each vehicle arrival, a researcher located off the roadway noted the DAD phase and the driver's reaction.

During the controlled field study, 43 percent of the participants (i.e., three out of seven) had to be stopped from making the wrong turn by the researcher in the vehicle (one participant's data was removed due to potential interference). Two of these participants attempted to make a right turn when the DAD was displaying a flashing yellow left arrow (i.e., only left turns allowed). The other participant attempted to make a left turn when the DAD was displaying a flashing yellow right arrow (i.e., only right turns allowed).

After observing the DAD cycle through its various phases, all the controlled field study participants correctly understood which direction they could turn when a flashing yellow arrow indication was displayed and that they needed to yield to vehicles on the main road. All the controlled field study participants also indicated they could not turn onto the main road when the steady circular red indication and R10-11 sign were displayed.

While the DAD was deployed, 39 vehicles not involved with the controlled field study arrived on the minor approach (i.e., county road), averaging 7 vehicles per hour. Of these drivers, 13 percent (i.e., five) made incorrect maneuvers and thus were considered non-compliant. Three drivers turned the opposite direction indicated by the flashing yellow arrows, while two drivers turned when the steady circular red indication was displayed. These vehicles were intercepted by workers and allowed to proceed when it was safe to do so. Other than the non-compliant vehicles, there were four drivers (i.e., 10 percent) that asked workers what action they were expected to take.

The field study findings revealed that drivers might be initially confused by the DAD indications, especially since the STOP sign was covered. Due to the limited sample size and impact of the covered STOP sign, researchers recommended the conduct of additional field studies and the consideration of a second supplemental sign to provide additional information regarding the proper direction of travel.

Since 2013, many other states have experimented with several different DAD designs. Based on a state-of-the-practice conducted by TTI researchers in 2019, TxDOT begin using a TURN ONLY IN DIRECTION OF ARROW sign with the three-section doghouse DAD.

In 2019, TxDOT also been experimenting with a four-section stacked DAD design (see Figure 39). This DAD design included two 12-inch steady red arrow indications, two 12-inch flashing yellow indications, a modified R10-11 sign, and a YIELD IN DIRECTION OF FLASHING YELLOW ARROW sign. The steady red arrows indicate which direction a driver cannot turn, while the flashing yellow arrows indicate which direction a driver may turn. During the all-red phase, both steady red arrows are illuminated.

More recently, research sponsored by the Smart Work Zone Deployment Initiative investigated DAD design configurations and supplemental sign messages (*46*). In February 2022, TTI researchers reviewed this research and provided the following recommendations to TxDOT regarding future DAD applications in Texas.

- Keep testing the three-section doghouse and four-section stacked configurations in the field to assess driver violation rates.
- Continue to require a NO TURN ON RED sign (R10-11) to be mounted on the DAD directly below the display indications.

- Begin using a WAIT TURN ONLY IN DIRECTION OF ARROW sign instead of TURN ONLY IN DIRECTION OF ARROW sign.
- Conduct human factors studies to assess motorist comprehension of the three-section doghouse and four-section stacked configurations (including the modified R10-11 sign and other supplemental signs).

Figure 39. Example of Four-Section Stacked DAD.

Currently, TxDOT allows the two DAD designs in Figure 40 and Figure 41 to be used and evaluated in Texas with prior approval from the TxDOT Traffic Safety Division.

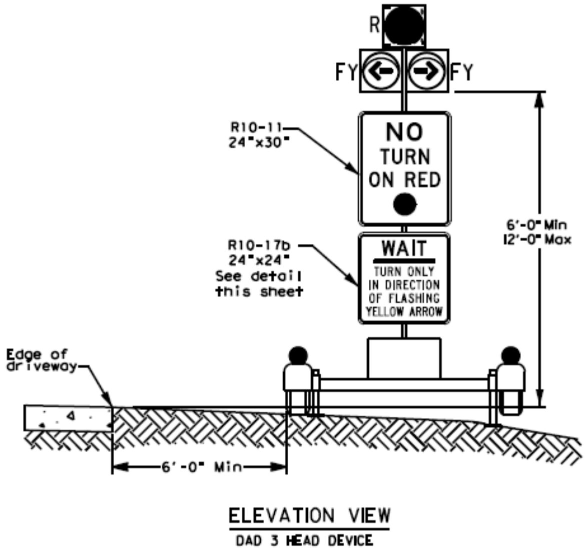


Figure 40. TxDOT Three-Section Doghouse DAD Design.

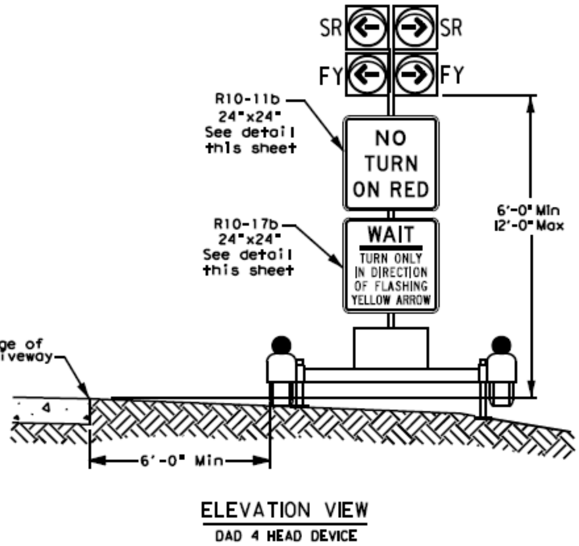


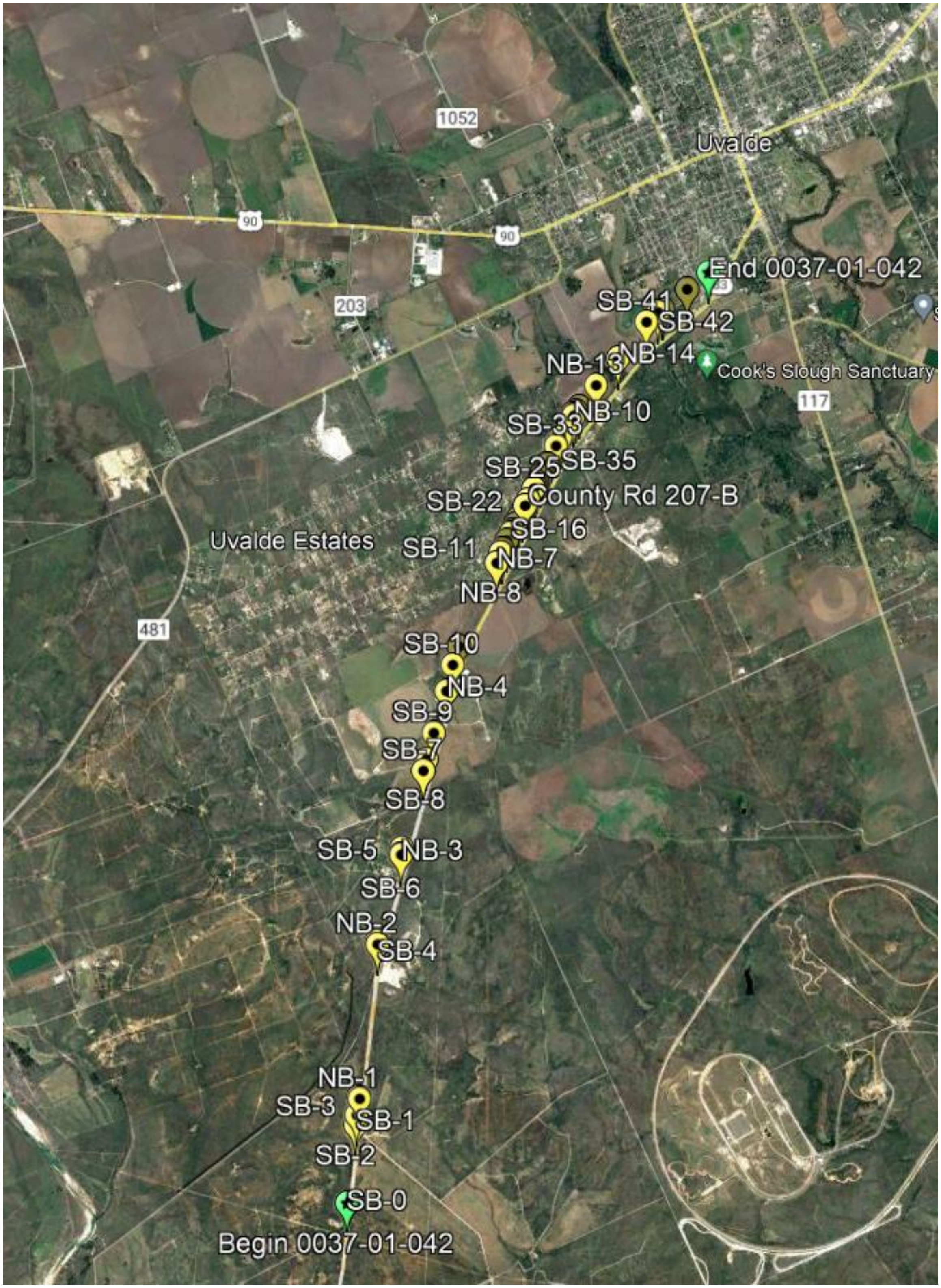
Figure 41. TxDOT Four-Section Stacked DAD Design.

FIELD STUDY DATA COLLECTION

From March 2019 to May 2022, TTI researchers documented and evaluated the use of DADs on three projects in Texas. This section contains information about the projects and data collection methodology.

Project 1 US 83 CSJ 0037-01-042

Project 1 involved the rehabilitation of US 83 in Uvalde County from FM 1435 to the Zavala County Line (see Figure 42). The construction sequence included seven sections where the two-lane, two-way roadway would be reduced to one lane. Work began near the Zavala County Line and progressed north toward Uvalde. The one-lane sections ranged in length from approximately 0.5 mile to 2 miles. The contractor used PTSs at both ends of the one-lane section to control the flow of traffic on the main road. The planned one-lane sections included intersections with three county roads, 45 private driveways (e.g., gated residential, oil field, and utility access), and six business or multi-home residential driveways (see yellow pins with circles in Figure 42). Since the three county roads where interconnected, the construction was sequenced such that only one county road intersection was within a one-lane section, and that intersection was closed during construction. The contractor used the three-section doghouse DAD with a R10-11 sign and a TURN ONLY IN DIRECTION OF ARROW sign (see Figure 43).



(Source: © 2021 Google Earth)

Figure 42. Project 1 US 83 South of Uvalde.

a. Steady Stop Indication. **b. Flashing Proceed Indication.**

Figure 43. Example of Project 1 DAD.

Researchers first visited Project 1 on April 24, 2019, when construction was occurring in Section 1. Researchers regularly corresponded with TxDOT and visited the project throughout construction to document the use of DADs (see Table 7).

Based on the initial site visit, project plans, construction schedule, and discussions with TxDOT, researchers decided to collect data in Sections 5 and 6 at business driveways. Researchers planned to use the controlled field study format used in previous research (*45*) so data could be compared between the studies. Researchers also planned to survey residents and business owners that routinely entered the main road from the driveways where the DADs were located. However, in-person human factors research could not be conducted in 2020 due to the pandemic. Instead, researchers solely focused on monitoring select driveways to observe drivers encountering a DAD on their own (i.e., non-controlled field study).

In July 2020, researchers collected non-controlled field data at a convenience store driveway. In July 2020 and August 2020, researchers collected non-controlled field data at driveways that served a recreational vehicle (RV) park and residential area.

Table 7. Project 1 Timeline and Summary of DAD Use.

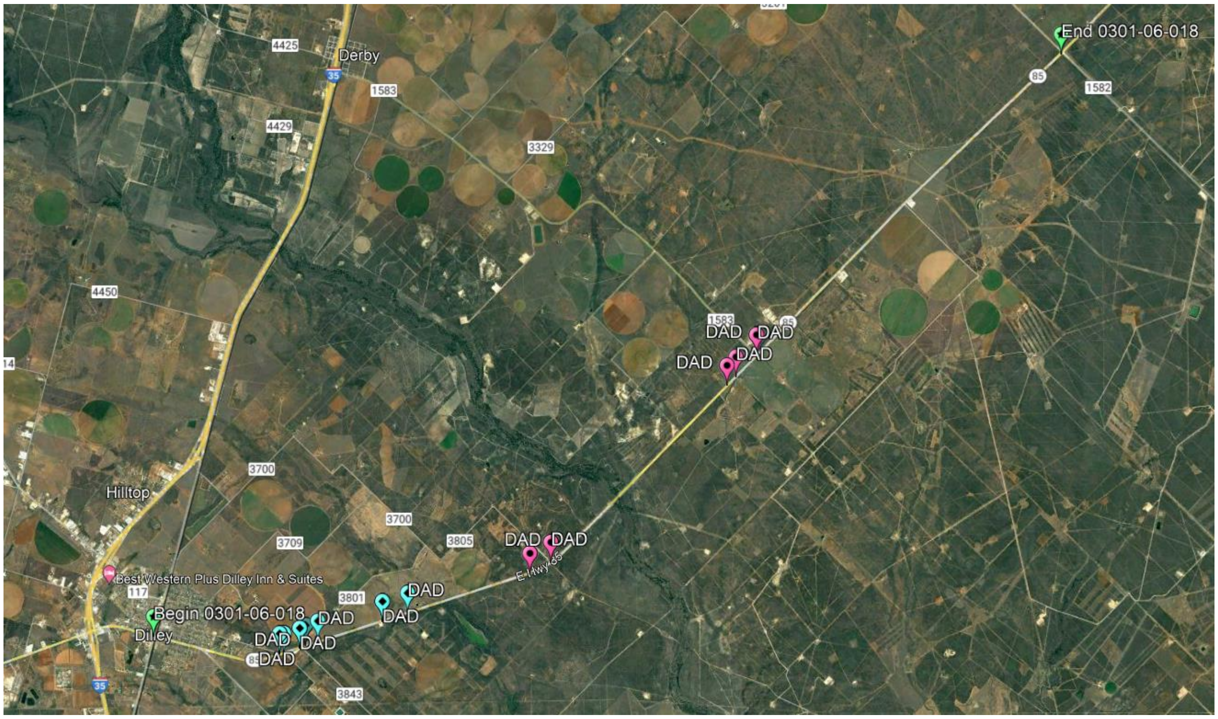
Date	Event	Section Under Construction	Direction Closed	Number of DADs Deployed
3/15/2019	Construction Began	1	NB	Unknown
4/15/2019	DAD Design Changed[a]	1	NB	Unknown
4/29/2019	TTI Site Visit	1	NB	5
5/7/2019	Second Supplemental Sign Added to DADs[b]	1	Unknown	Unknown
8/9/2019	Section 2 Work Began	2	SB	Unknown
10/9/2019	TTI Site Visit	2	NB	7
12/13/2019	Section 3 Work Began	3	SB	Unknown
1/23/2020	TTI Site Visit	3	SB	10
4/14/2020	Section 4 Work Began	4	NB	Unknown
6/1/2020[c]	TTI Site Visit	4	SB	11
Unknown	Section 5 Work Began	5	NB	Unknown
6/29/2020	Section 5 Switch	5	SB	Unknown
7/14/2020	TTI Site Visit	5	SB	9
7/14/2020–7/15/2020	TTI Data Collection at Driveway SB-33	5	SB	9
7/20/2020	Section 6 Work Began	6	SB	Unknown
7/28/2020	TTI Site Visit	6	SB	5
7/28/2020–7/30/2020	TTI Data Collection at Driveway NB-12	6	SB	5
8/10/2020	Section 6 Switch	6	NB	Unknown
8/25/2020	TTI Site Visit	6	NB	5
8/25/2020–8/27/2020	TTI Data Collection at Driveway NB-11	6	NB	5
9/3/2020	Section 7 Work Began	7	NB	Unknown
9/16/2020	TTI Site Visit	7	NB	4
9/29/2020	Section 7 Switch	7	SB	Unknown

NB = Northbound; SB = Southbound.
[a] The contractor initially deployed DADs that contained three sections in a horizontal alignment, which did not meet the TxDOT special specification. DADs changed to the three-section doghouse design in mid-April 2019.
[b] Initially, the DADs only had a NO TURN ON RED (R10-11) sign.
[c] Pandemic travel restrictions did not allow researchers to visit the site from March to May 2020.

Project 2 SH 85 CSJ 0301-06-018

Project 2 involved the rehabilitation and widening of SH 85 in Frio County from Business 35 to FM 1582 (see Figure 44). The contractor used the four-section stacked DAD design in Figure 39.

Researchers conducted a site review on June 21, 2021. At that time, two sections of roadway were under construction. PTSs controlled traffic on SH 85, and six DADs directed traffic at four private driveways, one low-volume county road, and one low-volume state road (see pink pins with circles in Figure 44). Based on discussions with TxDOT, researchers collected non-controlled field data in July 2021 at the intersection of SH 85 and FM 1853.



(Source: © 2021 Google Earth)

Figure 44. Project 2 SH 85 East of Dilley.

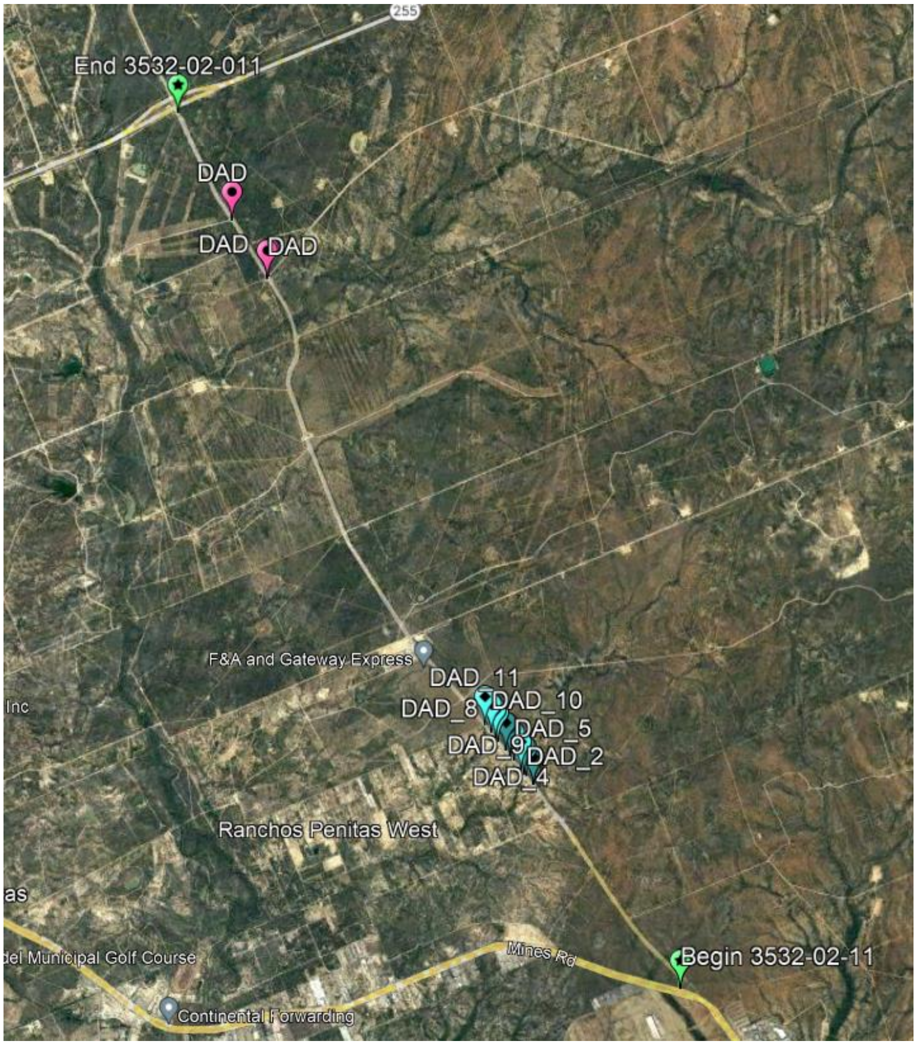
Later in the project, work progressed westward toward the city of Dilley. Eight DADs directed traffic at three private driveways, one business driveway, and four low-volume county roads (see blue pins with diamonds in Figure 44). Researchers collected non-controlled field data in March 2022 and in May 2022 at the intersection of SH 85 and CR 3800.

Project 3 FM 3338 CSJ 3532-02-011

Project 3 involved the rehabilitation of FM 3338 in Webb County from FM 1472 to SH 255 (see Figure 45). The DAD design was the same as that used at Project 2 (see Figure 39). Researchers conducted a site review on June 21, 2021. At that time, two sections of roadway were under construction, but only one section included three DADs at private driveways (see pink pins with circles in Figure 45). Based on discussions with TxDOT, researchers decided to collect non-controlled field data in a roadway segment near the south end of the project (i.e., closer to FM 1472).

In the spring of 2022, the contractor was working near Ranchos Penitas West. PTS controlled the traffic on FM 3338. Eleven DADs directed traffic at five private driveways, four business driveways, and two low-volume county roads (see blue pins with diamonds in Figure 45). In

August 2021, researchers collected non-controlled field data at the intersection of FM 3338 and Rancho Penitas Road (i.e., DAD_11).



(Source: © 2021 Google Earth)

Figure 45. Project 3 FM 3338 Northwest of Laredo.

FIELD STUDY RESULTS

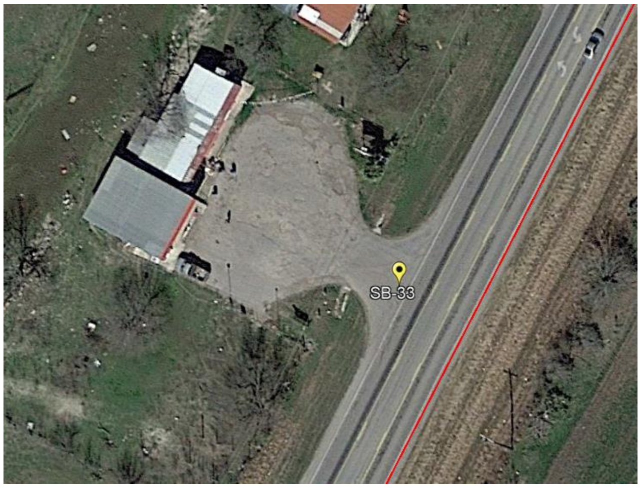
This section documents the findings from non-controlled field studies at three projects.

Project 1 US 83 CSJ 0037-01-042

Researchers studied driver reactions to DADs at three Project 1 driveways: southbound (SB)-33 (business driveway), northbound (NB)-12 (RV park and residential area), and NB-11 (RV park and residential area).

Business Driveway

On July 14–15, 2020, TTI researchers observed traffic exiting a convenience store driveway (SB-33) in Section 5 (see Figure 46). The DAD was located directly across the main road from the driveway since construction was occurring in the SB lanes (see Figure 47). Data collection began around 11:00 a.m. on Tuesday, July 14, and ended around 8:00 a.m. on Wednesday, July 15. The average phase duration for the DAD (i.e., red and flashing yellow arrow indications for one direction of travel) was approximately four minutes with a two-minute red clearance interval. The total DAD cycle length was about eight minutes. Due to the pandemic, traffic volume at the store was much lower than initially expected.



(Source: © 2020 Google Earth)

Figure 46. Project 1 Business Driveway SB-33.

Figure 47. Project 1 DAD at Business Driveway SB-33.

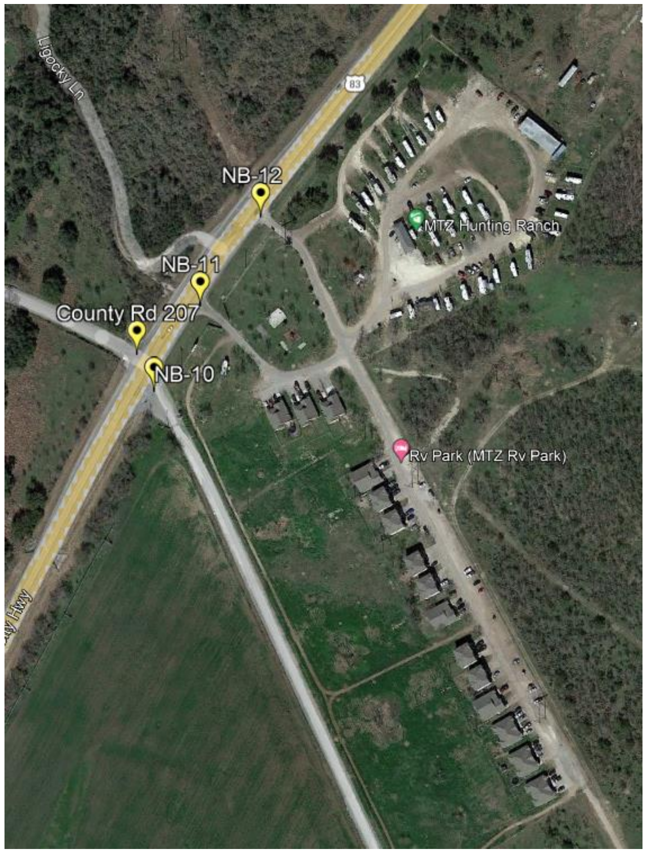
Over the 21-hour data collection period, only 17 vehicles exited the business. Three motorists (i.e., 18 percent) did not comply with the DAD. Two of the motorists arrived on a red indication at separate times, remained through the flashing yellow left arrow indication, and then waited through most of the next red indication before turning right prior to the activation of the flashing yellow right arrow. The third motorist arrived when the DAD was displaying a flashing yellow right arrow. The motorist waited until the DAD turned red and all oncoming vehicles had passed before turning left (while the indication was still red). The DAD had been in place for over two weeks when researchers collected data. Researchers presumed these motorists were frequent customers and thus knew the DAD was about to activate the flashing yellow arrow in the direction they desired to go.

RV Park and Residential Area Driveways

On July 28–30, 2020, TTI researchers observed traffic exiting a driveway that served an RV park and residential area (NB-12) in Section 6 (see Figure 48). The DAD was located to the right of the driveway since construction was occurring in the SB lanes (see Figure 49). The DAD had been in place for about two weeks. Data collection began around 11:30 a.m. on Tuesday, July 28, and ended around 11:00 a.m. on Thursday, July 30. The average phase duration for the DAD was the same as at SB-33.

At NB-12, 246 vehicles arrived at the DAD over the 47 hours and 21 minutes of data collection. Twenty-four motorists (i.e., 10 percent) did not comply with the DAD. Researchers grouped the violations into the following categories:

- *Turned on Red Prior to Flashing Yellow Arrow—Same Direction (15 violations).* Driver arrived when the DAD displayed a flashing yellow arrow or just as the DAD displayed the steady circular red indication. Driver wanted to turn in the opposite direction of travel from the last flashing yellow arrow. After the DAD turned red and the vehicles on the main road passed by, the driver turned in the desired direction of travel prior to the display of the flashing yellow arrow for that direction.
- *Turned on Red to Join Main Road Traffic—Same Direction (5 violations).* Driver arrived when the DAD displayed a flashing yellow arrow or just as the DAD displayed the steady circular red indication. After the DAD displayed the steady circular red indication, the driver turned in the direction of the last flashing yellow arrow. In most cases, the driver was waiting for a gap in the main road traffic or to join the end of the platoon.
- *Turned on Red—Opposite Direction (2 violations).* Driver arrived when the DAD displayed the steady circular red indication. Driver turned either right (one driver) or left (one driver) on red in the opposite direction of the subsequent flashing yellow arrow.
- *Turned in Opposite Direction of Flashing Yellow Arrow (2 violations).* While the DAD displayed a right or left flashing yellow arrow, the driver turned in the opposite direction of travel. Most drivers waited until after the platoon of vehicles on the main road passed by.



(Source: © 2021 Google Earth)

Figure 48. Project 1 Residential Driveways NB-12 and NB-11.

Figure 49. Project 1 DAD at Residential Driveway NB-12.

On August 25–27, 2020, TTI researchers observed traffic exiting a second driveway that served the RV park and residential area (NB-11) because NB-12 was closed (see Figure 48). The DAD was located directly across the main road from the driveway since construction was occurring in the NB lanes (see Figure 50). The DAD had been in this location for about two weeks, but a DAD had been at the NB-11 driveway since July 20, 2020 (about six weeks). Data collection began around 11:00 a.m. on Tuesday, August 25, and ended around 10:00 a.m. on Thursday, August 27. The average phase duration for the DAD was the same as at NB-12.

Figure 50. Project 1 DAD at Residential Driveway NB-11.

At NB-11, 341 vehicles arrived at the DAD over the 47 hours and 6 minutes of data collection. Sixty-nine motorists (i.e., 20 percent) did not comply with the DAD. Most of the violations were either drivers turning on red prior to the flashing yellow arrow (39 violations) or drivers turning on red to join main road traffic (28 violations). Two violations were drivers turning on red in the opposite direction of the subsequent flashing yellow arrow. The violation rate was 10.0 violations per 100 stop periods (i.e., 69 violations divided by 692 stop periods multiplied by 100).

Summary

Table 8 contains the violation rate for each Project 1 driveway. The violation rate represents the number of violations per 100 stop periods. SB-33 had the lowest violation rate (i.e., 1.0 violations per 100 stop periods), while NB-11 had the highest violation rate (i.e., 10.0 violations per 100 stop periods). Overall, the violation rate for Project 1 was 5.7 violations per 100 stop periods.

In addition to the violation rate, it is important to look at the type of violations being committed at each driveway (see Table 9). More than half of the violations were drivers turning on red prior to the flashing yellow arrow for their desired direction of travel. This may be contributed to drivers that have learned how the PTS/DAD system works and want to get ahead of the main lane traffic platoon. The long red clearance interval (approximately 2 minutes) may have also contributed to this behavior.

Table 8. Project 1 Violation Rate Statistics.

Driveway	Location of DAD	Hours of Study	Number of Stop Periods	Number of Violations	Violations per 100 Stop Periods[a]
SB-33	Farside	21.0	308	3	1.0
NB-12	Nearside	47.4	696	24	3.4
NB-11	Farside	47.1	692	69	10.0
Total	All	115.5	1696	96	5.7

[a] *Rate computed as violations/stop periods x 100.*

Table 9. Project 1 Summary of Violation Types.

Driveway	Turned on Red Prior to FYA Same Direction	Turned on Red to Join Main Road Traffic Same Direction	Turned on Red Opposite Direction	Turned in Opposite Direction of FYA
SB-33	100%	0%	0%	0%
NB-12	63%	21%	8%	8%
NB-11	56%	41%	3%	0%
Total	60%	34%	4%	2%

FYA = flashing yellow arrow.

About one-third of the violations were drivers turning on red to join the main road traffic platoon. This may be due to higher volumes on the main road limiting available gaps for the motorists at the driveway to turn. The contractor programmed the DADs to directly coordinate with the red and green phases of the PTSs. To help mitigate these types of violations, the flashing yellow arrow for the DADs could have been extended to allow the minor approach traffic to join the main road traffic platoon after the PTD turned red. If this is done, the duration of the red clearance interval will need to be adjusted to account for the extended flashing yellow arrow time at the driveways.

Researchers only classified six percent of the violations as unsafe maneuvers. These included drivers turning on red in the opposite direction of the subsequent flashing yellow arrow (four percent) and drivers turning in the opposite direction of travel from the flashing yellow arrow (two percent). No unsafe maneuvers were observed at the low-volume business driveway. Also, the number of unsafe maneuvers decreased over time at the residential driveways (16 percent at NB-12 and 3 percent at NB-11).

Researchers also analyzed violations by time of day (see Table 10). More than half of the violations occurred during the day (51 percent). However, as construction progressed in Section 6 more violations began to occur at night (NB-12 versus NB-11). This may be due to familiar drivers not wanting to wait for the proper indication under lower volume main road conditions.

Table 10. Project 1 Violations by Time of Day.

Driveway	Daytime	Nighttime
SB-33	100%	0%
NB-12	58%	42%
NB-11	46%	54%
Total	51%	49%

Project 2 SH 85 CSJ 0301-06-018

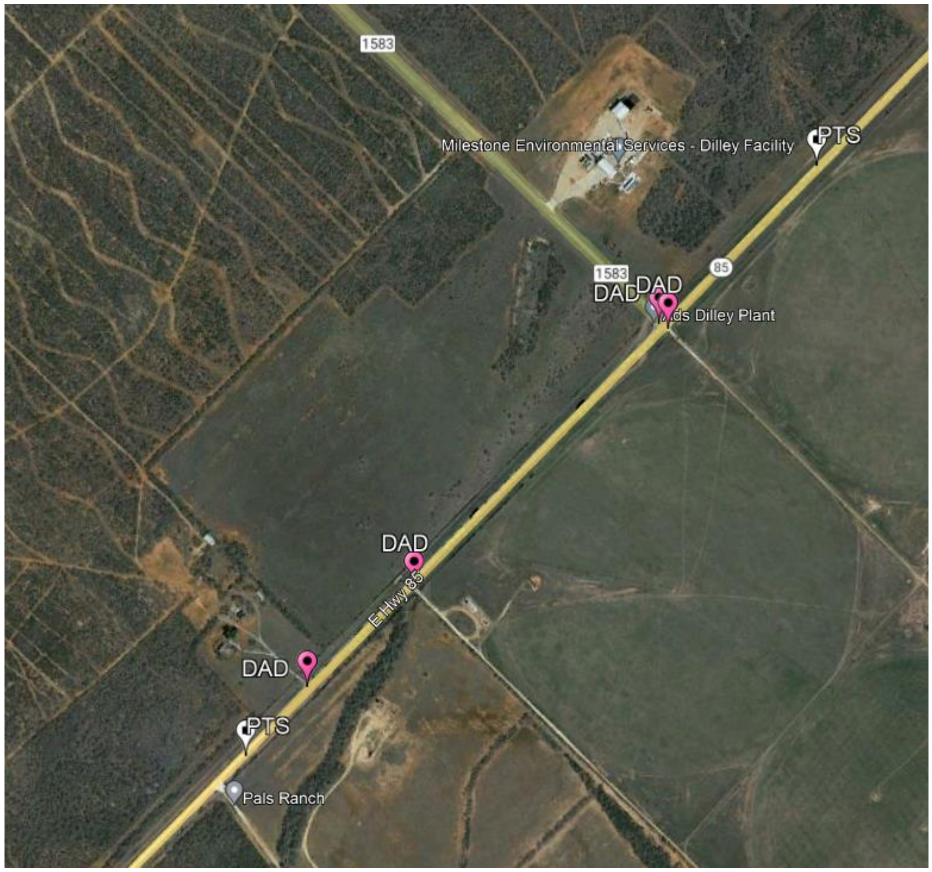
Researchers studied driver reactions to DADS at two locations at Project 2: FM 1583 (i.e., low-volume roadway) and CR 3800 (i.e., low-volume roadway).

FM 1583

On July 6–8, 2021, TTI researchers observed traffic approaching SH 85 on FM 1583 (see Figure 51). This intersection was near the north end of a one-lane section, which was approximately 4500 ft long. The DAD installation date was unknown. The DAD was located on the nearside of the intersection next to a STOP sign and CROSS TRAFFIC DOES NOT STOP sign assembly (see Figure 52). In this one-lane section, DADs were also used at three private driveways (see Figure 51).

Data collection began around noon on Tuesday, July 6, and ended around 1:00 p.m. on Thursday, July 8. The average phase duration for the DAD (i.e., red and flashing yellow arrow indications for one direction of travel) was approximately five minutes and two minutes for the NB and SB directions, respectively. The DAD cycle length was about seven minutes. Construction was occurring in the NB lanes.

Over the 47 hours and 57 minutes of data collection, 112 vehicles arrived at the DAD. Nineteen drivers (i.e., 17 percent) did not comply with the DAD. All but one of the violations were drivers turning in the opposite direction of the flashing yellow arrow. The other violation was a driver turning on red prior to the display of the flashing yellow arrow for their desired direction of travel. Most of the violators (79 percent) turned left (NB) when a right flashing yellow arrow was displayed. Researchers noted that the intersection was approximately 1200 ft from the SB PTS and that drivers at the intersection could see this PTS and the roadway between this PTS and the intersection. Drivers waited until the SB main lane traffic had passed the intersection and the roadway between the intersection and PTS was clear before turning left.



(Source: © 2021 Google Earth)

Figure 51. Project 2 SH 85 July 2021 One-Lane Study Section.

Figure 52. Project 2 DAD at Intersection of SH 85 and FM 1853.

CR 3800

On March 29–31, 2022, and May 10–12, 2022, TTI researchers observed traffic approaching SH 85 on CR 3800 (see Figure 53). The intersection was near the west end of the one-lane section approximately 0.5 miles from the PTS controlling the eastbound (EB) traffic. The contractor installed the DAD on February 20, 2022. During both data collection periods, the DAD was located on the nearside of the intersection next to a STOP sign (see Figure 54). Figure 55 and Figure 56 show views from CR 3800 looking east and west, respectively. The one lane section was approximately 2.7 miles long.

(Source: © 2022 Google Earth)

a. Entire One-Lane Section.

(Source: © 2022 Google Earth)

b. One-Lane Section Near CR 3800.

Figure 53. Project 2 SH 85 March and May 2022 One-Lane Study Section.

Figure 54. Project 2 DAD at Intersection of SH 85 and CR 3800.

Figure 55. Project 2 DAD at Intersection of SH 85 and CR 3800—Looking East.

Figure 56. Project 2 DAD at Intersection of SH 85 and CR 3800—Looking West.

In March 2022, data collection began around 12:30 p.m. on Tuesday, March 29, and ended around 1:45 p.m. on Thursday, March 31. Construction was occurring in the EB lanes, and the DAD had been in use for about five weeks. In May 2022, data collection began around noon on Tuesday, May 10, and ended around 11:00 a.m. on Thursday, May 12. Construction was occurring in the westbound (WB) lanes, and the DAD had been in place about 12 weeks. For both time periods, the average EB and WB DAD phase times were approximately three minutes and nine minutes, respectively, with an 11-second red clearance interval. The DAD cycle length was about 12 minutes.

Over the 48 hours and 3 minutes of data collection in March 2022, 91 vehicles arrived at the DAD. Thirty-seven drivers (i.e., 41 percent) did not comply with the DAD. Thirty-five violations were drivers turning in the opposite direction of the flashing yellow arrow. All these violations were drivers turning left (EB) when a right flashing yellow arrow (WB) was displayed. Researchers noted that the intersection was approximately 0.5 miles from the EB PTS and that drivers at the intersection could see the roadway between the EB PTS and the intersection (see Figure 56). Drivers waited until the WB main lane traffic had passed the intersection and the roadway between the intersection and EB PTS was clear before turning left. The long WB phase time (about nine minutes) may have also contributed to these violations. The other two violations were drivers turning on red in the same direction of the preceding flashing yellow arrow (i.e., joining main lane traffic platoon).

Over the 46 hours and 55 minutes of data collection in May 2022, 79 vehicles arrived at the DAD. Thirty-nine drivers (i.e., 49 percent) did not comply with the DAD. All the violations were drivers turning in the opposite direction of the flashing yellow arrow. All but one of these violations were drivers turning left (EB) when a right flashing yellow arrow was displayed. One of these violations was a driver turning right (WB) when a left flashing yellow arrow was displayed.

Drivers that violated the DAD at CR 3800 continued to obey the STOP sign. While the two traffic control devices (i.e., STOP sign and DAD) may conflict with one another, it was decided not to remove or cover the STOP sign. STOP signs are installed at intersections where a full stop is necessary, and removing one, even temporarily, could confuse drivers. STOP signs also have a high target value since they are easily recognizable because of their color and shape. Researchers had hoped that after coming to a complete stop, drivers would follow the directions given by the DAD. However, 45 percent of drivers at CR 3800 did not obey the DAD.

Summary

Table 11 contains the violation rates for each stop-controlled intersection studied on Project 2. FM 1853 had the lowest violation rate (i.e., 2.3 violations per 100 stop periods), while the second data collection period at CR 3800 had the highest violation rate (i.e., 8.6 violations per 100 stop periods). Overall, the violation rate for Project 2 was 5.4 violations per 100 stop periods.

Table 11. Project 2 Violation Rate Statistics.

Intersection	Location of DAD	Hours of Study	Number of Stop Periods	Number of Violations	Violations per 100 Stop Periods[a]
FM 1853	Nearside	47.9	823	19	2.3
CR 3800	Nearside	48.1	475	37	7.8
CR 3800	Nearside	46.9	455	39	8.6
Total	All	142.9	1753	95	5.4

[a] *Rate computed as violations/stop periods x 100.*

According to Table 12, 97 percent of violations at Project 2 were drivers turning in the opposite direction of travel from the flashing yellow arrow. Although most drivers waited for the main lane platoon to pass by before turning in the opposite direction, researchers considered this maneuver to be unsafe since motorists could still encounter oncoming traffic (e.g., a vehicle entering from a driveway or other intersection). Although the phase timing and sight distance may have exacerbated the violations, researchers believe the findings show that DADs should not be used at stop-controlled intersections.

Table 12. Project 2 Summary of Violation Types.

Intersection	Turned on Red Prior to FYA Same Direction	Turned on Red to Join Main Road Traffic Same Direction	Turned on Red Opposite Direction	Turned in Opposite Direction of FYA
FM 1853	5%	0%	0%	95%
CR 3800	0%	5%	0%	95%
CR 3800	0%	0%	0%	100%
Total	1%	2%	0%	97%

FYA = flashing yellow arrow.

Table 13 contains the violations by time of day at Project 2. Overall, 94 percent of the violations occurred during the day. The most likely reason is that 237 vehicles arrived at the DAD during the day. Only 45 vehicles arrived at night (after sunset and before sunrise).

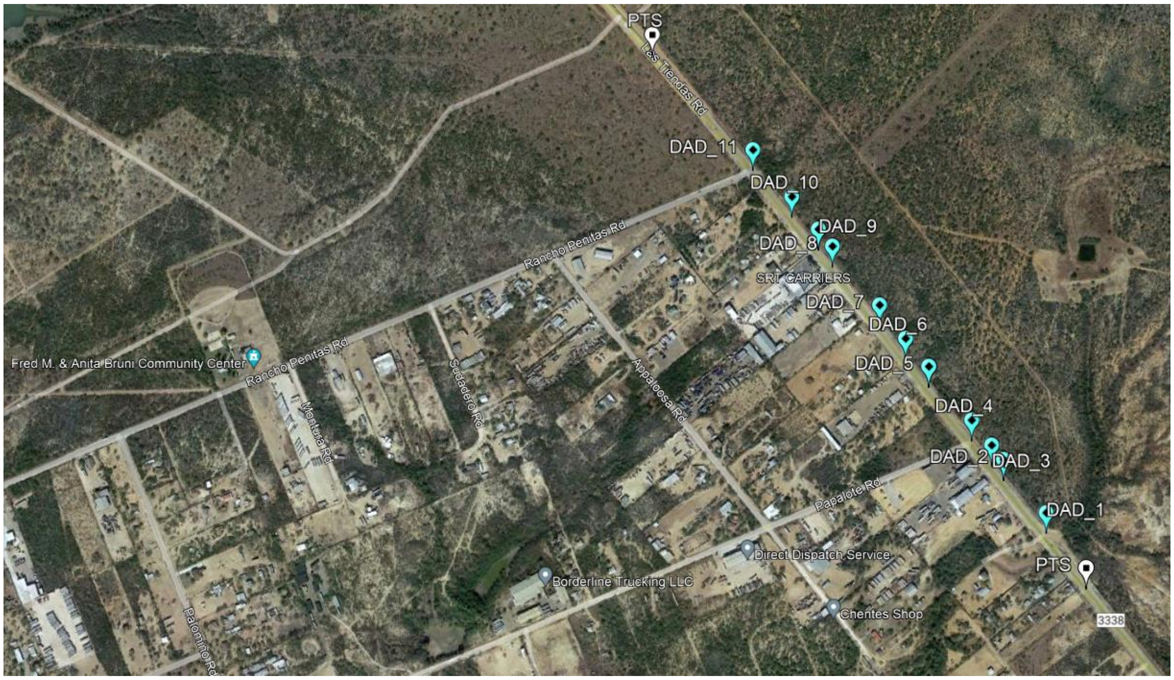
Table 13. Project 2 Violations by Time of Day.

Intersection	Daytime	Nighttime
FM 1853	89%	11%
CR 3800	95%	5%
CR 3800	95%	5%
Total	94%	6%

Project 3 FM 3338 CSJ 3532-02-011

On August 17–19, 2021, TTI researchers observed traffic approaching FM 3338 on Rancho Penitas Road (DAD_11) (see Figure 57). The contractor installed the DAD on August 9, 2021. The DAD was located on the farside of the intersection because construction was occurring in the SB direction. Figure 58 shows that construction material was piled in front of the DAD blocking the YIELD IN DIRECTION OF FLASHING YELLOW ARROW sign. Figure 59 shows that the intersection was stop-controlled.

Data collection began around 2:00 p.m. on Tuesday, August 17, and ended around noon on Thursday, August 19. The average NB and SB DAD phase times were approximately five minutes and three minutes, respectively, with a 10-second red clearance interval. The DAD cycle length was about eight minutes. The one-lane section was approximately 4700 ft long. The DAD was located approximately 1000 ft from the SB PTS. Drivers on Rancho Penitas Road could see the SB PTS and the roadway between the PTS and the intersection.



(Source: © 2022 Google Earth)

Figure 57. Project 3 FM 3338 August 2021 One-Lane Study Section.

Figure 58. Project 3 DAD at Intersection of FM 3338 and Rancho Penitas Road.

Figure 59. Project 3 Intersection of FM 3338 and Rancho Penitas Road.

Over the 45 hours and 57 minutes of data collection at the intersection of FM 3338 and Rancho Penitas Road, 1254 vehicles arrived at the DAD. One hundred and eleven drivers (i.e., 9 percent) did not comply with the DAD. Ninety-three violations were drivers turning in the opposite direction of the flashing yellow arrow. Of these violations, approximately three-quarters were drivers turning right when a left flashing yellow arrow was displayed and one-quarter were drivers turning left when a right flashing yellow arrow was displayed. Other violations included:

- Drivers turning on red in the same direction of the preceding flashing yellow arrow (i.e., joining main lane traffic platoon): 9 violations.
- Drivers turning on red in the opposite direction of the subsequent flashing yellow arrow (i.e., turning in the direction of oncoming traffic): 6 violations. All these violations were drivers turning right on red when the next display was a left flashing yellow arrow.
- Drivers turning on red in the same direction of the subsequent flashing yellow arrow (i.e., getting ahead of the main lane traffic platoon): 3 violations.

Almost one-quarter of the violations (i.e., 23 percent) at Project 3 occurred at night. Overall, the violation rate was 15.9 violations per 100 stop periods (i.e., 111 violations divided by 699 stop periods multiplied by 100). Researchers suspect that drivers may not have seen the DAD or been able to read the supplemental signs since the DAD was on the far side of the intersection and partially blocked by construction material. In addition, many violations were made by commercial motor vehicle drivers. However, from the camera view researchers could not determine whether these violations were associated with construction (e.g., material delivery).

SUMMARY AND CONCLUSIONS

Table 14 and Table 15 provide a summary of the violation rates and types, respectively, for the three projects studied. Overall, the violation rates are quite varied. The violation rate for the three-section doghouse DAD design ranged from 1.0 to 10.0 violations per 100 stop cycles. The violation rate for the four-section stacked DAD design ranged from 2.3 to 15.9 violations per 100 stop cycles.

Table 14. Summary of Violation Rate Statistics.

Project	Type of DAD	Driveway/ Intersection	Location of DAD	Number of Minor Approach Vehicles	Number of Violations	Violations per 100 Stop Periods[a]
1	3-section	SB-33	Farside	17	3	1.0
1	3-section	NB-12	Nearside	246	24	3.4
1	3-section	NB-11	Farside	341	69	10.0
2	4-section	FM 1853	Nearside	112	19	2.3
2	4-section	CR 3800	Nearside	91	37	7.8
2	4-section	CR 3800	Nearside	79	39	8.6
3	4-section	Rancho Penitas Road	Farside	1254	111	15.9

[a] *Rate computed as violations/stop periods x 100.*

Table 15. Summary of Violation Types.

Project	Type of DAD	Driveway/ Intersection	Turned on Red Prior to FYA Same Direction	Turned on Red to Join Main Road Traffic Same Direction	Turned on Red Opposite Direction	Turned in Opposite Direction of FYA
1	3-section	SB-33	100%	0%	0%	0%
1	3-section	NB-12	63%	21%	8%	8%
1	3-section	NB-11	56%	41%	3%	0%
2	4-section	FM 1853	5%	0%	0%	95%
2	4-section	CR 3800	0%	5%	0%	95%
2	4-section	CR 3800	0%	0%	0%	100%
3	4-section	Rancho Penitas Road	3%	8%	5%	84%

FYA = flashing yellow arrow.

Trends are hard to determine from the limited number of sites. Even so, it appears that violation rates increased when DADs were located on the farside of the intersection (i.e., NB-12 versus NB-11 and Rancho Penitas Road). Violation rates also appear to be higher when DADs were located at a stop-controlled intersection (i.e., CR 3800 and Rancho Penitas Road). In addition, the primary violation type at the stop-controlled intersections (i.e., drivers turning in the opposite direction of the flashgun yellow arrow) was deemed unsafe by researchers.

The primary types of violations for the three-section doghouse DAD were turning on red to either get ahead of or join the main lane traffic. While these maneuvers were considered violations, they are not necessarily unsafe driving actions. A long red clearance interval and limited gaps in the main lane traffic platoon may have contributed to these behaviors. With some DADs, the flashing yellow arrow can be extended to allow the minor approach to join the main lane traffic after the PTS has turned red. If this is done, the red clearance interval may need to be adjusted to account for the extended flashing yellow arrow time at the driveways.

Most violations for the four-section stacked DAD involved the unsafe behavior of drivers turning in the opposite direction of the flashing yellow arrow (i.e., potentially into oncoming traffic). However, to date, the four-section stacked DAD has only been studied at stop-controlled intersections, making it difficult to assess the actual effectiveness of the four-section stacked DAD. In future applications, TTI researchers recommend that DADs not be used at stop-controlled intersections. In addition, TTI researchers recommend that TxDOT closely monitors and evaluates four-section stacked DADs at low-volume residential or business driveways.

TTI researchers also recommend the conduct of a study to assess driver comprehension of the two DAD designs and select supplemental signs. TTI researchers would not duplicate the work conducted in previous research (*46*). Instead, researchers would build upon it to further contribute to the body of knowledge and assist TxDOT with future DAD applications.

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