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16. Abstract

Traffic control devices are a primary means of communicating highway information to road users and play a key role in highway automation. The design, application, and maintenance of traffic control devices are under constant transformation as new technologies, methodologies, and policies are introduced. In addition, vehicle technologies and the roadway infrastructure industry are rapidly evolving, spurred by technology advancements, customer demand, changes in the vehicle fleet, and changes in national and state policies. This project provides the Texas Department of Transportation with a mechanism to conduct high-priority, limited-scope evaluations of issues related to traffic control devices. Research activities conducted and concluded during the 2024 fiscal year that are included in this report are:

- Evaluation of driveway assistance devices in lane closures on two-lane, two-way roads.
- Compilation of a synthesis of practices to deter pedestrians from crossing freeways.
- Assessment of the safety experience at rural intersections with flashing beacons.

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TRAFFIC CONTROL DEVICE ANALYSIS, TESTING, AND EVALUATION PROGRAM: FY 2024 ACTIVITIES

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DISCLAIMER

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

This report is not intended for construction, bidding, or 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 and play a key role in highway automation. The design, application, and maintenance of traffic control devices are under constant transformation as new technologies, methodologies, and policies are introduced. In addition, vehicle technologies and the roadway infrastructure industry are rapidly evolving, spurred by technology advancements, customer demand, changes in the vehicle fleet, and changes in national and state policies. This project provides the Texas Department of Transportation (TxDOT) with a mechanism to conduct high-priority, limited-scope evaluations of issues related to traffic control devices. Research activities conducted during the 2024 fiscal year (September 2023–August 2024) included:

- Evaluate driveway assistance devices (DADs) in lane closures on two-lane, two-way roads.
- Compile a synthesis of practices to deter pedestrians from crossing freeways.
- Assess the safety experience at rural intersections with flashing beacons.
- Analyze the use of maintenance work zone speed limits by TxDOT districts.
- Develop technical briefs documenting the safety effects of centerline buffers on two-lane and four-lane undivided roadways.
- Recommend updates to TxDOT Pavement Marking Handbook.
- Test innovative applications of work zone intrusion alarms.

The findings from the first three activities are documented in this report. The analysis of the use of maintenance work zone speed limits by TxDOT districts and the development of technical briefs were considered internal in nature, so they are not included herein. The remaining activities are ongoing and will be documented in future reports, as deemed appropriate.

CHAPTER 2: 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 [PTSs]) 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 the Texas A&M Transportation Institute (TTI) developed DADs to control traffic entering the one-lane road section from low-volume driveways (*1*). DADs are neither a 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. TxDOT received approval to experiment with DADs from the Federal Highway Administration (FHWA) on June 27, 2013. TxDOT continues to use and evaluate DADs since the 11th Edition of *Manual on Uniform Traffic Control Devices* (*2*) did not include DADs.

As of August 2024, TxDOT has approved the use of DADs on 26 projects, of which seven projects have been completed, five projects are ongoing, 12 projects have not started, and two projects decided not to use DADs. To date, TTI has collected and analyzed data for seven projects. This chapter documents the findings from field studies conducted between September 2023 to December 2023. Background on the development and application of DADs by TxDOT and results from prior studies conducted from March 2019 to August 2023 can be found in previous research reports (*3*, *4*).

FIELD STUDY SITES

Between September 2023 and December 2023, 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 5 SH 97 CSJ 0483-01-056

Project 5 involved the rehabilitation and widening of SH 97 in La Salle County from FM 624 to just west of the La Salle/McMullen County Line. Project 5 started in March 2020 near Cotulla and progressed toward Fowlerton. The DAD design for this project was the four-section stacked DAD that includes two 12-inch steady red arrow indications and two 12-inch flashing yellow indications (see Figure 1). 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. Since the four-section stacked DAD displays steady red arrow indications, a modified R10-11 sign is typically used with a second supplemental sign (YIELD IN DIRECTION OF FLASHING YELLOW ARROW) (see Figure 1). However, based on previous study findings, TxDOT requested that TTI change out the two supplemental signs at the driveway where researchers collected data to a R10-11b sign (NO TURN ON RED) and a WAIT/TURN ONLY IN DIRECTION OF FLASHING YELLOW ARROW sign (see Figure 2).

Figure 1. Example of Four-Section Stacked DAD.

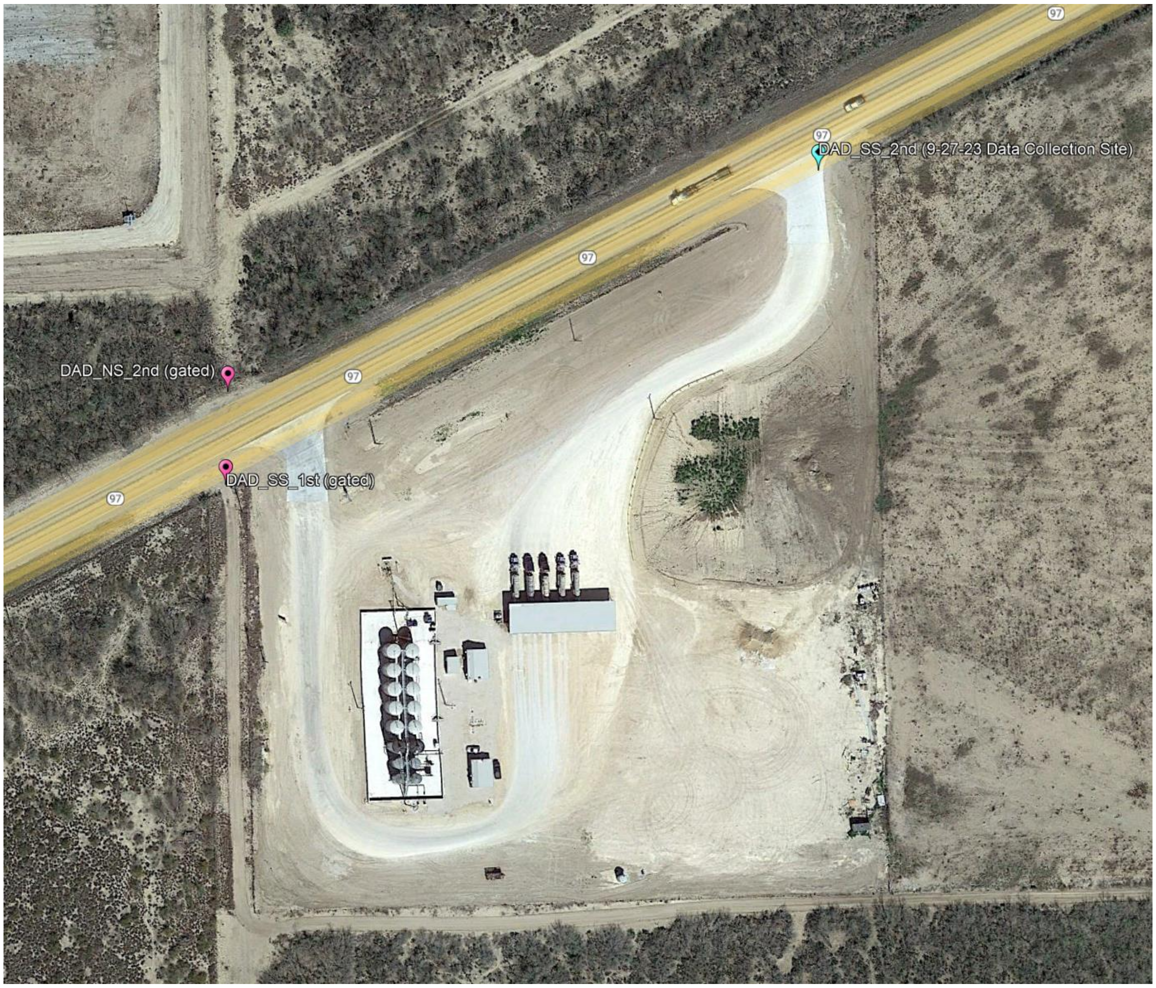
Figure 2. Project 5 Supplemental Signs Used at Driveway Studied.

Figure 3 shows the section of roadway under construction in September 2023. The one-lane section was controlled by PTSs and was approximately 2.6 miles long (see white pins with squares in Figure 3). The eastbound and westbound cycle times were approximately 3 minutes and 49 seconds and 10 minutes and 45 seconds, respectively. The average red time was 10 seconds for both cycle times with very little deviation. DADs were used at 14 locations (see pink pins with circles and aqua pin with a diamond in Figure 3).

(Source: © 2024 Google Earth Pro)

Figure 3. Project 5 SH 97 September 2023 One-Lane Study Section.

TTI collected data at a driveway that provided access to a saltwater disposal company (SS_2nd) on September 26–28, 2023 (see aqua pin with a diamond in Figure 4). The driveway was located approximately 2.2 miles from the westbound PTS and approximately 0.4 mile from the eastbound PTS. Vehicles entering SH 97 from the driveway could see the eastbound PTS. The DAD was located on the nearside of the intersection, and construction was occurring in the westbound lanes (see Figure 5). Data collection began around noon on Tuesday and ended around 5:00 a.m. on Thursday.



(Source: © 2024 Google Earth Pro)

Figure 4. Project 5 SH 97 One-Lane Section near Driveway SS 2nd.

Figure 5. Project 5 Driveway Exit SS 2nd from across the Road.

Project 13 FM 99 CSJ 0348-07-018

Project 13 involved the rehabilitation of FM 99 in Atascosa County from the Atascosa/Karnes County line to the Live Oak/Atascosa County Line (approximately 9.5 miles). The contractor used the four-section stacked DAD design in Figure 1, and TTI did not alter the supplemental signs at this site.

Figure 6 shows the section of roadway under construction in December 2023. The one-lane section was controlled by PTSs and was approximately 1.3 miles long (see white pins with squares in Figure 6. The northbound and southbound cycle times were approximately 3 minutes each. The average red time was 2 minutes and 36 seconds for both cycle times, so the green time for most cycles was less than 30 seconds. The red time appeared to be calculated assuming that vehicles were traveling 30 mph through the one-lane section. DADs were used at two locations (see the pink pin with a circle and the aqua pin with a diamond in Figure 6) although there were four other driveways in the one-lane section.

(Source: © 2024 Google Earth Pro)

Figure 6. Project 13 FM 99 December 2023 One-Lane Study Section.

TTI collected data at CR 411, which provided access to one residential home and several oil/gas industry pads, on December 20–22, 2023 (see aqua pin with a diamond in Figure 6). The driveway was located approximately 0.5 mile from the northbound PTS and approximately 0.75 mile from the southbound PTS. Vehicles entering FM 99 from CR 411 could not see either PTS due to a horizontal curve in the northbound direction and a vertical curve in the southbound direction. The DAD was located on the nearside of the intersection, and construction was occurring in the northbound lane (see Figure 7 and Figure 8). Data collection began around 11:00 a.m. on Tuesday and ended around 2:00 a.m. on Thursday.

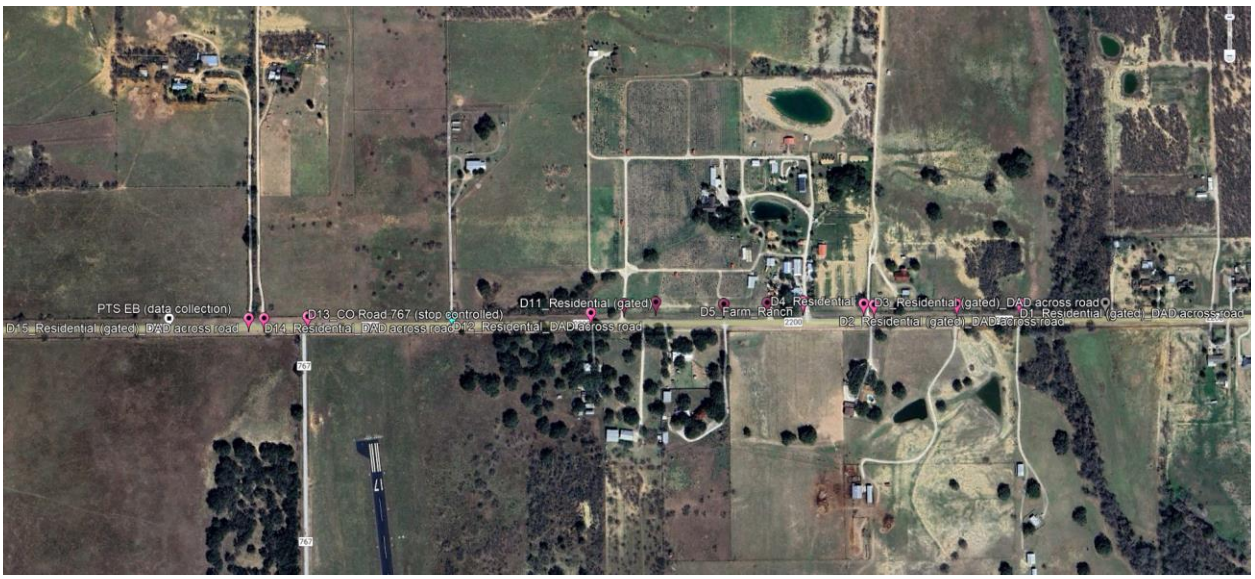
Figure 7. Projet 13 DAD at CR 411 from across the Road.

Figure 8. Project 13 DAD at CR 411 from Approaching Traffic Viewpoint.

Project 14 FM 2200 CSJ 2520-01-016

Project 14 consisted of widening FM 2200 in Medina County from Virginia Drive to CR 764 (Huntzer Lane) (approximately 2.1 miles). The contractor used the four-section stacked DAD design in Figure 1, and TTI did not alter the supplemental signs at this site.

Figure 9 shows the section of roadway under construction in December 2023. The one-lane section was controlled by PTSs and was approximately 0.9 mile long (see white pins with squares in Figure 9). The eastbound and westbound cycle times were approximately 2 minutes and 4 minutes, respectively. The average red time was 10 seconds for both cycle times with very little deviation. There were 15 driveways in the one-lane section, but DADs were used at 14 locations since two driveways shared one DAD (see pink pins with circles and aqua pin with a diamond in Figure 9).



(Source: © 2024 Google Earth Pro)

Figure 9. Project 14 FM 2200 December 2023 One-Lane Study Section.

TTI collected data at a driveway (D12) that provided access to one residential home on December 12–14, 2023 (see aqua pin with a diamond in Figure 9). The driveway was located approximately 1480 ft from the eastbound PTS and approximately 3460 ft from the westbound PTS. Vehicles entering FM 2200 from the driveway could see the eastbound PTS. The DAD was located on the far side of the intersection and construction was occurring in the westbound lane (see Figure 10 and Figure 11). Data collection began around 10:30 a.m. on Tuesday and ended around 1:30 a.m. on Thursday.

Figure 10. Project 14 DAD at D12 Looking Westbound.

Figure 11. Project 14 DAD at D12 from Approaching Traffic Viewpoint.

FIELD STUDY RESULTS

For each site, researchers computed the hours of study, number of minor approaches vehicles, number of stop cycles, number of violations, and a violation rate (i.e., number of violations per

100 stop cycles). Researchers also described each violation in detail and then categorized the violation into one of the following categories:

- *Turned on Red Prior to Flashing Yellow Arrow—Same Direction.* Driver arrived when the DAD displayed a flashing yellow arrow or just as the DAD displayed the 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. Researchers did not consider this maneuver to be an unsafe driving action.
- *Turned on Red to Join Main Road Traffic—Same Direction.* Driver arrived when the DAD displayed a flashing yellow arrow or just as the DAD displayed the red indication. After the DAD displayed the 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. Researchers did not consider this maneuver to be an unsafe driving action.
- *Turned on Red—Opposite Direction.* Driver arrived when the DAD displayed the red indication. Driver turned either right or left on red in the opposite direction of the subsequent flashing yellow arrow. Researchers considered this maneuver to be an unsafe driving action.
- *Turned in Opposite Direction of Flashing Yellow Arrow.* While the DAD displayed a right or left flashing yellow arrow, the driver turned in the opposite direction of travel. Researchers considered this maneuver to be an unsafe driving action.

Project 5 SH 97 CSJ 0483-01-056

Over the 40 hours and 53 minutes of data collection at a driveway that provided access to a saltwater disposal company, 123 vehicles arrived at the DAD. Seven drivers (6 percent) did not comply with the DAD. Out of the seven violations that occurred, four (57 percent) were related to motorists turning right (going eastbound) when a flashing yellow left arrow (westbound) was displayed (i.e., turning in the opposite direction of the flashing yellow arrow). This is likely due to the longer cycle time in the westbound direction (over 10 minutes). These violations were considered an unsafe driving action.

The other three violations (43 percent) were motorists “jumping” the flashing yellow right arrow either in anticipation of the next phase and/or getting ahead of the mainlane traffic queue (i.e., turned on red prior to flashing yellow arrow). This is likely because the driveway was near the eastbound PTS and within view of drivers exiting the driveway. While this type of maneuver was considered a violation, it was not considered an unsafe driving action. Overall, the violation rate for Project 5 was 2.1 violations per 100 stop cycles (7 violations divided by 334 stop cycles multiplied by 100).

Project 13 FM 99 CSJ 0348-07-018

Over the 38 hours and 57 minutes of data collection at the intersection of CR 411 and FM 99, 74 vehicles arrived at the DAD. Thirty-four drivers (46 percent) did not comply with the DAD. Out of the 34 violations that occurred 15 (44 percent) were drivers that turned on red in the opposite direction of the subsequent flashing yellow arrow (i.e., turning in the direction of oncoming traffic). Of these violations, 64 percent were drivers turning right on red and 36 percent were drivers turning left on red. This is likely due to the longer red time used for clearance. In addition, three violations (9 percent) were related to motorists turning right (going southbound) when a flashing yellow left arrow (northbound) was displayed (i.e., turning in the opposite direction of the flashing yellow arrow). Both of these violation types were considered unsafe driving actions.

The other violations (47 percent) were either drivers "jumping" the flashing yellow arrows either in anticipation of the next phase and/or getting ahead of the mainlane traffic queue (2 violations) or drivers turning on red to join the mainlane traffic queue (14 violations). While these types of maneuvers were considered violations, they were not considered an unsafe driving action. Overall, the violation rate for this site was 4.7 violations per 100 stop cycles (34 violations divided by 731 stop cycles multiplied by 100).

Project 14 FM 2200 CSJ 2520-01-016

Over the 38 hours and 52 minutes of data collection at a driveway that provided access to one residential home, only seven vehicles arrived at the DAD. Two drivers (29 percent) did not comply with the DAD. Both violations were drivers "jumping" the left flashing yellow arrow to get ahead of the mainlane traffic queue. While this type of maneuver was considered a violation, it was not considered an unsafe driving action. Overall, the violation rate for this site was 0.3 violations per 100 stop cycles (2 violations divided by 732 stop cycles multiplied by 100).

SUMMARY AND CONCLUSIONS

Table 1 contains a summary of the DAD characteristics at each site studied to date. Table 2 and Table 3 provide a summary of the violation rates and types, respectively, for all projects to date. The overall violation rate for the three-section doghouse DAD is 6.5 violations per 100 stop cycles and ranged from 1.0 to 10.7 violations per 100 stop cycles. However, most of the violations (92 percent) were not considered to be unsafe driving behaviors (i.e., anticipating the next flashing yellow phase or joining the mainlane traffic queue). The overall violation rate for the four-section stacked DAD is 5.9 violations per 100 stop cycles and ranged from 0.3 to 15.9 violations per 100 stop cycles. While the overall violation rate for the four-section stacked DAD is slightly lower than the three-section doghouse DAD, most of the violations (86 percent) were considered to be unsafe driving maneuvers (i.e., turning in the opposite direction of allowed travel). Based on the study findings analyzed to date, researchers continue to recommend the use of the three-section doghouse DAD with a NO TURN ON RED sign (R10-11) and TURN ONLY IN DIRECTION OF ARROW sign.

Table 1. Summary of DAD Characteristics at Each Site.

Project	Type	Supplemental Sign 1[a]	Supplemental Sign 2	Access Point Number	Access Point Description	Location Relative to Access Point
1	3-head	R10-11	TURN ONLY IN DIRECTION OF ARROW	SB-33	Business driveway	Farside
				NB-12	Business and residential driveway	Nearside
				NB-11	Business and residential driveway	Farside
3	4-head	Modified R10-11	YIELD IN DIRECTION OF FLASHING YELLOW ARROW	FM 1583	Farm-to-Market Road	Nearside
				CR 3800	County Road	Nearside
				CR 3800	County Road	Nearside
4	4-head	Modified R10-11	YIELD IN DIRECTION OF FLASHING YELLOW ARROW	DAD_11	Local Road	Farside
5	4-head	R10-11b	WAIT TURN ONLY IN DIRECTION OF FLASHING YELLOW ARROW	SS_2nd	Business driveway	Nearside
8	3-head	R10-11	WAIT TURN ONLY IN DIRECTION OF ARROW	18	Business driveway	Nearside
				20	Business driveway	Nearside
13	4-head	Modified R10-11	YIELD IN DIRECTION OF FLASHING YELLOW ARROW	CR 411	County Road	Nearside
14	4-head	Modified R10-11	YIELD IN DIRECTION OF FLASHING YELLOW ARROW	D12	Residential driveway	Farside

[a] R10-11 is “NO TURN ON RED (red ball)”, a modified R10-11 is “NO TURN ON RED (two red arrows)”, and a R10-11b is “NO TURN ON RED.”

Table 2. Summary of Violation Rate Statistics.

Project	Type of DAD	Access Point Number	Hours of Study	Number of Minor Approach Vehicles	Number of Stop Cycles	Number of Violations	Violations per 100 Stop Cycles[a]
1	3-head	SB-33	21.0	17	308	3	1.0
1	3-head	NB-12	47.4	246	696	24	3.4
1	3-head	NB-11	47.1	341	692	69	10.0
1	3-head	*Total*	*115.5*	*604*	*1696*	*96*	*5.7*
8	3-head	18	48.6	97	728	31	4.3
8	3-head	20	48.5	125	727	78	10.7
8	3-head	*Total*	*97.1*	*222*	*1455*	*109*	*7.5*
3	4-head	FM 1583	48.0	112	823	19	2.3
3	4-head	CR 3800	48.1	91	475	37	7.8
3	4-head	CR 3800	46.9	79	455	39	8.6
3	4-head	*Total*	*143.0*	*282*	*1753*	*95*	*5.4*
4	4-head	DAD_11	46.0	1254	699	111	15.9
5	4-head	SS_2nd	40.9	123	334	7	2.1
13	4-head	CR 411	38.9	74	731	34	4.7
14	4-head	D12	38.9	7	732	2	0.3

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

Table 3. Summary of Violation Types.

Project	Type of DAD	Access Point Number	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-head	SB-33	100%	0%	0%	0%
1	3-head	NB-12	63%	21%	8%	8%
1	3-head	NB-11	56%	41%	3%	0%
1	3-head	*Total*	*60%*	*34%*	*4%*	*2%*
8	3-head	18	58%	32%	10%	0%
8	3-head	20	65%	24%	7%	4%
8	3-head	*Total*	*63%*	*27%*	*7%*	*3%*
3	4-head	FM 1583	5%	0%	0%	95%
3	4-head	CR 3800	0%	5%	0%	95%
3	4-head	CR 3800	0%	0%	0%	100%
3	4-head	*Total*	*1%*	*2%*	*0%*	*97%*
4	4-head	DAD_11	3%	8%	5%	84%
5	4-head	SS_2nd	43%	0%	0%	57%
13	4-head	CR 411	6%	41%	44%	9%
14	4-head	D12	100%	0%	0%	0%

FYA = Flashing Yellow Arrow

CHAPTER 3: PRACTICES TO DETER PEDESTRIANS FROM CROSSING FREEWAYS

INTRODUCTION

TxDOT has seen an increase in recent years in crashes involving pedestrians crossing freeways and other high-speed roadways. Texas saw 4,481 motor vehicle traffic fatalities in 2022. While this was a decrease of 0.36 percent from the 4,497 deaths recorded in 2021, it still represents, on average, one person killed on Texas roads by motor vehicles every one hour and 57 minutes (*5*). Among those fatalities were 828 pedestrians, an increase of 0.24 percent from 2021.

Some work has been done in select TxDOT districts and in other states to address this issue, focusing on developing a selection of countermeasures and other strategies to reduce the number of crossings and, by extension, the number and severity of associated crashes. TxDOT requested TTI compile information from recent studies and current practices in TxDOT districts and elsewhere for the purpose of developing a toolbox of countermeasures, as well as identify applicable research needs. This chapter documents the literature review, synthesizes existing information on relevant practices found through a review of literature, and includes a list of related research needs. TTI recently conducted a survey of TxDOT district practices and will include those findings in future reports, as deemed appropriate.

LITERATURE REVIEW

Crash Trends

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 12). TxDOT Project 0-6702, conducted by TTI in 2017 (*6*), reviewed the crash reports for all fatalities involving pedestrians on interstates in Texas. Researchers found that 21 percent of all fatal pedestrian crashes (474 of 2232) occurred on limited-access highways (i.e., freeway main lanes, entrance/exit ramps, medians and shoulders), and 43 percent of those 474 crashes involved a pedestrian crossing the main lanes. About 26 percent of those 474 crashes were found to be related to a stalled vehicle or a previous crash. Pedestrians were found to be under the influence of alcohol or other drugs in 28 percent (132 of 474) of the crashes on freeways. Also, the study concluded that most fatal pedestrian crashes on freeways (82 percent) were associated with dark conditions.

Figure 12. Pedestrian Crossing the Main Lanes of a Texas Interstate.

In February 2019, TTI researchers collected video data in Austin for a week on a section of I-35 that experienced pedestrian crossings (*3*). Results indicated that an average of one pedestrian per day crossed the main lanes over the seven-day period. It appeared that the crossing pedestrians traveled from hotels on the west side of the freeway to restaurant and shopping destinations on the east side of the highway.

Other evidence of pedestrian activity was documented through calls made to 9-1-1 to report pedestrians on high-speed roadways (*3*). The Austin Police Department (APD) established the call code to better understand locations with pedestrian safety concerns. Between April 2017 (when the call code was established) and December 2019, more than 3,600 9-1-1 calls were made to APD about pedestrians on I-35. Figure 13 shows a density map of the 9-1-1 call data; locations with the highest call density, as circled on the map, tend to be concentrated within the central part of the city.

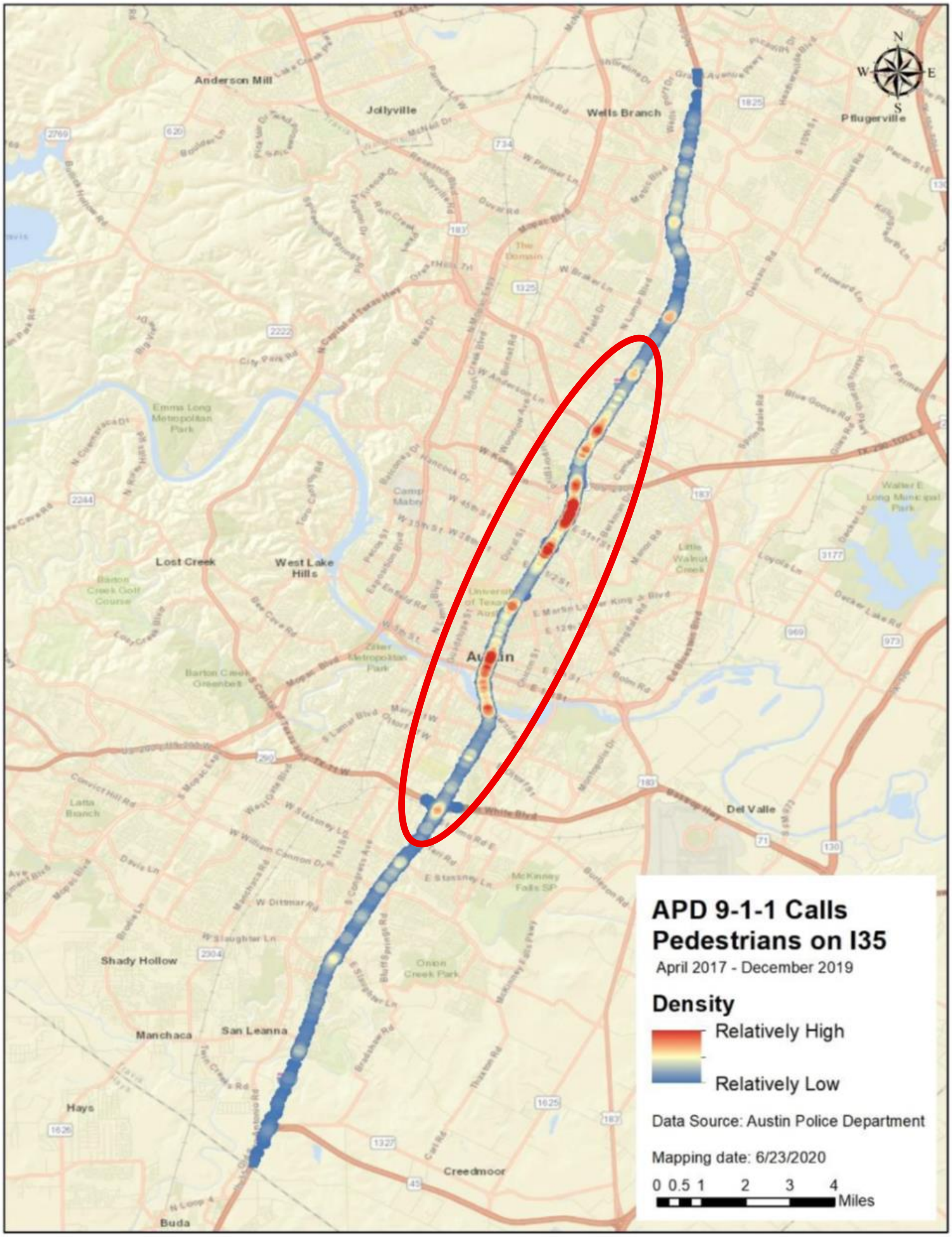


Figure 13. 9-1-1 Call Data Heat Map on I-35 in the City of Austin Limits (*3*).

Undocumented immigrants running across high-speed limited-access roadways to avoid being apprehended by authorities is also 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 (*7*). 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 (*7*). The Texas Strategic Highway Safety Plan (SHSP) created 77 programs and projects related to pedestrian safety issues, including the Highway Safety Improvement Program (HSIP), Vision Zero, and driver feedback signs. However, no project specifically addresses undocumented immigrants crossing border areas.

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 highway on purpose, for reasons such as making a shortcut to nearby destinations (*8*). Thus, intentional pedestrians are similar to undocumented immigrants in that they knowingly cross the highway.

A TTI study of crashes during 2008–2017 (*9*) conducted for the TxDOT Dallas District revealed that 328 crashes (7 percent of 8,332 total pedestrian-related crashes) in Dallas occurred on freeways. Of those 328 pedestrian-related crashes, 129 (39 percent) were fatal pedestrian crashes and 65 (51 percent) of the pedestrians in fatal crashes intended to be on the freeway.

Past studies rely on pedestrian collision data to understand the nature of the issue (*10, 11, 12*). Other data sources include surveys from department of transportation (DOT) employees (*13*) and traffic speed/vehicle size data collected at the crash site (*14*). Some studies successfully identified locations that are collision prone (*8*, *12*, *14*). 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.

Contributing Factors

Dada (*15*) investigated the factors that influenced illegal freeway crossing in Cape Town, South Africa. Results from a 300-person survey indicated that crossing choice was largely influenced by a combination of built environment, vehicular and pedestrian traffic, and sociodemographic characteristics. Among the factors considered in the survey, traffic volumes, walking distance, and law enforcement presence had the most influence on the risk perception of pedestrians. Increased vehicle traffic and presence of law enforcement were associated with an increased likelihood that pedestrians would walk a greater distance to a bridge to cross. Barriers and fencing also lowered the preference to cross at-grade in favor of a footbridge. Results showed that younger pedestrians were more risk-seeking than their older counterparts and that tenure (i.e., the length of time that a pedestrian lived in Cape Town) reduced the risk perception levels of traffic safety. Moreover, pedestrians were more likely to cross with a footbridge over the freeway rather than at-grade under normal circumstances.

A review of conditions on I-35 in Austin between 51st Street and St. Johns Avenue for a pedestrian road safety assessment (PRSA) (*16*) revealed that one contributing factor for pedestrians crossing the freeway was a number of pedestrian generators (e.g., shopping, restaurants, services, hotels, etc.). The reviewers determined that from many locations along the study area, users could easily see destinations on the other side of the freeway (e.g., from a hotel on one side of the freeway a restaurant was visible on the other side) but walking routes to get there were not readily visible. Overpasses had large spacing between them and were not always clear as to whether they would allow pedestrian access across the freeway. A discussion of conditions along the corridor's frontage road also mentioned high speeds; inadequate lighting and wayfinding aids; a need for improved sidewalk connectivity, width, and buffers; and a need for more consistent driveway design that encourages drivers to check for crossing pedestrians. The reviewers concluded that these concerns may have contributed to observed risky pedestrian actions such as crossing the freeway.

Countermeasures

Hudson et al. (*8*) reviewed the literature to investigate potential countermeasures designed for pedestrian safety on high-speed roadways. While they found that such countermeasures were not prevalent, they did conclude that suggestions to restrict pedestrian activity on freeways could be divided into five categories: educating pedestrians, building barriers to discourage pedestrian travel, accommodating pedestrians, warning drivers, and fining pedestrians. Specific countermeasures included:

- Education Programs: Educational campaigns and public announcements were advocated by several respondents in Johnson's (*7*) survey. A 2002 study by Duperrex et al. (*17*) indicated that pedestrian safety education can affect road crossing behavior. A separate study by Emry et al. (*10*) indicated that the language and timing of educational messages need to target the vulnerable population of interest. For example, to reduce the crash rate for undocumented persons in San Diego, Emry et al. found that making announcements in Spanish and concentrating efforts on weekends were efficient methods.
- Pedestrian Barriers: Right-of-way fencing and median barriers can be built to keep pedestrians off the roadway.
- Pedestrian Accommodations: To accommodate pedestrians, the PEDSAFE system (*18*) redesigned an interstate interchange in Englewood, Ohio, to make it a safer place for travelers using all transportation modes. Another suggested accommodation is a grade-separated crossing, such as an underpass or overpass, that provides an alternative pathway for

pedestrians. On a system level, Johnson (*7*) suggested providing a well-connected street network. Using land use regulations to discourage the construction of residential properties adjacent to freeways has also been suggested (*7*).

- Pedestrian Violation Penalty: Many states and regions have enacted laws that specifically prohibit pedestrians from entering controlled-access roadways. Connecticut, Washington, and the City of New York have statutes in place. Fines can create a disincentive to pedestrians who may otherwise enter the interstate.
- Driver Warning Signs: In some cases, states have recognized that pedestrians cross the freeway and have installed warning signs to alert drivers of possible pedestrian crossings (*7*). Nighttime signs with graphics were to be more effective than text signs, according to Emry et al. (*10*).

The effectiveness of the above countermeasures had not been confirmed at the time of the Hudson study (*8*). In lieu of that confirmation, Hudson et al. observed a conclusion from Fegan (*19*), which stated that traditional pedestrian or roadway-oriented engineering countermeasures such as those listed can reduce up to 50 percent of the pedestrian crashes investigated, but Johnson (*7*) later claimed that there are no proven engineering countermeasures for unintended pedestrians.

Hunter (*11*) reviewed crash data and potential countermeasures for pedestrian crashes on I-40 in Texarkana and West Memphis, Arkansas. Looking at the differences between the number and rate of crashes between the two cities, Hunter concluded the single most effective countermeasure (based on available crash modification factors) was installing barriers or fencing, and the single most cost-effective solution (based on crash reduction compared to estimated installation cost) was driver signage. Other countermeasures considered in the review included increased lighting, overpass improvements, public transportation, and public educational programs with increased law enforcement. A supplemental treatment was an upgraded pedestrian facility on an existing overpass for a local street that crossed over the freeway, to include an actual sidewalk to connect the two sides of the freeway rather than requiring pedestrians to walk on the shoulder of the overpass.

The PEDSAFE system (*20*) lists a selection of recommended countermeasures for pedestrians crossing expressways and other limited-access facilities. When the issue is an unintended pedestrian (e.g., for a person in a disabled vehicle who crosses the roadway to seek help), the list of recommended countermeasures includes install/upgrade roadway lighting, educate drivers on what to do if a vehicle is disabled, increase police surveillance, and provide a motorist assist program. When the issue is intentional pedestrians (e.g., pedestrians routinely cross a section of an expressway), the list of recommended countermeasures includes install/upgrade roadway lighting, provide pedestrian overpass/underpass, install large pedestrian warning signs, increase police surveillance, and install pedestrian fencing or barriers along the roadway right-of-way.

Researchers on the Hudson study (*8*) also asked state highway safety engineers about strategies and regulations used to reduce pedestrian crashes on high-speed roadways. They received responses from representatives of 20 state transportation agencies including TxDOT. Policies and practices for unintended pedestrians were more frequently cited than those addressing intentional pedestrians. These strategies include move over and collision clearance laws and campaigns or design features that try to reduce friction between unintended pedestrians and highway drivers. Several states offer roadside assistance programs to aid travelers in support of these policies. Often, these strategies are implemented through clear policies, roadway signing, and/or educational campaigns. In contrast, other than enforcement, ongoing or systematic practices addressing intentional pedestrian safety strategies on highways, such as evaluation of pedestrian crossings, were rarely mentioned. The majority of surveyed states prohibit pedestrians on controlled-access highways and have limited evidence of specific practices or countermeasures focused on pedestrian safety on high-speed roadways.

Specific countermeasures discussed in the survey from the Hudson study (*8*) include the following:

- Overpasses and Underpasses: The survey results indicated that while overpasses or underpasses are used in many states, most states do not evaluate their use or collect the pedestrian volume data to do so. While some respondents noted that pedestrians are expected to use crossings wherever they exist, others noted that they have observed pedestrian fatalities in proximity to pedestrian crossings, suggesting this expectation is not always realistic. Underpasses were noted as a strategy that can be successful in contexts where they are well traversed and secure but unsuccessful if they are underutilized and uncomfortable for pedestrians.
- Barriers and Fences: Barriers and fences were mentioned by many survey respondents; however, none were able to provide documented evidence of their success or failure to protect pedestrians. Fencing or other barriers are used for channelization, but they can sometimes be easily traversed. Crash data do not typically provide information on the motivations that brought pedestrians to controlled-access roadways. This could be a focus of future research, particularly for intentional pedestrians.
- Lighting: Lighting as a practice was only cited by one respondent despite evidence that many fatal pedestrian crashes happen at night. Most pedestrian fatalities on high-speed roadways occur in dark conditions, but the improvement from the addition of lighting on high-speed roadways would need to be empirically evaluated. One system proposed by Wanvik (*21*) had an adaptive mode that automatically brightens when objects approach and dims when the roadway is vacant. Adaptive lighting could reduce operational costs and potentially have better warning effect due to its changeable lighting, but those effects would have to be studied to quantify any benefits.
- Move Over Laws: Many respondents discussed move over/slow down laws or policies present in their state. A move over law stipulates that drivers must take precautions such as

slowing down or moving over when approaching and passing an emergency vehicle along the roadway. Precautions that are suggested or required in such laws can include slowing down, changing lanes, or giving a signal. Effectiveness of these laws relies on drivers' awareness and cooperation, which is heavily dependent on education and enforcement.
- Collision Clearance Laws: Survey respondents cited requirements for motorists to clear disabled vehicles from the main lanes and other precautions after a breakdown on a highway. Although these policies are often focused on high-speed roadways, the priority typically is reducing congestion and delay rather than improving safety. These laws are sometimes paired with roadside assistance programs to help with incident management and clearing the road after breakdowns or collisions.

Countermeasures recommended by the Austin I-35 PRSA related to pedestrians attempting to cross the freeway included the following:

- Provide information to those who may be tempted to try and cross the main lanes or are trying to get to locations across the expressway. Strategies may include:
    - Pedestrian wayfinding signs to nearest safe crossing opportunity.
    - Pedestrian warning and regulatory signs to discourage unsafe/illegal crossings.
    - Provide maps or electronic displays for navigation to hotels, Greyhound station, day labor center, and other pedestrian generators.
- Provide aesthetic lighting on overpasses to help illuminate the nearest safe crossing location.
- Explore the creation of a circulator bus service that could reduce the time impact of walking to the nearest crossing.
- Explore technology for monitoring pedestrian activities and responses (e.g., laser motion detectors, infrared cameras, count studies, monitoring by Transportation Management Center) to help prioritize future pedestrian improvements.
- Develop a barrier plan for this segment of I-35 to analyze the needs, context, and appropriate countermeasures within the segment. An effective barrier would preferably offer sufficient height to be difficult to traverse, block the view of destination draws on the opposing side, be difficult to climb, and be resistant to tampering (e.g., graffiti, cutting, or other damages). The type and height of the barrier would need to consider visibility of businesses for drivers on I-35, aesthetics, and crashworthiness, among other concerns.
- Establish a monitoring plan to log Austin Police Department dispatches, crashes, video to record crossings, and feedback from stakeholders. Working with TTI and the City of Austin, evaluate performance and consider further installations such as between the northbound main lanes and frontage road between 51st Street and US-290, and from US-290 to St. Johns Avenue.
- Develop a plan for sidewalks or shared-use paths to provide 10 ft of width, buffered separation from back of curb, connectivity, and driveway treatments to improve the walkability of the area adjacent to the frontage road.

- Further investigate the value of adding a pedestrian overpass within this segment, considering cost, likely demand, stakeholder support, and network connectivity.

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 (*3*). In 2020, the district installed an additional barrier on top of the existing concrete median barrier to reduce pedestrian crossings (see Figure 14 and Figure 15).

Figure 14. No Pedestrian Crossing Stencil and Signs on I-35 in Austin.

Figure 15. Stencil and Barrier on Top of Center Median on I-35 in Austin.

At a broader level, TxDOT implemented the Texas SHSP (*22*) in 2016 to address motor vehicle fatalities on Texas roads. 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.

Researchers on TxDOT Project 0-7096 (*3*) reviewed available information on other states' practices related to crashes involving undocumented immigrants crossing roadways. 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 was one of the more cost-effective countermeasures suggested by multiple pieces of literature. Although California was the only state that designed safety measures to address undocumented immigrant road safety (e.g., warning signs on limited-access highways to warn motorists of potential pedestrian activity), other states actively developed countermeasures to increase pedestrian highway safety in general. A 1997 study collected information from the National Association of Governor's 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 (*7*); adding lighting, overpass/underpass, barriers, and signs or markings; or increasing law enforcement (*8*, *13*). Others mentioned adding dynamic message signs (*13*), increasing the road friction (*23*), and adding a glare screen median pedestrian fence (*24*).

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 (*25*). However, the study was focused on overall pedestrian crashes. Also, some have concerns that pedestrian warning signs induce more pedestrian crossings on the highway (*13*).

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 (*10*). Texas, California, Arizona, and Rhode Island have installed warning signs to reduce pedestrian-related interstate highway collisions (*8*). The design of the sign should consider the graphics and readability as well as high-visibility reflectivity to increase effectiveness (*13*).

Researchers on TxDOT Project 0-7096 (*3*) conducted 12 interviews with TxDOT districts and border state DOTs to investigate an increase in pedestrian crashes involving undocumented immigrants crossing high-speed limited-access roadways to avoid being apprehended by authorities, as well as related countermeasures and effects. 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. Most of the urban districts 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 also considered the installation of these countermeasures. In addition, urban districts have a motor vehicle assistance program (e.g., HERO) that removes the disabled vehicle and its occupants from the high-speed roadway, thereby reducing the likelihood of an unintended pedestrian crash. Several interviewees mentioned the Pedestrian Crossing symbol signs and stenciled No Pedestrian Crossing symbols used in Austin as something they were considering.

Feedback from border states (i.e., California, Arizona, and New Mexico) 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 (*3*). 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 were often the same or similar in each scenario. In New Mexico and Arizona, DOTs had recently conducted safety studies to implement solutions to improve the pedestrian safety.

Although installing signs is relatively low cost and can be effective, some literature and interviewees suggested its limitations. 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; urban district interviewees 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, the study concluded, it is challenging to select locations to install warning signs (*3*).

Researchers on TxDOT Project 0-7082 (*26*) conducted an extensive literature review and completed surveys with TxDOT districts and other transportation agencies to identify existing implementation guidelines and practices for attachments to concrete barriers to deter pedestrians. Concrete rigid barriers are used in medians to separate traffic and on the roadside to shield hazards from motorists and motorists from hazards. Attachments may be deployed on top of concrete barriers for various reasons, including deterring pedestrians from crossing highways. Such hardware attachments, however, had not been investigated to MASH standards.

Survey participants (*26*) were asked questions related to their experiences with pedestrians crossing highways, implemented solutions, and efficacy of implemented solutions. Survey results showed that freeways, expressways, and divided highways were the most common roadways on which states face an issue with pedestrians crossing. For state DOTs, some used top-mounted attachments to deter pedestrians from crossing, while others used warning signs. Other solutions used were issuing citations or installing right-of-way fencing. Results also showed that most of the responding states have not investigated the efficiency of implemented solutions. For Texas districts, many commonly use pedestrian crossing and glare prevention attachments but do not have specific attachments. Of those that have used pedestrian or glare prevention attachments, most have not investigated the system crashworthiness or conducted an implementation study.

Based on findings from the literature review and surveys, researchers (*26*) prioritized existing attachment systems and then conducted full-scale crash testing to verify the crashworthiness of the system attachments at high-speed TL-3 and TL-4 MASH impact conditions. The crash tests for the attachments on the single-slope concrete median barrier were performed in accordance with TL-4, and the crash tests for the attachments on the F-shape concrete median barrier were performed in accordance with TL-3. All the evaluated attachments on concrete barriers met the performance criteria for MASH longitudinal barriers for their respective tests.

SYNTHESIS OF FINDINGS

The review of recent literature, which included a variety of research studies, practitioner interviews and surveys, and published resources and guidelines, produced a set of countermeasures that could be assigned to several broad categories. These countermeasures and categories are shown below in Table 4.

Table 4. Countermeasures for Freeways Identified from Literature Review.

• Accommodations ○ Overpass or underpass. ○ Pedestrian facilities on existing overpass or underpass. ○ Interchange redesign. ○ Shoulder design (e.g., wider to allow more space for unintended pedestrians to walk along the side of the roadway after a breakdown or collision). ○ Sidewalk or shared-use path on frontage roads. • Barriers ○ Pedestrian fencing along right-of-way. ○ Pedestrian barriers along right-of-way. ○ Median barrier (with optional attachments). • Education ○ Pedestrian safety education (e.g., risks inherent in crossing freeways, alternatives to crossing freeways). ○ Driver safety education (e.g., best practices for car breakdown, awareness of possible pedestrian presence). • Services ○ Increase police surveillance for motorist assistance. ○ Roadside assistance program. ○ Circulator bus service for local pedestrians. ○ Maps or electronic displays for local pedestrians.	• Laws ○ Fines for pedestrians entering freeways. ○ "Move over" laws. ○ Collision clearance laws. • Lighting ○ Freeway (corridor) lighting. ○ Overpass lighting. ○ Adaptive lighting. • Signs (Drivers) ○ Warning signs to alert drivers of possible pedestrian crossings (text and/or graphics). • Signs (Pedestrians) ○ Pedestrian warning and regulatory signs (perhaps in larger sizes). ○ Pedestrian wayfinding signs. ○ No Pedestrian Crossing symbol signs (R9-3) and No Pedestrian Crossing symbols stenciled on median barriers. • Other ○ Technology for monitoring pedestrian activities and responses to help prioritize future pedestrian improvements. ○ Monitoring plan to log police department dispatches, crashes, video recordings of crossings, and feedback from stakeholders.

In general, the review revealed that urban and border-area districts and agencies tend to have the largest issue with pedestrians crossing freeways. Those agencies have explored, recommended, and/or implemented various combinations of the countermeasures in Table 4, but studies of their effectiveness are not as common. 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 highway on purpose, for reasons such as making a shortcut to nearby destinations (*8*). Countermeasures to address these two categories of pedestrians are not necessarily the same; for example, unintended pedestrians are already within the freeway facility, so right-of-way fencing is not the same deterrent as it is for intentional pedestrians who are attempting to cross the freeway from one side to the other.

Table 5 contains a summary of the countermeasure studies revealed in the review, including where the study was conducted, what type of pedestrian is addressed by the countermeasure, and whether the reviewed source described the effectiveness of the countermeasure in a formal study.

Table 5. Summary of Countermeasure Studies for Pedestrians on Freeways.

Cat[a]	Countermeasure[b]	Where[c]	Ped Type[d]	Effectiveness[e]	Study?[f]	Source[g]
A	Interchange redesign	Englewood, Ohio	I	More welcoming environment, positive comments	Anecdotal	PEDSAFE (*18*)
A	Provide overpass/underpass	Nationwide	I	Varies	Anecdotal	Hudson (*8*), Harkey (*20*)
A	Shoulder design	Nationwide	U	Unknown	No	Hudson (*8*)
A	Plan for sidewalks or shared-use paths	Austin	I	Unknown	No	Allred (*16*)
A	Accommodations on over/underpasses	Texas	I	Unknown	No	Finley (*3*)
B	Pedestrian fencing or barriers at right-of-way	Nationwide	I	Unknown	No	Hudson (*8*), Harkey (*20*)
B	Median barrier	Texas	I	Unknown	No	Finley (*3*)
B	Barrier plan for specific corridor	Austin	I	Unknown	No	Allred (*16*)
E	Pedestrian safety education	San Diego, California	I	Language and timing of educational messages need to target the vulnerable population of interest	Yes	Emry (*10*)
E	Driver safety education	Nationwide	U	Unknown	No	Harkey (*20*)
LA	Fines for pedestrians entering controlled-access roadways	Nationwide	I	Fines can create a disincentive to pedestrians who may otherwise enter the freeway	No	Hudson (*8*)
LA	“Move over” and collision clearance laws	Nationwide	U	Unknown	No	Hudson (*8*)

Cat[a]	Countermeasure[b]	Where[c]	Ped Type[d]	Effectiveness[e]	Study?[f]	Source[g]
LI	Freeway lighting	Florida	I	Crash reduction factor of 25 percent for roadway segment crashes	Yes	Hunter (*11*), Gan (*25*)
LI	Freeway lighting	Nationwide	B	Unknown	No	Harkey (*20*)
LI	Freeway lighting	Nationwide	U	Unknown	No	Hudson (*8*)
LI	Freeway lighting	Texas	I	Unknown	No	Finley (*3*)
LI	Adaptive lighting system	Theoretical	B	Unknown	No	Wanvik (*21*)
LI	Aesthetic lighting on overpasses to help illuminate the nearest safe crossing location	Austin	I	Unknown	No	Allred (*16*)
SE	Roadside assistance program	Texas	U	Unknown	No	Finley (*3*)
SE	Roadside assistance program	Nationwide	U	Unknown	No	Hudson (*8*)
SE	Increase police surveillance	Nationwide	B	Varies	Anecdotal	Harkey (*20*)
SE	Provide maps or electronic displays for navigation	Austin	I	Unknown	No	Allred (*16*)
SE	Circulator bus service	Austin	I	Unknown	No	Allred (*16*)
SD	Warning signs to alert drivers of possible pedestrian crossings	Nationwide	I	Varies	Anecdotal	Johnson (*7*)
SD	Warning signs with graphics	San Diego, California	I	Signs with graphics were more effective than text signs	Yes	Emry (*10*)
SP	Large, visible pedestrian warning signs	Nationwide	I	Varies	Anecdotal	Harkey (*20*)
SP	Pedestrian wayfinding signs	Austin	I	Unknown	No	Allred (*16*)
SP	Pedestrian warning and regulatory signs	Austin	I	Unknown	No	Allred (*16*)
SP	No Pedestrian Crossing symbol signs (R9-3) and No Pedestrian Crossing symbols stenciled on concrete median barrier	Austin	I	Unknown	No	Finley (*3*)
O	Technology for monitoring pedestrian activities and responses to help prioritize future pedestrian improvements	Austin	I	Unknown	No	Allred (*16*)
O	Establish a monitoring plan	Austin	I	Unknown	No	Allred (*16*)

[a] Cat. = Countermeasure category where A = Accommodations, B = Barriers, E = Education, LA = Laws, LI = Lighting, SE = Services, SD = Signs (Drivers), SP = Signs (Pedestrians), and O = Other.
[b] Description of the countermeasure.
[c] Examples of where the countermeasure has been considered.
[d] Type of pedestrian where I = Intentional, U = Unintended, and B = Both.
[e] Summary of effectiveness of the countermeasure as identified in the literature review.

[f] Type of study where Yes = formal study conducted, No = no study identified for this countermeasure, and Ancedotal = observations on the perceived effectiveness of the countermeasure.
[g] References that discuss the countermeasure.

RESEARCH NEEDS

The review of previous findings produced a variety of suggestions for future research. A summary of research needs identified from the review is provided below. More details on these and other research needs can be found in the reports from the respective research projects that produced them (*6, 8, 26*).

- More resources for selecting appropriate countermeasures.
    - Investigation into appropriate countermeasures for freeway pedestrian crashes, which could include the following activities:
        - Increase data collection, evaluation, and monitoring of practices: Research results from multiple states revealed a lack of information about addressing safety of intentional pedestrian on high-speed roadways.
        - Evaluate intentional and unintended pedestrian activity independently: Crash data suggested that intended pedestrians walking or standing on the roadway make up a higher proportion of pedestrian fatalities on high-speed, controlled-access roadways, and intentional pedestrians pose a more complicated issue for transportation agencies, who are responding to an activity that is caused by pedestrians entering a roadway where their presence is illegal or formally prohibited.
        - Investigate relationships between pedestrian safety and the built environment along urban freeways: Information is lacking on how broader land use and transportation planning themes may contribute to and/or address pedestrian highway safety. Commercial and residential development along high-speed roadways will continue to create a demand for getting to destinations across a roadway. Thus, efforts need to be made to understand how to correlate land use and transportation planning to accommodate pedestrian activity safely.
    - Development of guidelines on selecting appropriate pedestrian crossing countermeasures based on, at a minimum, posted speed limit and number of lanes. In addition, this study could investigate and determine the appropriate value for the minimum number of pedestrians that should be included in TxDOT guidelines for installing pedestrian countermeasures
    - Development and implementation of a pilot study of the "Systemic Safety Project Selection Tool" focusing on pedestrian crashes in Texas. As a focus state, this tool offers a unique opportunity to address safety.
    - Development of other educational campaigns to address specific pedestrian behaviors (e.g., distracted walking, crossing freeways, walking during nighttime conditions) or to educate pedestrians regarding their visibility to drivers.

    - Evaluation of enforcement campaigns that target drivers not yielding to pedestrians and target jaywalking pedestrians, which could include investigating the expansion of "Move Over" laws. Generally, such laws are designed to protect emergency responders and enforcement officers on the road; however, unintended pedestrian fatalities on high-speed roadways suggest that the dangers facing emergency and enforcement agents can be a problem for everyday travelers as well. Extending this law to include all vehicles could greatly expand the benefits and would be unlikely to increase costs significantly, but it may require regulatory changes at the state level.
- Improve understanding of, and performance of, crashworthiness of barriers and related treatments.
    - An implementation study to verify the efficacy of attachment systems used to deter pedestrians from crossing highways. The implementation study could also be utilized to understand potential needs and setbacks related to repairs when such systems are struck in real-world crashes.
    - The design and investigation of the crashworthiness of non-redirective systems that might be placed on the roadside with the specific purpose of deterring pedestrians from crossing. Practitioner feedback indicates there is interest in understanding the crashworthiness of systems such as chain-link fences mounted on the side of the roadway to deter pedestrians from crossing.
    - Development of future research and testing to determine the crashworthiness of attachments implemented on top of post-and-beam guardrail systems as pedestrian crossing deterrents. A semi-flexible system would allow considerable lateral deflection during vehicle impact. Therefore, the interaction between the impacting vehicle and the system's attachment is expected to potentially be more critical in terms of system crashworthiness due to potential vehicle instability and occupant compartment deformations/intrusions.

CHAPTER 4: TEXAS SAFETY EXPERIENCE AT RURAL INTERSECTIONS WITH FLASHING BEACONS

INTRODUCTION

Background

Beacons can be used to supplement intersection traffic control and to emphasize the presence of a rural intersection and the need for the driver on the minor road to stop. This activity on TxDOT Project 0-7198 was to identify experiences with different beacon types used at stop-controlled rural intersections in Texas. Specifically, does the type of beacon installed influence safety at the intersection (e.g., the stopping behavior for approaching drivers)? A better understanding of the relationships between roadway characteristics and the various types of rural intersection beacons can help identify locations where the treatment may or may not be of value. The activity initially considered crashes; however, safety surrogates were also investigated because there were not sufficient crash data for a full crash analysis. The availability of data from connected vehicles (CVs) sparked the question of whether the speed pattern of drivers on the minor road approaching a stop-controlled intersection could be obtained and converted into a measure that could be compared, and whether those speed patterns are different for different types of intersection traffic control.

Objectives

The objectives of this activity were to answer the following questions:

1. Can CV data be used to obtain speed profiles for vehicles approaching a STOP sign?
2. What cleaning or filtering is needed to identify appropriate speed profiles for vehicles approaching a STOP sign?
3. What speed measures can be used to evaluate these speed profiles?
4. Can differences be seen in those speed measures/profiles depending on the type of STOP sign countermeasure (i.e., beacon treatments)?

STATE OF THE PRACTICE

Types of Beacon Treatments

Rural intersection beacons are flashing lights intended to draw a driver’s attention to the intersection and the associated traffic control present at the intersection. In the context of this evaluation effort, these beacons are intended to reinforce awareness of existing STOP signs. The types of treatments used at rural intersections include the following:

- **Typical.** A typical STOP sign is installed at the intersection.
- **Overhead.** Overhead beacons are signal heads mounted overhead at an intersection that flash a circular red or yellow to draw attention to the STOP signs on the minor approaches and to the presence of the intersection on the major roadway.
- **LED-E.** LED-embedded STOP signs are STOP signs where LEDs are embedded along the border.
- **Roadside Intersection Beacon.** Roadside beacons are beacons mounted on the STOP sign located at the intersection.

Beacons mounted on Stop Ahead and Intersection Ahead signs can also be called roadside beacons; however, they are not the focus of this evaluation effort, because these signs are located in advance of, rather than at, the rural intersection.

Installation and maintenance cost for overhead beacons are generally much higher than roadside beacons or LED-embedded STOP signs. If these alternative devices are just as effective, the districts could forgo overhead installations in the future and focus on more cost-effective roadside beacons or LED-embedded STOP signs. The growing interest in LED-embedded STOP signs raises the question of whether they provide the same benefits (e.g., safety or driver compliance) as overhead or roadside intersection beacons.

The three treatments selected for this research are illustrated in Figure 16 and include the following:

- **STOP Sign.** A typical STOP sign installed at the intersection.
- **LED-E.** LED-embedded STOP signs.
- **R-Bea.** Roadside intersection beacons where the beacons are mounted above and below the STOP sign located at the intersection.

(a) STOP Sign **(b) LED-E** **(c) R-Bea**

Figure 16. Examples of Beacon Treatments Being Considered in This Research.

Research on Beacon Treatments

Past research has explored the benefits of flashing beacons as safety devices for increasing awareness of intersection traffic control; however, most research identified was done over 15 years ago. One recent study was done in 2018 in Iowa (*27*). They found the presence of roadside beacons (i.e., STOP-sign mounted beacons) was associated with a 5–54 percent reduction in nighttime crashes. Injury nighttime crashes decreased by 54 percent and total nighttime crashes reduced by 18 percent. A 2020 study done at TTI for TxDOT (*28*) examined the safety performance of the standard overhead beacon treatment installed at two-way stop-controlled intersections. The statistical analysis of crashes before and after indicated that both total crashes and fatal and injury crashes tended to increase after the installation of overhead flashing beacons. However, due to the limited number of sites and crashes, this result cannot be stated definitively. The 2020 Texas study did not compare overhead to roadside beacons.

Experiences in Districts

The research team compiled a list of intersections with known or anticipated beacon treatments. Researchers began with lists generated in two previous IAC efforts, one with the Traffic Safety Division and one with the Corpus Christi District. Based on the information contained in those lists on potential treatment sites, the research team developed a single list of 141 sites in 14 districts, which they used to follow up with contacts in districts to identify which sites had in fact received treatments, which were under construction, and which were still planned but not yet implemented.

In particular, researchers contacted TxDOT staff in the Bryan, Corpus Christi, El Paso, and Odessa Districts to learn more about the beacons they have installed or planned, as well as their experiences with them. These staff members provided information about additional sites not contained on the original list, and they discussed how their beacon treatments are typically installed. Overhead beacons have been used statewide for a much longer time period than LED-E and R-Bea, so they have a longer track record, but general impressions from staff indicated that some locations see potential issues with overhead beacons because stopped drivers on the minor road sometimes think that the major road also has a stop condition and try to enter the major road in conflict with approaching traffic. Overhead beacons may also obscure the view of an isolated intersection that does not have illumination, which can cause approaching minor road drivers (especially those who are impaired) to be overwhelmed by the beacon and not notice where to stop at the intersection.

When asked about the funding source for these beacons, the general response was that maintenance funds are the quickest way to implement these types of treatments if they are isolated; however, maintenance budgets generally provide only enough funds for limited installations. Programming through safety funding (CAT 8 or CAT 11SF) can be more useful if they are installed in multiple locations as a systematic treatment (perhaps with a roadway/safety lighting component), in which case they can be bid as a compiled project. Installation costs for overhead beacons tended to be higher than for LED-E or R-Bea. Maintaining the inventory of these beacons can be difficult because of the various ways that they are funded and installed.

Evaluation Methods

The preferred method for evaluating the safety effectiveness of a treatment is to use crashes. Because of the relatively small number of sites treated with a roadside beacon mounted on the STOP sign or treated with an LED-embedded STOP sign, using crashes was not feasible. This study explored whether the speed profile on the approach to an intersection varies depending upon whether the approach is controlled by one of the following conditions:

- STOP sign (traditional STOP sign).
- LED-E (LED-embedded STOP signs).
- R-Bea (roadside beacons where the beacon is mounted on the STOP sign).

IDENTIFICATION OF SITES

Locating Intersections with Beacon Treatments

The research team used the following sources to identify treated sites.

- Sites already known by the research team.
- Sites used in previous research.

- Sites identified from the TxDOT HSIP database. Considered sites with estimated letting dates of 2007 to 2026 and work codes for LED STOP signs and Roadside Flashers.

In all, researchers compiled a list of almost 700 potential intersection beacon or comparison sites. Of those, about 650 were set aside from further consideration because they had not yet completed construction, they contained a combination of beacon types, they contained only advance (i.e., stop ahead) beacons, their key details (e.g., type of beacon, specific location, etc.) could not be confirmed, or the treatment was determined to not be of interest in this study.

A total of 37 existing or planned LED-E installations were identified along with five sites with existing R-Bea (see Table 6). Very few LED-E sites were installed in sufficient time to permit inclusion since the CV data are only available between November 1, 2021, and June 1, 2023. The research team selected the five sites that could be confirmed with Google Earth. The data from the HSIP database did not always identify the exact location of the intersection; rather, the data cited a corridor and that the proposed treatments would be used within that corridor. In those cases, the research team noted those sites as "could not confirm site in Google Earth."

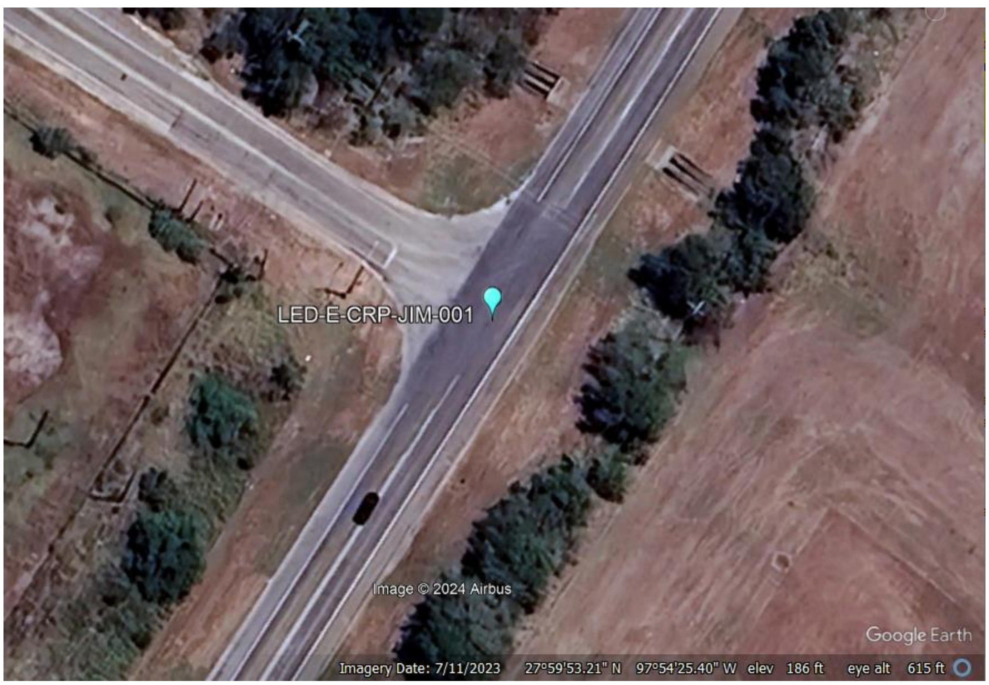
Table 6. Number of Intersections by District Letting Year for LED-E or R-Bea on Stop Signs.

Site Type	Priority for Study	2016	2018	2019	2023	2024	2025	2026	Total
LED-E	Selected for study			4	1				5
LED-E	Rejected due to low volume and short approach			1					1
LED-E	Could not confirm site in Google Earth, or site was planned for installation after CV data are available				7	1			8
LED-E	LED-E is planned or was installed after CV data are available, intersection found in Google Earth				4	17	1	1	23
LED-E Total	**All**			**5**	**12**	**18**	**1**	**1**	**37**
R-Bea	Selected	2	2	1					5
Grand Total		**2**	**2**	**6**	**12**	**18**	**1**	**1**	**42**

Once the sites treated with either a R-Bea or an LED-E beacon were identified, sites with similar roadway characteristics that were near the treated site were identified. Typically, the team members would look for intersections along the same major street that just had a STOP sign on the minor street (i.e., no beacons). The preference was to match the number and types of lanes on the minor street along with the anticipated average daily traffic. Ultimately, researchers selected 16 legs for further study (see Table 7). Figure 17 shows an example site. It is the Google Earth aerial for the LED-E-CRP-JIM-001.

Table 7. List of Treated and Control Sites Selected for Study.

Site Type	Site Name	Lat	Long	Legs	Legs Being Studied
LED-E	LED-E-CHS-BRI-001	34.4642815	−101.2540910	3	1
LED-E	LED-E-CRP-JIM-001	27.9978153	−97.9063699	3	1
LED-E	LED-E-WAC-BEL-001	31.2042815	−97.4495872	4	1
LED-E	LED-E-WAC-BEL-004	31.0562028	−97.5334056	4	1
R-Bea	R-Bea-ABL-BOR-001	32.7605383	−101.6489210	4	1
R-Bea	R-Bea-ODA-AND-001	32.2609435	−102.7762000	4	2
R-Bea	R-Bea-ODA-AND-005	32.3044706	−102.5417810	4	1
Stop Sign	LED-E-CHS-BRI-001_C2	34.4662472	−101.2602639	4	1
Stop Sign	LED-E-CRP-JIM-001_C2	27.9954167	−97.9079917	3	1
Stop Sign	R-Bea-ABL-BOR-001	32.7605383	−101.6489210	4	1
Stop Sign	R-Bea-ODA-AND-001_C2	32.3814585	−102.7801350	4	2
Stop Sign	R-Bea-ODA-AND-004_C1	32.3049722	−102.3936472	3	1
Stop Sign	R-Bea-ODA-AND-005_C5	32.3092955	−102.5435180	4	2



(Source: © 2024 Google Earth Pro)

Figure 17. Aerial Image of Study Site LED-E-CRP-JIM-001.

Obtaining Roadway Characteristics

The research team collected the site characteristics for each identified site using views available from Google Earth, Google Earth Street View, or Google Earth Historical Data. The following data were gathered for each site:

- Legs. Number of legs at the intersection.
- IntersecAngle. Notes whether the angle for the intersection is 90 degrees (for 90 or nearly 90) or < 90 (where the angle could affect driver behavior).
- CrossTrafficSign. Notes whether a Cross Traffic Does Not STOP sign present (yes or no).
- Posted speed limit (PSL). The PSL in mph for the leg.
- PSL_Source. The source of the PSL. In most cases the PSL value was identified by searching Google Earth Street View for a view of an installed sign. In a few cases the PSL value would need to be estimated because a sign could not be found in Google Earth Street View.

LEVERAGING CONNECTED VEHICLES DATA

Connected Vehicles Dataset

Wejo was one of the unique data providers that offered granular CV data provided either in real-time or as historical data. TxDOT purchased Wejo data and has TTI hosting the dataset. The datasets cover Texas for 18 months (November 2021 to May 2023).

Wejo had two main datasets, named Movements and Events datasets. The Movements dataset provides telematic data such as coordinate location, time, speed, and heading, and the Events dataset has additional behavioral data such as ignition turned on/off, seatbelt latched/unlatched, hard break, or hard acceleration. The Movements dataset, which is of interest for this study, has a typical recording frequency of 3 seconds (ranges from 1 to 9 seconds). The Movements and Events datasets are stored in Microsoft Azure blob storage. The Wejo Movement dataset was selected as the CV dataset for the rest of this activity.

The Wejo Movement dataset's attributes related to this study are journey ID, data point ID, latitude, longitude, speed, heading, and time stamp. A unique journey ID is generated every time the vehicle is turned on and stays the same until the vehicle is turned off. Thus, each journey ID defines a trip or trace that can be analyzed. Each record along this journey/trip has a unique data point ID. The heading attributes help to define the vehicle direction. The time stamp attribute defines the date and time that the attributes were measured and transmitted to the Wejo servers.

Potential Speed Measures

Several potential speed measures were examined that could be generated from the available CV data. Stopping sight distance for a 55-mph road is about 500 ft and about 900 ft for 80-mph road. The study area needed to at least include these distances to capture the entire deceleration of the minor road drivers along with the drivers' typical approach speed. The recording frequency of 3 seconds was also considered so that enough speed readings would be present within the study area. The research team decided to set the study area as being 1200 ft upstream of the stop bar.

After reviewing plots of the CV data and preliminary results, the research team decided to move forward with the following:

- DisUpStop_40mph. The distance upstream when driver is at 40 mph.
- DisUpStop_20mph. The distance upstream when driver is at 20 mph.
- SpdTypBtw600&1200. The average speed for a given vehicle for all readings between 600 and 1200 ft upstream of the STOP sign.
- SpdMaxBtw600&1200. The maximum speed for a given vehicle for all readings between 600 and 1200 ft upstream of the STOP sign.
- SpdMinBtw600&1200. The minimum speed for a given vehicle for all readings between 600 and 1200 ft upstream of the STOP sign.
- SpdStdBtw600&1200. The standard deviation speed for a given vehicle for all readings between 600 and 1200 ft upstream of the STOP sign.
- DisUpStop_SpdTypMinus10 The distance upstream when driver is at 10 mph below that driver's typical speed (SpdTypBtw600&1200).
- DisUpStop_SpdTypMinus15 The distance upstream when driver is at 15 mph below that driver's typical speed (SpdTypBtw600&1200).
- Decel. The deceleration between speed at 600 ft and minimum speed for the trace. (The research team initially considered the speed at the 0-ft point; however, this value was not always available because of the nature of the original data. Therefore, when the speeds were being read, the minimum speed for the speed trace was used, which may be a few feet before or after the 0-ft point.)

Obtaining the Speed Measures

The CV data storage and analysis are hosted in the cloud (Microsoft Azure services) to overcome local machines' processing power limitations and comply with privacy requirements. The defined speed measures in the previous section require having data points within 1200 ft upstream of the intersection. Thus, a boundary with the length of 1500 ft was drawn in QGIS/ArcGIS for each site to subset the Movements data in the upstream (see Figure 18) and create a buffered polygon. Figure 19 highlights the selected waypoints (triangle markers) during the subsetting process at site R-Bea-ODA-AND-005. Extending the 1200 ft requirement by an additional 300 ft provides a short history (speed and trace) of the drivers before they enter the study zone. This prior information of the vehicle entering the study zone helps to define and implement the filtering process explained in the following section.

Figure 18. Buffered Polygon at Site R-Bea-ODA-AND-005.

Figure 19. Data Points Selection (Subsetting) along a Trace at Site R-Bea-ODA-AND-005.

Dataset Abnormalities

Investigating the dataset and understanding the nature of it is a crucial step before making any inference based on the data. A series of sample speed profiles (sampled over multiple hours or days to provide enough traces in the dataset to analyze) was generated to understand the driving patterns at these intersections. Figure 20 illustrates the speed profiles at site LED-E-CHS-BRI-001_C2, where the x-axis origin shows the STOP sign location and negative distances are waypoints past the sign. Traces shown in Figure 20 reflect the waypoints contained within the buffered polygon at site LED-E-CHS-BRI-001_C2. These traces have at least one waypoint's heading toward the intersection. Each marker shows a single vehicle. Clearly, the fluctuation or the "jitter" in the yellow and the red traces are not normal; a typical profile does not constantly alternate between acceleration and deceleration. Plotting the waypoints against time (instead of distance) helps to understand the scenario here. Analyzing the vehicle's bearing and distance-to-sign time histories clarifies the driving pattern. The majority of the Vehicle B's (shown in Figure 20) trace data points were recorded every 3 seconds. However, a long gap of 23 minutes was observed in the middle of the vehicle's distance/bearing time history, which indicates that the vehicle has left the buffered polygon and re-entered it. Additionally, the vehicle distance to sign increases over time at the beginning of the time history and decreases at the end. The bearing time history also confirms the same pattern. The vehicle's bearing is about 0 or 360 degrees (moving northbound) in the first part of the bearing time history, and it is about 180 degrees (moving southbound) in the second part of the trip. Vehicle B's travel history is summarized as follows:

1. Vehicle is moving in northbound direction and going away from the intersection.
2. Vehicle exits the buffered polygon.
3. After a longtime gap, the vehicle re-enters the buffered polygon and travels southbound toward the intersection.

In fact, Vehicle B's trace generates two speed profiles: one is accelerating and moving away from the intersection, and the other is decelerating and moving toward the intersection. Figure 21 shows the corrected speed profiles, where the dashed lines are the split of Vehicle B's trace to northbound and the dotted lines are Vehicle B's trace to southbound.

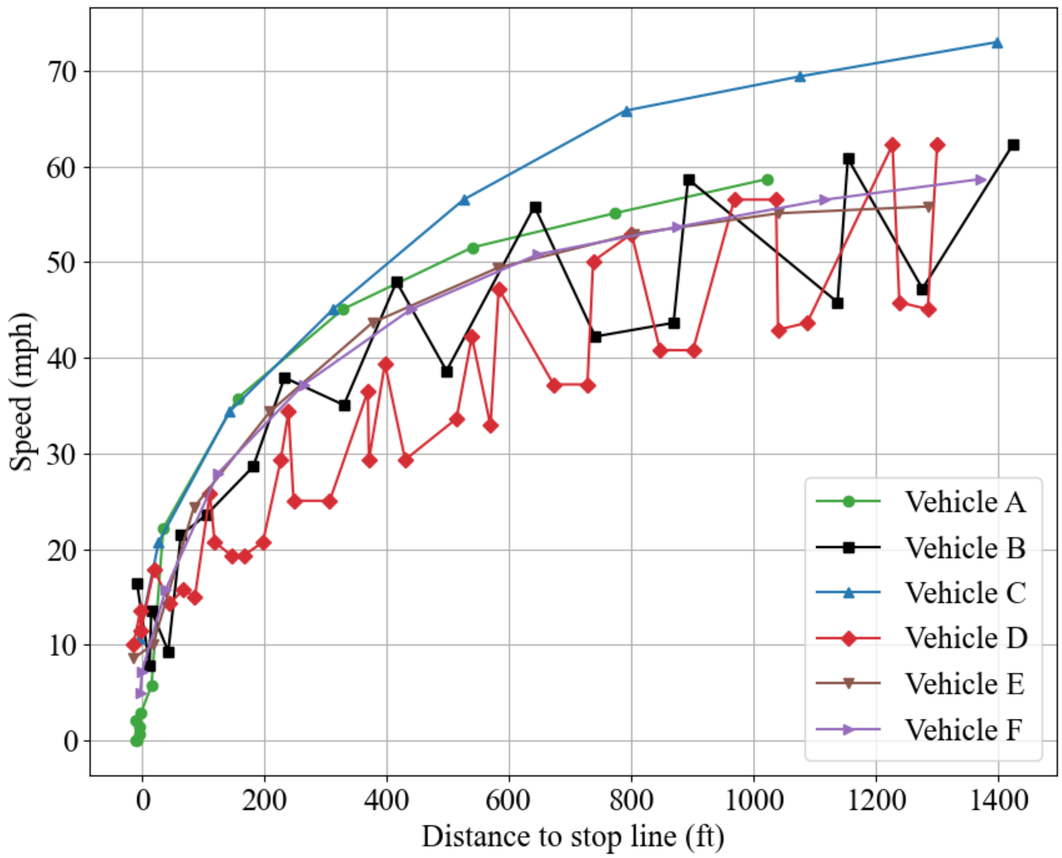


Figure 20. 7-Days Sample Speed Profiles at Site LED-E-CHS-BRI-001_C2.

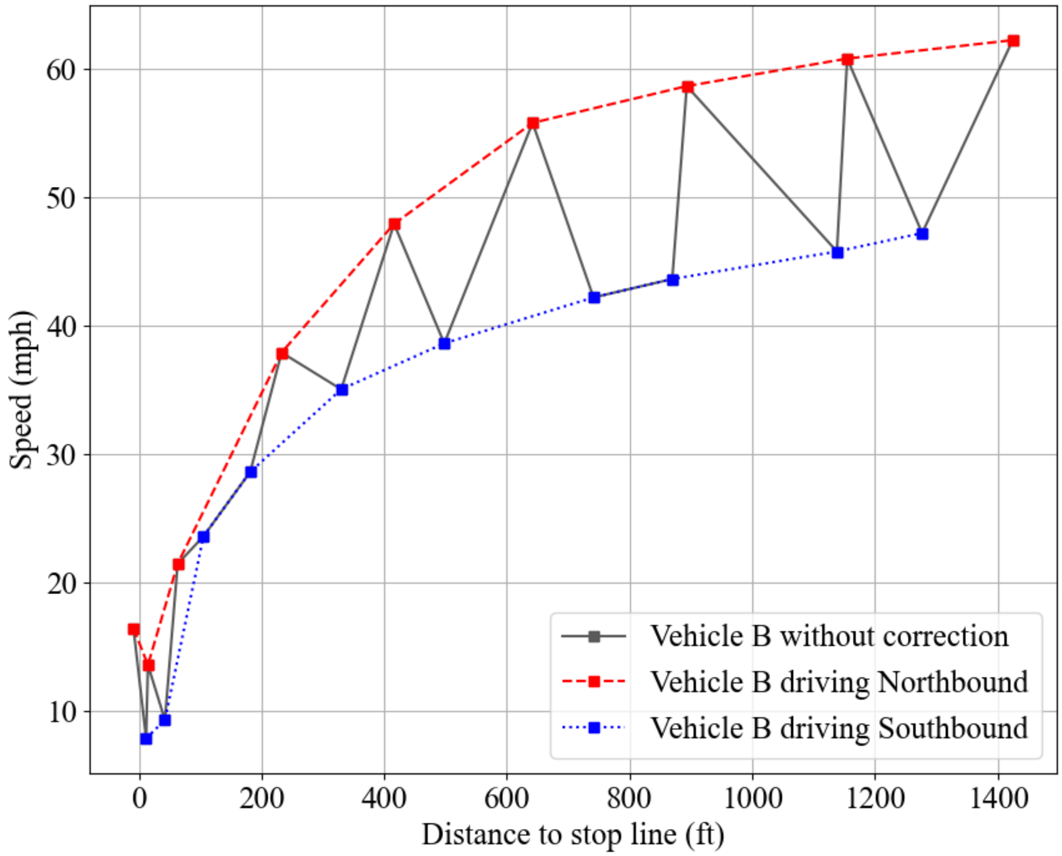


Figure 21. Corrected Speed Profile Separating Northbound and Southbound Travel.

In other words, only a small portion of a trip is being subsetted because the study approach defines a very small, buffered polygon. Figure 22 schematically illustrates the waypoints that are subsetted (noted with closed circles) from a trip by applying the polygon overlay; waypoints with open circles are outside the study area and are not included in the analysis. The process results in waypoints in both directions, which need to be filtered out in the subsequent filtering process.

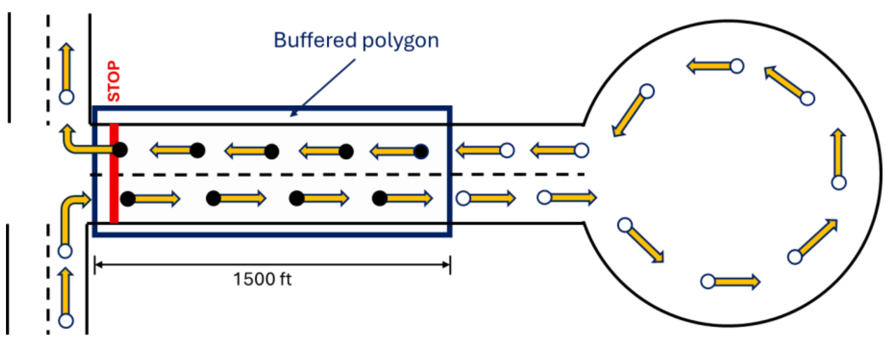


Figure 22. Schematic Illustration of the Subsetting with Polygon Definition.

Ideally, the buffered polygon could be drawn such that it includes only one direction of travel; however, that is not a feasible option for narrow roads such as the study sites in this activity. The GPS data accuracy (up to 3 meters) and the error introduced when projecting coordinates limits results in the need to define a narrow boundary. It is probable that it would not include waypoints near the edges of the polygon. Thus, having a wider polygon and filtering the waypoints with other criteria is a more accurate selection process.

The preliminary criterion of having at least one waypoint align with the road bearing is usually used in curvy roads to ease the subsetting process. If the criterion is strictly defined to have trips (i.e., all of its waypoints' headings) that always match the road bearing, a large portion of the data is lost. Thus, it is recommended to have two step filtering. First, find trips that at least part of their traces aligns with the study area (road segment). Then, filter out waypoints (from these traces) that are not in the targeted direction (toward intersection in this case).

Connected Vehicles Data Processing and Filtering

The selected CV data nominal reporting interval is about 3 seconds. This high resolution is one of the unique characteristics of the Movements data, which provides the possibility to draw individual vehicles traces and patterns, although it still comes with some caveats. Since the data are not captured at any specific location (e.g., at stop line), it makes it difficult to have a measurement at a specific distance. It requires the measurements or evaluation in a buffer area around that specific point (e.g., 50 ft buffer). Moreover, the traveled distance between the two consecutive points in time is a function of speed. In a higher speed road segment, the reported points for a specific journey are more scattered along the road. In contrast, the density of the points is higher in low-speed road segments for a given trip. Considering the 3-second reporting interval characteristics and the observed data abnormalities led to three defined filters to prepare the dataset for speed measure calculations:

1. Direction filter.
2. Study zone coverage filter.
3. 9-sec filter.

Direction Filter

The subset of the Movements data might contain waypoints in both road directions. However, only the traffic flow moving toward the intersection is of interest, not the one exiting the intersection. The drivers moving along the north/eastbound and the south/westbound were separated from each other. First, the road bearing toward the intersection was measured in Google Earth. Then, the road bearing was compared with the vehicle's reported bearings along the study area. Only data points with a maximum bearing difference of 25 degrees from the road bearing were included in the filtered dataset. The threshold of 25-degrees difference is defined to accommodate for the possible changes of the vehicle's heading at the intersection before reaching the complete stop position, or a slight bearing change in the curved road reaching the intersection. Additionally, this criterion solves the issue described in Figure 22. If a trip has data points in both directions, only those toward the intersection are selected in this step.

Study Zone Coverage Filter

In the initial review of traces near the intersection, researchers found drivers entering or exiting the road within 1200 ft upstream. However, the defined speed measures require the vehicle to travel the entire distance from 1200 ft upstream of the STOP sign to the intersection. Therefore, the logic applied was to confirm that each trip:

- Has at least one data point within 50 ft of the stop bar associated with the STOP sign.
- Has at least one data point that is more than 1200 ft upstream of the stop bar associated with the STOP sign.

As discussed earlier, the nominal reporting interval prevents the speed measurement at any specific location. Thus, two buffers were defined to confirm the data point availability at the beginning and end of the study zone. Each trip is required to have at least one waypoint before the 1200-ft limit and one after the 50-ft limit, as illustrated in Figure 23 and Figure 24, where the waypoints highlighted in closed circles demonstrate the waypoints being checked. These figures also illustrate commonly observed traces that are not suitable for study. The acceptable scenario is shown in Figure 25. If a journey does not satisfy having at least one waypoint within those specific areas (i.e., before 1200 ft and after 50 ft upstream of stop bar), the entire trace is removed from the dataset.

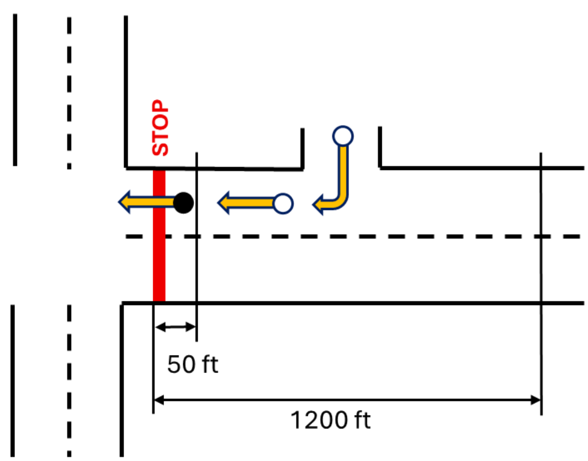


Figure 23. Observed Maneuver Case 1: Driver Enters in the Middle of the Study Zone.

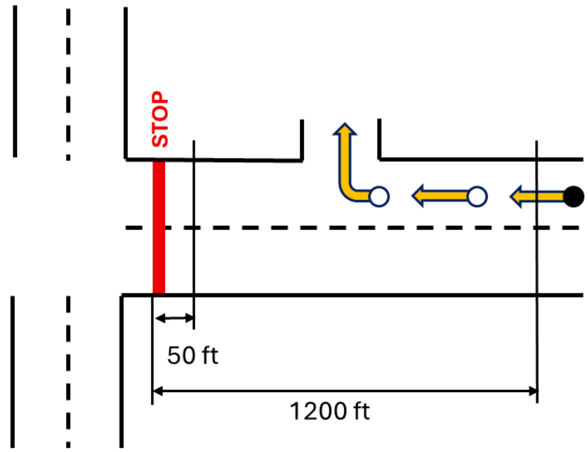


Figure 24. Observed Maneuver Case 2: Driver Exits in the Middle of the Study Zone.

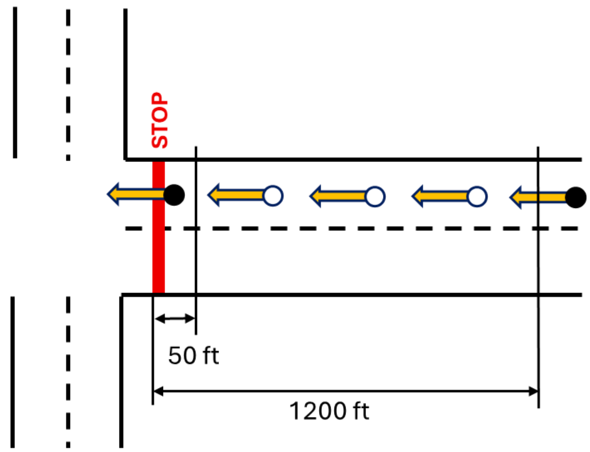


Figure 25. Observed Maneuver Case 3: Driver Trace Covers the Entire Study Zone.

Less than 9-Second Reporting Interval (9-Sec Filter)

The Movement dataset recording interval is between 1 and 9 seconds, where 95 percent of the data points are reported every 3 seconds. Consequently, any trip with a reporting interval of more than 9 seconds was removed to limit irregularities due to the data quality.

Order of Applying Filters

The order of applying the filters affects the ability to obtain the desirable dataset. The 9-sec filter must be applied last to not interfere with the direction filter. Specifically, the 9-sec filter interferes with the situation described in Figure 22 if not applied in order because the 9-sec filter removes the entire trip if a gap longer than 9 seconds is observed. If the direction filter is applied before the 9-sec filter, waypoints moving away from the intersection are already removed from the trace and no gap will be observed between the datapoints; as a result, the 9-sec filter will not then mistakenly remove an acceptable trace.

Calculating the Speed Measures

Many of the introduced speed measures depend on the typical speed. Thus, the typical speed needs to be calculated first. For each journey/trip, the average of the reported speeds within the 600–1200-ft range was calculated to obtain the typical speed (SpdTypBtw600&1200). Similarly, the maximum, minimum, and standard deviation of these speeds were calculated per trip to obtain the SpdMaxBtw600&1200, SpdMinBtw600&1200, and SpdStdBtw600&1200, respectively. There were typically two to five data points for each trip inside the 600–1200-ft limits, depending on the vehicle's speed and reporting interval (usually 3 sec). Certain speed measures (i.e., DisUpStop_20mph, DisUpStop_40mph, DisUpStop_SpdTypMinus10, and DisUpStop_SpdTypMinus15) were based on the distance at which a certain speed was measured. Because that specific distance was not always available, researchers used linear interpolation to estimate the distance for that speed based on the two closest readings for that speed and distance (i.e., the nearest upstream reading and nearest downstream reading). Similarly, researchers calculated the deceleration rate over the final 600 ft to the stop line by obtaining the linearly interpolated speed at 600 ft upstream. However, the recorded speed at the closest point before the stop line was used to calculate the change in speed over time and obtain the deceleration rate (Decel).

DATA ANALYSIS

Sites and Speed Traces

Table 8 provides the site characteristics for those sites considered in the study. Two of the four sites with LED-E had an intersection angle that was less than optimal. The CROSS TRAFFIC DOES NOT STOP sign is used on several of the approaches to remind drivers that they need to judge the main street gaps. The posted speed limits for the study approaches ranged between 35 and 75 mph. The two sites with 35 mph posted speed limits were removed from additional consideration because the speed limits were so much lower than the speed limits for the other sites.

Table 8. List of Treated and Control Sites Included in Study.

Site Type	Site Name	Leg Loc	Legs	PSL	Intersec Angle	Cross Traffic Sign
LED-E	LED-E-CHS-BRI-001	East	3	75	< 90	No
LED-E	LED-E-CRP-JIM-001	West	3	65	90	No
LED-E	LED-E-WAC-BEL-001	South	4	45	< 90	Yes
LED-E	LED-E-WAC-BEL-004	North	4	45	90	Yes
R-Bea	R-Bea-ABL-BOR-001	South	4	70	90	Yes
R-Bea	R-Bea-ODA-AND-001	East	4	60	90	Yes
R-Bea	R-Bea-ODA-AND-001	West	4	60	90	Yes
R-Bea	R-Bea-ODA-AND-005	East	4	45	90	Yes
Stop Sign	LED-E-CHS-BRI-001_C2	North	4	55	90	No
Stop Sign	LED-E-CRP-JIM-001_C2	East	3	50	90	No
Stop Sign	R-Bea-ABL-BOR-001	North	4	45	90	Yes
Stop Sign	R-Bea-ODA-AND-001_C2	East	4	60	90	No
Stop Sign	R-Bea-ODA-AND-001_C2	West	4	60	90	No
Stop Sign	R-Bea-ODA-AND-004_C1	West	3	55	90	No
Stop Sign	R-Bea-ODA-AND-005_C5	East	4	35	90	No
Stop Sign	R-Bea-ODA-AND-005_C5	West	4	35	90	No

Table 9 shows the number of speed traces considered along with selected average speed measures per site. The minimum number of speed traces was 162 for one of the approaches with a STOP sign. The maximum number of speed traces was 39,645 for one of the approaches with R-Bea. Table 10 provides additional average speed measures per site.

Method of Evaluation

The steps used in this effort demonstrated large variation in speed profiles along a segment. Part of this effort was to explore speed patterns as a driver approaches a STOP sign and whether a single measure could best describe the patterns. Once the better speed measures and speed measure trends are identified, the findings for those measures were compared to identify if differences exist by type of STOP sign treatment.

The research team decided to focus on the distance upstream when a driver was at a particular speed; for this evaluation those speeds were 20 mph and 40 mph. By selecting speeds that were less than all the present posted speed limits, the driver’s speed choice should be more influenced by the downstream traffic control rather than the speed limit for the road.

Table 9. Number of Speed Traces and Average of Key Speed Measure by Site.

Site Type	SiteNameR	Count	Average of DisUpStop_40mph	StdDev of DisUpStop_40mph	Average of DisUpStop_20mph	Average of DisUpStop_SpdTypMinus10	Average of SpdTypBtw600&1200
LED-E	LED-E-CHS-BRI-001_LED-E-East	4001	306	170.89	51	437	60
LED-E	LED-E-CRP-JIM-001_LED-E-West	36523	311	174.54	69	293	52
LED-E	LED-E-WAC-BEL-001_LED-E-South	6297	428	247.48	51	236	46
LED-E	LED-E-WAC-BEL-004_LED-E-North	26834	464	221.00	86	329	47
LED-E Total	All	**73655**	**376**	**212.52**	**73**	**309**	**50**
R-Bea	R-Bea-ABL-BOR-001_R-Bea-South	2065	358	147.81	70	497	60
R-Bea	R-Bea-ODA-AND-001_R-Bea-East	7140	369	203.58	68	408	57
R-Bea	R-Bea-ODA-AND-001_R-Bea-West	4980	307	177.76	62	427	59
R-Bea	R-Bea-ODA-AND-005_R-Bea-East	39645	608	261.21	111	315	43
R-Bea Total		**53830**	**539**	**270.44**	**99**	**345**	**48**
Stop Sign	LED-E-CHS-BRI-001_C2_StopSign-North	299	364	157.49	66	435	57
Stop Sign	LED-E-CRP-JIM-001_C2_StopSign-East	9063	364	214.15	49	277	49
Stop Sign	R-Bea-ODA-AND-001_C2_StopSign-East	5408	269	127.04	59	412	61
Stop Sign	R-Bea-ODA-AND-001_C2_StopSign-West	2603	300	142.77	58	378	56
Stop Sign	R-Bea-ODA-AND-004_C1_StopSign-West	18041	304	126.67	69	393	57
Stop Sign	R-Bea-ABL-BOR-001_StopSign-North	162	601	313.09	77	245	42
Stop Sign Total		**35576**	**316**	**160.68**	**62**	**365**	**56**
Grand Total		**163061**	**417**	**241.00**	**79**	**333**	**51**

Table 10. Average of Select Speed Measure by Site.

Site Type	SiteNameR	Average of DisUpStop_SpdTypMinus10	Average of DisUpStop_SpdTypMinus15	Average of SpdTypBtw600&1200	Average of SpdMinBtw600&1200	Average of SpdMaxBtw600&1200	Average of SpdStdBtw600&1200	Average of SpdCntBtw600&1200	Average of DecelBtw600ft&MinSpd
LED-E	LED-E-CHS-BRI-001_LED-E-East	437	318	60	54	61	4.54	2	−2.86
LED-E	LED-E-CRP-JIM-001_LED-E-West	293	214	52	49	52	0.54	3	−2.76
LED-E	LED-E-WAC-BEL-001_LED-E-South	236	154	46	44	46	0.34	4	−2.21
LED-E	LED-E-WAC-BEL-004_LED-E-North	329	223	47	45	48	1.25	3	−2.33
LED-E	**LED-E Total**	**309**	**218**	**50**	**47**	**50**	**0.89**	**3**	**−2.56**
R-Bea	R-Bea-ABL-BOR-001_R-Bea-South	497	386	60	54	61	4.57	2	−2.70
R-Bea	R-Bea-ODA-AND-001_R-Bea-East	408	293	57	51	57	3.46	3	−2.64
R-Bea	R-Bea-ODA-AND-001_R-Bea-West	427	315	59	54	60	2.95	2	−2.96
R-Bea	R-Bea-ODA-AND-005_R-Bea-East	315	215	43	42	45	0.99	3	−1.98
R-Bea	**R-Bea Total**	**345**	**241**	**48**	**44**	**48**	**1.36**	**3**	**−2.18**
Stop Sign	LED-E-CHS-BRI-001_C2_StopSign-North	435	319	57	51	57	1.51	3	−2.65
Stop Sign	LED-E-CRP-JIM-001_C2_StopSign-East	277	189	49	46	49	0.63	3	−2.48
Stop Sign	R-Bea-ODA-AND-001_C2_StopSign-East	412	303	61	56	61	2.97	2	−3.04
Stop Sign	R-Bea-ODA-AND-001_C2_StopSign-West	378	266	56	51	57	2.44	3	−2.79
Stop Sign	R-Bea-ODA-AND-004_C1_StopSign-West	393	291	57	53	57	0.78	3	−2.89
Stop Sign	R-Bea-ODA-AND-005_C5_StopSign-East	160	97	38	35	41	2.06	4	−2.10
Stop Sign	R-Bea-ODA-AND-005_C5_StopSign-West	115	50	31	24	39	6.54	4	−2.19
Stop Sign	R-Bea-ABL-BOR-001_StopSign-North	245	166	42	42	45	0.76	3	−2.04
Stop Sign	**Stop Sign Total**	**363**	**263**	**56**	**51**	**55**	**1.04**	**3**	**−2.79**
All	**Grand Total**	**333**	**236**	**51**	**47**	**51**	**1.08**	**3**	**−2.49**

Evaluation

After a review of the available speed measures, the research team focused on the distance upstream when the driver was either at 40 mph or 20 mph. The plot of the distance upstream when drivers are at 40 mph by approach and by treatment is provided in Figure 26 by individual sites and in Figure 27 by treatment. Figure 28 shows the distances when drivers are at 20 mph by site, while Figure 29 shows those distances when the sites are grouped by treatment.

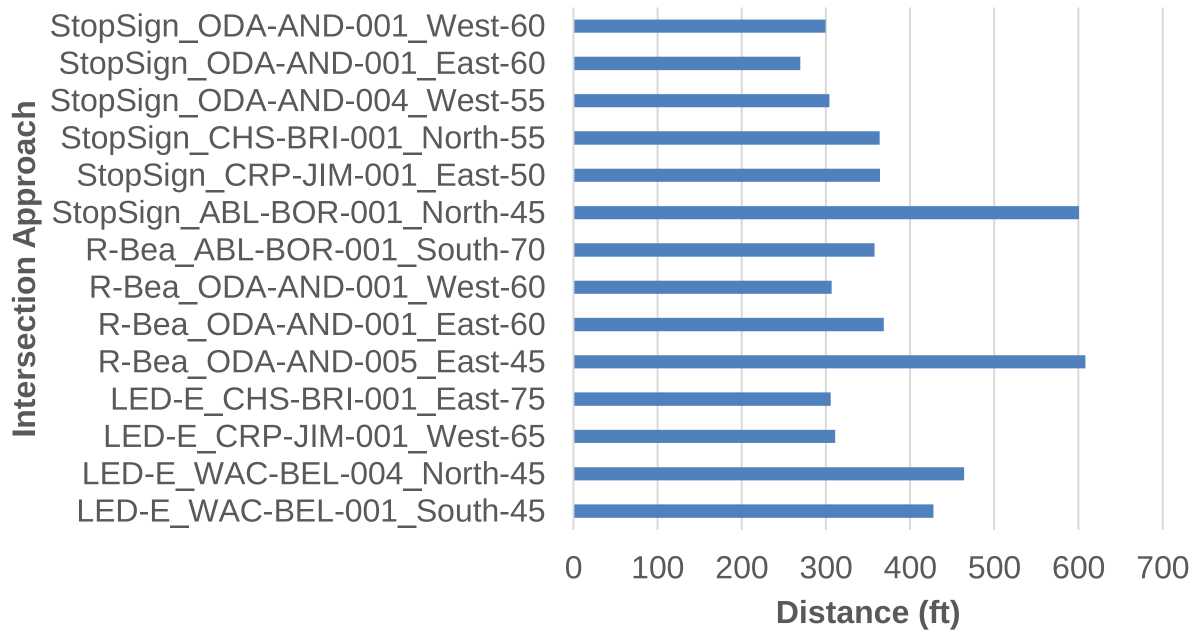


Figure 26. Average Distance Upstream When Drivers Were at 40 mph by Approach.

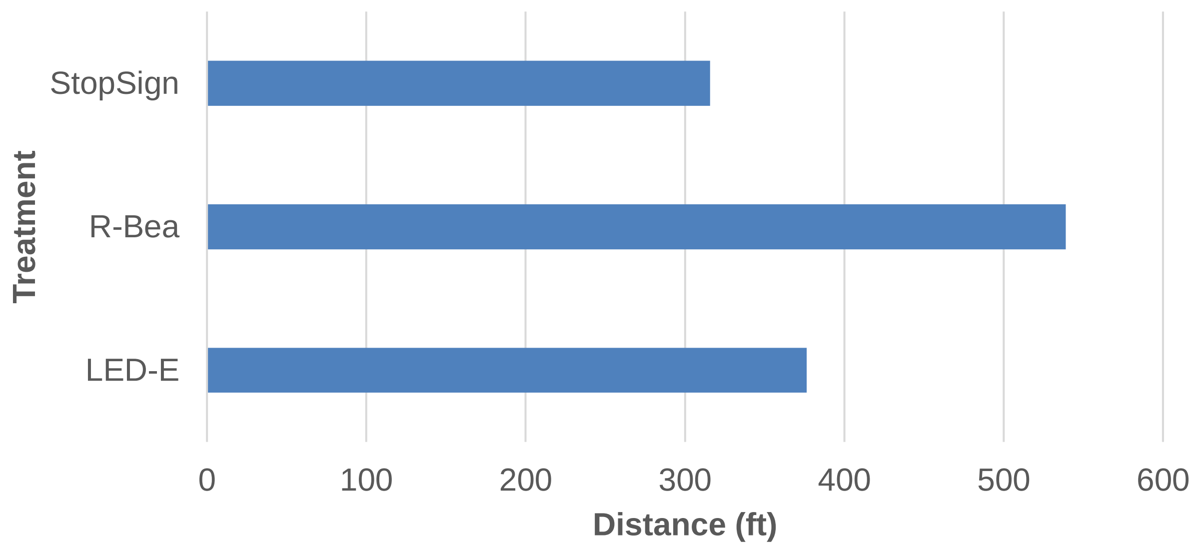


Figure 27. Average Distance Upstream When Drivers Were at 40 mph by Treatment.

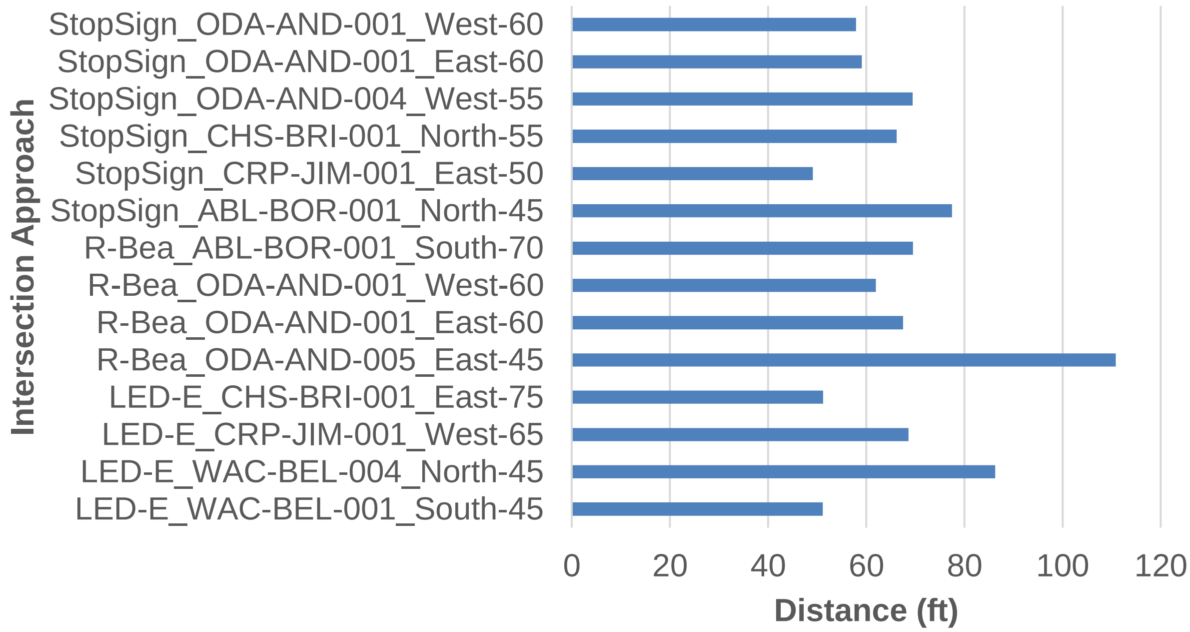


Figure 28. Average Distance Upstream When Drivers Were at 20 mph by Approach.

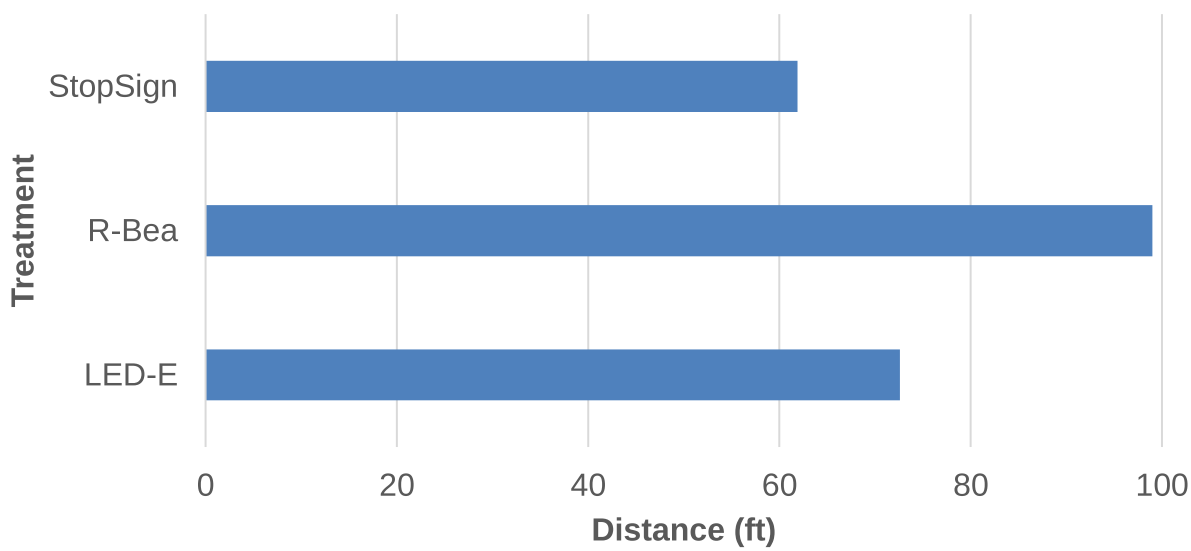


Figure 29. Average Distance Upstream When Drivers Were at 20 mph by Treatment.

As shown in Figure 27, drivers are at 40 mph at a greater distance upstream when approaching the R-Bea (539 ft) as compared to the LED-E (376 ft) or the STOP sign (316 ft). The research team theorizes that the brighter R-Bea as compared to the LED-E and certainly the STOP sign that does not have any supplementary lights may be influencing the drivers to be at a slower speed at a greater distance. This observation also holds for when the drivers are at 20 mph (see Figure 29). Drivers are a greater distance upstream when they are at 20 mph for the R-Bea (99 ft) as compared to the LED-E (73 ft) or the STOP sign (62 ft). Drivers on the approaches with the

LED-E and the STOP sign will need to decelerate at a higher rate to reach the required stop as compared to the deceleration drivers approaching a R-Bea would need.

RESULTS

Several questions were identified for consideration in this effort (see Objectives section in the Introduction). Following are those questions along with a discussion of the key findings from the research:

1. Can CV data be used to obtain speed profiles for vehicles approaching a STOP sign?

   This activity demonstrated that it is possible to use CV data as a method of obtaining speed profiles for vehicles approaching specific locations, such as STOP signs at intersections. When using this method, the user should understand the limitations associated with CV data, namely that Wejo does not necessarily contain data for every vehicle on the roadway segment of interest, and that speed data are typically recorded every three seconds, which affects the level of detail available in the speed profile when investigating deceleration and stopping over a short distance and/or time.

2. What cleaning or filtering is needed to identify appropriate speed profiles for vehicles approaching a STOP sign?

   The CV data preprocessing section explained that the Movements dataset should be subsetted using polygons covering 1500 ft upstream. Then, the three-step process of data filtering is applied: selecting the parts of the journeys that are traveling toward the intersection, excluding traces that do not cover the entire study area (i.e., 1200 ft upstream of stop bar), and making sure the reporting intervals for the selected journeys are less than 9 seconds. These filters must be applied in order to obtain the desirable data. To ensure the vehicle is moving toward the intersection without removing too many data points, the defined buffered polygon should first cover both directions, and then the vehicle's direction should be checked to align with road bearing, which is specific for each intersection approach. For each trace, having one data point within 50 ft of the sign and one farther than 1200 ft from the sign verifies that the trace covers the entire study area. Finally, the 9-second reporting intervals filter guarantees the continuity of the data points along the road without exiting and re-entering the study area.

3. What speed measures can be used to evaluate these speed profiles?

   This research approach frequently provided thousands of speed traces for an approach. Converting each speed trace into an appropriate speed measure is necessary to be able to compare between sites. This research explored several potential speed measures including measures that identified the typical speed for each driver upstream of the intersection, distance when the driver was at a particular speed (20 or 40 mph), and the deceleration rate between 600 ft and the intersection. In some cases, how the speed measure was calculated had to be refined. For example, deceleration initially was envisioned to be calculated using the speeds at the 600-ft upstream distance and 0 mph for the speed at the intersection. Because drivers did not always come to a complete stop, the speed measure was refined to use the minimum speed for the driver. The speed measure that appears to provide the clearest message was the average distance upstream of the intersection when the drivers were at 40 mph or at 20 mph.

4. Can differences be seen in those speed measures/profiles depending on the type of STOP sign countermeasure (i.e., beacon treatments)?

   The following speed measures clearly showed differences by the type of STOP sign countermeasure: DisUpStop_40mph and DisUpStop_20mph. Drivers are at 40 mph at a greater distance upstream when approaching the R-Bea (539 ft) as compared to the LED-E (376 ft) or the STOP sign (316 ft). The research team theorizes that the brighter R-Bea as compared to the LED-E and certainly the STOP sign that does not have any supplementary lights may be influencing the drivers to be at a slower speed at a greater distance. This observation also holds for when the drivers are at 20 mph. Drivers are a greater distance upstream when they are at 20 mph for the R-Bea (99 ft) as compared to the LED-E (73 ft) or the STOP sign (62 ft). Drivers on the approaches with the LED-E and the STOP sign will need to decelerate at a higher rate to reach the required stop as compared to the deceleration drivers approaching a R-Bea would need.

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