Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-08/5-4084-01-1		

4. Title and Subtitle	5. Report Date
APPLYING TECHNIQUES TO INCREASE WARNING OF SIGNALS BEYOND VERTICAL CURVES	September 2007 Published October 2007
	6. Performing Organization Code
7. Author(s) Steven P. Venglar and Kwaku O. Obeng-Boampong	8. Performing Organization Report No. Report 5-4084-01-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 5-4084-01
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Technical Report: September 2005-August 2007 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Improving Driver Awareness of Signals Beyond Vertical Curves

URL: http://tti.tamu.edu/documents/5-4084-01-1.pdf

16. Abstract

This implementation project was designed to improve the utilization of the recommendations and findings from TxDOT research project 0-4084, "Countermeasures to Reduce Crashes at Signalized Intersections near Vertical Curves." The original research identified the conditions under which motorists approaching a vertical curve could not see ahead with decision sight distance due to the artificial horizon created by the curve. The crest of the curve, in turn, could prevent motorists from seeing a queue of vehicles at a signal beyond the curve, and possibly even the signal itself. Researchers developed guidelines for the type and location of supplemental, advance warning signing to provide advanced motorist notification of this situation during project 0-4084.

Providing Texas Department of Transportation staff and other potential users with the guidelines and recommendations of project 0-4084 was the primary goal of the implementation effort. This report thoroughly documents the application of project 0-4084 guidelines to study sites in Austin and Laredo, Texas. Site conditions are described in detail and the complete process of signing and communications design, field installation, and field review is documented. This report is most effectively used in conjunction with implementation product 5-4084-01-P1, a digital video disc (i.e., DVD) that provides video and audio documentation of the site conditions, signing design and application of 0-4084 findings, installation, and results of both field installations.

17. Key Words	18. Distribution Statement
Signal, Vertical Curve, Sight Distance	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	56	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

APPLYING TECHNIQUES TO INCREASE WARNING OF SIGNALS BEYOND VERTICAL CURVES

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TEXAS TRANSPORTATION INSTITUTE
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DISCLAIMER

The contents of this report reflect the views of the authors, who are solely responsible for the facts and accuracy of the data, opinions, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard or regulation, and its contents are not intended for construction, bidding, or permit purposes. The engineer in charge of this project was Steven P. Venglar, P.E. (Texas #84027).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names may appear herein solely because they are considered essential to the object of this report. The names of specific products or manufacturers listed herein do not imply endorsement of these products or manufacturers.

ACKNOWLEDGMENTS

This implementation effort was conducted during a two-year project under a cooperative research program between the Texas Transportation Institute (TTI), TxDOT, and FHWA. Carlos A. Lopez was the Director of the TxDOT Office of Primary Responsibility. Imelda Barrett of the TxDOT Austin District was the Implementation Director. Other TxDOT members of the Project Monitoring Committee included Implementation Advisors Danny Magee, David Mitchell (retired), and Derryl Skinnell. Wade Odell and Sandra Kaderka of TxDOT's Research and Technology Implementation Office were active participants in both project management meetings and field site visits.

TxDOT staff in the TxDOT Austin and Laredo Districts played critical roles in the design and deployment of active, supplemental advanced warning signing used during the implementation project. In the Austin District support was provided by Robert Guydosh, Mark Mohr, and Jimmy Mullings; in the Laredo District support was provided by Armando Sanchez, Jorge Rodriguez, Luis Villarreal, and James Deliganis. TTI staff providing professional support included Clyde Hance and David Dennis performing video collection and editing and Gary Barricklow conducting field investigations and data collection studies.

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CHAPTER 1. INTRODUCTION AND SOURCE RESEARCH

Vertical curves close to traffic signals create the possibility that queued vehicles, or even the signal indications themselves, will be obscured or fully hidden by the artificial horizon the roadway surface creates at the crest of the curve. Existing signing standards contained within the Texas Manual on Uniform Traffic Control Devices, or TMUTCD (*1*), address this situation by providing specific locations for SIGNAL AHEAD signs when at least two signal indications cannot be seen a certain distance upstream from the signalized intersection. However, there are some instances where complexities of the driving environment indicate that supplemental devices be used even beyond those required and suggested by the TMUTCD.

The TMUTCD also allows for the placement of supplementary advanced warning BE PREPARED TO STOP signs at locations that have SIGNAL AHEAD signs in the proscribed location. However, little guidance is provided on the proper location of the BE PREPARED TO STOP signing. Texas Department of Transportation (TxDOT) research project 0-4084 sought to resolve this situation by producing guidelines and recommendations on when to use and where to place supplemental advanced BE PREPARED TO STOP signing.

TXDOT RESEARCH PROJECT 0-4084 OVERVIEW

Research project 0-4084 examined the roadway environment and driver line of sight for situations where crest vertical curves are found on the approach to a signalized intersection. Researchers identified a segment of roadway along the approach where stopping sight distance is provided as per geometric design standards, but where extra sight distance for complex situations, known as *decision sight distance*, was not provided despite the fact that intersections require a driver to safely make decisions regarding vehicle speed and path. The researchers labeled this zone the *reduced decision zone*, or RDZ, and provided easy-to-use nomographs to determine its location for a range of rural and urban design speeds and vertical curve grades. Researchers also used this information to produce signing nomographs for the location of BE PREPARED TO STOP supplemental advanced warning signing.

Current Practice

TxDOT research project 0-4084 was conceived as a means of improving methods for alerting drivers of the presence of a downstream traffic signal or stopped queue from such a signal in locations where the line of sight is blocked by a vertical curve. Traditional signing practice in such situations is outlined in the TMUTCD, which states that a text (W3-3a) or symbolic (W3-3) SIGNAL AHEAD warning sign should be used when there is insufficient visibility distance for a motorist to correctly respond to the traffic control device. At a signalized intersection, it is necessary for the motorist to be able to continuously view at least two signal faces for the approach that he/she is traveling on for the distances specified in Table 1.

The TMUTCD allows for a warning beacon or beacons to be installed in conjunction with the SIGNAL AHEAD sign. In addition, a BE PREPARED TO STOP (W20-7b) sign with or without warning flashers can be installed on those approaches where significant queuing or stopped traffic results at the traffic signal. Although not mandatory by the guidelines, the

TMUTCD suggests that a WHEN FLASHING supplemental plaque be used when the flashers on the BE PREPARED TO STOP sign are interconnected with the traffic signal or a queue detection device.

Table 1. TMUTCD Guidelines for the Need and Placement of SIGNAL AHEAD Signs (*1*).

85th Percentile Speed (mph)	Visibility Distance (ft) [Table 4D-1] [1]	Sign Placement (ft) [Table 2C-4] [2]
30	270	100
35	325	150
40	390	225
45	460	300
50	540	375
55	625	450
60	715	550

[1] The minimum distance required for a motorist to see two signal faces on the approach to the signalized intersection. In locations where visibility is diminished, a SIGNAL AHEAD sign should be used.

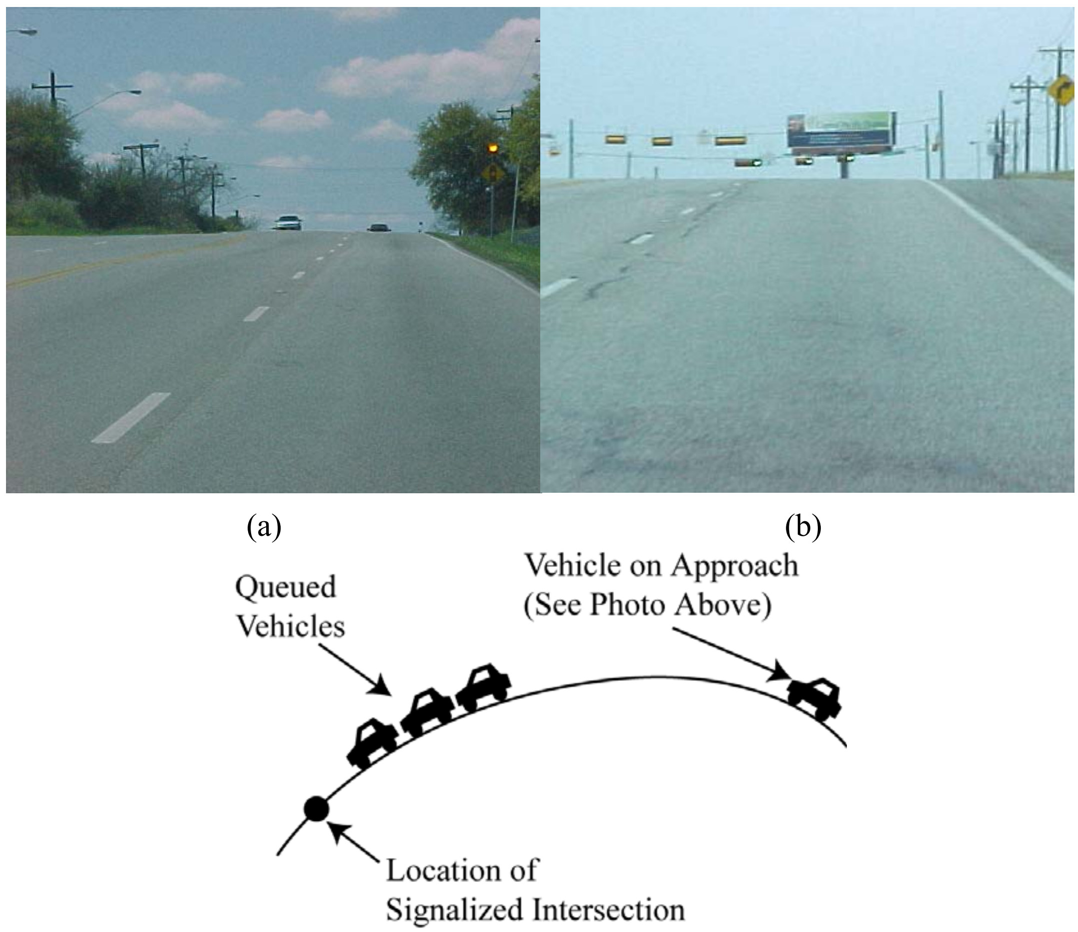
[2] Placement location for signs warning of a potential stop situation. The distances are based on the 1990 AASHTO policy for stopping sight distance providing a PIEV time of 2.5 seconds, friction factor of 0.30 to 0.40, minus the sign legibility distance 175 ft. The distances are adjusted for a sign legibility distance of 175 ft, which is the appropriate legibility distance for a 5 inch Series D word legend. The distances may be adjusted by deducting another 100 ft if symbol signs are used. Adjustments may be made for grades if appropriate.

Project 0-4084 Findings

During the course of the project 0-4084 investigation, researchers discovered that it was the location of advanced signal and signal queue warning signing, rather than the signing type, that was not well delineated in existing standards and guidelines (*2*). TMUTCD standards are specific about the location of the SIGNAL AHEAD sign (see Table 1), but they are not specific about the location of the supplemental advanced warning BE PREPARED TO STOP signing.

Over the course of project 0-4084, researchers analyzed the range of vertical profile geometric conditions that could exist along a roadway approach to a traffic signal. The situation of most interest to researchers for this investigation was that depicted in Figure 1, wherein approaching motorists cannot see either the signal (a) or the queue from the signal (b).

Along the entire length of any roadway, geometric design principles ensure that stopping sight distance (SSD) is available to the motorist. SSD is the distance a driver would need to perceive an unexpected hazard (such as an object) in the road, react to the situation by pressing the brake, and stop the vehicle before reaching the hazard. Additional distance, known as decision sight distance (DSD), is required where the driver must perceive the need to change speed or path (i.e., lane change) and execute the appropriate action upstream of an intersection or decision point. Since intersections involve both a potential stop situation and decision-making regarding their route, longer sight distances (such as DSD) are desired.



(c)

Figure 1. Reduced Sight Distance at Signalized Intersections near Vertical Curves.

In analyzing the mathematical equations that describe both the roadway vertical profile of crest vertical curves and the driver's line of sight, researchers developed a means to determine the sight distance available to a motorist based on the grades and lengths of grades for the crest vertical curves present along the alignment. Due to the presence of a vertical curve along the approach to a signalized intersection, a zone labeled the "reduced decision zone" was found to exist. The reduced decision zone, or RDZ, identifies the length of roadway approaching the signal where a driver has the required SSD but not DSD due to line of sight interference from the pavement surface of the vertical curve. In essence, the vertical curve "hill" blocks a driver's view of the signal and/or the standing queue of vehicles at the signal.

Since SSD and DSD values vary depending on whether the roadway is found in urban versus rural conditions, researchers developed two nomographs to help roadway designers identify the location of the RDZ (*2*, *3*). Given any design speed and change in grade, A, users of the nomographs can identify the beginning and ending of the RDZ with respect to the location of the vertical point of intersection (VPI) of the grade lines of the vertical curve. Figure 2 presents the RDZ definition for urban conditions, while Figure 3 documents the RDZ for rural design.

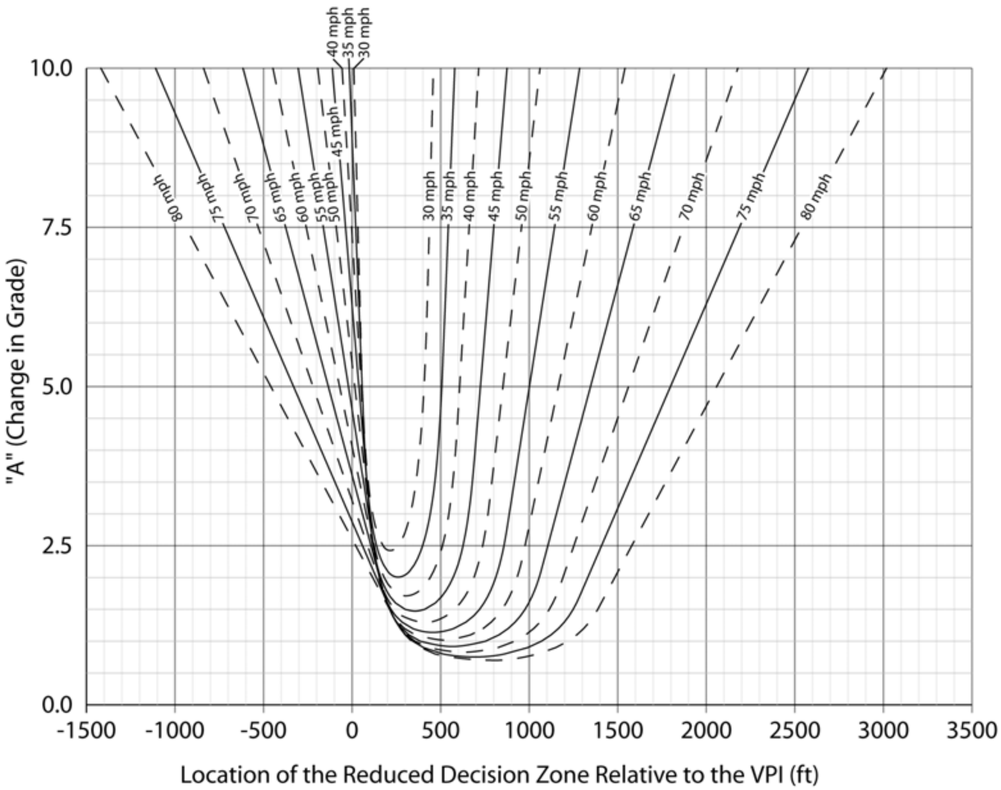


Figure 2. Reduced Decision Zone Location for Urban Roadway Applications.

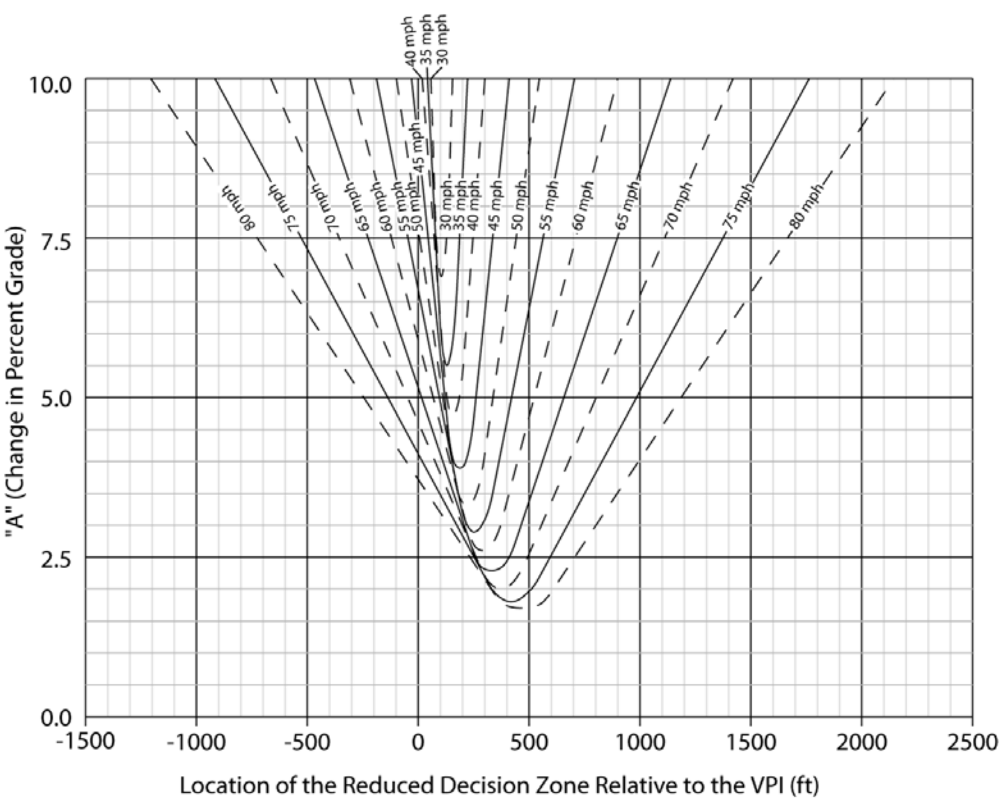


Figure 3. Reduced Decision Zone Location for Rural Roadway Applications.

Project 0-4084 Recommendations

In addition to identifying the location of the RDZ, researchers took the added step of identifying sign locations for advanced warning BE PREPARED TO STOP (W20-7b) signing based on the location of the RDZ. Essentially, W20-7b sign locations were identified (*2*, *4*) so that drivers would have warning of the downstream signal and/or signalized intersection queue before they entered the segment of roadway where their DSD sight line was affected by the crest vertical curve (i.e., the RDZ). Figure 4 identifies the W20-7b sign location that results from this process for urban conditions, and Figure 5 contains sign location recommendations for rural conditions. As with the RDZ nomographs, roadway designers simply need to use the change in grade, A, of the crest vertical curve and the design speed of the roadway to determine the sign location with respect to the VPI of the vertical curve.

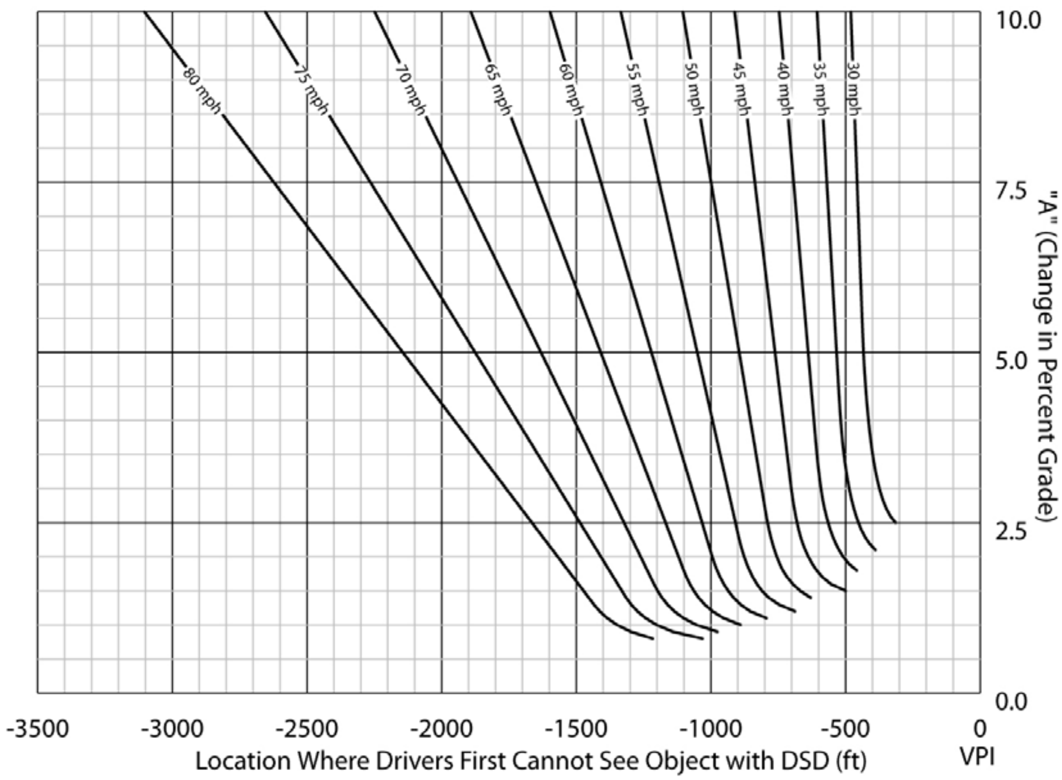


Figure 4. Countermeasure Placement Location for Urban Roadway Applications.

The researchers emphasized that in all cases, the RDZ definition and advanced warning sign locations are recommended as a supplement to the information contained in the TMUTCD. The guidelines developed under project 0-4084 apply only to the supplemental BE PREPARED TO STOP signing. The TMUTCD stipulates that BE PREPARED TO STOP signs only be used at locations where SIGNAL AHEAD signing is also used, and that the BE PREPARED TO STOP signing is intended for situations where the driver needs additional warning about stopped or queued traffic near traffic signals where queues occur regularly. Also, flashing beacons may be used to supplement the BE PREPARED TO STOP warning sign. In situations where the flashing beacons are connected with the traffic signal, the TMUTCD encourages (though does not require) the use of a WHEN FLASHING plaque.

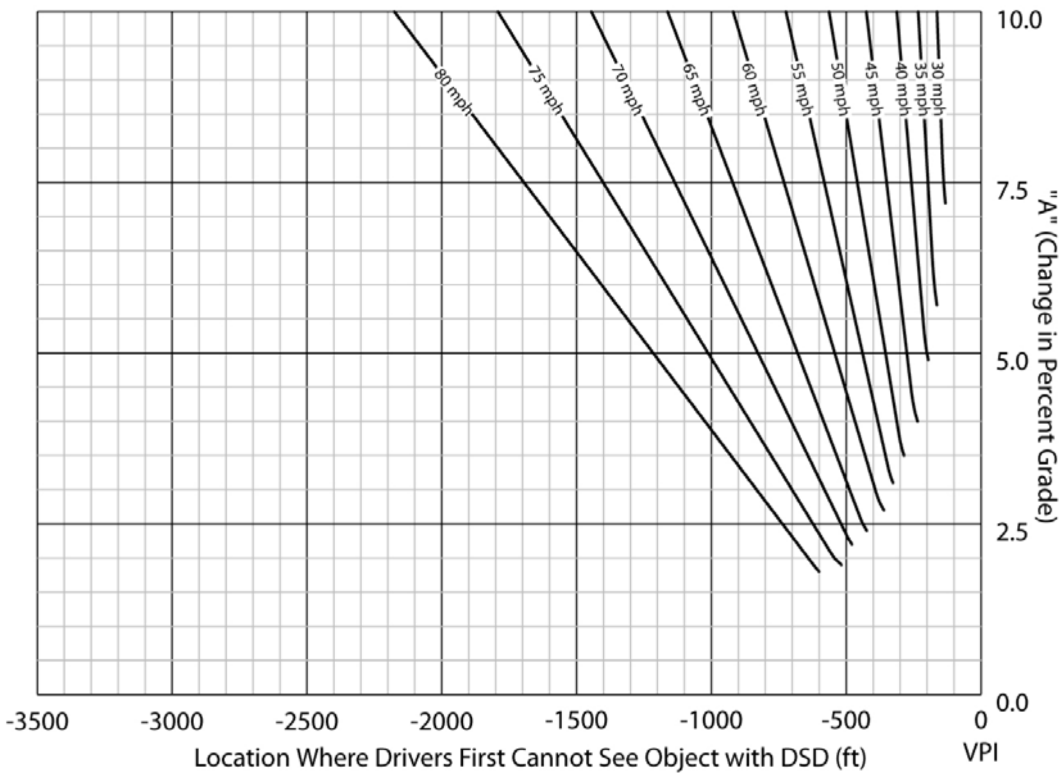


Figure 5. Countermeasure Placement Location for Rural Roadway Applications.

PURPOSE OF THE IMPLEMENTATION PROJECT

The identification of the RDZ (*2*, *3*) and the use of nomographs (*2*, *4*) for locating advanced warning BE PREPARED TO STOP signing for signals close to crest vertical curves are new procedures. The implementation effort was designed to improve and facilitate the adoption of these procedures within TxDOT as a means of increasing the safety of signalized intersection approaches that involve crest vertical curves. The implementation project itself was directed toward achieving two distinct goals:

1. Working with TxDOT staff in two districts to provide full field implementation of advanced warning signing based on project 0-4084 guidelines, and
2. Documenting the site analysis and the equipment specification, procurement, and installation in a video format that can be used as an instruction guide for TxDOT districts around the state.

SCOPE OF THE IMPLEMENTATION PROJECT

This implementation effort was designed to increase Texas Department of Transportation (TxDOT) staff awareness of the findings of research project 0-4084 and to provide detailed step-by-step guidance on how to use the research project's nomographs to identify locations where an RDZ is present and locate advanced warning signing to alert motorists of signals beyond vertical curves. The research team achieved these goals by fully documenting the analysis of two separate sites, one in the TxDOT Laredo District and one in the TxDOT Austin District.

Research agency staff worked cooperatively with TxDOT staff in each district to apply project 0-4084 guidelines to the design, equipment procurement, and equipment installation of the advanced warning sign system. Researchers video documented before and after conditions at each site to produce a TxDOT digital video disc (DVD) that explains and provides case study examples from the two project sites. The resulting video product combines with this report to form a complete documentation package on applying project 0-4084 guidelines to a site with a signal beyond a vertical curve.

CHAPTER 2. AUSTIN STUDY SITE: RM 620 AT COMANCHE TRAIL

RM 620 is a circumferential route around western Austin, Texas. Due to the hilly terrain west of Austin, roadways in the region frequently feature vertical curves and sometimes form intersections with crossing roadways at non-ideal locations either on hillsides or between hills. One such location is the junction of RM 620 and Comanche Trail, which is east of Lake Travis and is located just west of a hilly ridge (Figure 6). Westbound traffic cannot easily see the intersection due to the crest vertical curve formed as the roadway passes over the ridge (see Figure 6). Average annual daily traffic (AADT) on RM 620 near this intersection is approximately 27,000 vehicles per day accordingly to 2005 data from TxDOT's Transportation Planning and Programming Division (*5*). Figure 7 contains photographs along the westbound RM 620 approach to Comanche Trail as a vehicle approaches the intersection.

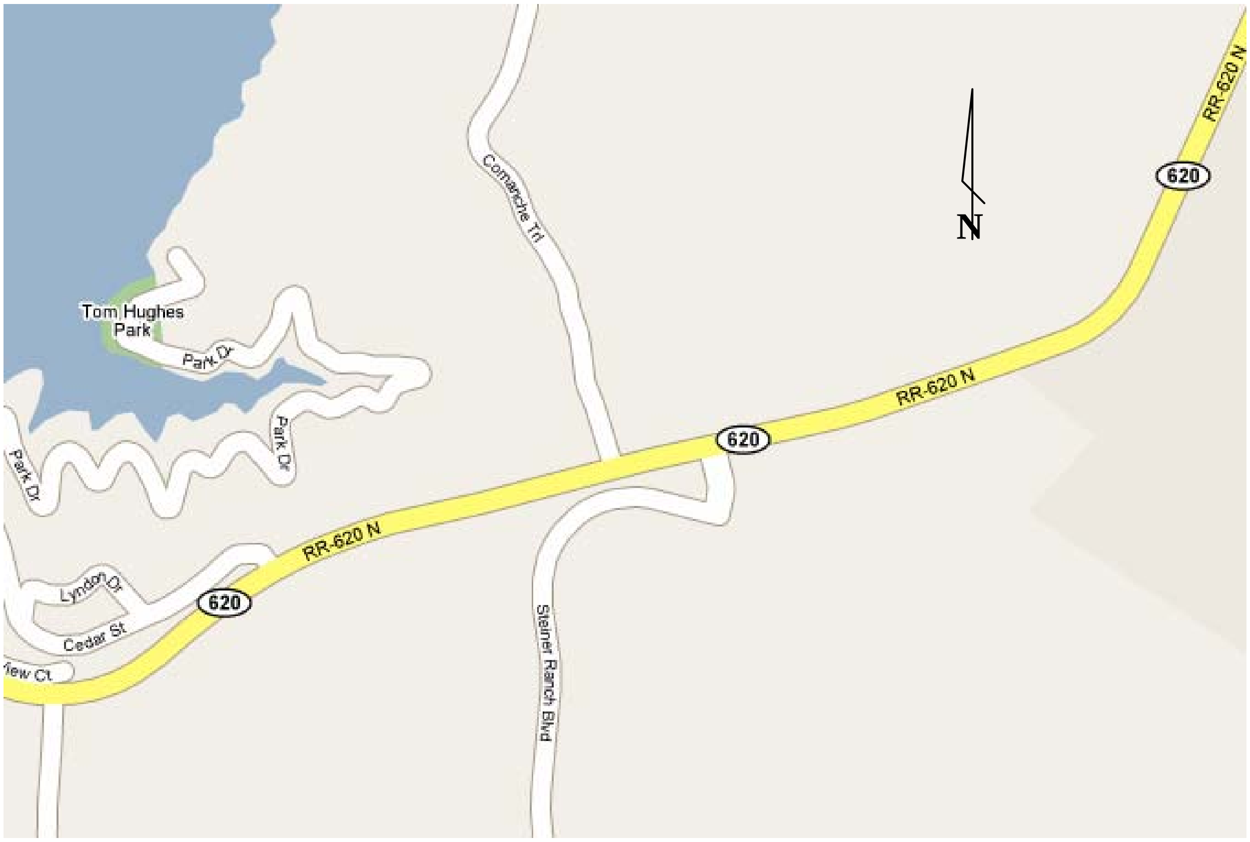


Figure 6. RM 620/Comanche Trail Junction in Austin, Texas (*6*).

This site was previously a study site for the original 0-4084 research project and already featured the recommended BE PREPARED TO STOP sign (see top frame, Figure 7) at a location between the project 0-4084 recommended distances for urban and rural conditions. The current implementation project upgraded this installation from a static sign to one supplemented by active flashers, and located the sign closer to the signalized intersection to bring the location in better compliance with the rural sign location curves (Figure 5) recommended by project 0-4084.

Figure 7. Westbound RM 620 Approaching Comanche Trail.

"BEFORE" CONDITIONS

Researchers used a variety of methods to document conditions at the RM 620 at Comanche Trail intersection before the supplemental, advanced warning signing was changed. Portable traffic counters were used both at and downstream of the proposed sign location so that relative speed and traffic count could be compared to the condition that would exist after the active flashers were installed. Stationary video of the intersection was collected both to produce peak and off-peak turning movement count data and to measure green allocation to RM 620 westbound traffic under varying daily traffic conditions. Lastly, TTI crews collected drive-through video to produce a simulated driving experience along the studied, westbound approach as a point of comparison to the condition that would exist after the signing was modified.

Field data that needed to be collected included the locations of existing signing along westbound RM 620 approaching Comanche Trail; cross section, plan, and profile details for RM 620; vertical clearance of the signal heads for westbound RM 620 traffic at Comanche Trail; and, position and height of mounting locations for the spread spectrum radio antenna that will link the interchange signal controller with the active supplemental warning signs installed on the project. Each item is discussed in detail below.

Existing Signing

The existing signing on westbound RM 620 approaching Comanche Trail was documented to determine whether there was the potential for signing message confusion or sign placement proximity problems when the supplemental advanced warning signing is installed. Researchers used the Texas Manual on Uniform Traffic Control Devices (TMUTCD) to designate each sign. The following signs and their approximate locations were found on the westbound approach:

- Symbolic BE PREPARED TO STOP (text), TMUTCD W20-7b, 1479 feet upstream of the stop bar of the RM 620/Comanche Trail intersection; sign installed here originally for TxDOT research project 0-4084.
- Symbolic Signal Ahead Warning Sign, TMUTCD W3-3, 520 feet upstream of the stop bar of the RM 620/Comanche Trail intersection.
- Recreational and Cultural Interest Sign, TMUTCD D7 series (text); message text "TRAVIS CO. – LCRA PARKS/HIPPIE HOLLOW 2 →/WINDY POINT 3 →"; located 287 feet upstream of the RM 620/Comanche Trail intersection stop bar.

Since the symbolic BE PREPARED TO STOP sign was installed for project 0-4084, it is in the approximate location the sign would normally be located using the supplemental, advanced warning signing location guidelines from the research. However, the location chosen for the initial research was between the 0-4084 guideline locations for urban and rural locations. For the current implementation installation, TxDOT staff decided to locate the sign to better represent the location identified for rural signs from the project 0-4084 recommendations. None of the other signing on the approach was proximate either upstream or downstream of this location, so no signing conflicts were noted.

Cross Section, Plan, and Profile

Cross section, plan, and profile details for westbound RM 620 were provided on engineering design plans for RM 620 obtained from the TxDOT Austin District during the original 0-4084 research project. The plans were developed by TxDOT (Austin District) staff and pertain to Control Section Job 0683-02-039; the plans were dated under professional engineering seal on April 11, 1994. Details from the plans were used in conjunction with the supplemental advanced warning sign location guidelines from project 0-4084 to determine the length of the reduced decision zone along RM 620 where approaching drivers could not see ahead with decision sight distance (see Figure 8), and the location of the supplemental warning signs themselves (Figure 9).

The design plans revealed that the vertical curve preceding the signal on westbound RM 620 was created by a slight uphill grade of 1.17 percent followed by a steep downgrade of 7.69 percent. The vertical point of intersection (VPI) of the grade line tangents for this curve was located approximately 300 feet upstream of the stop bar for westbound RM 620. The algebraic difference in grade for this condition was computed as 8.86 percent. When this information was combined with the speed limit of 60 miles per hour (mph), use of the project 0-4084 curves revealed both the location of the RDZ (see Figure 8), which is from 520 feet upstream of the stop bar to 510 feet beyond the stop bar, and the recommended warning sign location (see Figure 9; driver location at first RDZ visibility point is 1140 feet upstream of the stop bar). Note that a sign legibility distance of 175 feet is subtracted from the driver location in Figure 9 to get the desired sign location, which is 965 feet upstream from the stop bar.

Note that the supplemental BE PREPARED TO STOP sign's current location is roughly midway between the urban and rural locations recommended in the guidelines of project 0-4084. However, since the sign foundation and support had to be completely changed for the addition of the solar powered flashing assembly, the new sign was installed 450 feet closer to the intersection at the location specified by the rural curve in the project 0-4084 guidelines.

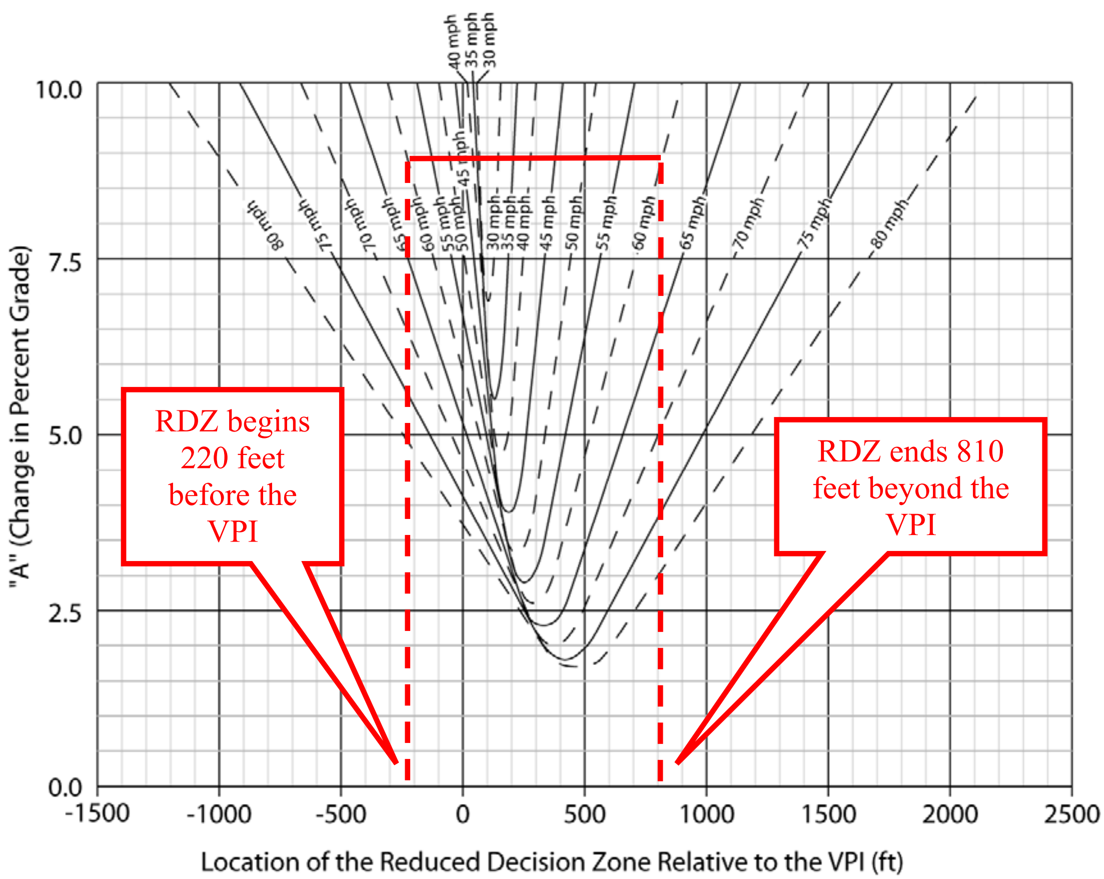


Figure 8. Project 0-4084 Rural Curves for Identifying the RDZ.

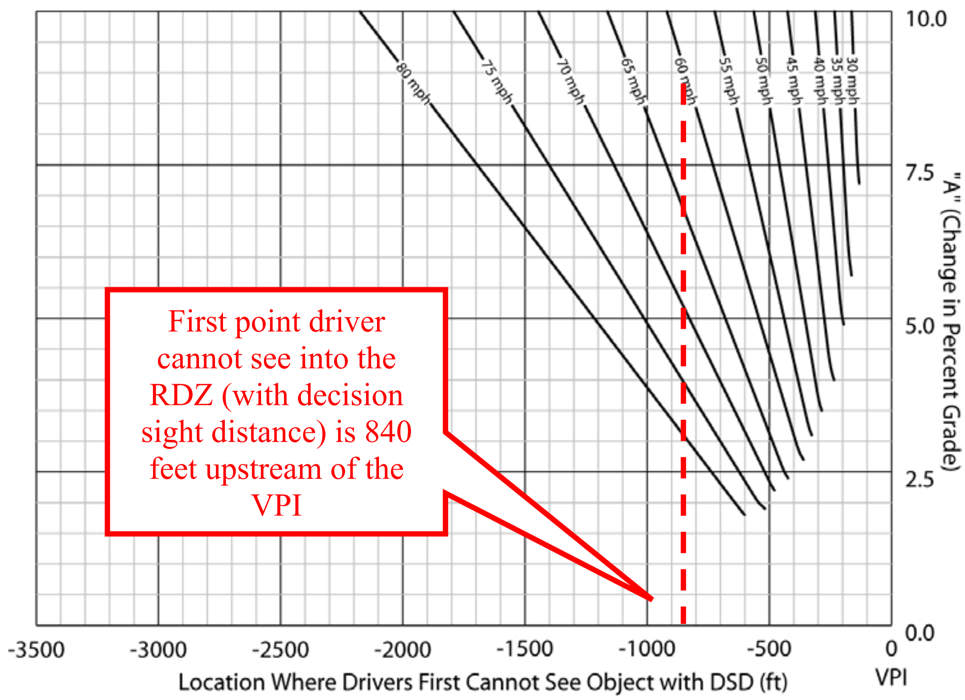


Figure 9. Project 0-4084 Rural Curves for Locating the Supplemental Warning Sign.
(Note: Sign location is actually 175 feet (the sign legibility distance) closer to VPI)

Vertical Clearance of the Signal Heads

During the site visit, the intersection of RM 620 and Comanche Trail was in the middle of a signal upgrade project. The existing single diagonal span wire design (see Figure 10) was being replaced by a box span, which relocated the signal heads for westbound RM 620 traffic slightly to the west, at the western edge of the signalized intersection. Note that the near side supplemental signal head for westbound traffic and the signal pole on which it is mounted remained as components of the new design. Because of the signal upgrade, TTI staff waited until the new signal heads were installed for westbound RM 620 traffic before making clearance/height measurements for these heads.

Antenna Location

Line of sight is required between the supplemental BE PREPARED TO STOP sign location and the antenna (proximate to the signal controller cabinet) mounted on a signal pole or other structure. For this project, TxDOT and TTI decided that a closed contact radio was the best option to communicate between the control cabinet and the remote radio. When the signal is in its yellow change or red clearance interval for the phase serving westbound RM 620 traffic (approaching Comanche Trail), the remote sign's flashers are operational.

Figure 10. Westbound Approach to RM 620/Comanche Trail Intersection.

The previous location of the traffic signal controller cabinet for the RM 620/Comanche Trail intersection was at the base of the signal pole (i.e., it is a pole mounted cabinet) on the northeast corner of the intersection (see Figure 10, lower right side). Logically, the radio communication antenna for the project could have simply been mounted on this pole. However, the signal upgrade project relocated the signal control cabinet to a ground location near the southeast corner of the intersection at the top of the roadway cut whose southwest side is shown in the left side of Figure 10. Accordingly, the current plan is to locate the antenna on the signal controller cabinet itself, as line of sight is easily provided between the hilltop cabinet location and the remote sign's new location. The power lines visible in the figures were not expected to interfere in the radio communications since the radios are spread spectrum (i.e., the radio signal is spread over a wide band of frequencies).

"AFTER" CONDITIONS

As per the research project 0-4084 rural guidelines, the active, supplemental advanced warning signing was located 965 feet upstream of the intersection stop bar. Before and after conditions are compared in Figure 11. The batteries, controller, and radio for the solar powered remote sign are found in a small box behind the warning sign.

Before

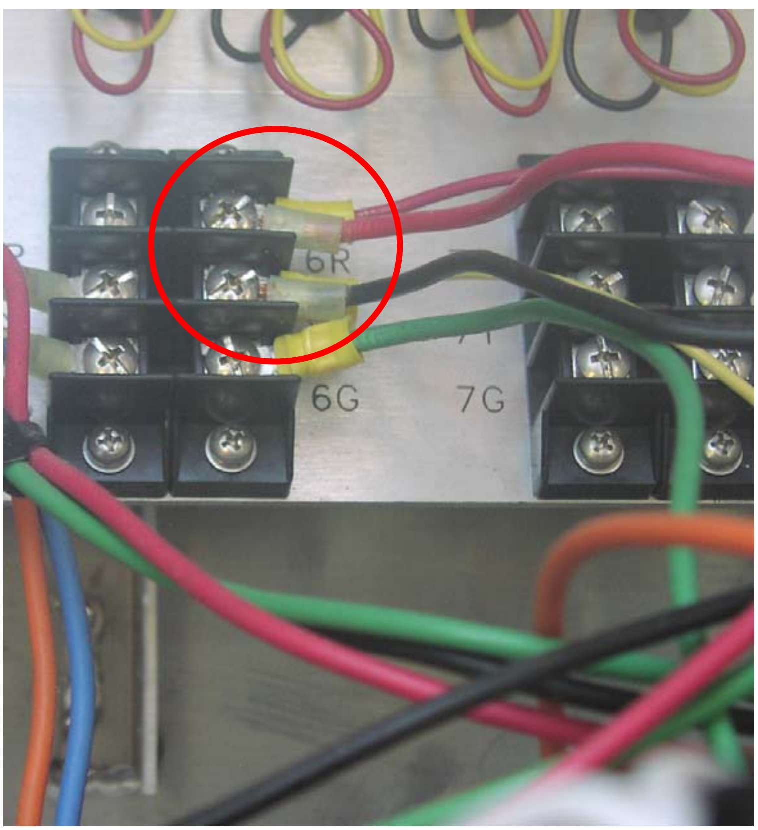
After

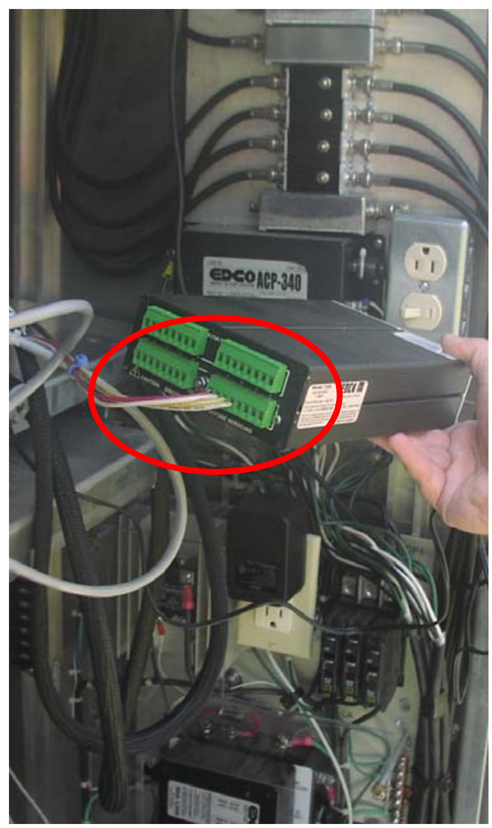
Figure 11. Before and After Site Conditions on Westbound RM 620 At Comanche Trail.

All of the signal controller components utilized for the radio connection to the remote sign are shown in Figure 12. Note that the antenna coaxial cable and power connect to the front of the radio unit and the red and yellow wires connected to the load switch (120V) outputs for the westbound through phase (Phase 6) red and yellow indications connect to the back of the radio on the input (bottom) bank. Figure 13 displays all of the active sign components at the remote sign location. Note the red and black connections to the radio from the output (top) bank and these same wires connecting to the remote flasher's traffic control input.

Antenna Mounting

Spread Spectrum Contact Closure Radio



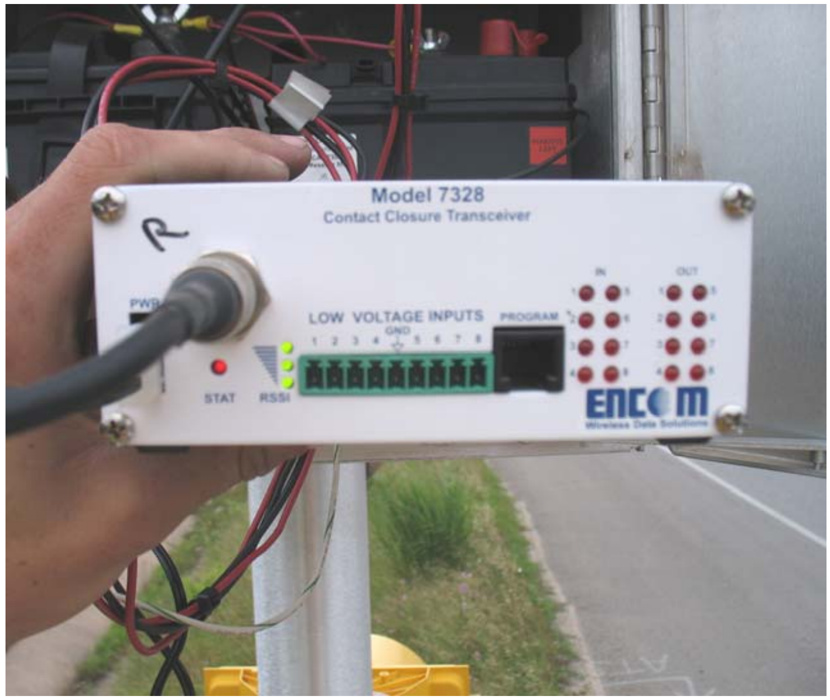


120V Phase 6 Red and Yellow Connection Outputs

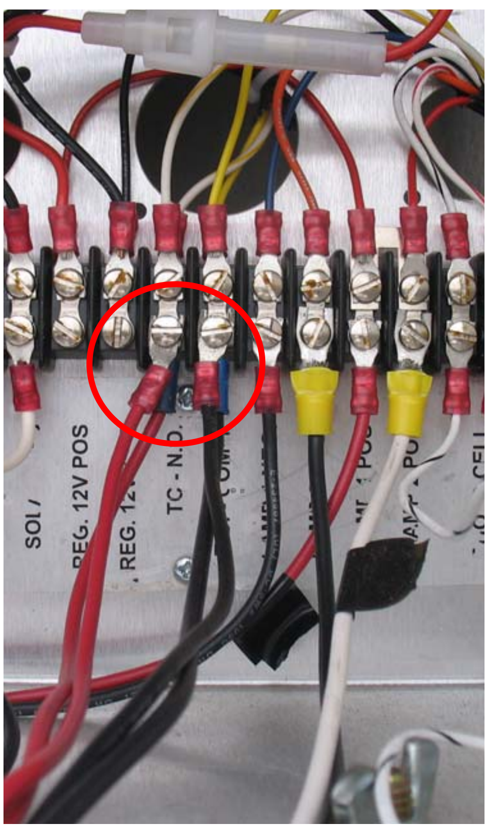
Red and Yellow Radio Inputs

Figure 12. Signal Cabinet Active Flasher Equipment Components.

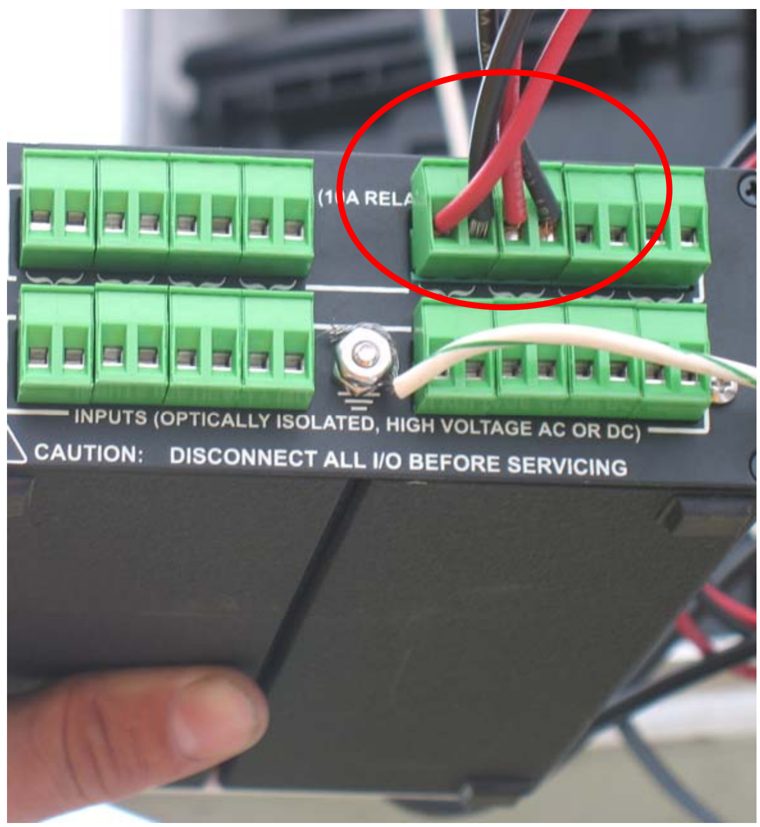
Antenna and Solar Panel



Spread Spectrum Contact Closure Radio



Flash Control Inputs



Radio Outputs for Flash Control

Figure 13. Remote Active Sign Components.

IMPACT ASSESSMENT

Project technicians measured the before and after conditions with respect to active, supplemental advanced warning sign placement using road tube traffic counting and monitoring equipment aligned in a "speed trap" configuration. Count and speed were measured where the sign was installed as well as 400 feet downstream of this location. Whereas the initial intent was to simply compare the before and after speeds both at and downstream of the sign location, changes in the roadway operating environment precluded a direct computation of sign placement impacts.

Over the timeline from project inception to sign installation, TxDOT was in the process of upgrading the signal installation at RM 620 and Comanche Trail. TxDOT staff replaced the existing diagonal span supporting the intersection's signal heads with a box span, which relocated the signal heads for westbound RM 620 traffic slightly to the west. In addition, a protected left turn (previously only a permitted left) was added for eastbound traffic turning into Comanche Trail. Finally, a speed limit change unknown to the research team was underway that would convert the previously existing 60 mph zone where the project's sign would eventually be located into a 65 mph zone.

To account for these differences, the project team identified a relative speed difference measurement for the sign's impact that would be – to the extent possible – immune to some of the roadway environmental changes described above. The outcome was a relative difference in speed between the data collection locations at and downstream of the new sign's location for both the before and after data. Because a relative speed difference was measured, the change in speed limit was neutralized in terms of its potential impact on speed changes due to sign installation. Technicians also monitored videos used to count traffic at the study intersection for both the before and after condition to identify whether or not the introduction of the left turn phase for eastbound traffic changed the average green time for westbound (i.e., study approach) traffic. After evaluating both peak and off-peak traffic conditions, researchers determined that the green times for westbound traffic were statistically the same between the before and after conditions. Finally, the relocation of the signal heads due to the new box span was effectively neutralized by a slight (i.e., approximately 10 inch) increase in signal head height that resulted when the heads were moved from the diagonal to the new box span.

Figure 14 details the changes in speed along the westbound RM 620 approach to Comanche Trail for both before and after conditions. Note when observing the figure that the average speed changes for each hour of the day are represented and that each line of data is the average speed difference of motorists at the sign's location versus 400 feet downstream of the sign. Before the sign was installed, motorists changed speed (or slowed down) an average of 4.6 mph between the sign's installation location and a point 400 feet downstream of where the sign would be installed. After sign installation, motorists slowed down an average of 8.4 mph between these same two locations. Notice that the greater average decrease in speed of 3.8 mph (approximately 4 mph) for after conditions occurs across all times of the day, indicating a motorist impact of the sign's presence under both day- and night-time lighting conditions.

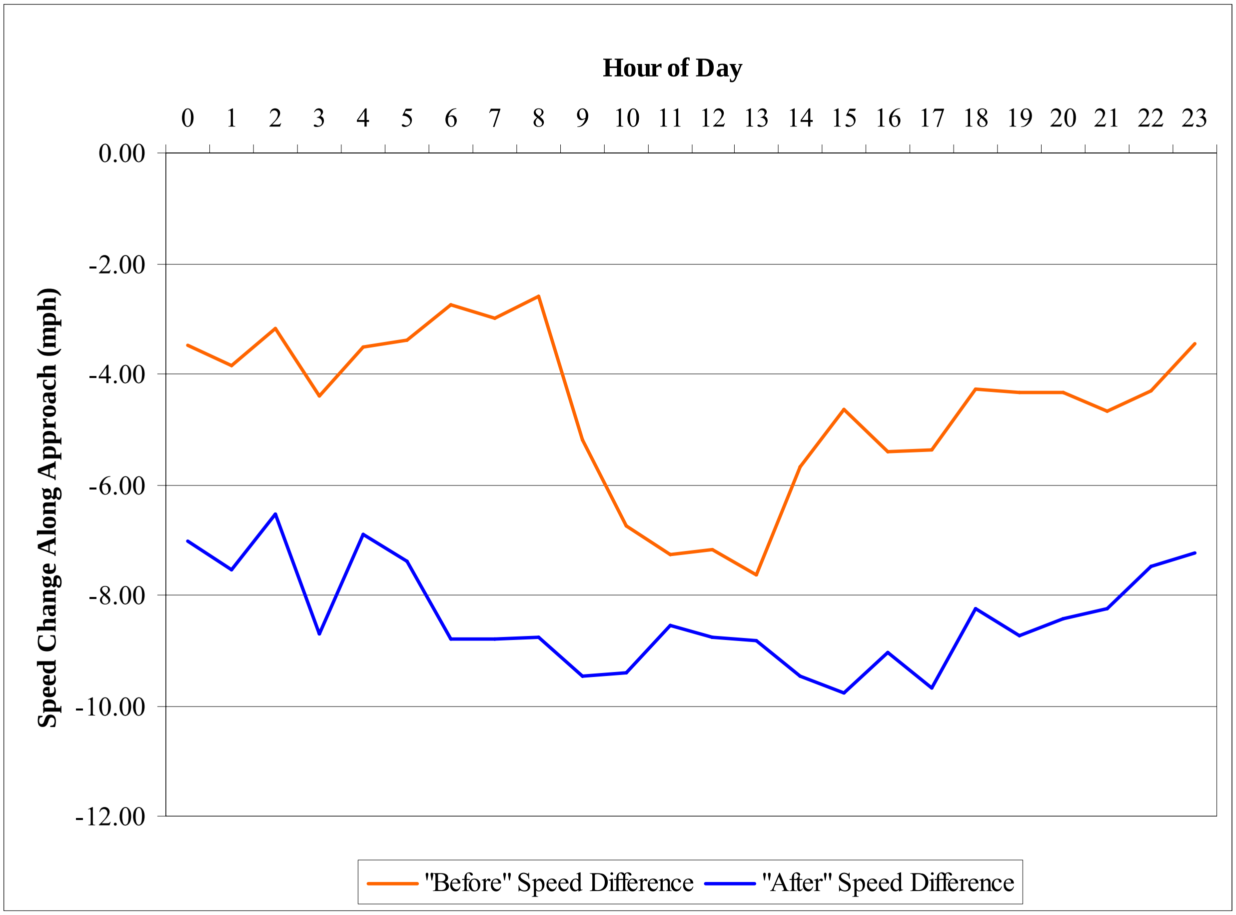


Figure 14. Speed Change along Westbound RM 620 Approaching Comanche Trail.

CHAPTER 3. LAREDO STUDY SITE: LOOP 20 AT INTERSTATE 35

Loop 20 in northern Laredo is in the midst of large-scale, ongoing improvement projects. The roadway will eventually feature grade-separated mainlanes supported by frontage roads, but the access-controlled portions of the facility have not yet been constructed. Accordingly, Loop 20 traffic passes through the interchange formed where the Loop 20 (eastbound and westbound) one-way frontage roads intersect the I-35 (northbound and southbound) one-way frontage roads (see Figure 15). Four signalized "subintersections" are formed where each one-way frontage road crosses the intersecting facilities' one-way frontage roads. Two separate signal controllers previously operated the interchange, but due to synchronization concerns TxDOT staff converted interchange control to operate using one controller. The Union Pacific (UP) railroad tracks seen in Figure 15 overpass the existing Loop 20 infrastructure.

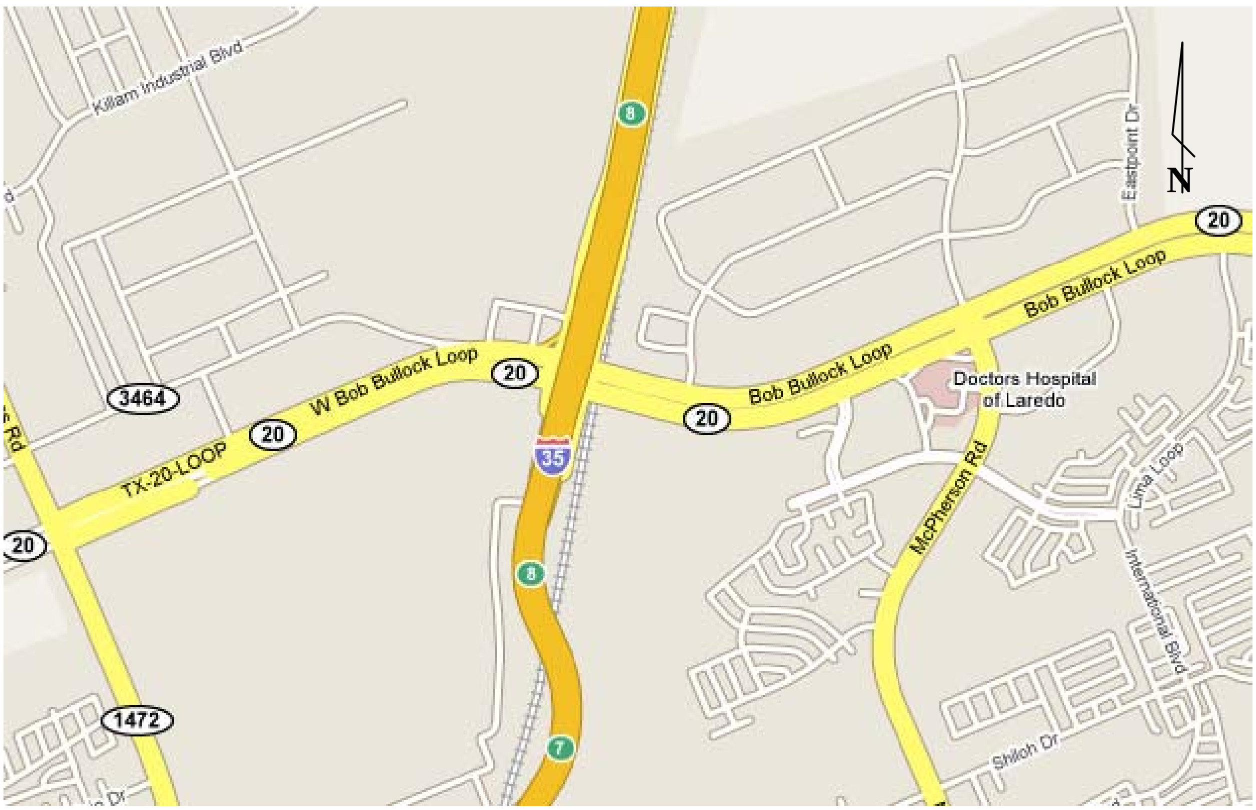


Figure 15. Loop 20/Interstate 35 Junction in Laredo, Texas (*6*).

Figure 16 shows the approach condition that existed before sign implementation. Both vertical and horizontal curves impede approaching motorists' view of any queue that may be formed downstream. The warning signs to either side of the road indicate trucks ahead, and the junction of the roadway Grand Central with westbound Loop 20 is just past the horizontal curve (see Figure 20). Once drivers pass the vertical and horizontal curves, they are on a downgrade approaching the Loop 20/I-35 interchange (see Figure 19). Note that the railroad overpass bridge further limits motorists' view of the signals controlling the interchange.

Figure 16. Westbound Loop 20 Approaching Interstate 35 in Laredo, Texas.

"BEFORE" CONDITIONS

As with the Austin study site, a range of field data was required for the eventual comparison between the situations that existed before and after the implementation project's supplemental, advanced warning signs were installed. As will be revealed, the signing, visibility, and modal mix in Laredo provided a complex situation not experienced in Austin. However, the necessary data were similar and included the locations of existing signing along westbound Loop 20 approaching I-35; cross section, plan, and profile details for the Loop 20 westbound frontage road; vertical clearance and dimensions of the Union Pacific railroad bridge (which the Loop 20 frontage road passes under just east of the I-35 northbound frontage road); vertical clearance of the signal heads for westbound Loop 20 traffic at the northbound I-35 frontage road; and position and height of mounting locations for the spread spectrum radio antenna that linked the interchange signal controller with the active supplemental warning signs installed on the project. Each item is discussed in detail below.

Existing Signing

Researchers documented the existing signing on westbound Loop 20 approaching I-35 to determine whether there was the potential for signing message confusion or sign placement proximity problems when TxDOT's contractor crews installed the supplemental advanced warning signing. Researchers used the Texas Manual on Uniform Traffic Control Devices (TMUTCD) to designate each sign. The following signs and their approximate locations were found on the westbound approach:

- Speed Limit 45 Sign, TMUTCD R2-1 (45 mph), approximately 4400 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction.
- Symbolic Right-Side Intersection Ahead Warning Sign, TMUTCD W2-2R, approximately 2500 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (one sign on each side of westbound Loop 20); includes name placard "Grand Central."
- Symbolic Trucks Ahead Warning Sign, TMUCTD W11-10L, approximately 2200 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (right side of westbound Loop 20).
- Symbolic Right Turn Only Sign, TMUTCD R3-5R, approximately 1800 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (right side of westbound Loop 20); located for the right-hand turn bay lane drop for Grand Central.
- Symbolic Pedestrian Warning Sign, TMUTCD W11-2, approximately 1700 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (right side of westbound Loop 20); continuously flashing solar-powered operation located for pedestrians along westbound Loop 20 at the Grand Central junction.
- Symbolic Right Turn Only Sign, TMUTCD R3-5R, approximately 1500 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (right side of westbound Loop 20); located for the right-hand turn bay lane drop just upstream from Grand Central.
- Symbolic Pedestrian Warning Sign, TMUTCD W11-2, approximately 1500 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (right side of westbound Loop 20); located at the Loop 20/Grand Central junction, includes arrow placard pointing to a crosswalk parallel to Loop 20 both to and from a right-turn directional island.
- Symbolic Signal Ahead Warning Sign, TMUTCD W3-3, approximately 500 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (one sign on each side of westbound Loop 20).
- Symbolic U-turn Only Sign, TMUTCD R3-8U, approximately 350 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (left side of westbound Loop 20); located for U-turn bay for westbound to eastbound Loop 20 movement.
- Symbolic Lane Use Sign, TMUTCD R3-8 series, approximately 300 feet upstream of the stop bar of the Loop 20 westbound/I-35 northbound junction (right side of westbound Loop 20); shows two left lanes as through lanes and the right lane as a right-turn only to the northbound I-35 frontage road.

Though no sign messages were determined to conflict with the TMUTCD W20-7b (text) BE PREPARED TO STOP signs to be installed by the project, TTI researchers and TxDOT staff identified a potential location problem because the project 0-4084 sign placement recommendations located the signs (which included solar-powered active flashers linked by radio to the yellow change and red clearance intervals of the westbound Loop 20 signal at the I-35 northbound frontage road) very close to the location where the existing TMUTCD W2-2R

Right-Side Intersection Ahead warning signs are found for Grand Central. TxDOT staff decided the practical solution was a slight relocation adjustment to the proposed signs.

Cross Section, Plan, and Profile

Cross section, plan, and profile details for the westbound Loop 20 frontage road were provided on engineering design plans for Loop 20 obtained from the TxDOT Laredo District. The plans were developed for TxDOT by consulting firm Brown and Root, and they pertain to Control Section Job 0086-14-023; the plans were dated under professional engineering seal on March 6, 2000. Researchers and TxDOT staff used details from the plans in conjunction with the supplemental advanced warning sign location guidelines from project 0-4084 to determine the RDZ (Figure 17) and the location of the supplemental warning signs themselves (Figure 18). Note that the project 0-4084 urban curves were used since this location is in the urbanized area of Laredo.

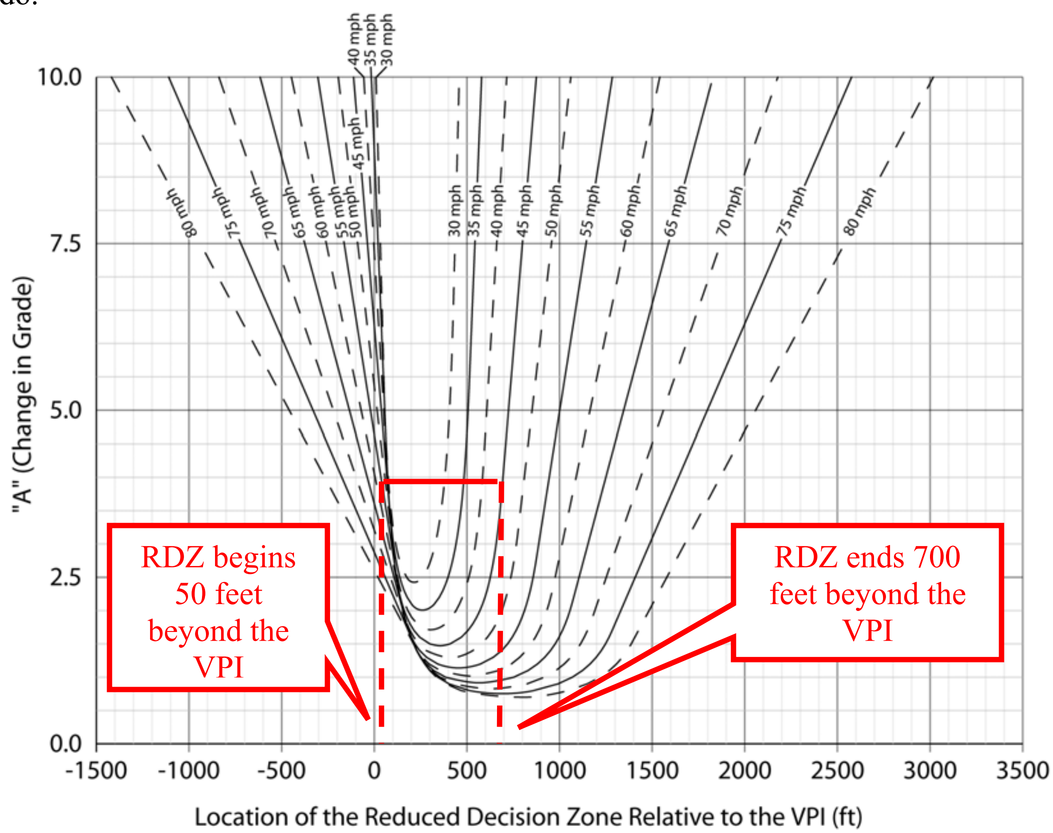


Figure 17. Project 0-4084 Urban Curves for Identifying the RDZ.

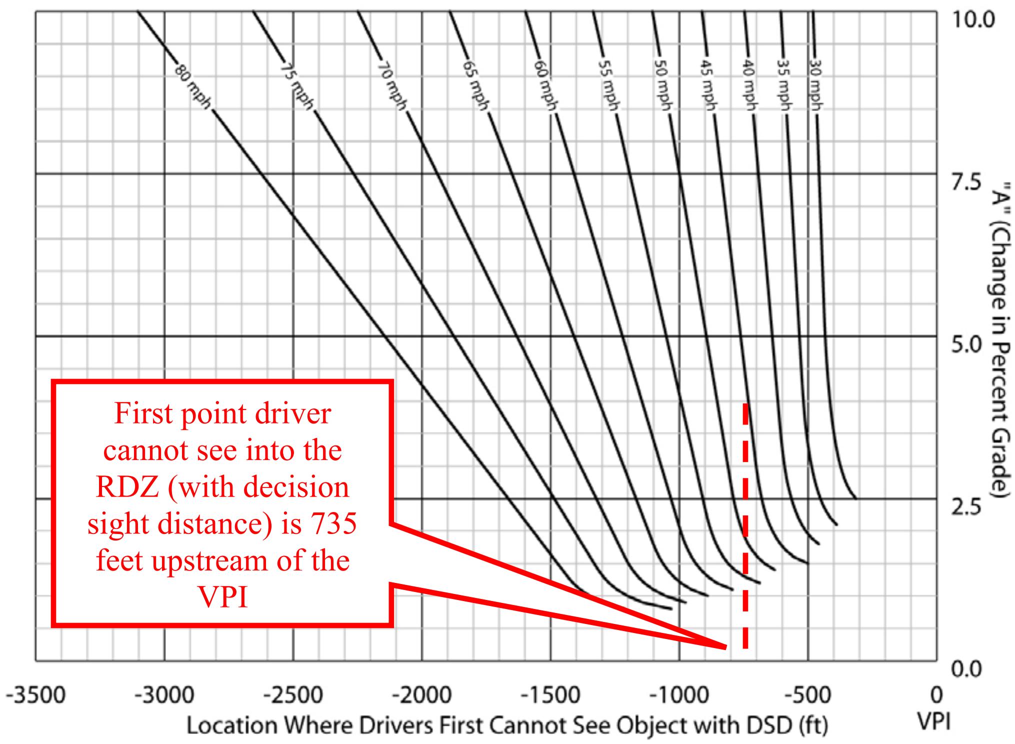


Figure 18. Project 0-4084 Urban Curves for Locating the Supplemental Warning Sign.
(Note: Sign location is actually 175 feet (the sign legibility distance) closer to VPI)

The design plans revealed that the vertical curve preceding the signal on westbound Loop 20 was created by a downgrade of 0.61 percent followed by a much steeper downgrade of 4.50 percent. The vertical point of intersection (VPI) of the grade line tangents for this curve was approximately 1900 feet upstream of the stop bar for westbound Loop 20 approaching the I-35 northbound frontage road. The algebraic difference in grade for this condition was computed as 3.89 percent. When researchers combined this information with the speed limit of 45 miles per hour, the project 0-4084 curves revealed that the RDZ exists from 1200 to 1850 feet upstream from the stop bar, and the recommended supplemental advanced warning sign location is 2460 feet upstream of the stop bar. Note that a sign legibility distance of 175 feet is subtracted from the driver location of 2635 feet (VPI location of 1900 feet upstream of the stop bar plus driver location 735 upstream of VPI) in Figure 18 to get the desired sign location, which is 2460 feet upstream from the stop bar.

Union Pacific Railroad Bridge

An additional factor affecting sight distance to the signal heads along Loop 20 in the westbound direction is a Union Pacific railroad bridge that overpasses the Loop 20 westbound frontage road approaching I-35. The centerline of the bridge is approximately 180 feet east of the stop bar of westbound Loop 20 approaching the northbound I-35 frontage. The proximity of the bridge, coupled with the bridge's clearance and height, presents a direct sight line obstacle for westbound motorists (see Figure 19).

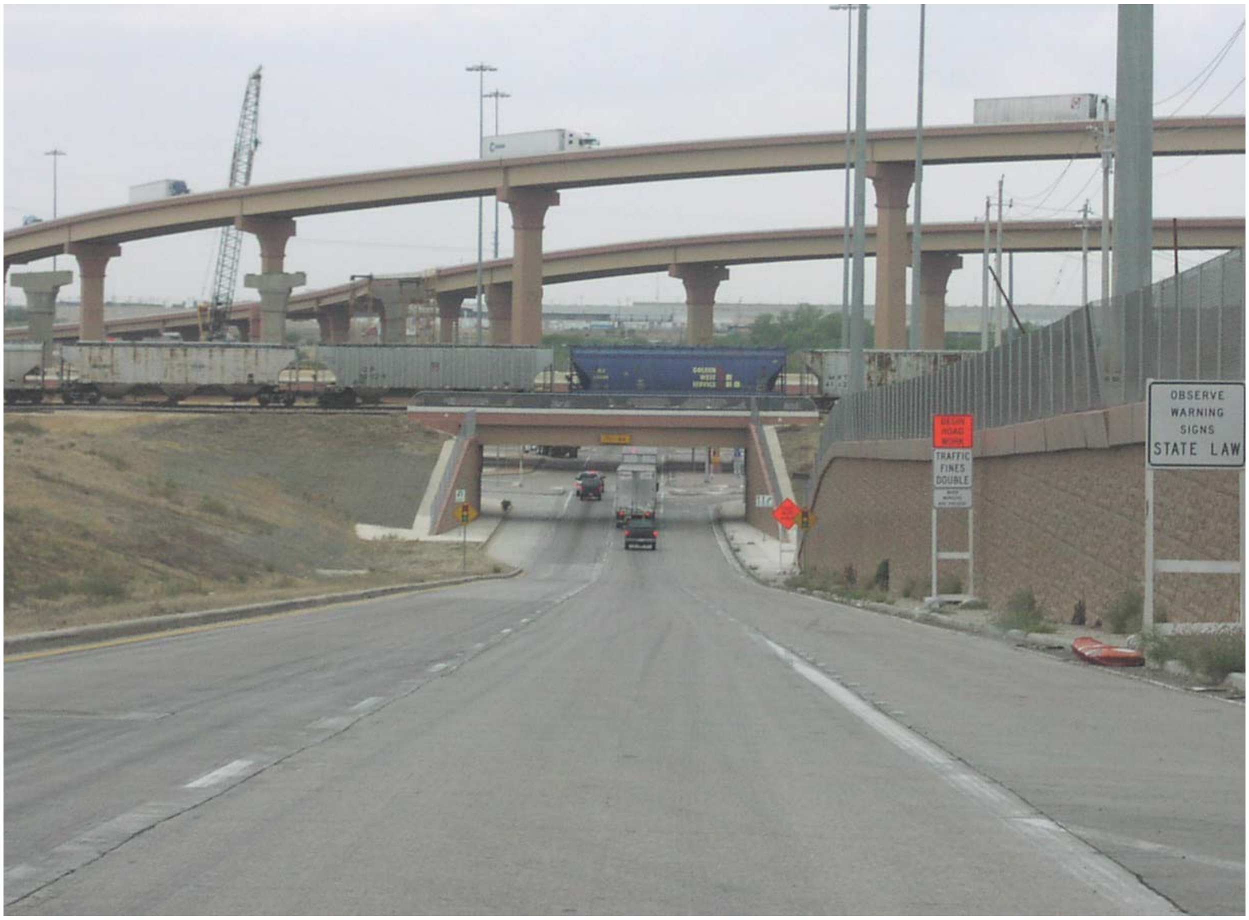


Figure 19. Westbound Loop 20 Approaching the Union Pacific RR Bridge and I-35.

Height of the bridge was measured in the field to verify the bridge's posted clearance of 17 feet 4 inches. The height of the bridge structure was measured to be 8 feet 4.5 inches and the width of the structure (parallel to Loop 20) was measured to be 40 feet. The fact that the railroad bridge obscures the sight line to the signal heads for approaching Loop 20 motorists led to the installation of the symbolic SIGNAL AHEAD signs visible in Figure 19. The signs being installed by the current implementation project are supplemental to these advance warning signs and alert approaching motorists of the potential queue located in the RDZ that they cannot see from the upstream side of the vertical curve. This site is located near an international bridge (i.e., the World Trade Bridge) with Mexico that carries the majority of the commercial traffic in the Laredo region. As a result of these factors, this site has a high percentage of heavy vehicles and experiences long queues, especially during peak traffic hours of the day.

Vertical Clearance of the Signal Heads

During the site visit, TxDOT and TTI staff measured the vertical clearance of the signal heads serving the westbound Loop 20 approach to the northbound I-35 frontage road. Researchers and TxDOT staff measured this height as 18 feet 11 inches in the field and used these details to establish the distance from which approaching motorists can first see the signal heads using a sight line beneath the railroad bridge.

Antenna Location

Line of sight for radio communications is required between the antenna used for the supplemental BE PREPARED TO STOP active sign and the antenna (proximate to the signal controller cabinet) mounted on a signal pole or other structure. For this project, TxDOT decided to again use spread spectrum radios to communicate between the signal controller cabinet and the remote radio for the active sign installation. When the signal is in its yellow change or red clearance interval for the phase serving westbound Loop 20 traffic (approaching the northbound I-35 frontage road), the remote sign's flashers are operational. The receiving radio can only function properly if continuous line of sight is maintained between the remote antenna and the signal controller's antenna. While line of sight is usually possible at most field locations, the project site has a number of complicating factors, including:

- A right-hand horizontal curve (see Figure 20) along the Loop 20 westbound frontage road approaching I-35 between the remote sign location and the intersection (where the cabinet is located);
- A large warehousing building located north of the Loop 20 westbound frontage road that is inside of the vertical curve referred to above (see Figure 20);
- The vertical curve along the approach to the signal (i.e., the impetus for the project);
- High-volume heavy vehicle, or truck, traffic along westbound Loop 20 and along Grand Central, which intersects Loop20 between the sign location and the intersection;
- The Union Pacific railroad bridge located near the signalized intersection; and
- Train locomotives and cars along the Union Pacific railway, which effectively raise the height of the bridge by an additional 15 to 20 feet (during train passage).

Fortuitously, the research team captured a site photograph from the top of the vertical curve during the time a train was occupying the UP tracks. Zooming in on a portion of the photograph (see Figure 21) revealed that a TxDOT South Texas Regional Advanced Traveler Information System (STRATIS) traffic monitoring camera and its pole were visible above the train, indicating that line of sight would be possible in terms of vertical clearance above the train and tracks. TxDOT staff identified a pole supporting the camera as one possible solution for antenna mounting for the project's communication needs. Another alternative was to use an existing TxDOT radio repeater station (i.e., a transceiver) located proximate to the southeast quadrant of the Loop 20/I-35 interchange that was used for communications between Loop 20's I-35 and McPherson interchanges. The project team concluded that further consultation with TxDOT Laredo District staff and Traffic Operations Division staff was necessary to identify the best solution for the communications issues at the site.

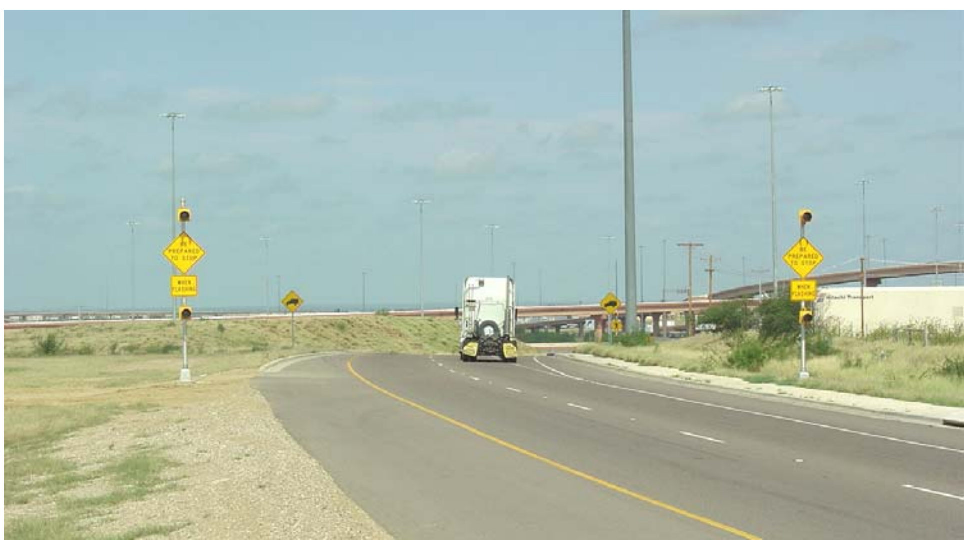
Figure 20. Warehousing Building North of Loop 20 Westbound Approaching I-35.

Figure 21. TxDOT STRATIS Camera and Pole Above UP Train and Tracks.

“AFTER” CONDITIONS

As per the research project 0-4084 urban guidelines, TxDOT staff attempted to locate the active, supplemental advanced warning signs 2460 feet upstream of the stop bar. However, existing symbolic INTERSECTION AHEAD warning signs were already located 2600 feet upstream of the stop bar. Using engineering judgment, TxDOT staff decided to install the project’s signs 300 feet upstream of the intersection ahead signs, which was 260 feet closer to the VPI than the project 0-4084 nomographs indicate. Before and after conditions are compared in Figure 22. Note that this installation is more complex than the Austin site due to the need to elevate the antenna on a 40-foot timber pole and the placement of the batteries in underground vaults. Also, it was necessary to bore underneath the Loop 20 westbound lanes in order to provide cabling for the batteries and flasher activation for the flasher assembly on the south side of the roadway.

Before

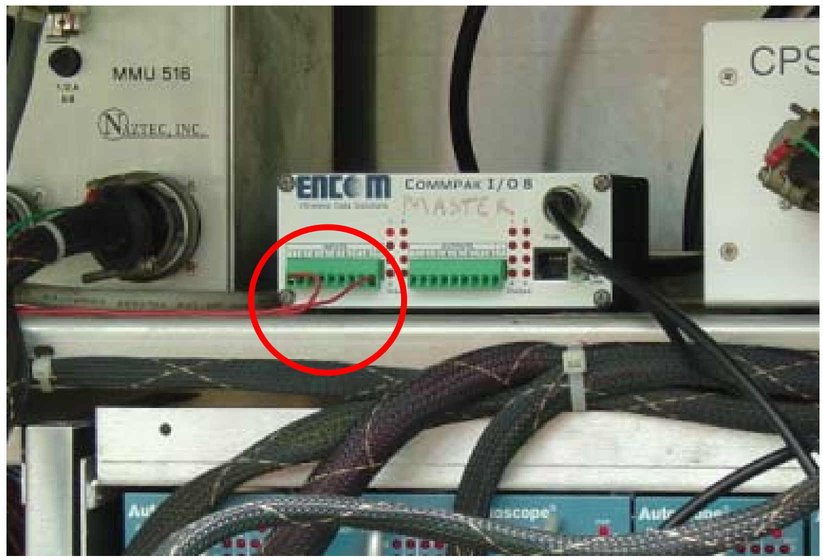


After

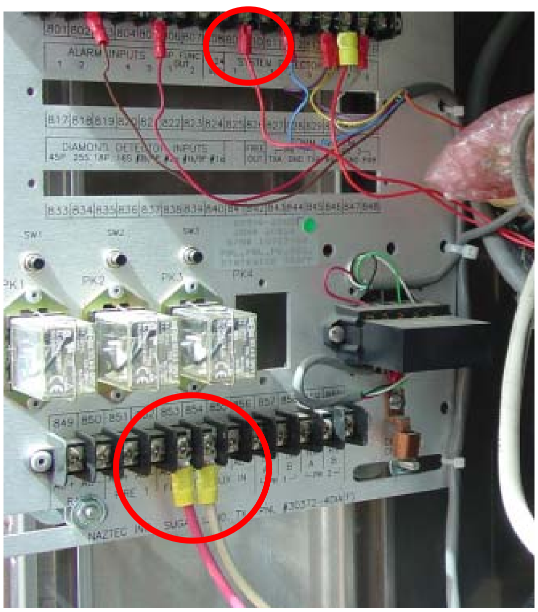
Figure 22. Before and After Site Conditions on westbound Loop 20 Approaching I-35.

All of the signal controller components utilized for the radio connection to the remote sign are shown in Figure 23. Unlike the direct connection configuration in Austin, the radio was integrated into the controller cabinet by using the preemption panel. The antenna coaxial cable and power connect to the front of the radio unit and the radio input is connected to the previously unused preemption panel. The selected preemption circuit is then connected to the load switch (120V) output for the westbound through phase (Phase 6) green indication. This "reverse logic," normally closed circuit approach activates the flashers whenever Phase 6 is not green. Figure 24 displays all of the active sign components at the remote sign location. In this case the radio is connected to the remote cabinet relay that activates the flashers.

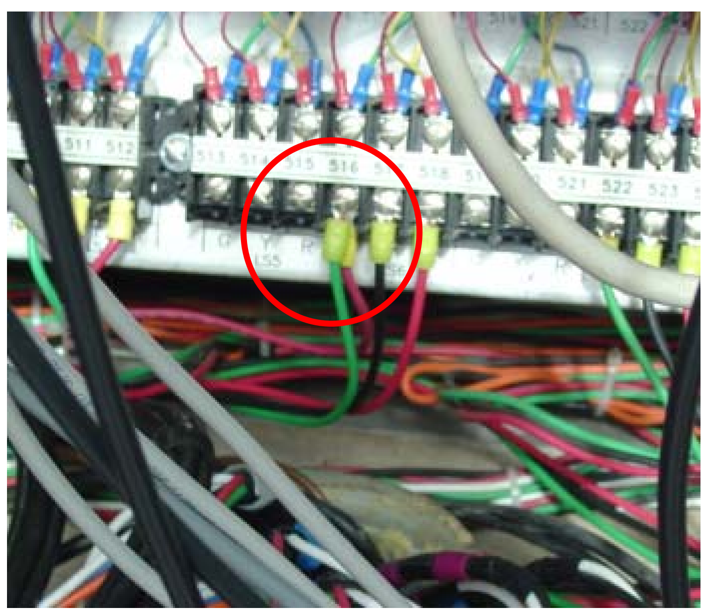
Antenna Mounting



Spread Spectrum Radio



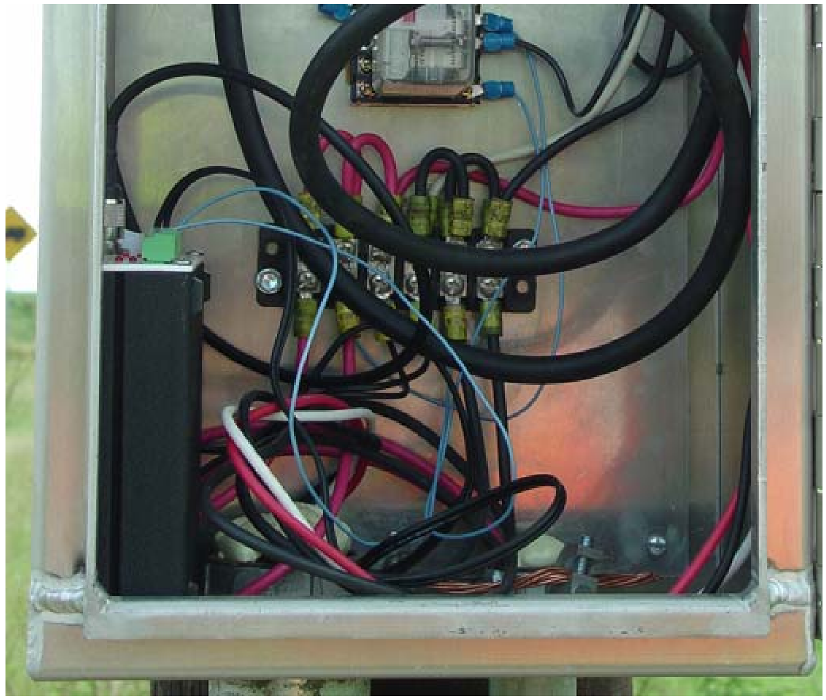
Connections to Preemption Panel



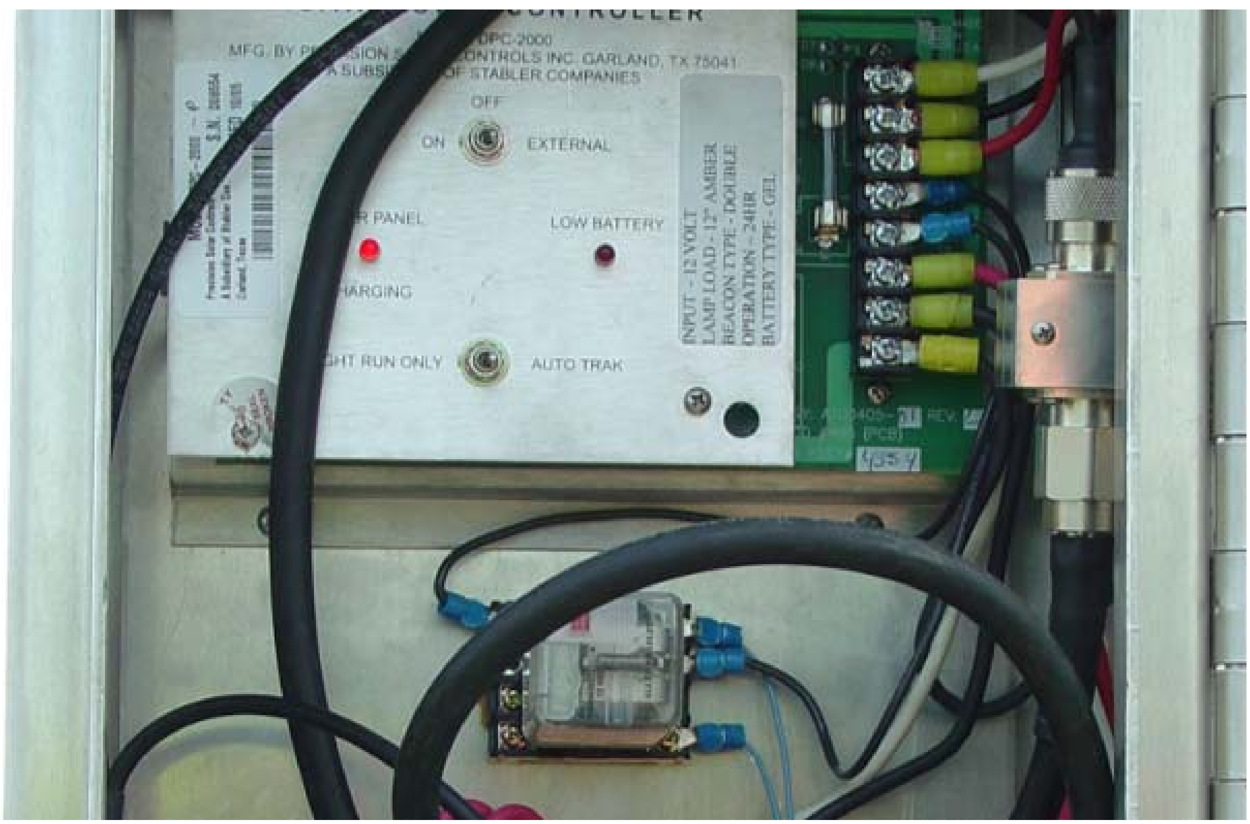
Phase 6 Green Connection to Preemption Panel

Figure 23. Signal Cabinet Active Flasher Equipment Components.

Antenna and Solar Panel



Spread Spectrum Radio (left)



Radio Flash Control Inputs (blue wires from bottom) and Flash Control Relay (bottom center)

Figure 24. Remote Active Sign Components.

IMPACT ASSESSMENT

The Laredo implementation site along Loop 20 westbound did not have changing background environment factors to the extent of the Austin study site. Though the controller configuration changed from two-controller to one-controller operation at the interchange of Loop 20 and I-35, the basic timing pattern was retained. As a result, the only significant change in the operating environment over the course of the advanced warning signing system implementation was the installation of the active signs. Researchers were able to directly compare before and after speeds to determine the impact of the active supplemental, advanced warning BE PREPARED TO STOP signing system.

Figure 25 compares before and after speed ranges observed in the field along the westbound Loop 20 approach to Interstate 35. Data collection locations were the same for both the before and after studies and were 300 feet upstream (the thicker lines in the figure) and 200 feet downstream (the thinner lines in the figure) of the signs installed for the implementation project. From Figure 25 it is clear that there is a significant speed reduction for the after condition for all times of day (i.e., all lighting conditions). While Figure 25 compares the upstream and downstream before and after speeds to establish a speed range in the vicinity of the installed signs, Figure 26 shows a direct comparison between before and after overall average speeds. The average speed change brought about by the signs was 5.3 mph. This result compares favorably with the approximate 4 mph relative speed reduction observed at the Austin site, but direct comparison is not possible given the differences in site conditions and the analytical approach employed at each location.

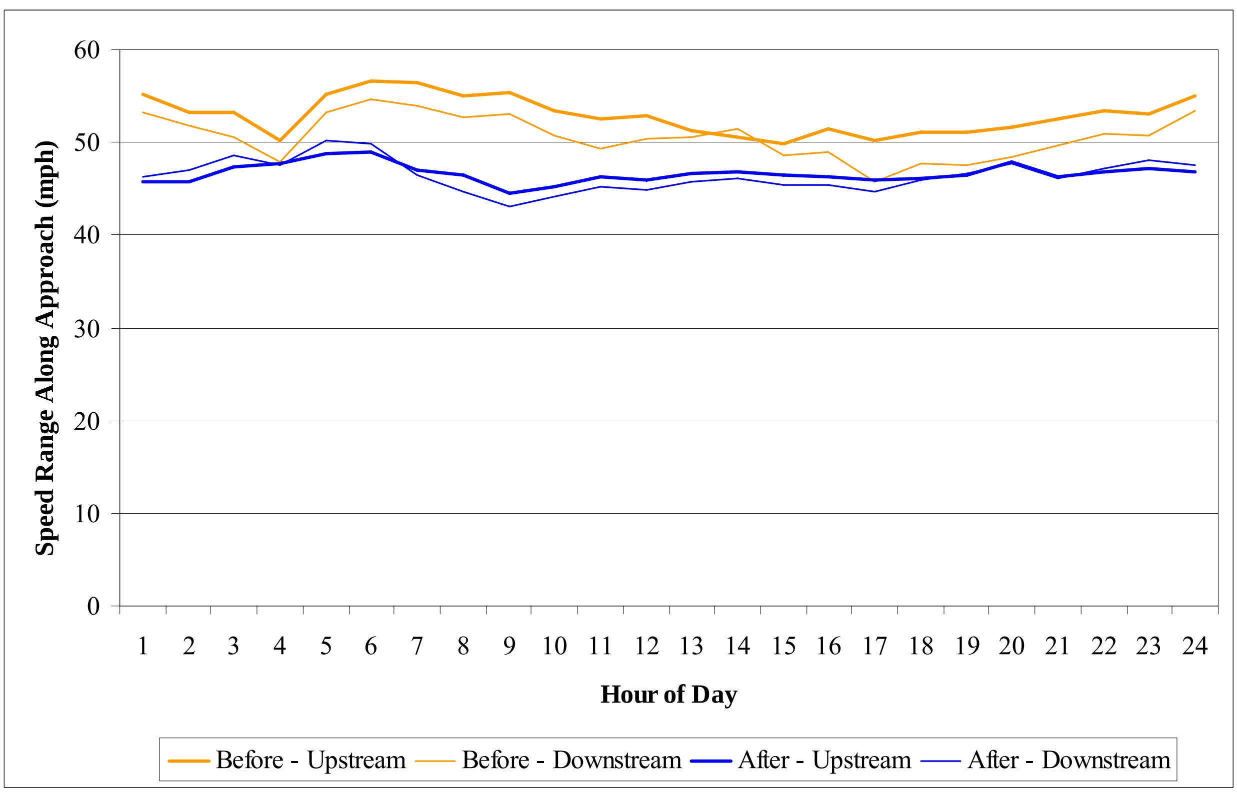


Figure 25. Before and After Speed Range Comparison Along Westbound Loop 20.

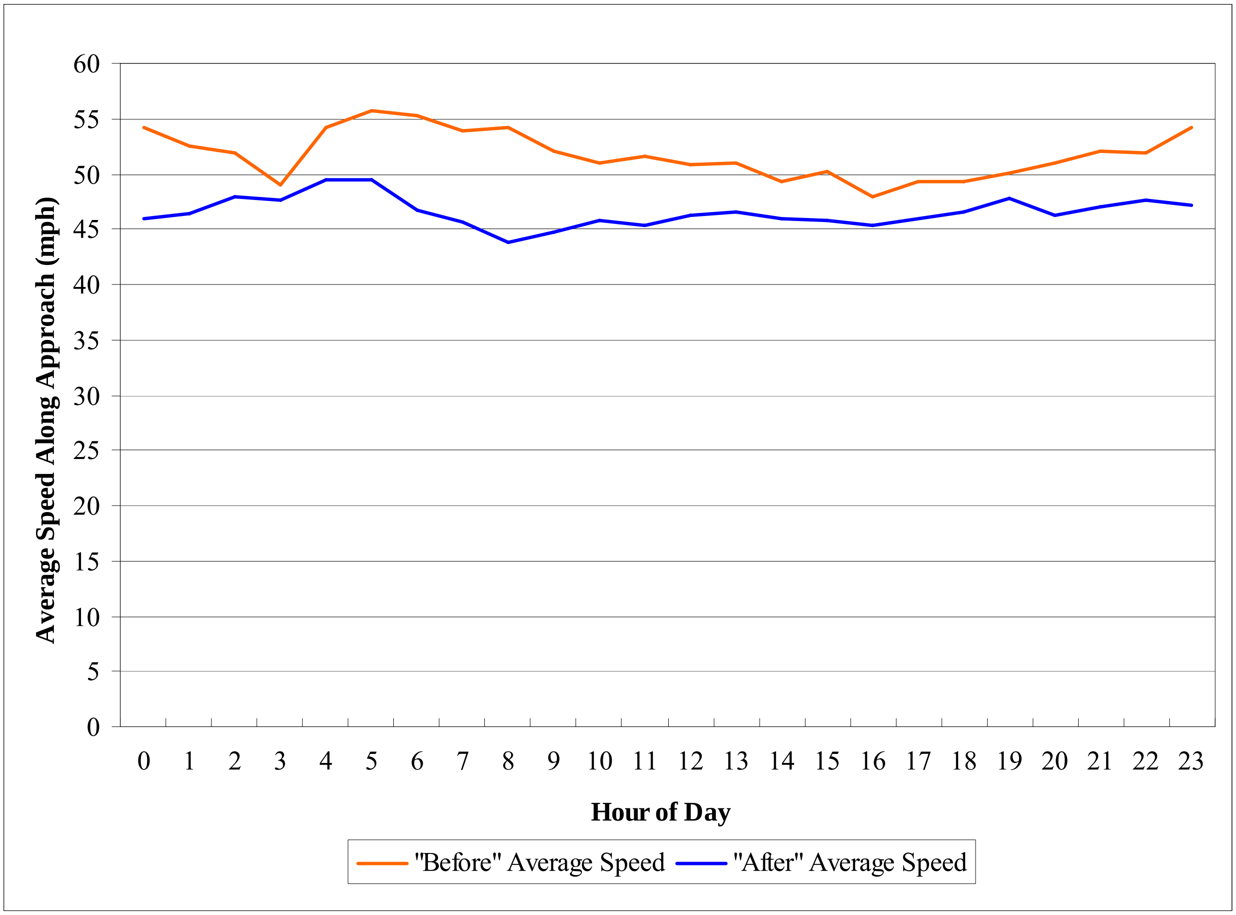


Figure 26. Before and After Speed Comparison for Westbound Loop 20.

CHAPTER 4. IMPLEMENTATION CONSIDERATIONS

COST

Comparing the Austin and Laredo implementation sites, it is clear that a range of methods exists to deploy the supplemental, advanced BE PREPARED TO STOP signing recommended in TxDOT project 0-4084 for warning motorists of signals or their queues beyond vertical curves. If static signs are deployed, the cost is less than a thousand dollars. If active flashers are used, the costs can range between $7,000 and $25,000 dollars. If active flashers are supplemented with a queue detection system, costs of up to $35,000 are possible.

In Austin's deployment, a single roadside solar flasher warning assembly was used with spread spectrum radio communications back to the signal control cabinet. The approximate cost of this system was $7,000 ($4,500 equipment plus $2,500 installation). In Laredo, two flasher assemblies were necessary so that signs and flashers could be located on both sides of the one-way through lanes. It was necessary to bore beneath the Loop 20 through lanes to run conduit and cable for powering and activating the flashers. Laredo's sight line issues also necessitated the installation of the antenna on a 40-foot timber pole to provide continuous line of sight between the remote and signal cabinet antennas. In addition, Laredo located the batteries for its solar flashers in underground vaults. The total cost of this installation was approximately $24,500 ($7,700 equipment plus $16,800 installation).

SIGN SPACING

Though no absolute requirements exist for roadside sign spacing, the typical approach within Texas is to space such signs a minimum distance of 200 feet apart. Part 6 of the TMUTCD (*1*) suggests minimum advanced warning sign spacings in construction work zones that could logically be extended to the supplemental advanced signs suggested in project 0-4084. Distances in feet are computed by multiplying the speed limit in mph by a value of four (4) for a speed of 30 mph up to a value of 10 or greater for higher speed applications (see Table 2). Adequate spacing ensures that the motorist has adequate time to read and process the information on each sign before encountering the next.

Though the project 0-4084 curves recommend a given distance for sign location based on motorists reaching the first point along a signalized intersection approach where they can no longer see objects ahead with DSD, there exists a range of locations downstream of this point where the motorist cannot see ahead with DSD. Locating the supplemental, advanced warning signing slightly upstream or downstream of the suggested location to avoid interference with other signing is appropriate. Engineering judgment in this case will either: 1) determine that the proximity of the signal or its queue is critical and will locate the sign further upstream to provide sufficient warning, or 2) determine that the recommended location is sufficiently upstream of the signal and queue such that the supplemental sign can be moved slightly downstream to avoid interference with other signs while still providing adequate warning of the signal and potential queue ahead.

Table 2. Suggested Advance Warning Sign Spacing (*1*).

Road Classification	Posted Speed (mph)	Sign Spacing (ft)
Conventional Highways	30	120
	35	160
	40	240
	45	320
	50	400
	55*	500
	60*	600
	65*	700
	70*	800
	75*	900
	80*	1000
Expressways or Freeways	All Speeds	See Typical Applications **

Notes:
* Distance between signs should be increased to have 1500 feet advance warning
** Distance between signs should be increased to have ½ mile or more advance warning

PRESENCE OF OTHER VERTICAL OR HORIZONTAL CURVES

In addition to concerns about sign placement with respect to other signs along the approach to a signal beyond a vertical curve, there also exists the possibility of other vertical or horizontal curves affecting motorist sight distance. In these situations, the same engineering judgment approach should be applied as with locating supplemental, advanced BE PREPARED TO STOP signs relative to other signing. If the project 0-4084 guidelines locate a sign along a horizontal or vertical curve upstream of or in conjunction with the vertical curve creating an RDZ along the approach to the signal, the BE PREPARED TO STOP signs should be located further upstream to also account for sight distance limitations introduced by the second (vertical or horizontal) curve. If the second (vertical or horizontal) curve is not substantial enough to produce sight limitations, the originally recommended project 0-4084 location may still be viable.

SIGN LOCATION RELATIVE TO QUEUE

Particularly in urban areas, there exists the likelihood that the recommended supplemental, advanced warning signing location using the project 0-4084 nomographs will be distant from the signalized intersection. Motorists may pass the sign location recommended in the original research just before the active flashers begin operation and still be in a situation where they will be stopped by the traffic signal or its queue as they approach the downstream intersection. One potential remedy to this situation is to start the advanced sign’s active flashers (if present) before the onset of the yellow change and red clearance intervals (i.e., just before the end of green). One simple method of achieving this type of operation is to use an overlap to control the downstream through phase whose parent phases are the primary extensible through phase and a short-duration fixed length phase that is linked to flasher operation. Note, however, that such operation eliminates the possibility of having dilemma zone protection on the subject approach. Another option for sites where this issue is of concern is to provide advanced flasher operation design incorporating the requirements for an advanced warning for end of green (AWEGS) system (*7*).

In addition to the above concern regarding motorists passing the supplemental advanced warning signing while it is inactive but still being in a situation to stop at the signal, there exists the possibility of the active flashers ceasing operation at a time when an approaching motorist reaches an end of queue that has not started moving for the downstream signal's green indication (i.e., before the queue has had a chance to begin clearing). As the original research points out – and as is mentioned further below – the optimum solution for this situation is to install a queue detection system along the approach where the supplemental advanced warning signing with active flashers is located. When either the downstream through phase is yellow or red OR a queue is present, the active flashers are in operation. Alternatively, if the queue size and its dissipation rate are fixed and stable over time, a time delay relay can be used to activate remote flasher control and extend activation beyond the end of green for the through phase. As shown in Figure 27 below, such relays can be programmed for a variety of durations that correspond to the (known) queue dissipation time, thus keeping the active flashers operational a fixed time after the downstream through phase has ended.

Figure 27. Time Delay Flasher Control Relay.

QUEUE DETECTION SYSTEM

A recommendation from the original project 0-4084 research is reiterated here with respect to the use of active flashers with BE PREPARED TO STOP text or symbolic SIGNAL

AHEAD signing. Whereas common practice is to activate the flashers a few seconds before the end of green and continue flashing operation until the end of red for the through phase on the subject approach, there is no sensitivity in this practice to the presence of the queue (as discussed above). A standing queue may remain on the approach for 20 seconds or more after the signal has turned green, especially where volumes are high and queues are long. If the active flashers deactivate before the end of the queue begins moving and accelerates to speed, approaching motorists would be given the impression (because the flashers became inactive) that the downstream signal is green and the roadway is clear, and they may not be as vigilant in anticipating a queue of vehicles ahead. For this reason, researchers recommend that in locations where the queue from the signal extends into a reduced decision zone, active flashers should be tied not only to the downstream through phase of the signal, but also to a queue detection system. An alternative and less expensive form of operation for this situation is simply to operate the flashers in a continuously flashing mode.

CHAPTER 5. SUMMARY

The original TxDOT research for this implementation project identified a methodology for using driver line of sight and design height objects within the driver's view as a means of identifying areas along a signalized intersection approach where vertical curves limit the information-gathering process. Researchers identified a "reduced decision zone" along the approach to a signal (or intersection) that includes a vertical curve. Within this zone, stopping sight distance is provided as per roadway geometric design standards, but any extra decision-making time that would otherwise be provided by decision sight distance is not. The research team developed graphs referenced to the vertical point of intersection of the vertical curve to identify the segments of roadway along the signalized intersection approach where a (standard) 2-foot object would not be visible (using decision sight distance criteria) to motorists on the roadway approaching the signal. The implementation team used these graphs to identify locations at two study sites where reduced decision zones exist.

Analysts used additional graphs developed during the original research project to identify where motorists would be located along the intersection approach when they reach a point along the roadway where they could not see a 2-foot object within the reduced decision zone. The distances indicated in these graphs (less a sign visibility distance of 175 feet) were the recommended locations for active, supplemental advance warning signing systems installed during the implementation project. The signing systems deployed by TxDOT staff at each site used the BE PREPARED TO STOP sign recommended by the original research and employed solar-powered active flashers that were linked to the traffic signal controller using spread spectrum radio communications.

Data collected before and after each installation revealed a speed reduction at both sites. In western Austin, Texas, an average speed change difference close to the new warning sign of 3.8 mph was observed, while in Laredo, Texas, an average overall speed reduction of 5.3 mph was found. Researchers interpreted both results as desirable outcomes as the intent of the implemented signing systems was to alert approaching motorists of signal presence and potential queues beyond the vertical curve at each site.

TxDOT and TTI staff encountered a range of implementation concerns as the signing systems were designed and installed. During signing design, engineering concerns such as proximity to existing signs and the presence of horizontal curves emerged. Though the project 0-4084 sign location curves produce a single sign location distance with respect to the vertical curve along the approach, the signs may need to be located upstream or downstream of this location if there is inadequate spacing with respect to existing signs, or other vertical or horizontal curves are present. In the case of horizontal curves, the sign would most likely be relocated further upstream to alert approaching motorists to the fact that horizontal and vertical curves hide potential stopped traffic ahead. Engineering judgment and the actual conditions at each site will determine the best course of action.

Researchers developed a project video on DVD based on the experience of applying project 0-4084 to the implementation sites in Austin and Laredo. The DVD documents site conditions, reveals TxDOT staffs' engineering concerns at each site, shows you how to apply the project 0-4084 curves to determine where to install the recommended BE PREPARED TO STOP sign(s), discusses the different installation methods used at each site, and shows the impact of each implementation.

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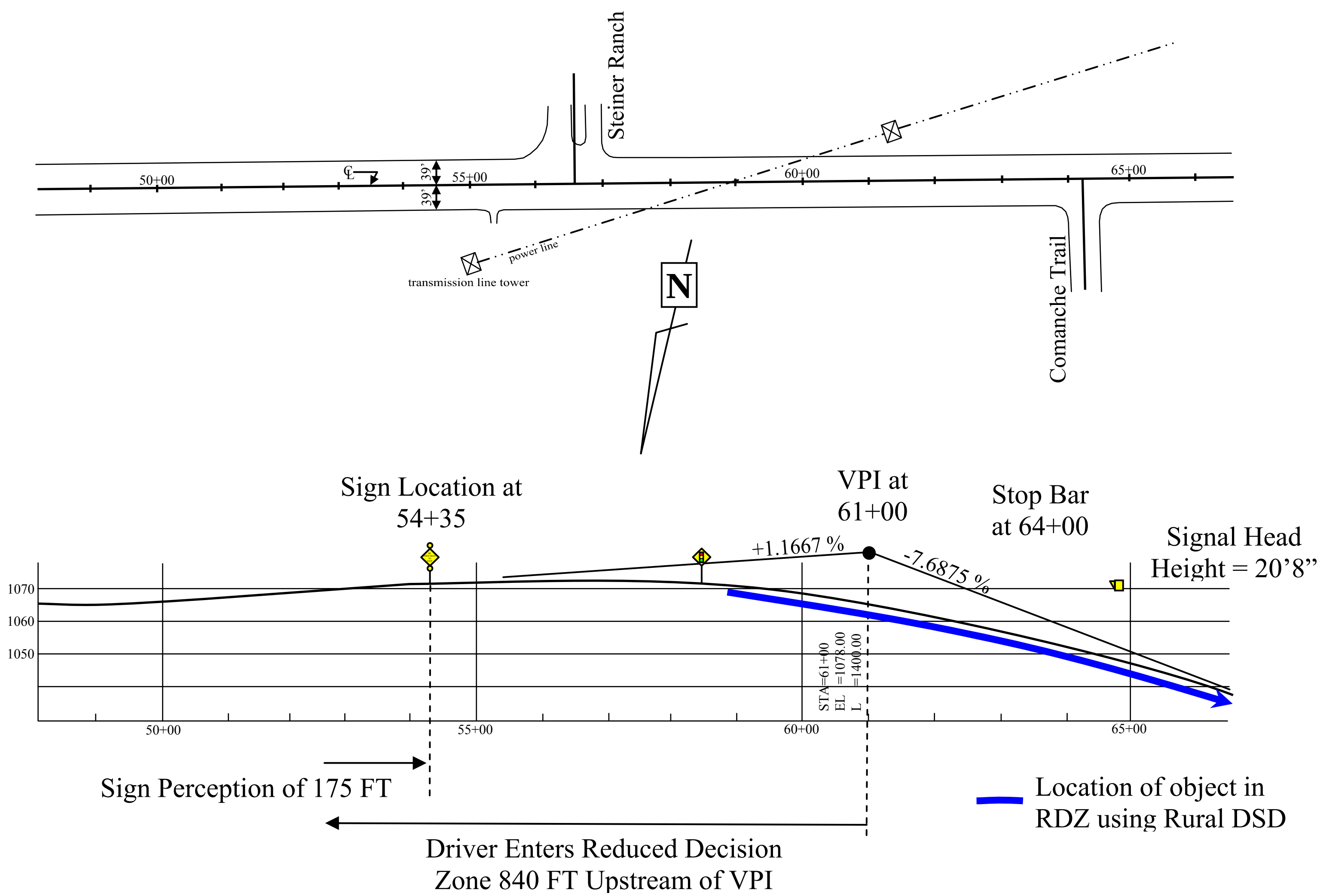
APPENDIX

Austin Implementation Site Details – Westbound RM 620 at Comanche Trail
(Austin District)

Laredo Implementation Site Details – Westbound Loop 20 at Interstate 35
(Laredo District)

Austin Implementation Site Details – Westbound RM 620 at Comanche Trail (Plan and Profile)



Laredo Implementation Site Details – Westbound Loop 20 at Interstate 35 (Plan and Profile)