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Evaluation of End-of-Queue Crash Mitigation Strategies at Flagging Stations on Two-Lane Roads

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Cooperative Research Program

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16. Abstract

The objective of this research project was to identify and evaluate strategies to mitigate end-of-queue crashes at flagging stations on two-lane roads. The research team evaluated the following treatments based on feasibility and advantages of each treatment:

- Install light-emitting diodes (LEDs) or a warning light on the static BE PREPARED TO STOP (BPTS) sign.
- Switch to a portable changeable message sign (PCMS) in lieu of the static BPTS sign.
- Use a portable traffic signal (PTS) in lieu of the flagger at flagging operations.

Researchers collected speed profile data of decelerating vehicles at 18 sites across Texas for the baseline (static BPTS sign) treatment and one or more other treatments. The results did not show any meaningful differences between mean speeds of baseline treatment and the BPTS sign with LED lights, BPTS sign with a warning light, or PCMS. Differences were detected when a PTS was used in lieu of a flagger, but only a limited amount of data was available for analysis. Researchers conducted a benefit-cost analysis, which only included capital costs, operation and routine maintenance costs, and transportation costs, when available. Cost savings of utilizing PTSs in lieu of flaggers were realized in just 2 years. However, more research is needed to determine its effectiveness in reducing end-of-queue crashes at flagger stations.

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DISCLAIMER

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

This report is not intended for construction, bidding, or permit purposes. The engineer (researcher) in charge of the project was LuAnn Theiss, P.E., #95917 (TX).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1: INTRODUCTION

Many maintenance and construction activities on two-lane, two-way highways utilize flagging operations. Previous research has consistently shown that one of the most common types of work zone crashes is rear-end crashes. For flagging operations on two-lane, two-way roads, rear-end crashes typically occur when slowed or stopped vehicles at the end of the queue are struck from behind by an approaching vehicle that fails to recognize the presence of stopped/slowed traffic. This incident occurs despite the presence of a series of static advance warning signs, the use of high-visibility clothing on the flagger, and the use of standard stop/slow paddles, referred to herein as the baseline treatment. Consequently, research was needed to identify and evaluate enhanced temporary traffic control (TTC) solutions to alert approaching vehicles of the presence of stopped traffic near flagger stations.

This report documents the research activities completed by the Texas A&M Transportation Institute (TTI) during the course of a 3-year project for the Texas Department of Transportation (TxDOT). The description of all activities completed is organized as follows in this report:

- *Chapter 2: Assess State of the Practice and Select Treatments*—Researchers reviewed previous research, interviewed TxDOT personnel, and reached out to vendors to identify a list of potential countermeasures to reduce queue-end crashes at work zones. The list was reduced based on a feasibility assessment and analysis of advantages and disadvantages of each potential countermeasure considered. This assessment resulted in the selection of four countermeasures to test.
- *Chapter 3: Investigate Crash Statistics*—Researchers obtained and analyzed crash data to develop descriptive statistics about queue-end work zone crashes on two-lane rural and multilane facilities. Researchers also investigated the potential usefulness of crash data for assessing work zone impacts and treatment effectiveness.
- *Chapter 4: Field Evaluations of Crash Countermeasures*—Researchers evaluated the baseline set of signs that included a static BE PREPARED TO STOP (BPTS) sign along with one or more alternative treatments at 18 sites across Texas. Researchers collected speed and location data of drivers approaching flagger stations. Researchers processed and analyzed the data to determine if the countermeasures had any effects on approaching vehicle speeds.
- *Chapter 5: Benefit-Cost Analysis*—Researchers analyzed the countermeasures and compared the cost for deploying each of them to the cost of the baseline (static BPTS sign) treatment.
- *Chapter 6: Summary, Conclusions, and Recommendations*—Based on the results of the research project, researchers developed recommendations regarding the performance of the countermeasures based on reducing approaching vehicle speeds and improving cost effectiveness.

CHAPTER 2: ASSESS STATE OF THE PRACTICE AND SELECT TREATMENTS

INTRODUCTION

The research team collected and reviewed information pertinent to technologies and strategies that could be used to reduce queue-end crashes at work zones by alerting motorists about slowed or stopped (queued) traffic ahead. Subtasks included a review of literature, discussions with TxDOT district personnel, and outreach to TTC vendors.

LITERATURE REVIEW

The research team used various electronic library search databases and contacts to gather information on existing standards used in Texas and in other states, as well as recent research performed on this topic.

Work Zone Crashes

For many years, Texas has led the nation in the number of fatal work zone crashes and work zone fatalities. Even more disconcerting is the fact that such crashes have been on the rise both in Texas and nationally in recent years. Whereas fatal work zone crashes nationally increased 25.2 percent between 2013 and 2018 (from 536 crashes in 2013 to 673 crashes in 2018), the increase of fatal crashes in Texas work zones was 48.4 percent (from 95 crashes in 2013 to 141 crashes in 2018) (*1*). While fatalities are undoubtedly the most tragic, work zones in Texas also experience significant numbers of injury and property-damage crashes. According to data from TxDOT's Crash Records Information System (CRIS), Texas experienced over 26,000 crashes in work zones statewide in 2019, with approximately 8,000 of them involving fatalities and/or injuries/possible injuries (*2*).

Multiple analyses performed over the years have found that rear-end collisions are the predominant type of work zone crash that occurs and the crash type that most often experiences the largest increase in a work zone (*3*, *4*, *5*, *6*, *7*, *8*, *9*, *10*, *11*, *12*, *13*, *14*). As might be expected, some studies have found that the biggest increase in rear-end crashes occurs in the advance warning area of the work zone (*10*). At least one study has shown that many of the rear-end collisions that occur at freeway and interstate work zones do so at locations where temporary lane closures are in place (*13*). Situations in which traffic has slowed or stopped on facilities that normally do not experience queues appear to be especially problematic. Limited data from I-35 in central Texas showed that when queues occurred at nighttime lane closures with no safety countermeasures implemented, crash risks increased by nearly 500 percent (*14*).

Causes of Work Zone Crashes

The underlying reasons for the occurrence of crashes in work zones has also been the focus of multiple studies. As has been found for traffic crashes overall, driver error is by far the most common factor cited in work zone crashes, particularly driver inattention and speeding (*15*, *16*, *17*, *18*, *19*, *20*). When researchers drill down into the crash report narratives, speed differentials caused by traffic queuing or by work vehicles entering and exiting the traffic stream at much slower speeds than the normal flow of traffic are commonly found to be contributing factors (*6*, *14*, *16*, *21*, *22*, *23*). These incidents occur despite the fact that roadways themselves are designed to always provide sufficient stopping sight distance to hazards, and that TTC layout requirements themselves are based on fundamental principles of positive guidance (*24*, *25*). Consequently, agencies continue to search for ways to enhance standard TTC in a way that reduces traffic crash risks in work zones.

Countermeasures to Mitigate Work Zone Crashes (Particularly Rear-End Collisions)

Various methods aimed at increasing driver attention and reducing speeds in work zones have the overall goal of reducing crash risk and improving safety. These methods include:

- Maintain credibility of advance warning signs.
- Increase advance warning sign conspicuity.
- Add more advance warning signs.
- Add portable changeable message signs (PCMSs).
- Use portable traffic signals (PTSs).
- Use advance (second) flagger.
- Use intelligent transportation system (ITS)–based end-of-queue warning systems.
- Use temporary portable rumble strips (TPRSs).
- Use law enforcement officers (LEOs).
- Use intrusion alarms.

More details about each of these concepts are provided in the following sections.

Maintain Credibility of Advance Warning Signs

Maintaining the credibility of work zone signs used to warn motorists about flagger stations and lane closures is important. When signs are left in place even though the hazard is removed, drivers notice that the information on the signs is not accurate. This observation can lead to reduced work zone signing credibility, which may impact a driver's trust in the sign the next time he or she sees it. In some cases, a driver may notice the advance warning signs but not believe the work is actually occurring, which leaves the driver with less time to respond to a flagger or vehicles already stopped in a queue. Many states, including Texas, require that work zone signs be removed or covered when the information displayed is not applicable to the field conditions (*26*). However, in reality, these informational updates do not always occur. Construction, maintenance, and utility workers need to understand the importance of removing or covering signs and the potentially negative consequences that can stem from signs being left in place when not appropriate.

Increase Advance Warning Sign Conspicuity

The use of flags or flashing warning lights on advance warning signs and drums as outlined in the *Texas Manual on Uniform Traffic Control Devices* and standard sheets is a way to increase the conspicuity and attention-getting value of these devices, and this measure has been in use statewide for several years (*27*).

The specification of orange fluorescent sheeting for certain advance warning signs has been shown to increase driver detection of such signs (*28*, *29*). Their greatest benefit has been noted during periods of reduced visibility, such as at dusk, at dawn, or during rain or fog. Some states, including Texas, allow fluorescent sheeting on advance warning signs. The extent to which these signs are used in the field is not known, but they are typically seen more often on long-term construction projects. For daily maintenance activities, which are performed between 9 a.m. and 4 p.m., little or no impact would be expected.

Some manufacturers now offer advance warning signs with light-emitting diodes (LEDs) embedded into the outline of the sign. These lights, shown in Figure 1, can be set to a steady-burn or flashing mode to attract driver attention (*30*). Although implemented primarily on stop signs and stop/slow paddles to date, the use of LEDs in the outline of other warning signs is also allowed (*27*). The effectiveness of these signs when used to prevent queue-end crashes at flagger stations would be diminished if large trucks blocked approaching motorists' view of the signs, or if the lights themselves were not bright enough to attract attention on a sunny day.

Manufacturers have also developed small, lightweight LED lights that are crashworthy and could be attached to signs (in lieu of embedding) and flashed to attract attention. To date, though, no studies have been performed to assess if and how effective such lighting could be in reducing crash risks at work zones where stopped traffic might be encountered. Furthermore, the ability to utilize such technology on flexible, vinyl roll-up signs that are often used for short-term work is also unknown.

Figure 1. Example of LED Lights Outlining a Traffic Sign to Increase Driver Attention (*30*).

Add More Advance Warning Signs

Many states, including Texas, require additional advance warning signs to be used in cases of extended queues or to relocate the advance warning sign system farther upstream prior to the queued traffic. In Texas, a BPTS (W3-4) warning sign is added to the typical ROAD WORK XX FT (W20-1), ONE LANE ROAD XX FT (W20-4), and Flagger Symbol (W20-7a) warning signs shown in the national *Manual on Uniform Traffic Control Devices* (MUTCD) (*31*, *32*). The California Department of Transportation (Caltrans) also specifies that extra BPTS (W3-4) warning signs be used in cases where queues develop at flagging operations (*33*). Similarly, the New York State Department of Transportation's typical application for short-term flagging operations addresses cases when a traffic queue extends into the advance warning area. A BPTS (W3-4) warning sign can be added to the sign series. In addition, the entire advance warning sign series can be moved to a location prior to the queued traffic (*34*). Meanwhile, the Pennsylvania Department of Transportation (PennDOT) includes provisions for the installment of a BPTS (W3-4) warning sign and/or a LANE CLOSED (W20-5) warning sign in advance of the ROAD WORK (W20-1) warning sign if traffic approaching the work zone is queued beyond all of the advance warning signs (*35*). The Utah Department of Transportation also calls for the use of extra signing upstream of advance warning signs if needed. The sign BE PREPARED TO STOP, X MILES (WS4-3a) is used at 1-mile increments. Additional ROAD WORK AHEAD X MILES (W16-3aP) warning signs are to be used in advance of the farthest upstream traffic backup signing (*36*). One of the challenges associated with using distances, such as X MILES, in conjunction with the static BPTS (W3-4) warning sign is that the distance to the end of the queue may change over time.

Add PCMSs

Another method of increasing driver attention/awareness and speed compliance in work zones is through the use of electronic PCMSs (*37*). PCMSs typically have high contrast values between the lighted message and the black background. Furthermore, the motion involved in switching between phases on two-phase messages also attracts driver attention (*38*).

A few states provide guidelines for the use of PCMSs for flagging operations and lane closures. For example, Caltrans includes provisions for the use of PCMSs in case of traffic backup. In these instances, the manual recommends either that the advance warning signs be moved back in advance of the queuing or that PCMSs be placed in advance of the upstream of queuing (*33*).

The Oregon Department of Transportation (ODOT) also recommends PCMS use for cases when extended queue lengths change frequently and significantly on roads with posted speed limits of 45 mph or higher. In these instances, PCMSs should be placed half a mile upstream of the initial ROAD WORK AHEAD (W20-1) warning sign and display a message alerting drivers to stop half a mile ahead or that there is stopped traffic ahead (*39*). PennDOT also allows for PCMSs to be added upstream of the static warning signs if traffic approaching the work zone is queued beyond all of the advance warning signs (*35*).

While TxDOT does allow for the use of PCMSs at lane closures on freeways, the operational and safety impacts of using them at flagging stations on two-lane roads have not been evaluated. Often, the availability of a PCMS and the sufficient space to deploy it can also be a challenge in some work zones. In addition, whether or not PCMSs should supplement or replace static sign(s) would need to be considered.

Use PTSs

PTSs are self-contained systems that are used to control the movement of vehicles through a one-lane section on a two-lane road (see Figure 2). While not previously identified as a tool for providing queue-end warnings, past research has found that PTSs have many advantages over the traditional flagger method, including:

- Improved visibility—PTSs are less likely to be obscured by traffic already stopped at the signal because at least one signal head is located a minimum of 17 ft above the pavement.
- Improved understanding—Drivers tend to have a greater familiarity and clearer understanding of traffic signals than flagger directions.
- Improved flagger safety—Flaggers are removed from the vehicle conflicts at the transition area. In addition, there is no longer the need to rotate flaggers to prevent fatigue and stress.
- Improved productivity—PTSs allow flaggers to perform other work tasks. This change allows for work to be completed in a timelier manner. In addition, another work crew may be formed in order to accomplish more work at different locations in the same period.

There are some disadvantages associated with using PTSs, which include:

- Increased worker exposure and time during TTC setup/removal because the signal itself must be set up and programmed for site-specific conditions.

- Higher level of expertise needed to ensure that the signal timing implemented is appropriate for conditions.
- Potential for increased work zone intrusions since a flagger is not present to stop non-compliant vehicles.
- Possible malfunctions.
- Maintenance.

Previous research efforts (*40*, *41*, *42*) have primarily focused on using PTSs to improve flagger safety, increase work productivity, and reduce delay to motorists. However, the improved visibility and driver understanding of PTSs may also help reduce queue-end crashes.

Figure 2. Example of a PTS in Texas.

Use Advance (Second) Flagger

Some state agencies are using an advance (second) flagger positioned upstream of the regular flagging station to increase awareness of the flagging operation and potential traffic queue ahead. For example, the Montana Department of Transportation's specifications require that a second flagger be provided when more than 10 vehicles are expected to be stopped at a flagging station at least 50 percent of the time. An additional Flagger Symbol (W20-7a) warning sign is placed between 500 and 1,000 ft ahead of the average end of the stopped vehicle line (*43*, *44*).

The Minnesota Department of Transportation allows for advance flaggers to be used when there is limited sight distance or long traffic queues. In the case of limited sight distance, the advance flagger should stop each vehicle and inform the driver of the situation ahead. If there is a long traffic queue, the advance flagger should move down the vehicle queue and inform each driver of the approximate length of the delay and the reason for the delay (*45*).

The Maine Department of Transportation (MaineDOT) also requires that additional flaggers be used when approaching vehicles do not have sufficient sight distance to a flagger or where there is not sufficient storage space for stopped vehicles. The additional flagger should be located at the rear of the stopped vehicles or at a point where approaching motorists have sufficient stopping sight distance to the rear of the stopped traffic (*46*).

ODOT also has provisions for the use of an advance flagger when an extended queue develops. The provisions require the ROAD WORK AHEAD (W20-1) warning sign to be moved farther upstream and additional BPTS (W3-4) and Flagger Symbol (W20-7a) warning signs to precede the advance flagger. The primary flagger remains in the same location. The advanced flagger and additional warning signs may also be used if the sight distance to the back of the normal queue is limited to less than 675 ft (*39*).

Placing another worker on foot raises some safety concerns, particularly in the advance warning area. For example, the use of a second flagger increases the exposure risk of workers on foot to approaching traffic. Drivers may also confuse the advance flagger with the primary flagger and not know how to properly respond. In addition, using an advance flagger requires an additional worker that could otherwise be performing the work activity.

Use ITS-Based End-of-Queue Warning Systems

End-of-queue warning systems are another example of innovative technology available to help reduce work zone crash risks associated with stopped traffic on multilane roadways. Figure 3 shows the use of this work zone ITS technology for real-time queue warning. Sensors are placed in advance of where queuing is anticipated in order to detect when traffic speeds have dropped below a selected threshold at one or more of the sensor locations, and an interconnected PCMS is activated when a queue is detected to warn approaching motorists of queue presence. Some systems simply display a STOPPED TRAFFIC AHEAD message, whereas other systems calculate and display the approximate location to that queue as part of the message.

End-of-queue warning systems with and without TPRSs have been shown to reduce crashes. Overall, the use of these countermeasures appeared to reduce crashes during periods of queuing and congestion by 53 percent to 60 percent from what would have been expected if the countermeasures had not been used. In addition, the crashes that did occur were significantly less severe when the countermeasures were deployed compared to the no-countermeasure condition. Without the countermeasures deployed, 50 percent of the crashes that occurred when queues were present involved injuries or fatalities; when the treatments were deployed, only 16 percent of the crashes involved injuries or fatalities (*14*, *47*, *48*). Many states, including Texas, are using end-of-queue warning systems at lane closures on multilane roadways (*49, 50*).

Figure 3. Example of Work Zone ITS Queue Warning Technology (*47*).

Use TPRSs

Despite the use of advance warning signs, many drivers involved in work zone crashes are reported to be completely unaware of the work zone. Distraction due to increased electronic device use in vehicles, daydreaming, or "highway hypnosis" are thought to be key contributing factors of many rear-end collisions. As a result, new ways are being sought to "pull" drivers into a more alert state so that they can react more quickly and appropriately to work zone conditions. To get the attention of those drivers who are not looking at the roadway scene due to in-vehicle distractions or who are experiencing highway hypnosis, some agencies are deploying TPRSs in advance of flagger stations and multilane closures, as shown in Figure 4. These devices create vibratory (haptic) and auditory alerts designed to pull motorists out of a distracted state so they concentrate on the driving task.

Various agencies utilize TPRSs during flagging operations on two-lane roads and lane closures on multilane roadways. These agencies include Caltrans (*51*), Colorado Department of Transportation (*52*), Illinois Department of Transportation (if PTS are present) (*53*), Iowa Department of Transportation (Iowa DOT) (*54*), Maine Department of Transportation (*55*), TxDOT (*56*), Virginia Department of Transportation (*57*, *58*), and others (*59*). Research studies out of Alabama (*60*), Canada (*61*), Illinois (*62*), Indiana (*63*), Iowa (*64*), Missouri (*65*), Kansas (*66*), and Texas (*67*) have investigated the effectiveness of TPRSs and supported their use in work zones. Most studies evaluated the effects of TPRSs on speed and found that they have a small effect in terms of speed reductions. In the Texas study at lane closures on I-35, the use of TPRSs reduced crashes by 60 percent when congestion and queues were present (*14*). While many states, including Texas, are using TPRSs at flagger stations, the effects of these devices on driver attention are not well documented in the body of research.

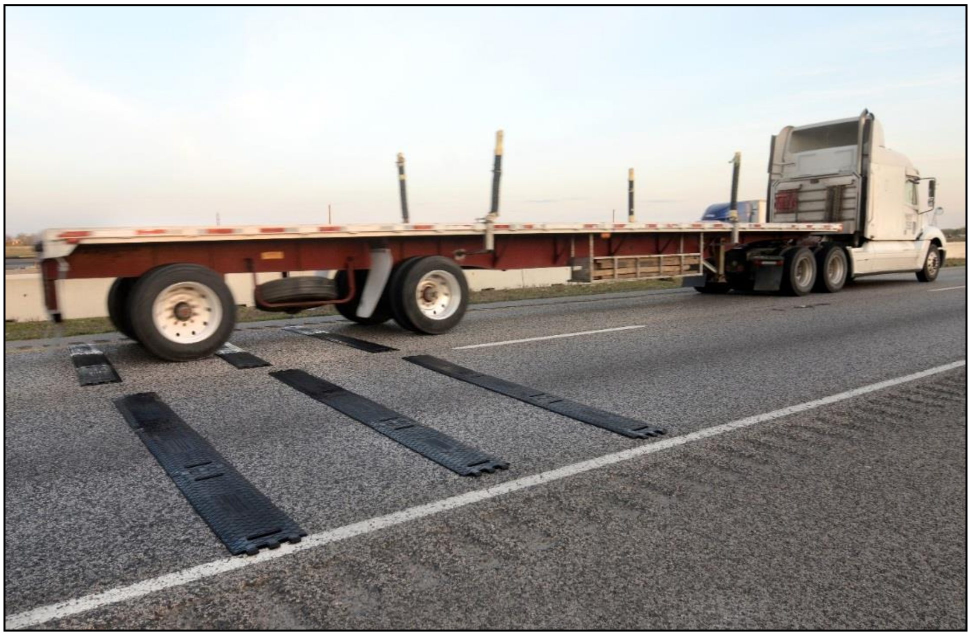


Figure 4. Example of TPRSs Deployed Upstream of an Interstate Lane Closure (*48*).

Use LEOs

The presence of an enforcement vehicle (with or without lights flashing) also attracts driver attention and has been shown to affect driver speeds in some instances (*68*). At least one study has concluded that the presence of enforcement in a work zone significantly reduced crash risk (*69*). Both Caltrans and the Massachusetts Department of Transportation frequently use LEOs in maintenance work zones (*33*, *70*). Enforcement usage in work zones can be challenging due to constraints in available enforcement staffing, lack of good enforcement staging areas, and lack of funding (*71*, *72*).

Use Intrusion Alarms

It is reasonable to assume that work zone intrusion alarms could be adapted to alert drivers who may be on a path to crash into the end of a queue. Efforts to develop an effective means of detecting work zone intrusions and warning workers with an audible alarm have existed since the late 1980s (*73*). Early systems utilized pneumatic tubes or infrared beams placed along the edge of the work space and activated an alarm for workers if a vehicle crossed the tube or broke the beam (*74*). Another design attached the alarm to channelizing devices that activated if the device was knocked over (*75*). However, these systems all suffered from frequent false alarms.

More recently, alarm systems have been designed to detect and track vehicles without the need for the vehicle to cross a line or strike a detection device in order to trigger an alarm. A new directional audible system (DAS) technology has been developed and tested in a mobile work zone field deployment (*76*). However, one study evaluated the accuracy of an alarm with DAS technology and found that the system performed poorly in horizontal curve situations (*77*).

Another example is the Advance Warning and Risk Evasion (AWARE) alarm system, which is being developed by a private-sector company. This system has been adapted for flagger stations on two-lane highways. The flagger station system, shown in Figure 5, consists of a suitcase-sized unit that unfolds and is positioned next to the flagger. Flashing lights and an audible alarm are incorporated into the unit, along with a proprietary advanced radar unit that detects approaching vehicles and tracks them relative to the flagger station. If the system detects that a vehicle is not slowing sufficiently to allow it to stop before reaching the flagger, the lights begin flashing and the alarm sounds to alert the driver in that approaching vehicle and the flagger. Although not commercially available, beta testing of the product is occurring across the country. Anecdotal comments from flaggers are that the technology has a significant benefit in attracting driver attention and reducing crash risks. In addition, the system has been successfully tested in a controlled environment (*78*, *79*). However, no field tests of its effectiveness in real work zones have yet occurred. In addition, this technology currently only tracks approaching vehicles relative to the flagger or work vehicle and has not been adapted to produce end-of-queue alerts.

Note: The images are courtesy of Oldcastle Materials.

Figure 5. Visual and Audible Warning System Under Development for Flagging Operations.

At least one state is actively using a manually operated work zone alarm. Iowa DOT has developed and fabricated a truck-mounted audible attenuator system that includes flashing lights and audible alerts when an errant motorist has been detected. The system, shown in Figure 6, is currently being used in mobile operations, such as applying pavement markings (*80*). It relies on a worker who must monitor all approaching vehicles and assess the risk of their speed and path posing a significant threat to the work operation. Because the alarm operator must view approaching vehicles through the truck's mirrors, the process of judging their speed and path is likely more difficult. While manual alarms, such as simple handheld air horns, could be used in other (non-mobile) operations, there are some implementation challenges associated with using these systems to try to prevent end-of-queue crashes, such as:

- Decrease in availability for the alarm operator to perform other work.
- Uncertainty as to the proper location of the alarm relative to the end of the queue.
- Difficulty in judging speed and path of approaching vehicles to identify real threats.

Figure 6. Iowa DOT Truck-Mounted Audible Attenuator System (*80*).

Existing TxDOT Standards

Researchers reviewed the existing TxDOT standards for work zone traffic control and found that many of these countermeasures have already been implemented by TxDOT. Traffic control plan (TCP) standard sheet (1-2)-18, shown in Figure 7, shows the TTC for one-lane, two-way traffic control (*31*). In this case, a flag tree has been added to the ROAD WORK AHEAD (CW20-1D) warning sign, and an optional BPTS (W3-4) warning sign has been added to the typical application shown in the national MUTCD (*32*). The notes also allow for an additional ROAD WORK AHEAD (CW20-1D) warning sign to be used if advance warning in front of the flagger is less than 1,500 ft.

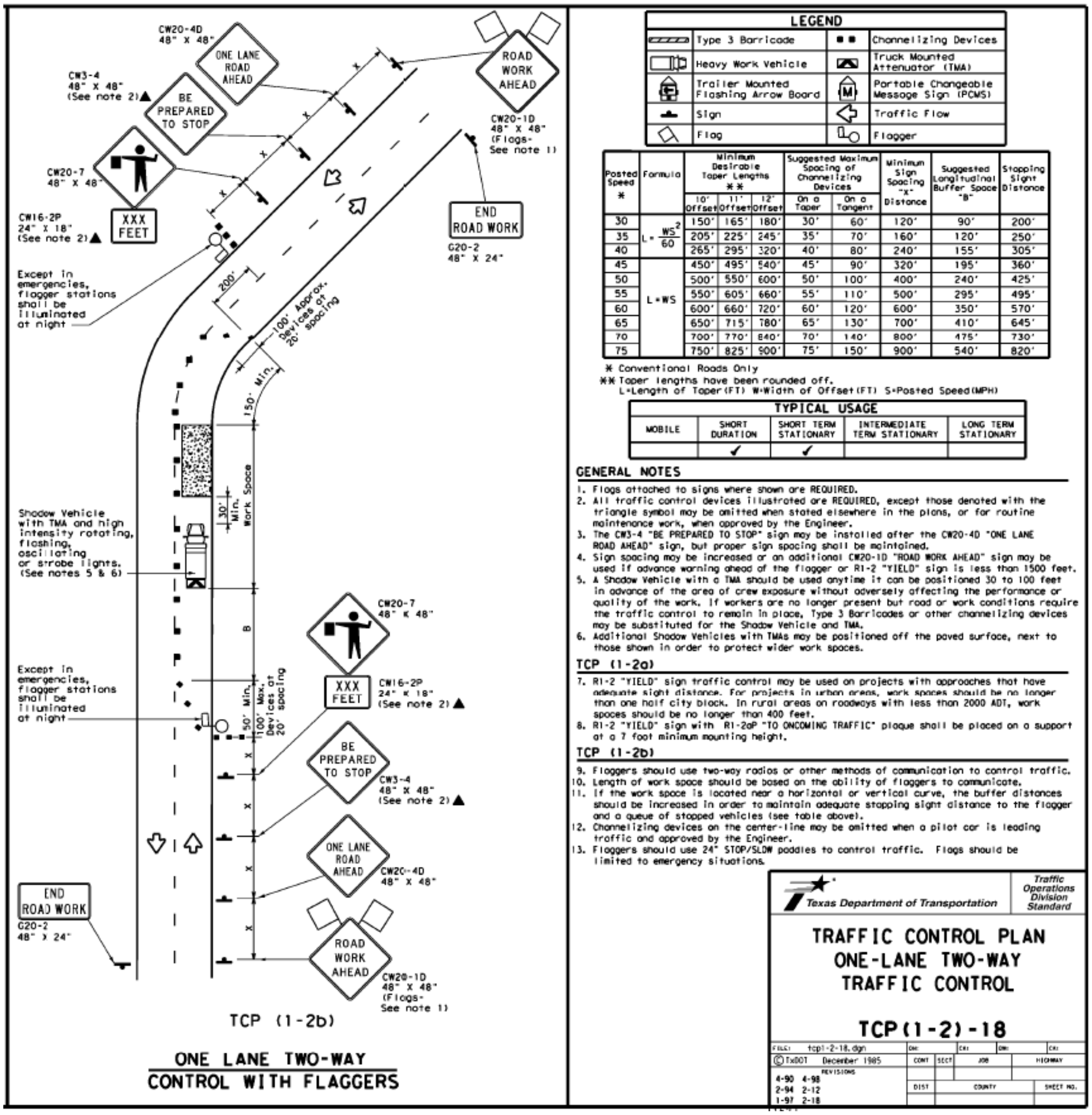


Figure 7. TxDOT TCP (1-2)-18 for One-Lane, Two-Way Traffic Control (*31*).

TxDOT also allows one-lane, two-way operations to be controlled by other means, including automated flagger assistance devices (AFADs) and PTSs. The TTC plan for using AFADs is shown in Figure 8 and includes minor changes to the advance warning signs compared to TCP (1-2)-18 (*81*). In this case, the Flagger Symbol (CW-20-7) warning sign is omitted and a STOP HERE ON RED (R10-6) regulatory sign is added near the AFAD location. Since AFADs are remotely operated, flaggers can position themselves off the roadway, reducing their exposure to moving traffic. However, flaggers cannot leave AFADs unattended because AFADs must be continuously controlled by a flagger (*27*).

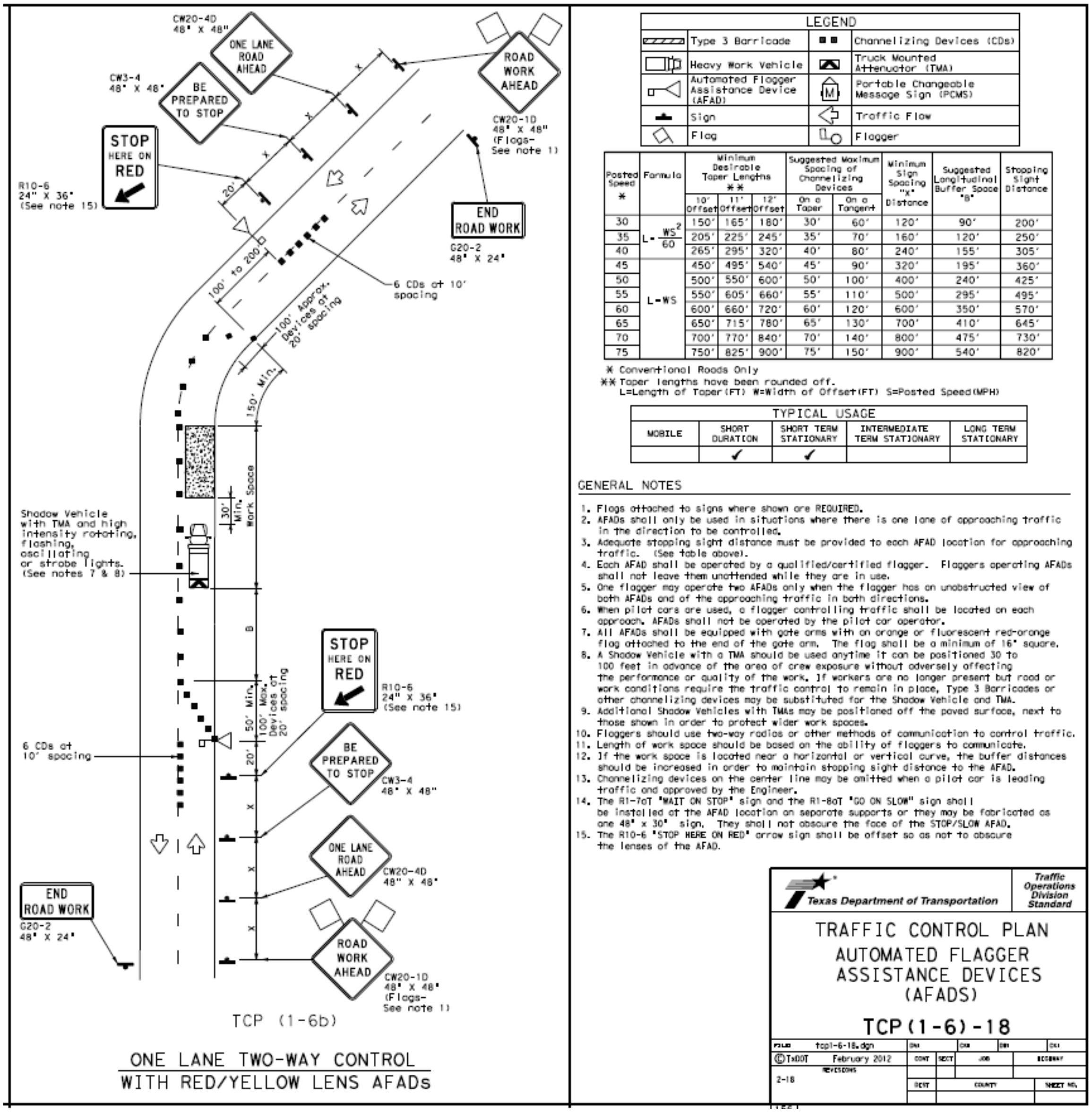


Figure 8. TxDOT TCP (1-6)-18 for One-Lane, Two-Way Traffic Control with Red/Yellow Lens AFADs (*81*).

The TTC plan for using PTSs is shown in Figure 9 and includes more significant changes to the advance warning signs compared to TCP (1-2)-18 (*82*). For example, a DO NOT PASS (R4-1) regulatory sign is added, and the BPTS (CW3-4) warning sign is replaced with a Signal Ahead Symbol (CW3-3) warning sign. Flag trees are included on all three advance warning signs instead of just the ROAD WORK AHEAD (CW20-1D) warning sign, and the STOP HERE ON RED (R10-6) regulatory sign is added near the PTS location. In addition, the flagger is removed from the roadway and replaced with a PTS that has a minimum clearance of 17 ft over the lane of traffic (*83*).

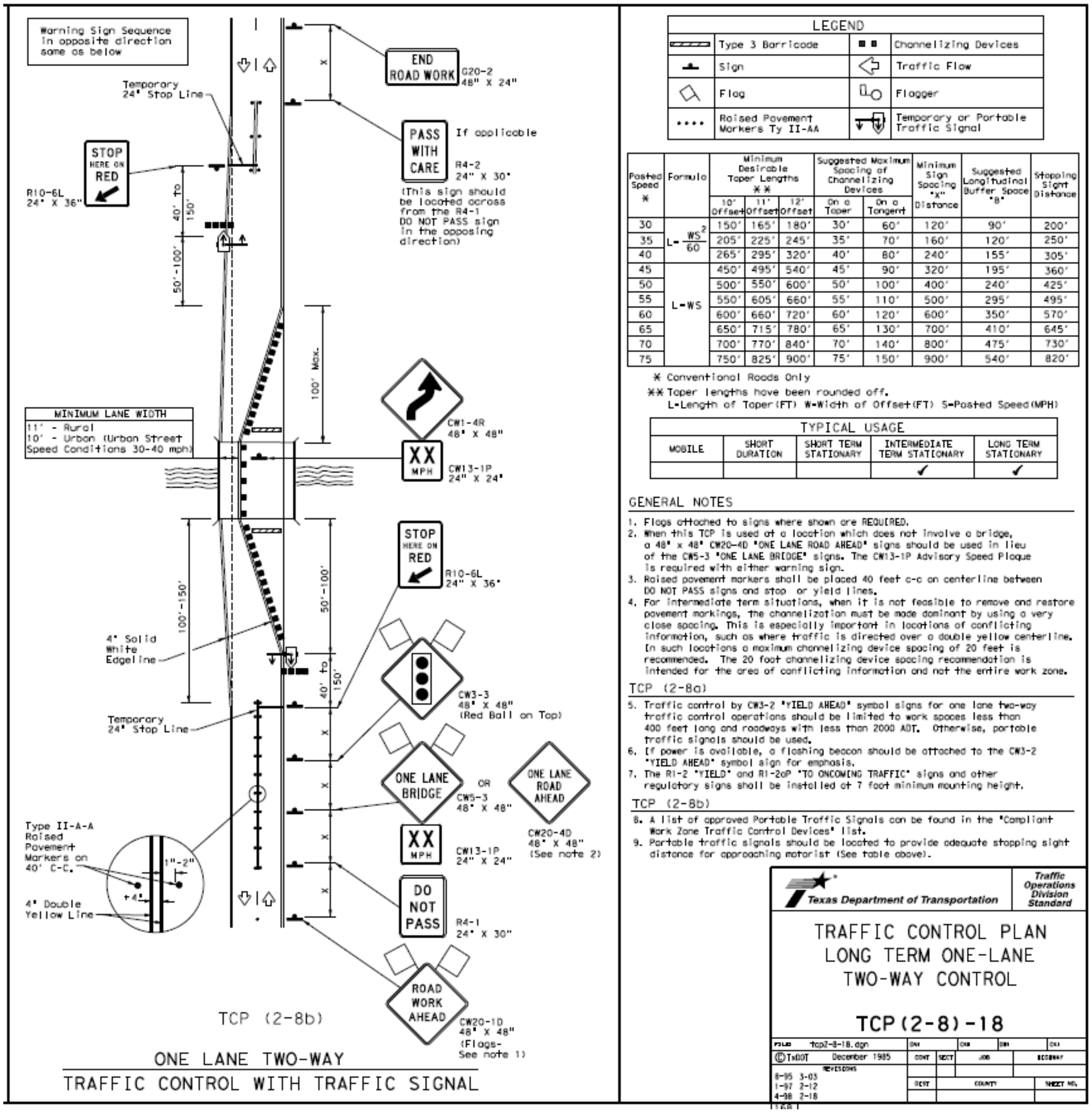


Figure 9. TxDOT TCP (2-8)-18 for One-Lane, Two-Way Traffic Control with Traffic Signal (*82*).

TCP standard sheets (1-4)-18 and (6-1)-18, shown in Figure 10 and Figure 11, respectively, show the TTC for lane closures on conventional roads and freeways (*84*, *85*). For conventional roads, the sheets include a note allowing the ROAD WORK AHEAD (CW20-1D) warning sign to be repeated if the visibility of the work zone is less than 1,500 ft. However, the notes do not address the length of the queue when making warning sign adjustments. For freeways, a two-phase PCMS has been added in the advance warning area to supplement the standard static warning signs.

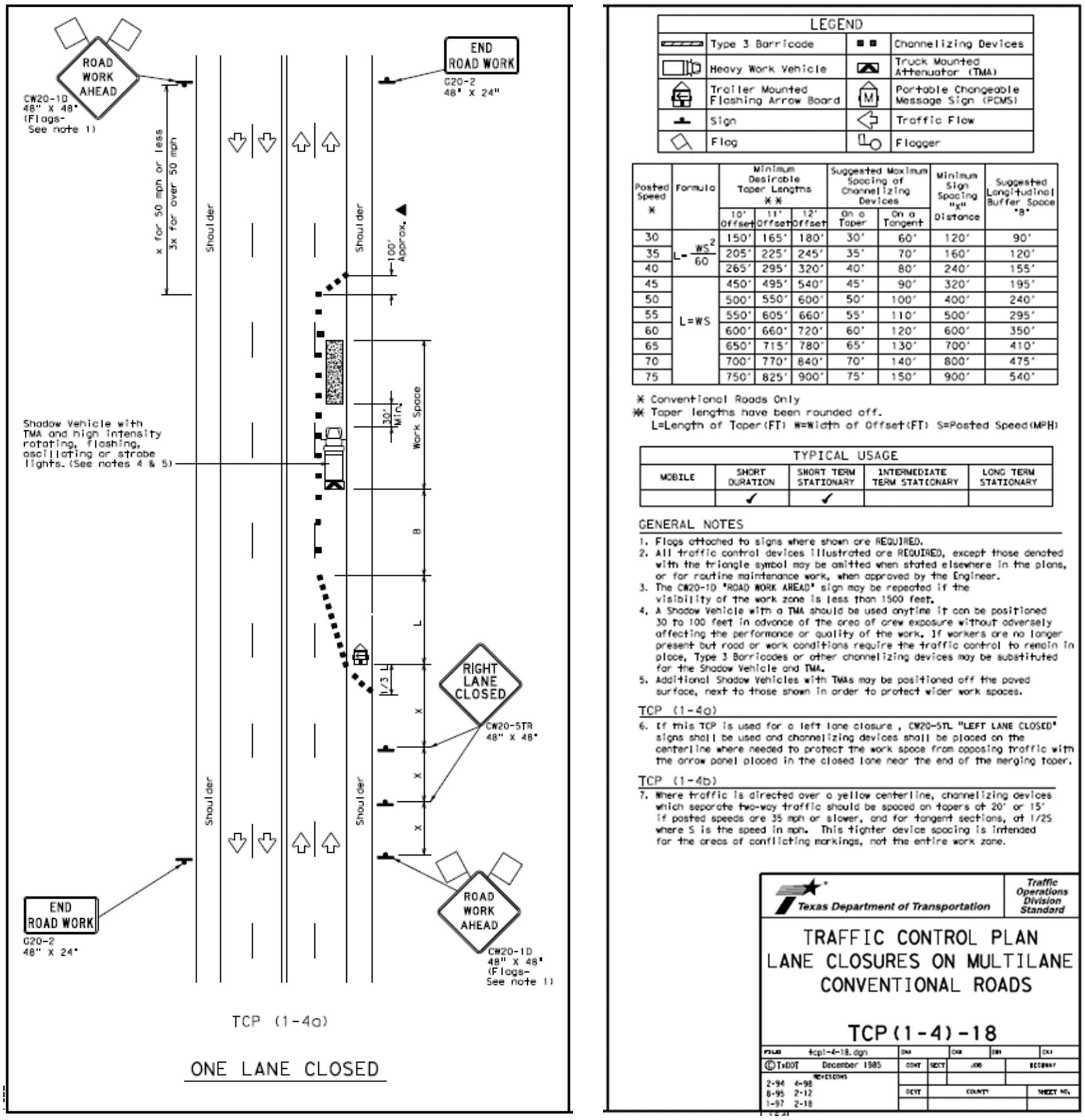


Figure 10. TxDOT TCP (1-4)-18 for Lane Closures on Multilane Conventional Roads (*84*).

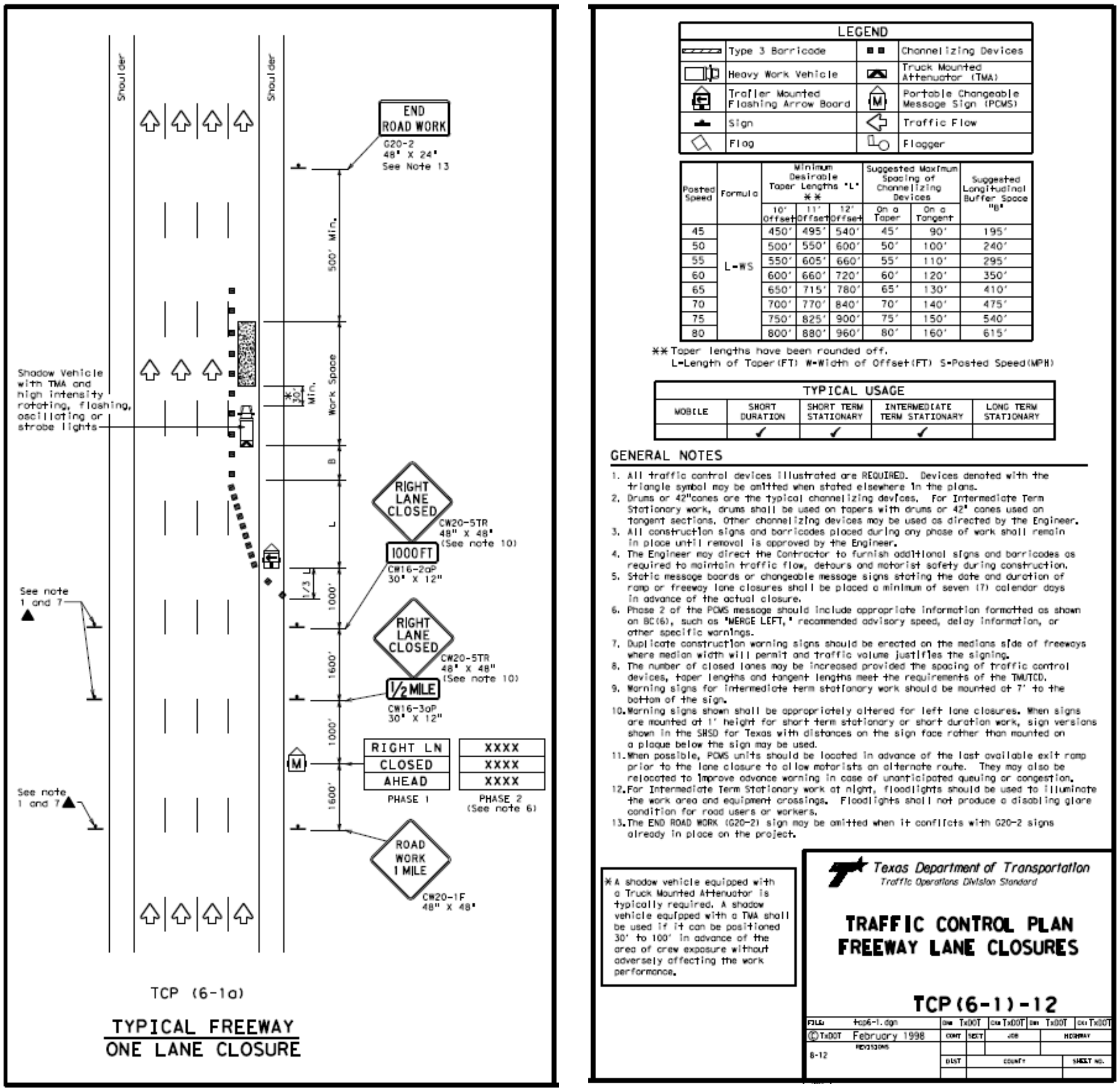


Figure 11. TxDOT TCP (6-1)-12 for Lane Closures on Freeways (*85*).

TxDOT work zone (WZ) standard sheet (RS)-16, shown in Figure 12, specifies the use of temporary rumble strips on both one-lane two-way and lane-closure-on-conventional-roadway (multilane) applications, in conjunction with any TCP (*56*). These rumble strips are required unless certain conditions are present, including horizontal curves, loose gravel, soft or bleeding asphalt, heavily rutted pavements, or unpaved surfaces. As shown in TABLE 1 of Figure 12, rumble strip deployments may consist of one or two arrays, depending on the length of the work area and average daily traffic volume of the roadway.

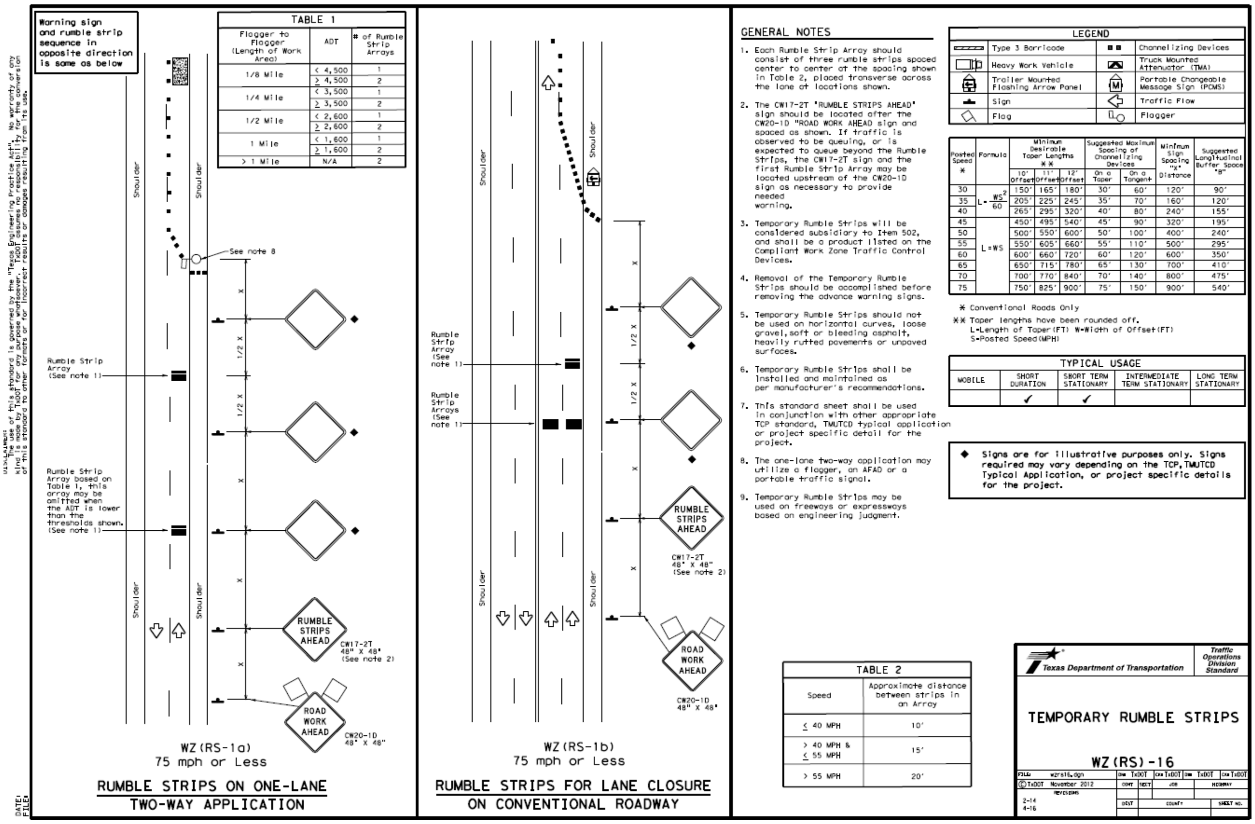


Figure 12. TxDOT WZ (RS)-16 for Temporary Rumble Strips (*56*).

TxDOT WZ(ITS)-19 standard sheets specify the use of temporary queue detection systems for various anticipated queue lengths due to work zones on multilane facilities (*49*, *50*). Figure 13 shows the arrangement when the queue is expected to be 7.5 miles or less (Type 1). A separate sheet shows the arrangement when the queue is expected to be 3.5 miles or less (Type 2). For both types of systems, the standard sheets contain operational guidelines for PCMS messages to be displayed as a function of vehicle speed averages over the previous 5 minutes at each sensor. Messages include ROAD WORK AHEAD, SLOW TRAFFIC AHEAD, SLOW TRAFFIC X MILES, STOPPED TRAFFIC AHEAD, and STOPPED TRAFFIC X MILES. Basic guidelines for the consistent and uniform application of queue detection systems are summarized in TxDOT's *Smart Work Zone Guidelines* (*86*). The guidelines recognize that "very short term projects such as lane closures for only a few hours or days may not justify the expense of a SWZ System unless there are extenuating circumstances."

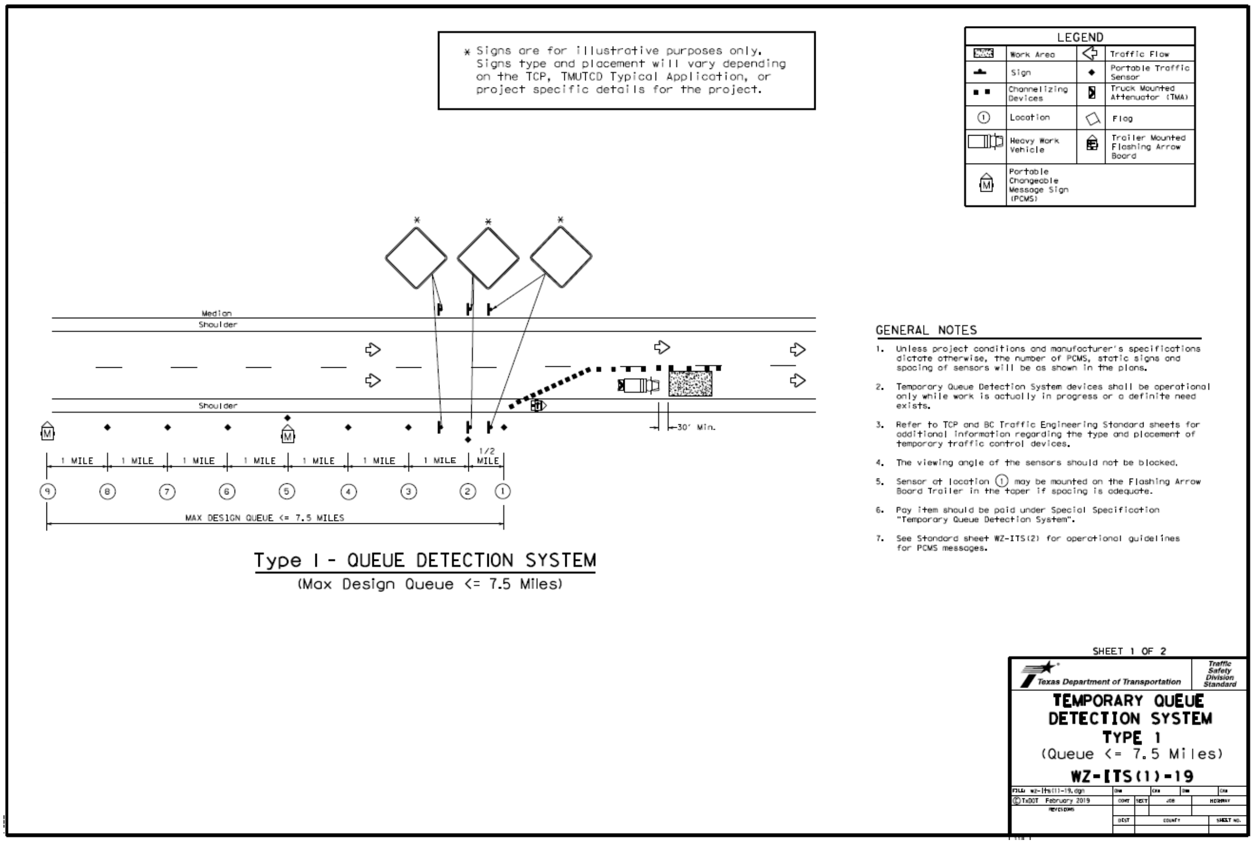


Figure 13. WZ-ITS(1)-19 TxDOT Temporary Queue Detection System—Type 1 (*49*).

DISCUSSIONS WITH TXDOT DISTRICT PERSONNEL

In order to gather information about the state of the practice regarding their experiences with queue-end crashes in work zones, TTI researchers conducted telephone interviews with TxDOT personnel in 21 of the 25 TxDOT districts. These telephone interviews included 30 responses from traffic operations directors, area engineers, and maintenance supervisors. Figure 14 shows the participating districts marked in gray.

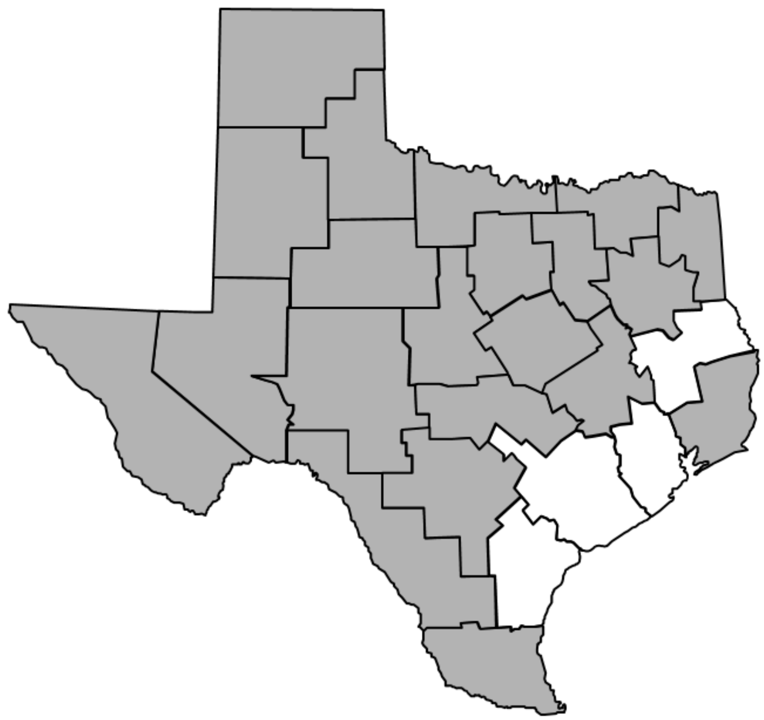


Figure 14. TxDOT District Participation in Telephone Interviews.

Discussion Questions

Researchers used the following questions for the discussions:

<u>TWO-LANE ROADS WITH FLAGGER STATIONS</u>

1. *The TxDOT TCP (1-2)-18 sheet shows a series of 4 advance warning signs at flagger stations on two-lane roads: ROAD WORK AHEAD (with flag tree), ONE LANE ROAD AHEAD, BE PREPARED TO STOP (optional), and the Flagger Symbol sign. Do you always use all of these signs when performing maintenance work? Yes No If No, which signs do you use and what are the conditions under which you would use different signage? Do you always use the BE PREPARED TO STOP sign?*

2. *The minimum spacing of the advance warning signs varies based on the posted speed limit. Do you ever adjust the spacing based on conditions? Yes No If yes, please describe the conditions under which you would adjust the spacing.*

3. *Do you feel that the standard advance warning setup is adequate to warn drivers of the conditions ahead? Yes No If no, please explain why not.*

4. *The TxDOT WZ (RS)-16 sheet shows the placement of rumble strips in the advance warning area at flagger stations. Do you use these at all flagger stations on two-lane roads? Yes No If No, under what conditions do you eliminate them?*

5. *Do you feel like the rumble strips are effective in getting driver attention as they approach the work zone? Yes No Why or why not?*

6. *Do you ever use portable traffic signals instead of flaggers on two lane roads? Yes No If Yes, describe the conditions under which you would opt for the portable traffic signals instead of flaggers.*

7. *Do you think that the use of portable traffic signals helps to increase the visibility of the work zone? Yes No*

8. *Do you ever use portable changeable message signs (PCMS) in the advance warning area of two-lane road flagger stations? Yes No If Yes, what are some typical messages that you use on the PCMS?*

9. *Do you think that PCMS do a good job of warning drivers of the conditions ahead? Yes No Why or why not?*

10. *Do you use any other techniques, methods, or procedures (not shown on the sheets) to alert motorists about slowed or stopped traffic ahead at flagger stations on two-lane roads? Yes No If Yes, please describe.*

11. *Have you ever observed a crash or near miss when traffic is stopped at the work zone? Yes No If Yes, please describe the circumstances (location of crash, vehicles involved, contributing factors, etc.)*

STATIONARY LANE CLOSURES ON MULTI-LANE ROADS

12. *The TxDOT TCP (1-4)-18 sheet shows a series of 3 advance warning signs at single lane closures on conventional multi-lane roads: ROAD WORK AHEAD (with flag tree) and two RIGHT (or LEFT) LANE CLOSED signs. Do you always use all of these signs when performing maintenance work? Yes No If No, which signs do you use and what are the conditions under which you would use different signage (including adding signs)?*

13. *The TxDOT TCP (1-4)-18 sheet shows a series of 4 advance warning signs at double lane closures on conventional multi-lane roads: ROAD WORK AHEAD (with flag tree) and three RIGHT (or LEFT) LANE CLOSED signs. Do you always use all of these signs when performing maintenance work? Yes No If No, which signs do you use and what are the conditions under which you would use different signage (including adding signs)?*

14. *The TxDOT TCP (6-1)-12 sheet shows the setup for double lane closures on freeways: ROAD WORK AHEAD, PCMS with 2 RIGHT LANES CLOSED, static 2 RIGHT LANES CLOSED, and a single static RIGHT LANE CLOSED and an arrow panel at the beginning of each merging taper. Do you always use all of these devices when performing maintenance work on freeways? Yes No If No, which signs do you use and what are the conditions under which you would use different signage (including adding signs)?*

15. *The minimum spacing of the advance warning signs varies based on the posted speed limit. Do you ever adjust the spacing based on conditions? Yes No If yes, please describe the conditions under which you would adjust the spacing.*

16. *The standard shows an arrow panel at the beginning of the merging taper for single lane closures. Do you use the incandescent bulb type, LED type, or something else? Do you think there are any visibility issues with the use of different types of arrow panels? Yes No If yes, please explain.*

17. *Do you feel that the standard advance warning setup for single lane closures on multilane roads is adequate to warn drivers of the conditions ahead? Yes No If no, please explain why not.*

18. *The TxDOT WZ(RS)-16 sheet shows the placement of rumble strips in the advance warning area at lane closures. Do you use these at all single lane closures on multi-lane roads? Yes No If No, under what conditions do you eliminate them?*

19. *Do you use any other techniques, methods, or procedures (not shown on the sheets) to alert motorists about slowed or stopped traffic ahead at lane closures on multi-lane roads? Yes No If Yes, please describe.*

IDEAS FOR RESEARCH

20. *We are looking for ideas that can be included in the evaluation phase of this research. Have you heard of any innovative technologies and/or strategies that could be used to alert motorists about slowed or stopped traffic ahead at flagger stations or lane closures? Yes No If Yes, please describe.*

The results of the district interviews are summarized below.

Two-Lane Roads with Flagger Stations

Question 1 asked the respondents about their use of the advance warning signs shown on TCP 1-2 (18) (see Figure 7) for notifying motorists about the conditions ahead. In addition, the respondents were asked if they ever used different signs in the advance warning area. Results showed that 28 of the 30 respondents (93 percent) used the sign sequence on the standard sheet (including the optional BPTS [CW3-4] warning sign) and added the RUMBLE STRIPS AHEAD (CW-17-2T) warning sign to the setup. Of the remaining two respondents, one indicated that his/her maintenance crews use red/yellow lens AFADs at almost all of the flagger stations. In this case, the sign sequence includes the STOP HERE ON RED (R10-6) regulatory sign in lieu of the Flagger Symbol (CW20-7a) warning sign, in accordance with TCP (1-6)-18 (*78*). In all cases, the BPTS (CW3-4) warning sign was always used. The remaining respondent indicated that he/she contracts all of the traffic control for flagging operations to an outside provider.

Question 2 referred to the table on TCP (1-2)-18 that provides the minimum spacing for signs based on the posted speed limit. Respondents were asked if the spacing of the advance warning signs was ever changed based on field conditions and why it would be changed. Of the 30 respondents, 27 (90 percent) indicated that they sometimes increase the spacing in situations where sight distance is limited, such as in horizontal or vertical curves or when vegetation may limit viewing distance. Additional field conditions warranting the spacing changes included the presence of large trucks and the location of intersections within the advance warning area. Two respondents (7 percent) indicated that they never adjust sign spacing, noting that they prefer to simply move the flagger station to a location where sight distance is not an issue. Again, one respondent indicated that he/she contracts all of the traffic control for flagging operations to an outside provider. In all cases, sign spacing was never reduced below minimums in the table.

Question 3 asked if respondents felt that the standard advance warning setup on TCP (1-2)-18 was adequate to warn drivers of the conditions ahead. Twenty-nine of the 30 respondents (97 percent) indicated that they thought those signs should be sufficient, but 12 respondents (40 percent) mentioned that inattentive or impaired drivers often do not see any of the signs.

The remaining respondent, from a district located in West Texas, said that the signs were not adequate for his/her district given the predominance of large trucks in the traffic mix. As a result, he/she often adds more ROAD WORK AHEAD (CW20-1D) warning signs upstream of the standard signs shown on the TCP sheet. The locations of the additional signs are based on the same spacing as the other signs.

Question 4 referred to the placement of rumble strips in the advance warning area at flagger stations in accordance with the WZ (RS)-16 standard sheet (see Figure 12). Respondents were asked if they used these rumble strips at all flagging operations and what conditions might cause them to eliminate the rumble strips from the advance warning area. Only two respondents indicated that they used rumble strips at all flagging operations without exception. One respondent, who used contracted traffic control, indicated that this decision was left to the traffic control provider. The remaining 27 respondents stated that they used rumble strips at all flagging operations except when the conditions mentioned on the standard sheet were present (i.e., horizontal curves, loose gravel, soft or bleeding asphalt, heavily rutted pavements, or unpaved surfaces). Additional field conditions warranting the elimination of rumble strips included presence of fresh seal coat, proximity of intersections, occurrence of rain, or during short-duration work. One of the 27 respondents indicated that he/she used two rumble strip arrays even when the table on the standard sheet allowed him/her to use only one.

Question 5 asked if respondents felt like the rumble strips were effective in getting drivers' attention as they approach the work zone. Twenty-seven of the 30 respondents (90 percent) answered "yes," but 14 of them indicated that people drive around them, often in the oncoming traffic lane, while three respondents noted that the physical bumps from driving over the rumble strips got the attention of drivers. The remaining three respondents (10 percent) answered "no," noting problems such as increased worker exposure time, irritation to drivers, and the fact that some drivers do not even acknowledge or feel the bumps as they drive over them.

Question 6 asked if respondents ever used PTSs on two-lane roads and what conditions might cause them to opt for signals in lieu of flaggers. Sixteen of the 30 respondents (53 percent) answered "yes," with several (seven respondents) indicating that they use them primarily for long-term jobs where the single, open lane must be left out overnight. One of these 16 respondents explained that he/she used the PTS in the yellow-flashing caution mode to draw attention to the presence of the work zone, while flaggers still controlled the flow of traffic at the flagger stations. In this case, the PTS was located near the ROAD WORK AHEAD (CW20-1D) warning sign. Others indicated that using PTSs frees up the flaggers to perform other tasks. Another respondent indicated that while he/she used PTSs regularly, he/she prefers to use flaggers so that non-compliant vehicles could be reported to the work crew over the radio. This warning would not be possible if a non-compliant vehicle passed an unattended PTS. The remaining 14 respondents answered "no," indicating that they either did not have any PTSs available or could not justify the setup time required for using them on daily flagging operations.

One respondent indicated that there was no manpower benefit to using PTSs since they still needed a person to monitor the PTS station, while two others noted a perceived lack of compliance with unattended signals.

Question 7 asked if respondents felt that the use of PTSs helped to increase the visibility of the work zone. All 16 of the respondents who reported using PTSs in Question 6 answered “yes.” Explanations included that they were taller, can be seen farther away, and can be seen over queues that might include large trucks. Four of the other (non-user) respondents speculated that they probably would increase visibility of the work zone, while the remaining 10 respondents had no opinion.

Question 8 asked if respondents ever used PCMSs in the advance warning area of two-lane road flagger stations, and if so, which messages were displayed. Twenty-four respondents (80 percent) said “yes,” with seven of those noting that they used PCMSs to warn of work to be performed at a future date. Nine respondents stated that they used the PCMS to warn of work currently in progress, using messages such as ROAD WORK AHEAD, FLAGGER AHEAD, EXPECT DELAYS, and BPTS. Three respondents noted the need for PCMSs especially when certain field conditions, such as limited sight distance or loose gravel, might impact the driver’s ability to stop. Four respondents reported using them for both future and current work. The remaining six respondents (20 percent) indicated that they did not use PCMSs at flagging operations.

Question 9 asked if respondents thought that PCMSs do a good job of warning drivers of the conditions ahead. Twenty-four respondents answered “yes,” noting that PCMSs commanded more attention than static signs normally do, and that the LEDs are brighter and thus make the signs more visible. The remaining respondents had no opinion because they did not use them.

Question 10 asked if respondents used any other techniques, methods, or procedures (not shown on the sheets) to alert motorists about slowed or stopped traffic ahead at flagger stations on two-lane roads. Eleven respondents said “yes” and explained their use of any one of the following concepts:

- Use a truck-mounted changeable message sign (TMCMS) on a work vehicle that backs up on the shoulder as the queue grows.
- Use LEO presence with lights at end of queue.
- Use a TxDOT work vehicle or truck-mounted attenuator (TMA) truck with lights on the shoulder to enhance visibility of flagger.
- Use a TMA truck with lights behind flagger station to enhance visibility.
- Use a PTS in yellow-flashing caution mode near a ROAD WORK AHEAD sign.
- Use a PTS instead of a flagger to increase visibility of work operation.
- Use asphalt rumble strips on long-term projects.

Question 11 asked if the respondents had ever observed a crash or near miss when traffic was stopped at the work zone. Sixteen respondents said "yes." When asked about the circumstances surrounding the incidents, 13 cited distracted driving as the cause of the incident, and two stated that the driver was impaired or drowsy. The remaining incident occurred at a flagging operation located approximately 1,500 ft beyond a crest curve. In this case, the queue had extended farther than expected but was still located within the advance warning signs. The driver of a loaded semi-truck came over the hill and was unable to stop quick enough to avoid hitting the end of the queue. While all crashes occurred within the advance warning area, the exact location of the crashes relative to each of the individual warning signs was not known.

Stationary Lane Closures on Multilane Roads

The survey continued with questions about lane closures on multilane roads. Question 12 referenced the TxDOT TCP (1-4)-18 standard sheet shown in Figure 10. Respondents were asked if they always used all of the signs shown in the figure when performing maintenance work. All 30 respondents answered "yes."

Questions 13 and 14 referred to TxDOT TCP (1-4)-18 (Figure 10) and TCP (6-1)-18 (Figure 11) standard sheets that show the series of advance warning signs required for double lane closures on conventional multilane roads and freeways. Twenty-five of the 30 respondents (83 percent) indicated that they either (a) do not have facilities where two lanes can be closed at the same time, or (b) simply did not set up double lane closures. The remaining five respondents indicated that they use the signs shown on the standard sheets.

Question 15 referred to the table on TCP (1-4)-18 that provides the minimum spacing for signs based on the posted speed limit, shown in Figure 10. Respondents were asked if the spacing of the advance warning signs was ever changed based on field conditions and why it would be changed. Of the 30 respondents, 26 (87 percent) indicated that they sometimes increase the spacing in situations where sight distance is limited. One respondent (3 percent) indicated that he/she never adjusts sign spacing, noting that he/she prefers to simply move the merging taper to a location where sight distance is not an issue. Two respondents (7 percent) indicated that there is no need to adjust sign spacing because they have sufficient sight distance on all of their multilane roads. The remaining respondent (3 percent) indicated that only the engineer could modify the sign spacing. In all cases, sign spacing was never reduced below minimums in the table.

Question 16 asked if the arrow boards typically used at the beginning of the merging taper were the conventional incandescent bulb type, the newer LED type, or a mixture of both.
Fifteen respondents (50 percent) answered that both types are in use in their districts.
The remaining responses were split, with seven (23 percent) using the incandescent bulb type and eight (27 percent) using the LED type. Overall, 19 respondents (63 percent) felt that the LED type arrow boards were better because they were brighter, two (7 percent) felt that incandescent

bulbs were brighter in the daytime, and four (13 percent) felt that there was no difference in visibility between the two types of signs. The remaining five participants (17 percent) had no opinion.

Question 17 asked if respondents felt that the standard advance warning setup for multilane roads was adequate to warn drivers of the conditions ahead. Twenty-seven of the 30 respondents (90 percent) indicated that they thought those signs should be sufficient; however, 10 of those respondents mentioned that inattentive and/or impaired drivers often do not see any of the signs. One of the 25 respondents said that the signs were not always adequate when a lengthy queue formed, so he/she often added more signs farther upstream of the required ROAD WORK AHEAD (CW20-1D) warning sign, as noted on the standard sheet. Another respondent felt that the distance from the merging taper to the first sign (e.g., 2,700 ft at 75 mph) may be so long that drivers forget or ignore the sign if they do not immediately see any work activity.

Question 18 referred to the placement of rumble strips in the advance warning area at lane closures in accordance with the WZ (RS)-16 standard sheet, shown in Figure 12. Respondents were asked if they used these rumble strips at all lane closures on multilane roads and what conditions might cause them to eliminate the rumble strips from the advance warning area. Only two respondents (7 percent) indicated that they used rumble strips at all lane closures. The remaining 28 respondents (93 percent) stated that they used rumble strips at all lane closures except when the conditions mentioned on the standard sheet were present (i.e., horizontal curves, loose gravel, soft or bleeding asphalt, heavily rutted pavements, unpaved surfaces, or on interstate highways).

Question 19 asked if respondents used any other techniques, methods, or procedures (not shown on the sheets) to alert motorists about slowed or stopped traffic ahead at lane closures on multilane roads. Fourteen respondents said "yes" and explained their use of any one of the following concepts:

- Use an overhead dynamic message sign (DMS), if available, to warn motorists of work ahead.
- Add a PCMS or TMCMS to extend the advance warning area.
- Use multiple TMA trucks with arrow boards activated on the shoulder in the advance warning area to encourage early merging.
- Use a zipper merge system.
- Use speed feedback trailers to slow motorists as they enter the work zone.
- Use LEO presence with lights at the end of queue.

Ideas for Research

The final survey question (Question 20) asked respondents if they had heard of any innovative technologies or strategies that could be used to alert motorists about slowed or stopped traffic ahead at flagger stations or lane closures that could be included in the evaluation phase of this research. Respondents offered the following suggestions:

- Use higher mounting for flexible roll-up signs.
- Use a dancing inflatable tube man to get attention.
- Use a large umbrella stand at flagger station to make flagger more visible.
- Use flashing LEDs in perimeter of roll-up signs.
- Use flashing beacons on advance warning signs.
- Use a new color of sheeting on advance warning signs.
- Use DON'T TEXT IN WORK ZONE as a required regulatory sign.
- Use a PCMS when end-of-queue warning systems are not justified.
- Use a TMCMS to warn of conditions ahead.
- Use new temporary queue detection system standard sheets.
- Use radio override to warn drivers about stopped traffic.
- Use a cellular signal interrupter in the work zone.
- Use LEO presence with lights at end of queue.
- Use whistles or air horns to warn workers of intrusions.

OUTREACH TO TTC VENDORS

The research team reached out to the Texas Chapter of the American Traffic Safety Services Association to obtain information regarding current and innovative technologies and strategies available to alert motorists of slowed or stopped traffic due to flagging operations or lane closures. Potential solutions include:

- Use LED lights in the flagger's SLOW/STOP paddle.
- Use LED lights in advance warning signs.
- Use an advance PCMS to provide warning information to motorists.
- Use LEO at or upstream of flagger station.
- Use a PTS to make operation more visible farther away.

SUMMARY

Based on the review of literature, discussions with TxDOT personnel, and outreach to TTC vendors, the research team developed a consolidated list of all potential countermeasures. Using a preliminary feasibility assessment, many of the countermeasures were eliminated from further consideration under this research project. Those countermeasures, along with the justification for their exclusion, are shown in Table 1. The remaining countermeasures are listed in Table 2. The researchers identified the potential advantages and disadvantages of each countermeasure with respect to preventing end-of-queue crashes at flagger stations on two-lane roads and lane closures on multilane roads. After careful consideration, the research team recommended the following countermeasures for evaluation:

- Use LEDs on advance warning signs at flagging operations and lane closures.
- Use a PCMS at flagging operations.
- Use TPRSs at flagging operations.
- Use a PTS in lieu of the flagger at flagging operations.

Table 1. Countermeasures Excluded from Further Consideration.

Potential Countermeasure	Application	Reason for Excluding from 0-6998
Maintain credibility of advance warning signs	F, LC	TxDOT standards already address covering and removing of signs when not applicable
Use fluorescent sheeting on advance warning signs	F, LC	TxDOT standards already allow fluorescent sheeting; benefits limited to certain conditions
Use TxDOT work vehicle or TMA truck with lights on shoulder	F, LC	Challenging to implement on roads with no shoulder
Use extra TMA trucks with arrow display on shoulder	LC	Arrow boards on the shoulder must display a caution mode (except at the merging taper)
Use TMA truck with lights behind flagger	F	Presence of TMA truck may obscure driver's view of the flagger; lights may be distracting
Use LEO presence with lights at end of queue	F, LC	LEO may not move as queue length changes; staffing, staging, and funding challenges
Use asphalt rumble strips for long-term projects	F, LC	Project schedule does not allow sufficient time for evaluation
Use overhead DMS warnings	LC	Few districts have DMSs available; impacts difficult to evaluate with driver observations
Use zipper merge system	LC	Designed to address driver behavior after entering queue
Use speed feedback trailers	F, LC	Does not detect or convey message about queue ahead
Use higher mounting for flexible roll-up signs	F, LC	1-ft mounting height is not required; impacts difficult to evaluate with driver observations
Use dancing inflatable tube man	F, LC	Not a traffic control device
Use large umbrella stand at flagger station	F	Not a traffic control device
Use new color of sheeting on warning signs	F, LC	Not MUTCD compliant
Use DON'T TEXT IN WORK ZONE regulatory sign	F, LC	State law already prohibits texting while driving
Use radio override to warn drivers of stopped traffic	F, LC	Not all drivers use car radios; impacts difficult to evaluate with driver observations
Use cellular signal interruption	F, LC	Impacts difficult to evaluate with driver observations
Embed LEDs in flagger paddle	F	Already addressed in TxDOT policy

Note: F = Flagging Operations; LC = Lane Closure; TMA = Truck-Mounted Attenuator; LEO = Law Enforcement Officer; DMS = Dynamic Message Sign; MUTCD = Manual on Uniform Traffic Control Devices; LED = Light-Emitting Diode.

Table 2. Matrix of Potential Countermeasures for Field Evaluations.

Countermeasure	Application	Advantages	Disadvantages
Use LED in or beacons on AWS	F, LC	Lights on signs have attention-getting capabilities	Light intensity may obscure sign legend at night
Use additional AWS	F, LC	Lengthens the advance warning area	May not be noticed by inattentive drivers; increases worker exposure and time to deploy; credibility may be reduced if too far ahead
Use PCMS	F, LC	PCMSs have better attention-getting capability than static signs; provides specific messages	Increases worker exposure and time to deploy; PCMS does not move as queue length changes; limited amount of information can be displayed
Use moving TMCMS on shoulder	F, LC	TMCMSs have better attention-getting capability than static signs; provides specific messages; can move as queue length changes	Work vehicle without attenuator is exposed to traffic; limited amount of information can be displayed; driver and vehicle unavailable to perform other tasks; difficult to implement if no shoulder is available
Use advance flagger	F	Advance flagger can move as queue length changes	Worker on foot is exposed to traffic in areas where unexpected; removes worker from crew; queue may grow faster than worker can move
Use ITS-based EOQ warning system	LC	Provides real-time, specific messages	Increases worker exposure and time to deploy; maintenance; possible malfunctions; higher level of expertise required to implement
Use TPRS	F, LC	Portable; alerts distracted drivers; reduces speeds; effective in LC	Increases worker exposure and time to deploy; driver avoidance; may shift or "walk" depending on traffic mix
Use automated work zone alarm system	F	Alerts workers to errant vehicles; alerts drivers	Alarm needs to be positioned at end of queue; system is not commercially available
Use manual work zone alarm system	F	Worker with alarm can move as queue length changes	Worker on foot is exposed to traffic in areas where unexpected; removes worker from crew; queue may grow faster than worker can move; difficult to consistently identify real threats
Use PTS in caution mode at ROAD WORK AHEAD sign	F	Light may draw attention to the sign	Increases worker exposure and time to deploy; does not provide a specific message
Use PTS in lieu of flagger	F	Improved visibility of operation; easier to understand; flagger can perform other work	Increases worker exposure and time to deploy; maintenance; possible malfunctions; higher level of expertise required to implement; potential for increased intrusions

Note: LED = Light-Emitting Diode; AWS = Advance Warning Sign; F = Flagging Operations; LC = Lane Closure; PCMS = Portable Changeable Message Sign; ITS = Intelligent Transportation System; EOQ = End of Queue; TPRS = Temporary Portable Rumble Strip; PTS = Portable Traffic Signal.

CHAPTER 3: INVESTIGATE CRASH STATISTICS

In order to better understand the issue being studied, researchers obtained and analyzed crash data to develop descriptive statistics about queue-end work zone crashes on two-lane rural and multilane facilities. Researchers also investigated the potential usefulness of crash data for assessing work zone impacts and treatment effectiveness.

DATASETS

Researchers obtained crash data from January 2016 to September 2018 (33 months) from the TxDOT CRIS database (*87*). Researchers only included crashes that occurred on TxDOT roadways and resulted in injury, death, or at least $1,000 in damage in the dataset. Researchers used the Road_Constr_Zone_Fl variable to identify crashes that occurred in or were related to construction, maintenance, or utility work zones. Researchers reviewed the manner of collision categories (FHE_Collsn_ID) and decided that queue-end crashes were best represented by codes 20 (same direction both going straight rear-end) and 22 (same direction one straight one stopped) categories. These crashes are collectively referred to as rear-end crashes herein.

In order to create the two-lane rural roadway dataset, researchers used the following variables:

- Road_Type_ID = 1 (two-lane, two-way).
- Nbr_Of_Lane = 2.
- Rural_Urban_Type_ID = 1 (rural [<5,000]).
- FHE_Collsn_ID = 20 (same direction both going straight rear-end) and 22 (same direction one straight one stopped).

The resulting dataset contained 978 work zone crashes on two-lane rural roadways. Researchers computed descriptive statistics using this dataset. Researchers were also able to extract and develop descriptive statistics for a subset of data specifically associated with flagging operations (Traffic_Cntl_ID = 4) (n = 271). In addition, researchers obtained crash narratives and diagrams associated with 30 crashes that occurred during flagging operations and resulted in a suspected serious injury or death.

Unlike rear-end collisions at work zones on two-lane rural roadways, rear-end work zone crashes on multilane roadways may often be attributed to other conditions besides lane closures (e.g., recurring congestion). There also is not a variable in CRIS that identifies whether or not a lane was closed. Therefore, simple comparisons of crash severities and frequencies for rear-end collisions could not be accomplished for multilane facilities. Instead, researchers chose to use an odds-ratio (OR) analysis to assess the roadway types (Func_Sys_ID) and time periods in which rear-end crashes were overrepresented in work zones, compared to their relative involvement in non-work-zone crashes. Mathematically, this analysis is represented as:

$$Odds\ Ratio\ (OR) = \frac{\left(\frac{\#\ RE\ WZ\ crashes}{\#\ RE\ NWZ\ crashes}\right)}{\left(\frac{\#\ NRE\ WZ\ crashes}{\#\ NRE\ NWZ\ crashes}\right)}$$

where,

RE = rear-end collision.
NRE = non-rear-end collision.
WZ = work zone.
NWZ = non-work-zone.

Researchers computed an OR for each roadway type and time period of interest including:

- Functional classifications:
    - Rural interstate.
    - Rural principal arterial.
    - Urban interstate.
    - Urban principal arterial (other freeway).
    - Urban principal arterial (other).
- Time periods:
    - Night (7:00 p.m. to 5:59 a.m.).
    - AM peak (6:00 a.m. to 8:59 a.m.).
    - Midday (9:00 a.m. to 3:59 p.m.).
    - PM peak (4:00 p.m. to 6:59 p.m.).

The standard error of the OR is simply the square root of the inverse of sample sizes used in the analysis. Finally, researchers estimated the 95th percentile confidence intervals of the ORs to determine which ORs were statistically significant at a 95th percentile level.

$$Standard\ Error\ (SE) = \sqrt{\frac{1}{\#\ RE\ WZ\ crashes} + \frac{1}{\#\ NRE\ NWZ\ crashes} + \frac{1}{\#\ NRE\ WZ\ crashes} + \frac{1}{\#\ RE\ NWZ\ crashes}}$$

$$95th\ Percentile\ Confidence\ Interval = e^{\ln(OR) \mp 1.96 \times SE}$$

Researchers hypothesized that work zone rear-end collisions during peak periods are likely the result of higher volumes and recurrent congestion that already existed at a location even before a work zone was implemented. In contrast, work zone rear-end collisions during off-peak periods may be more indicative of short-term or short-duration lane closures because that is when those closures tend to be performed more often.

In order to create the multilane roadway datasets, researchers used the following variables:

- Road_Type_ID = 2 (four or more lanes, divided) and 3 (four or more lanes, undivided).
- Nbr_Of_Lane ≥ 4.
- FHE_ Collsn_ID = 20 (same direction both going straight rear-end) and 22 (same direction one straight one stopped).

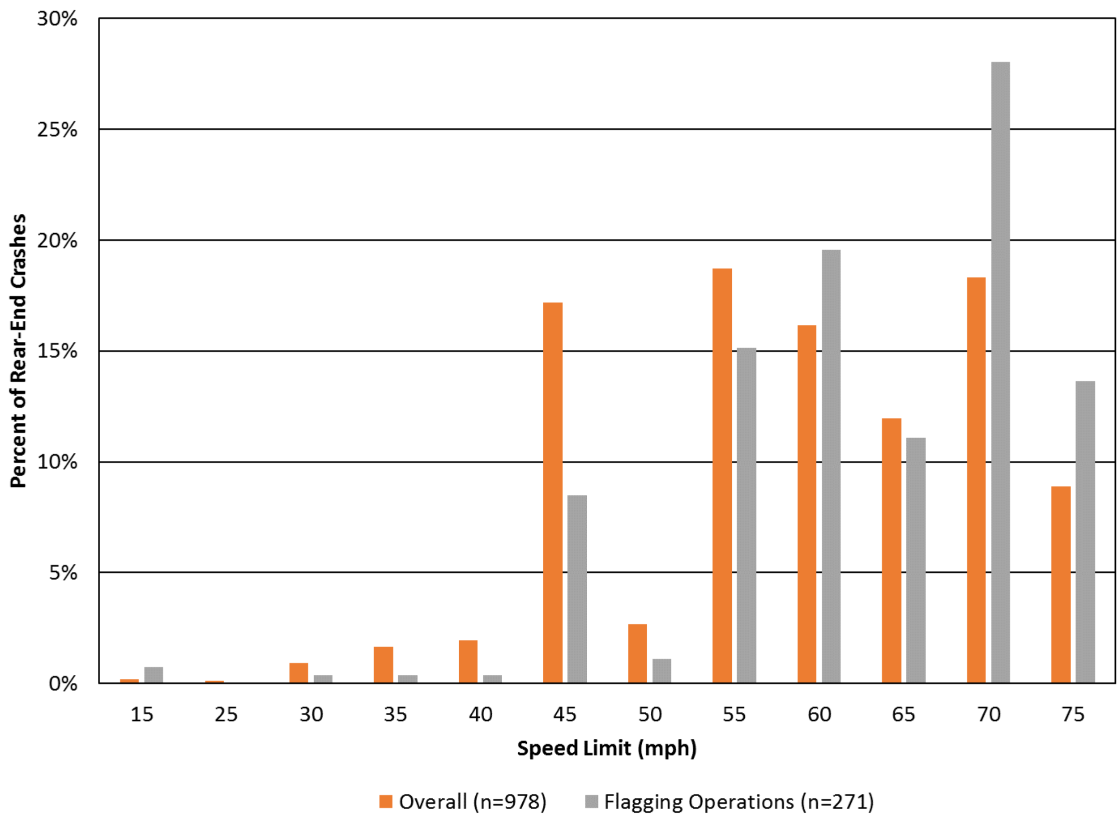
Researchers created four multilane roadway datasets from which to extract data to compute the ORs:

- Work zone crashes, all collision types (n = 44,362).
- Work zone crashes, collision types 20 and 23 (n = 19,342).
- Non-work-zone crashes, all collision types (n = 583,124).
- Non-work-zone crashes, collision types 20 and 23 (n = 219,738).

RESULTS

Two-Lane Rural Roadways

Figure 15 displays the percent of rear-end work zone crashes that occurred on two-lane rural roadways and those specifically associated with flagging operations, both stratified by speed limit. As expected, most of the rear-end crashes for both datasets occurred on roadways with speed limits greater than 50 mph (74 percent overall and 87 percent flagging operations). At least 90 percent of the rear-end crashes occurred during daytime operations (90 percent overall and 99 percent for flagging operations), and more than 90 percent happened when the pavement surface was dry (94 percent overall and 96 percent for flagging operations).



Note: The speed limit information was blank or unknown for 1 percent of the crashes in each dataset.

Figure 15. Rear-End Work Zone Crashes on Two-Lane Rural Roadways by Speed Limit.

Table 3 shows the severity of the rear-end work zone crashes in both datasets. Interestingly, the rear-end crashes associated specifically with flagging operations tended to be more severe. Table 4 contains the top five primary contributing factors for rear-end crashes on two-lane rural roadways. The findings were similar for both datasets. Three-quarters of the rear-end crashes were attributed to a driver's failure to control speed or operating the vehicle at an unsafe speed. Crash records indicate that approximately 10 percent of the rear-end crashes were cited as being caused by driver inattention. Additional crashes may have also been the result of driver inattention or distraction but were not cited as such in the crash database. Following too closely, driver distraction (including cell phone use), and disregarding a construction warning sign were the primary factors identified in less than 5 percent of the rear-end crashes.

Table 3. Severity of Rear-End Work Zone Crashes on Two-Lane Rural Roadways.

Crash Severity	Percent of All Rear-End Work Zone Crashes	Percent of Flagging Rear-End Work Zone Crashes
Killed	1%	3%
Suspected serious injury	5%	8%
Non-incapacitating injury	14%	18%
Possible injury	19%	21%
Not injured	60%	49%
Unknown	<1%	<1%
Total	100%	100%

Table 4. Primary Contributing Factors for Rear-End Work Zone Crashes on Two-Lane Rural Roadways.

Primary Contributing Factors	Percent of All Rear-End Work Zone Crashes	Percent of Flagging Rear-End Work Zone Crashes
Failure to control speed or unsafe speed	76%	76%
Driver inattention	10%	11%
Short following distance	4%	3%
Driver distraction (including cell phone)	2%	3%
Disregard of construction warning sign	1%	2%
Total	93%	95%

Researchers verified that 29 out of the 30 suspected serious injury or death rear-end work zone crashes on two-lane roadways for which researchers obtained crash narratives and diagrams were the result of queue-end collisions at flagging operations with human flaggers. One of the rear-end crashes occurred within the one-lane section and thus was removed from further review. In 14 percent of the rear-end crashes, the at-fault driver was under the influence of alcohol or drugs. In another 7 percent of the rear-end crashes, the at-fault driver fell asleep. On average, two vehicles were in the queue prior to the crash and three vehicles were involved in the crash. The minimum number of vehicles in the queue during a rear-end collision was one, and the maximum number of vehicles in the queue was six. However, for two crashes, the narrative noted that additional vehicles were in the queue but not involved with the crash.

Unexpectedly, 52 percent of the rear-end crashes involved a commercial motor vehicle (CMV). In 67 percent of those crashes, a CMV stopped or coming to a stop was hit. In 47 percent of these crashes, a CMV was at fault. These two percentages do not equal 100 because in two crashes, a vehicle that was hit and the at-fault vehicle were both CMVs. The involvement of CMVs in rear-end crashes at flagging operations could be one reason those crashes were found to be more severe (see Table 3).

Not all of the work zone crashes on two-lane roadways were queue-end crashes. In addition, some lane closures on two-lane roadways used PTSs. It was not clear from the sample whether crashes at these types of work zones would be coded as flagger or signal control. More importantly, the crash narratives and diagrams provided limited to no information about the TTC devices present. This information is critical to evaluating treatment effectiveness. Although in some cases this information may have been documented at the district in project diaries, the manual collection of this type of information was outside the scope and budget of this project. In addition, many flagging operations on two-lane rural roadways are conducted by maintenance crews, and records detailing the TTC are not kept. Therefore, researchers did not recommend the use of CRIS data alone to evaluate treatments that have previously been implemented by TxDOT to improve the safety of flagging operations on two-lane rural roadways (e.g., PTSs, portable rumble strips, etc.).

Multilane Roadways

Overall, 44 percent of the work zone crashes on multilane roadways in Texas were rear-end crashes. Comparatively, 38 percent of the non-work-zone crashes on multilane roadways were rear-end crashes, supporting past research that suggests that rear-end collisions tend to increase more significantly in work zones. Table 5 contains the computed ORs for rear-end work zone crashes by functional classification and time period. Asterisks indicate those ORs that are statistically significant at a 95th percentile level.

Table 5. Odds Ratio of Rear-End Work Zone Crashes by Functional Classification and Time Period.

	Rural Interstate	Rural Principal Arterial	Urban Interstate	Urban Principal Arterial (Other Freeway)	Urban Principal Arterial (Other)
Night	1.2* (0.085)	1.2 (0.164)	1.3* (0.029)	1.4* (0.039)	1.0 (0.057)
AM Peak	1.9* (0.128)	1.0 (0.180)	1.0 (0.039)	1.2* (0.051)	1.2* (0.067)
Midday	3.0* (0.056)	2.2* (0.087)	1.2* (0.024)	1.3* (0.033)	1.2* (0.037)
PM Peak	2.7* (0.085)	2.1* (0.117)	1.1 (0.035)	1.2* (0.047)	1.2* (0.054)
Total All Periods	2.4* (0.038)	1.8* (0.058)	1.1* (0.015)	1.2* (0.020)	1.1* (0.023)

Note: Values are odds ratio (standard error). ≤ 1 percent of work zone crashes on each of the following roadway types: rural minor arterial, rural major collector, rural minor collector, urban minor arterial, and urban collector.
* Significant at a 95th percentile level.

Rear-end crashes in work zones were overrepresented in most of the categories (i.e., ORs significantly greater than 1.0). Rural interstates had the highest overrepresentation of rear-end work zone crashes across all time periods except at night. This finding is not surprising since rural interstates typically have high-speed, free-flow traffic (not expecting queues) and lane closures are typically not limited to nighttime hours.

On urban interstates, rear-end work zone crashes were overrepresented at night and during midday. These are times when work zone lane closures would most likely occur. Still, overrepresentation is also evident in the peak periods for urban freeways and other principal arterials and is similar to the ORs during the off-peak midday period. Consequently, the use of the OR analysis does not appear to provide much insight into queue-end crashes on multilane facilities. It is likely that some of the increased rear-end collisions are indeed due to queues forming because of lane closures or other work activities. However, it is also possible that other contributors to those collisions may be occurring as well. Disabled vehicles unable to move out of a travel lane due to the loss of emergency shoulders, unsafe maneuvers of work vehicles pulling in and out of a work space, or confusion by certain motorists leading to their sharp reduction in speed that creates high-speed differentials may also be present in the data. Unfortunately, it is not possible to extract these other potential contributors from the data without accessing and reviewing the collision diagrams and crash narratives for the rear-end work zone collisions on these facilities, which was beyond the scope and budget for this project.

CHAPTER 4: FIELD EVALUATIONS OF CRASH COUNTERMEASURES

INTRODUCTION

Based on the selected countermeasures shown in Table 2, results of the crash analysis, and feedback from TxDOT, the researchers focused the evaluations on flagging operations on two-lane roadways. Researchers performed field evaluations to assess the safety and operational effectiveness of selected experimental treatments in real Texas work zones. These field evaluations were accomplished by identifying the treatments, developing a methodology, coordinating with TxDOT maintenance offices to collect the data, reducing and analyzing the data, and presenting the results.

TREATMENT IDENTIFICATION

The base treatment for the field studies was the one-lane, two-way traffic control shown in TxDOT standard sheet TCP (1-2)-18 (see Figure 7) (*31*). The ROAD WORK AHEAD (CW20-1D), ONE LANE ROAD AHEAD (CW20-4D), and Flagger Symbol (CW20-7) signs are required. In addition, TxDOT crews and TTC providers generally use the optional BPTS (CW3-4) sign. Of all the signs in the advance warning sign series, the BPTS sign was thought to contain the message that should be emphasized in this research addressing end-of-queue crashes.

Based on the information documented in previous chapters and discussions with the project panel, the following experimental treatments for the field studies were selected:

- Substitute a PCMS for the BPTS sign.
- Add flashing lights to an advance warning sign.
- Use a PTS in lieu of a flagger.

PCMS Treatments

For the PCMS treatments, the flexible roll-up BPTS sign was removed and replaced with a PCMS. The first PCMS treatment included displaying a flashing BPTS message. The second PCMS treatment included displaying a flashing STOPPED TRAFFIC AHEAD message. An example is shown in Figure 16.

Figure 16. PCMS Displaying STOPPED TRAFFIC AHEAD Message.

BPTS Sign with Flashing Light Treatments

For maintenance work, TxDOT crews and TTC providers typically use flexible roll-up advance warning signs at 1-ft mounting height for daily work operations. Researchers purchased several flexible roll-up BPTS signs and used temporary sign stands that were available from the TTI inventory. The signs conformed to TxDOT DMS-8310, Flexible Roll-Up Reflective Signs (*88*), and the sign stands were included in the Compliant Work Zone Traffic Control Devices List (*89*). The researchers identified two methods by which flashing lights could be added to a BPTS sign: (a) attach a warning light near the top of the sign, and (b) add LED lights to the border of the sign.

Warning Lights

Warning lights are readily available from many different suppliers and are typically powered by a small solar panel or by batteries contained in the plastic housing. The researchers purchased several flashing warning lights and attached them to the BPTS signs as shown in Figure 17.

Figure 17. Flashing Warning Light Added to BPTS Sign.

LED Lights in the Border of the Sign

The researchers contacted vendors and suppliers to identify readily available flexible roll-up advance warning signs that had LED lights in the border of the sign. Unfortunately, at the time of this research, such off-the-shelf products did not exist. Therefore, researchers purchased LED lights in prefabricated strips that could be mounted on the border of the fabricated BPTS signs. A corrugated plastic substrate was added to the flexible roll-up sign in order to facilitate the addition of the LED light strips. The assembled sign is shown in Figure 18. Even on the brightest setting, the LED lights did not seem very bright (relative to the ambient sunlight conditions) when deployed in the field.

Figure 18. LED Lights Added to the Border of a BPTS Sign.

PTS Treatment

TCP (2-8)-18 for One-Lane Two-Way Traffic Control with Traffic Signal (*82*) is typically used more frequently for long-term traffic control. Consequently, it was challenging to find TxDOT maintenance crews using PTSs as part of their daily maintenance work. Many TxDOT maintenance offices do not have PTSs in their inventory to complete TxDOT's planned maintenance work, which changes locations frequently. Thus, the researchers turned to TxDOT area engineers to identify construction jobs where PTSs were in use and where the researchers could collect data. One of the PTS deployments is shown in Figure 19.

Figure 19. PTS Deployed in TxDOT Construction Work Zone.

METHODOLOGY

Researchers developed an experimental plan for the field evaluation of each of the treatments, including the identification of conditions and factors being targeted, appropriate measures of effectiveness, and study methodology. The experimental plan focused on capturing driver behaviors, such as speed, location, stopping position, and hard braking, with the different treatments deployed.

DATA COLLECTION

Researchers contacted TxDOT personnel in several districts to identify work zone locations that would be suitable for the data collection effort (i.e., work on two-lane roads using flaggers for the TTC). Once the work zone locations were selected, researchers coordinated with traffic control providers and TxDOT personnel to deploy the desired treatment(s) at each site.

The conditions were documented at each site using a standardized data collection form.
The recorded data included the roadway number, direction, location, and other conditions such as speed limit, geometric features, cross section, lane widths, shoulder presence, etc. Researchers also noted weather conditions, work description, and global positioning system (GPS) locations

of the TTC elements including the flagger and the data collection vehicle. The times that data collection for each treatment began and ended were also recorded.

Once the treatment being evaluated was set up, the researchers parked their TTI fleet vehicle off the roadway in the right of way in such a manner that approaching vehicles could be seen. The position of the data collection vehicle was independently selected at each site based on field conditions (primarily roadway geometry and sight distance), and thus the location of the data collection vehicle relative to the flagger station varied by site. Light detection and ranging (LIDAR) equipment was used to capture continuous speeds and corresponding distances to create speed profiles of arriving vehicles, as shown in Figure 20.

Figure 20. LIDAR Speed Profile Data Collection.

The LIDAR equipment does not register speeds below 10 mph. As each vehicle stopped, its position in the queue and distance from the data collection vehicle were manually recorded. These distances were measured using a rangefinder. A video camera mounted inside the data collection vehicle was used to capture video of arriving vehicles.

Table 6 shows a summary of the data collection sites, treatments evaluated, and number of vehicles observed at each site. Overall, 2,025 vehicle observations were obtained across the 18 study sites. Researchers were able to collect data for at least two treatments, the baseline (static BPTS sign) and another treatment at most of the sites. At sites 11 and 14, researchers were not able to obtain speed profile data due to the presence of roadway curvature upstream of the flagging station. At site 11, the collection of speed profiles was not possible due to the presence of vertical curves and inability to view the flagger from the observation vehicle, which was parked 366 ft from the Flagger Symbol sign. At site 14, researchers could not view the human flagger from their parked position, which was 285 ft from the Flagger Symbol sign, and the flagger moved farther north while the data collection was in progress. Therefore, the researchers collected a limited amount of spot speed data for the baseline (static BPTS sign) and the two treatments for which the BPTS sign was equipped with either LED lights or the flashing warning light. At site 15, researchers attempted to collect baseline data but found that a sharp horizontal curve located upstream of the flagger station caused arriving vehicles to alter their speeds before reaching the data collection area, rendering those data unusable for the research. At sites 16 and 17, researchers were only able to collect speed profile data when the PTS was used because no flagging was being performed at these sites. With no other data for comparison (i.e., site 15), data from sites 16 and 17 were not used in the analysis.

Table 6. Summary of Data Collection Effort.

Site #	Roadway	District	Treatments						# of Vehicles Observed
			Baseline	PCMS (BPTS)	PCMS (STA)	Warning Light	LED Lights	PTS	
1	FM 3098	Atlanta	X	X					85
2	FM 3098	Atlanta	X		X				41
3	FM 3129	Atlanta	X	X	X				143
4	FM 3129	Atlanta	X	X	X				88
5	FM 8	Fort Worth	X	X					89
6	FM 8	Fort Worth	X	X	X				118
7	FM 8	Fort Worth	X	X	X				189
8	FM 3090	Bryan	X	X					32
9	FM 3062	Tyler	X			X	X		236
10	FM 3062	Tyler	X			X	X		304
11	FM 316	Tyler	X			X	X		176
12	FM 2038	Bryan	X			X	X		44
13	RR 165	Austin	X			X			111
14	RR 165	Austin	X				X		74
15	FM 186	Laredo	X						77
16	FM 133	Laredo						X	56
17	FM 133	Laredo						X	55
18	SH 85	San Antonio	X					X	107

Note: STA = STOPPED TRAFFIC AHEAD.

DATA REDUCTION AND ANALYSIS

First, the GPS data collected at each site location were mapped so that the researchers could determine the position of the flagger station relative to the data collection vehicle. The research team reviewed the vehicle speed profiles for each treatment, an example of which is shown in Figure 21. Due to the LIDAR’s inability to capture speeds below 10 mph, researchers used the threshold of 15 mph as the lower range of speeds for comparison purposes. The position where each vehicle reached a speed of 15 mph was called position zero and was specific to each vehicle based on that vehicle’s position in the queue. The examination of vehicle speed profiles showed that drivers typically do not slow down significantly until they reach a distance of about 400 ft upstream of their ultimate stopping position (position zero). Therefore, researchers used the vehicle speeds at this distance (400 ft) as the most upstream location where speeds would be compared across treatments. Additional locations for speed comparisons were then selected at distances of 300 ft, 200 ft, and 100 ft from position zero. Depending on the deceleration profile of each vehicle, some interpolation of speeds was required for those specific measurement locations. For each position of interest, the average speed and variance were computed.

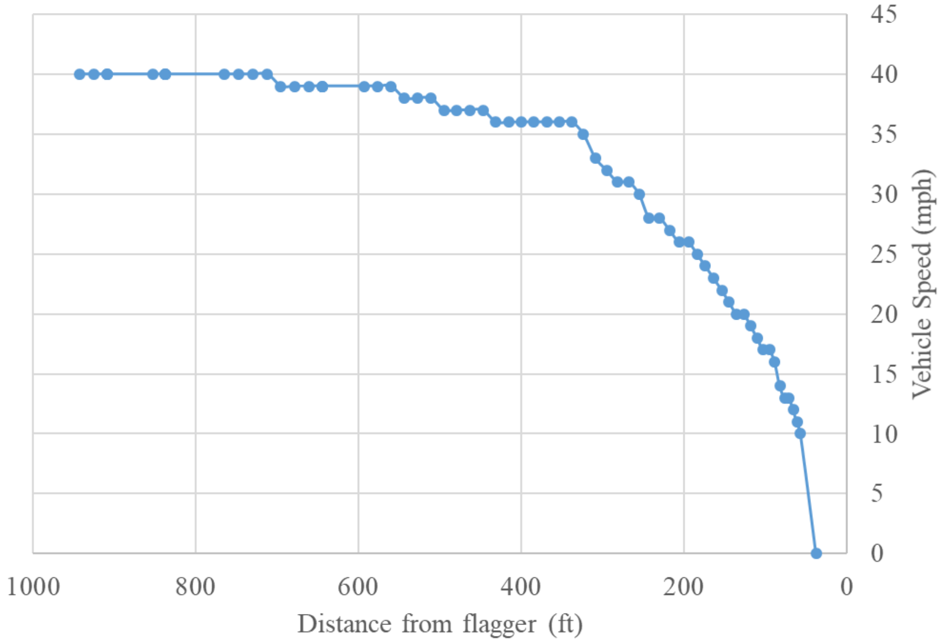


Figure 21. Speed Profile Example.

While graphically plotting the speeds provides clues about the speed differences at each point of interest, it does not convey any information on whether these differences are statistically significant. Therefore, researchers conducted one-way analysis of variance (ANOVA) tests for each site to compare the average speeds at each of the points of interest. Essentially, the test compared the means (averages) between two or more groups of interest and determined whether any of those means had statistically significant differences from each other. The null hypothesis states that the means of the two or more groups are not statistically different from each other. The test examines the differences between the groups and within each group and takes a ratio of the two values (F). If this ratio is lower than the critical test ratio (F_{crit}), the differences in the means of the two treatments are not statistically significant. The ANOVA test results for each site at each desired point of interest (400 ft, 300 ft, 200 ft, and 100 ft) were tabulated and are summarized in the Appendix.

RESULTS

PCMS

PCMS treatments were deployed at sites 1 through 8. At sites 1, 2, 5, and 8, data were collected for the baseline treatment (static BPTS sign) and only one PCMS treatment. At sites 3, 4, 6, and 7, data were collected for the baseline treatment and both PCMS treatments.

For sites 1, 5, and 8, the PCMS displayed a BPTS message. Figure 22 shows that practically no significant changes in average speeds were observed at site 1 (i.e., no more than a 1-mph difference is evident at any of the points of interest). Similarity, Figure 23 shows that there was no practical difference in the average speeds between the treatments at site 8. Statistical analyses also showed there were no significant differences in the treatment means at sites 1 and 8. Conversely, Figure 24 shows considerable differences in averages speeds at site 5 at 200 ft, 300 ft, and 400 ft (3.9 mph, 6.7 mph, and 4.7 mph, respectively). Statistical analysis found significant differences between the treatment means at 300 ft and suggestive evidence of differences at 200 ft and 400 ft. However, a review of the field data collection form showed that motorist behavior may have been influenced by the work operation. When the static BPTS sign was displayed, the paving operation was not visible because it was beyond a vertical curve. Later in the day, when the PCMS message was displayed, the paving operation was very close to the flagger (and visible to approaching vehicles). This likely accounted for the differences at this site.

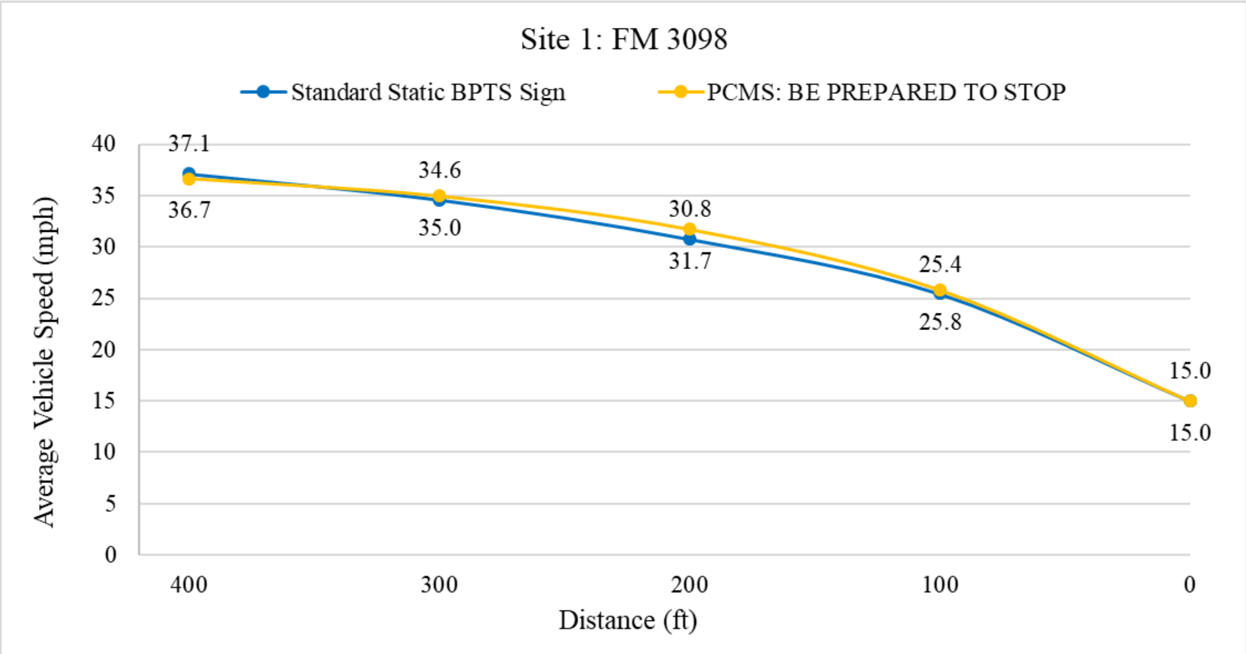


Figure 22. Site 1 Average Vehicle Speeds for Standard Static BPTS Sign and PCMS Displaying BPTS Message.

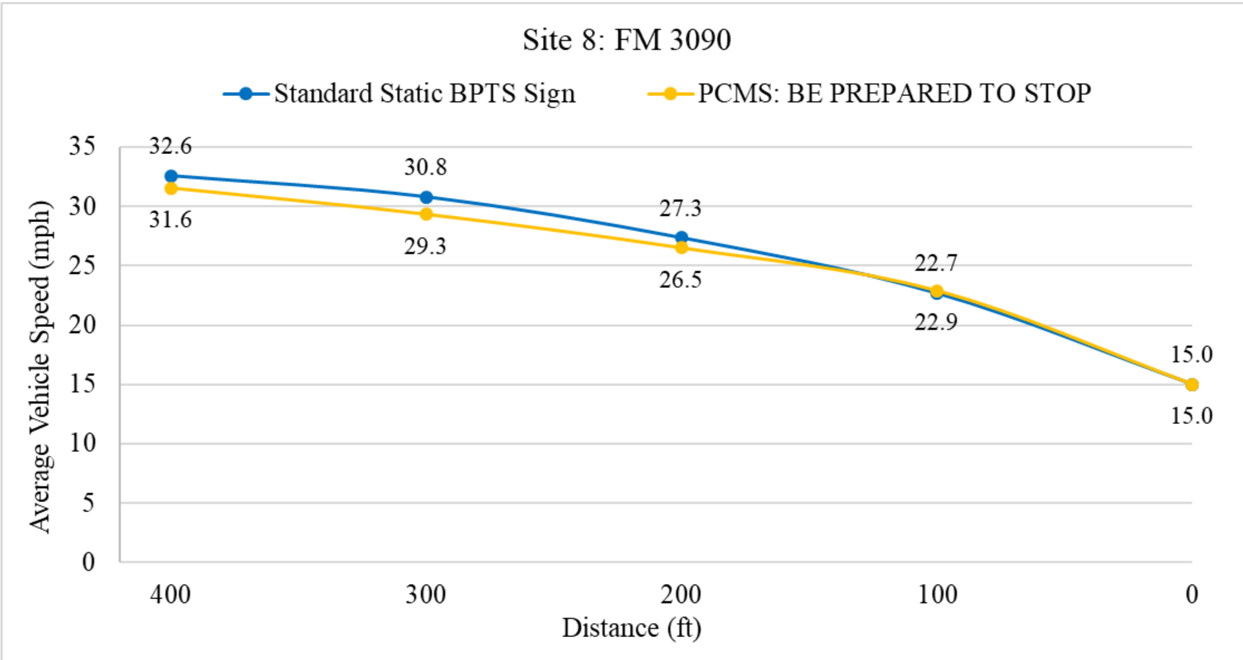


Figure 23. Site 8 Average Vehicle Speeds for Standard Static BPTS Sign and PCMS Displaying BPTS Message.

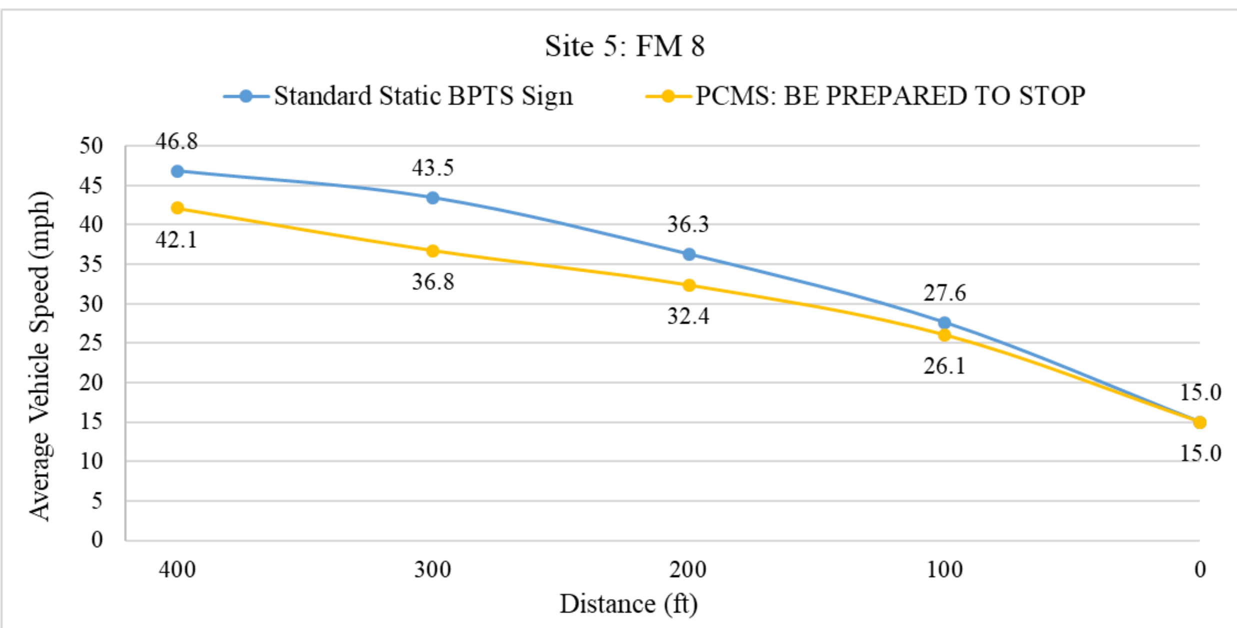


Figure 24. Site 5 Average Vehicle Speeds for Standard Static BPTS Sign and PCMS Displaying BPTS Message.

For site 2, the PCMS displayed a STOPPED TRAFFIC AHEAD message. Unfortunately, due to roadway curvature, the researchers were not able to record speeds as far as 400 ft upstream of when vehicles slowed down significantly (15 mph and below). Figure 25 shows that the greatest average speed difference was 2.6 mph at 200 ft. However, this difference was not found to be statistically significant.

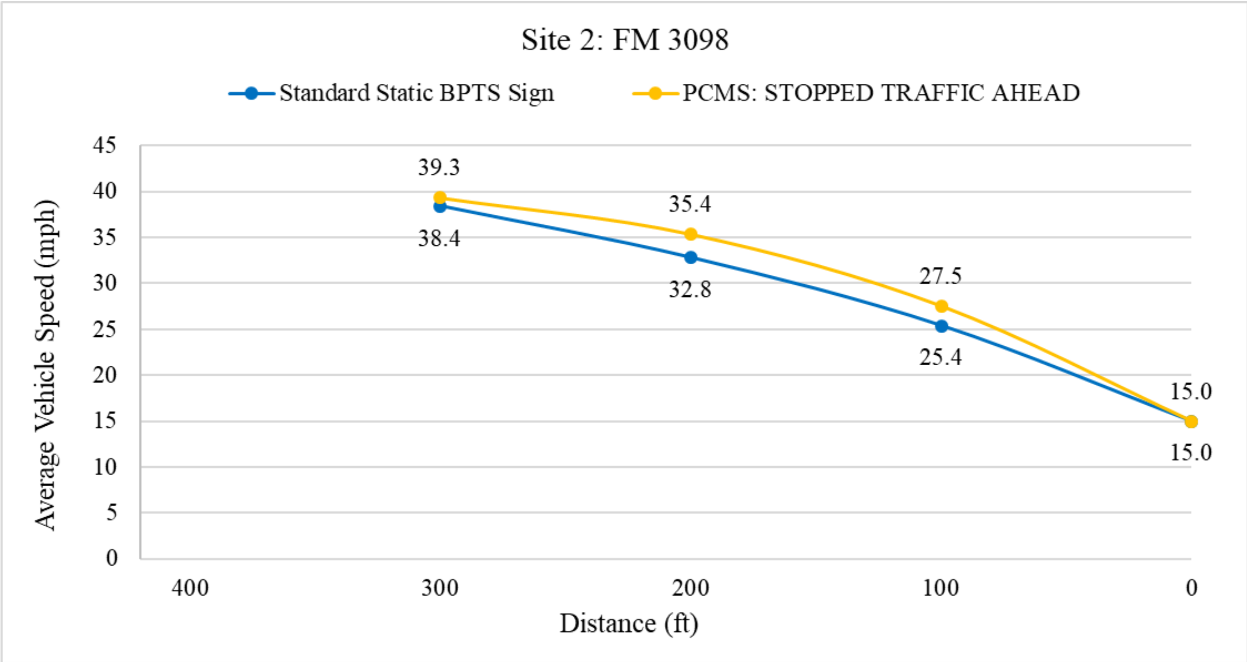


Figure 25. Site 2 Average Vehicle Speeds for Standard Static BPTS Sign and PCMS Displaying STOPPED TRAFFIC AHEAD Message.

For sites 3, 4, 6, and 7, data were collected for the baseline treatment (static BPTS sign) and both PCMS treatments. The results are shown in Figure 26 through Figure 29. The one-way ANOVA tests showed no significant differences for any treatments at any of the points of interest.

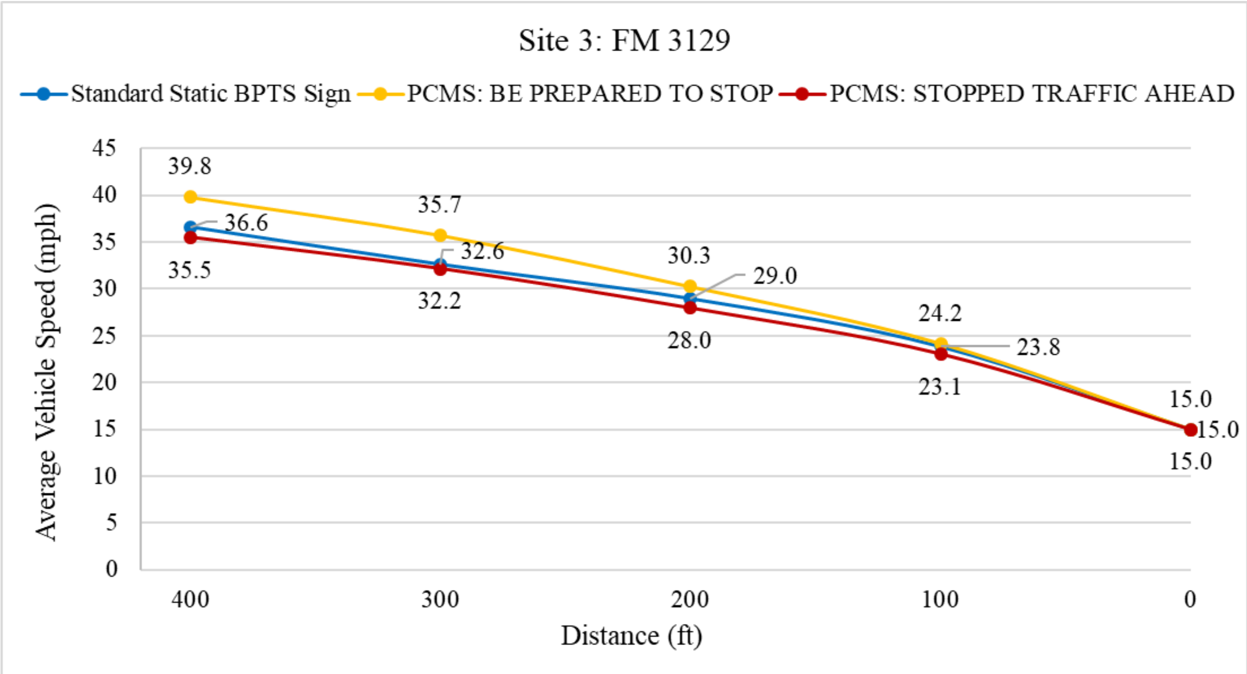


Figure 26. Site 3 Average Vehicle Speeds for Standard Static BPTS Sign, PCMS with BPTS Message, and STOPPED TRAFFIC AHEAD Message.

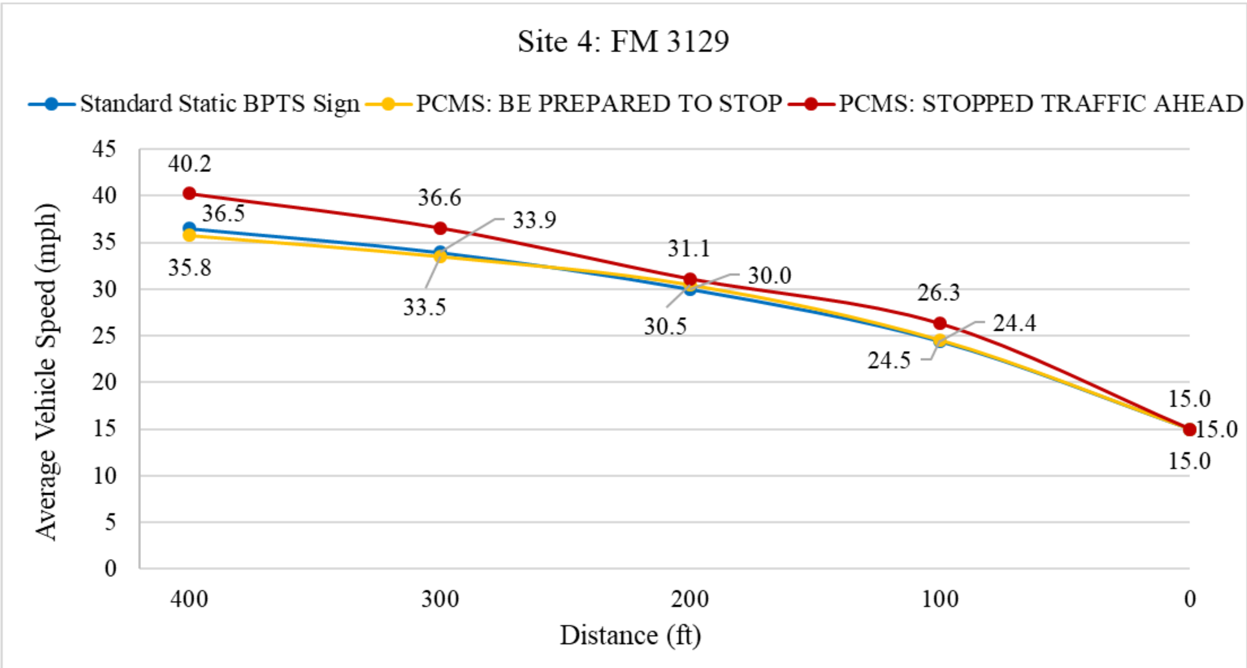


Figure 27. Site 4 Average Vehicle Speeds for Standard Static BPTS Sign, PCMS with BPTS Message, and STOPPED TRAFFIC AHEAD Message.

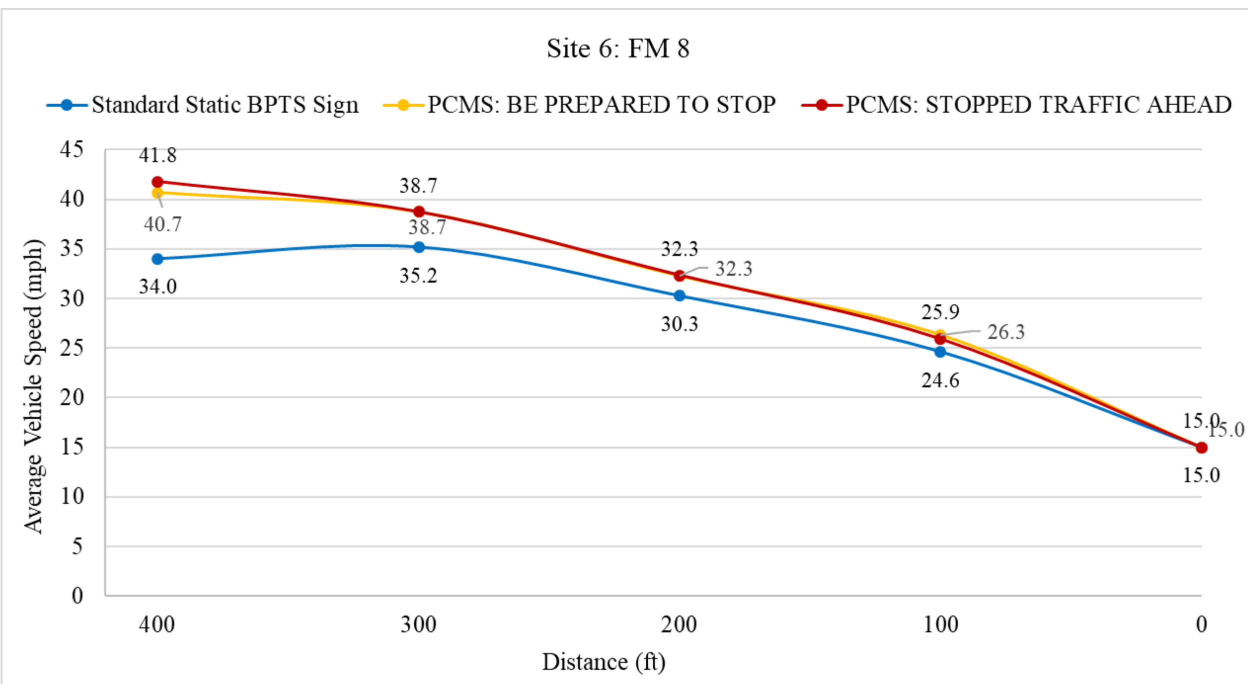


Figure 28. Site 6 Average Vehicle Speeds for Standard Static BPTS Sign, PCMS with BPTS Message, and STOPPED TRAFFIC AHEAD Message.

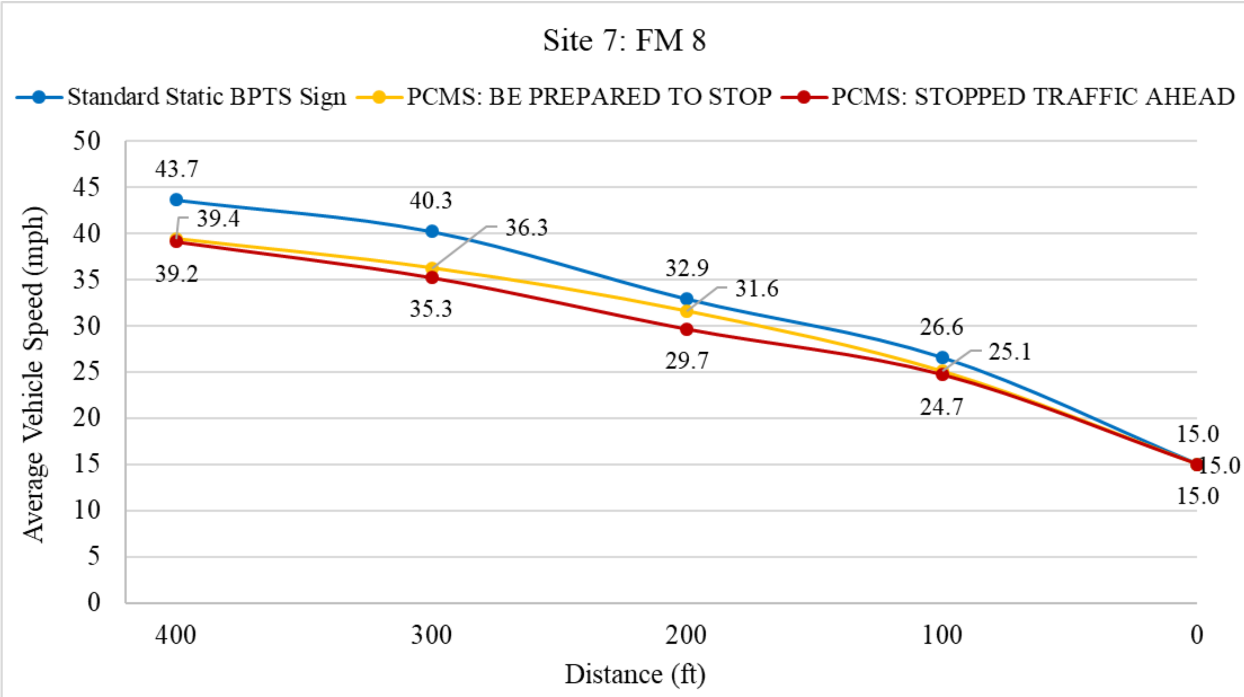


Figure 29. Site 7 Average Vehicle Speeds for Standard Static BPTS Sign, PCMS with BPTS Message, and STOPPED TRAFFIC AHEAD Message.

BPTS Signs with Flashing Lights

Flashing light treatments were deployed at sites 9 through 14. At sites 9, 10, 12, and 13, researchers were able to collect adequate speed profile data. However, at sites 11 and 14, researchers were not able to obtain adequate speed profile data. Instead, researchers pulled spot speed data for vehicles as they passed the Flagger Symbol sign located upstream of the flagger for each of the treatments.

At sites 9, 10, and 12, speed profile data were collected for the baseline treatment (static BPTS sign) treatment, the BPTS sign with warning light, and the BPTS sign with LED lights (shown in Figure 30 through Figure 32). At site 13, researchers were only able to collect data for the baseline treatment and the BPTS sign with warning light (see Figure 33). For the most part, the speeds were fairly similar, within a 3-mph range. The one-way ANOVA test results showed no statistically significant differences in the treatment means. Thus, the lights on the signs appeared to have no effect. This is not surprising given that all the data were collected in daylight conditions, where these lights may have been difficult to see against the ambient lighting on a sunny day. In addition, the sign stands had flexible springs that allowed the signs to blow in the wind, potentially reducing visibility of the lights.

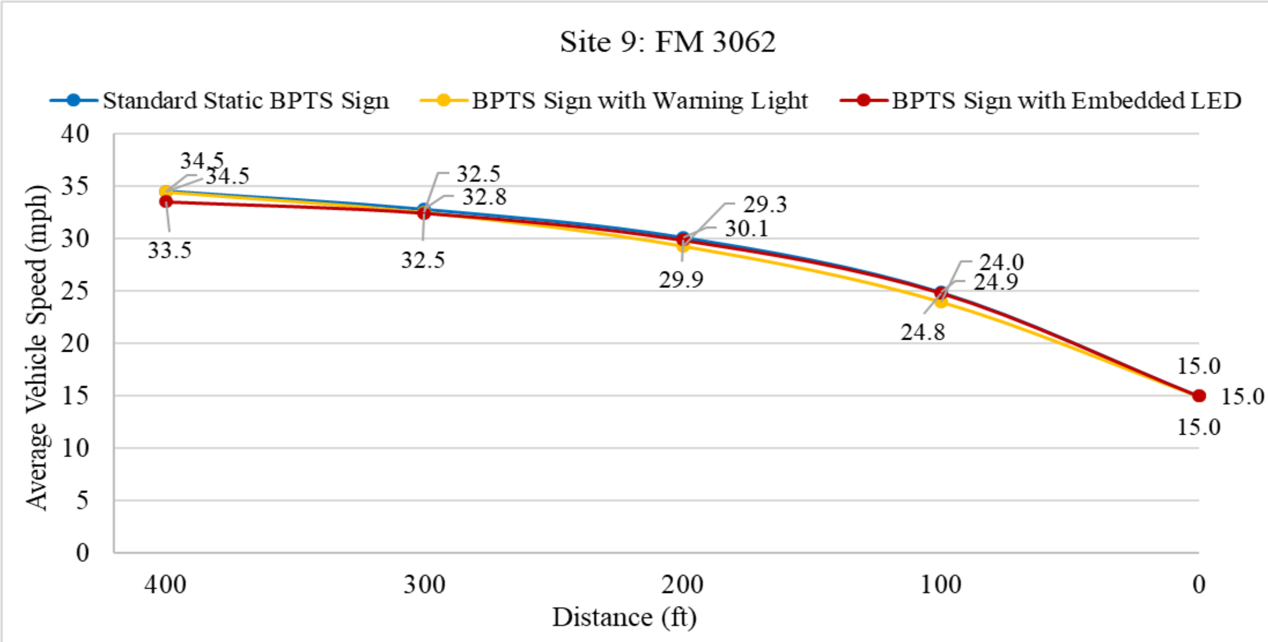


Figure 30. Site 9 Average Vehicle Speeds for Standard Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LED Lights.

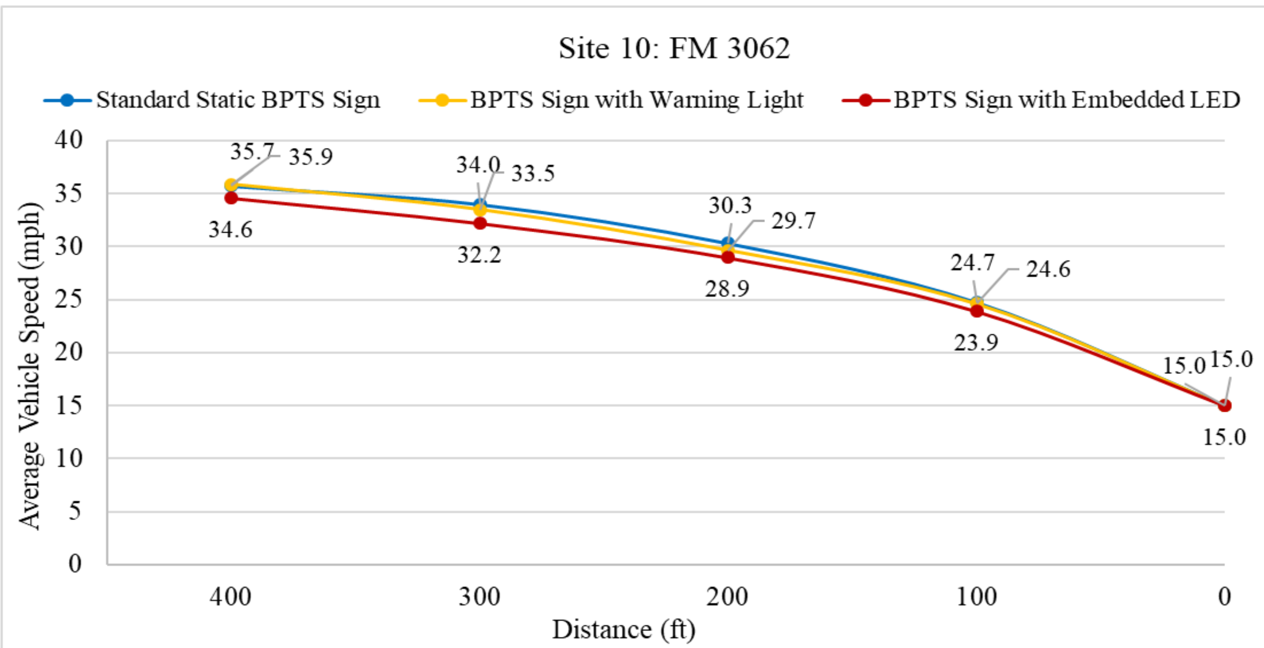


Figure 31. Site 10 Average Vehicle Speeds for Standard Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LED Lights.

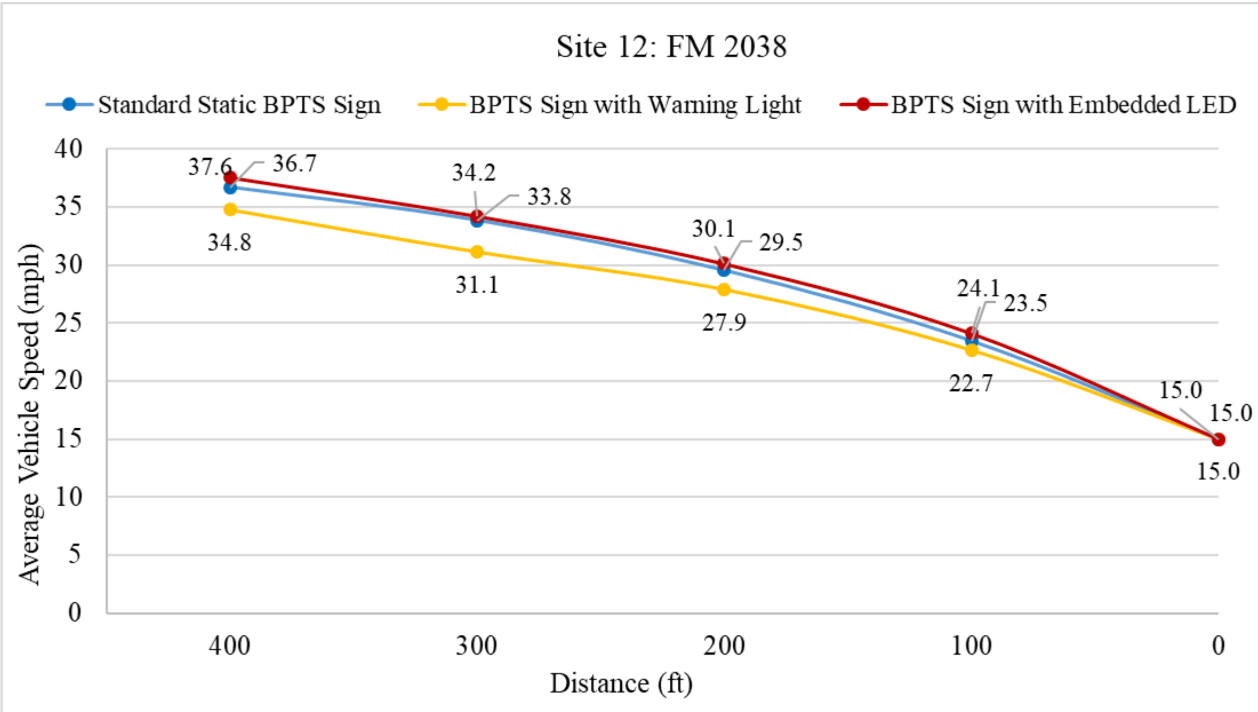


Figure 32. Site 12 Average Vehicle Speeds for Standard Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LED Lights.

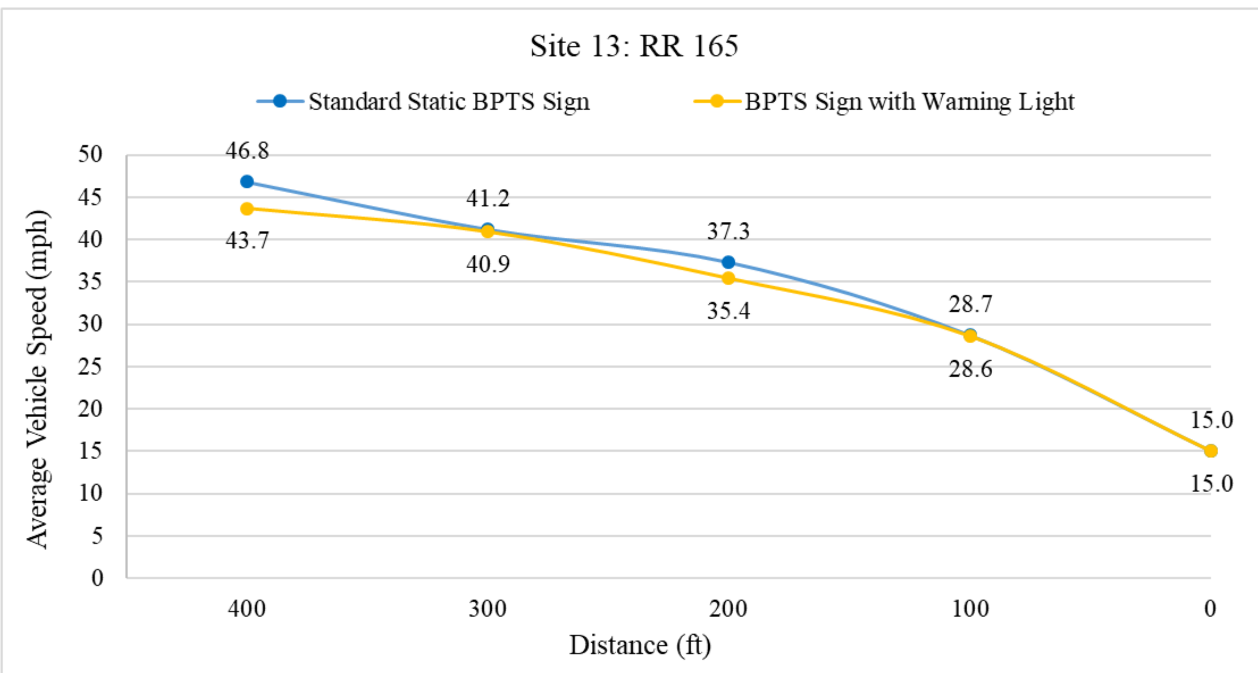


Figure 33. Site 13 Average Vehicle Speeds for Standard Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LED Lights.

At site 11, researchers collected spot speed data for the baseline treatment, the BPTS sign with warning light, and the BPTS sign with LED lights. At site 14, researchers collected spot speed data for the baseline treatment and the BPTS sign with LED lights. The results for sites 11 and 14 are shown in Table 7. Statistical tests were conducted to compare the spot speeds (see the Appendix), and they showed no statistically significant differences between the average spot speeds of the vehicles at either site.

Table 7. Average Spot Speeds for Standard Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LED Lights.

Treatments Evaluated	Average Spot Speeds (mph)	
	Site 11	Site 14
BPTS static sign	44.5	53.2
BPTS static sign with warning light	43.6	N/A
BPTS static sign with LEDs	45.2	51.1

Note: N/A = not applicable.

PTS

For site 18, researchers obtained data for both flagging (with the baseline static BPTS sign) and PTS treatments. The average vehicle speeds are shown in Figure 34. At 400 ft, the difference in the average speeds (3.4 mph) was statistically significant. While the difference was not statistically significant at 300 ft, there was suggestive evidence of a difference. For this one site, the data show that using the PTS did create a small change in driver behavior. Researchers hypothesize that the greater visibility and attention-getting ability of the PTS resulted in drivers slowing down at a farther distance from their eventual stopping location. Unfortunately, no additional data were available.

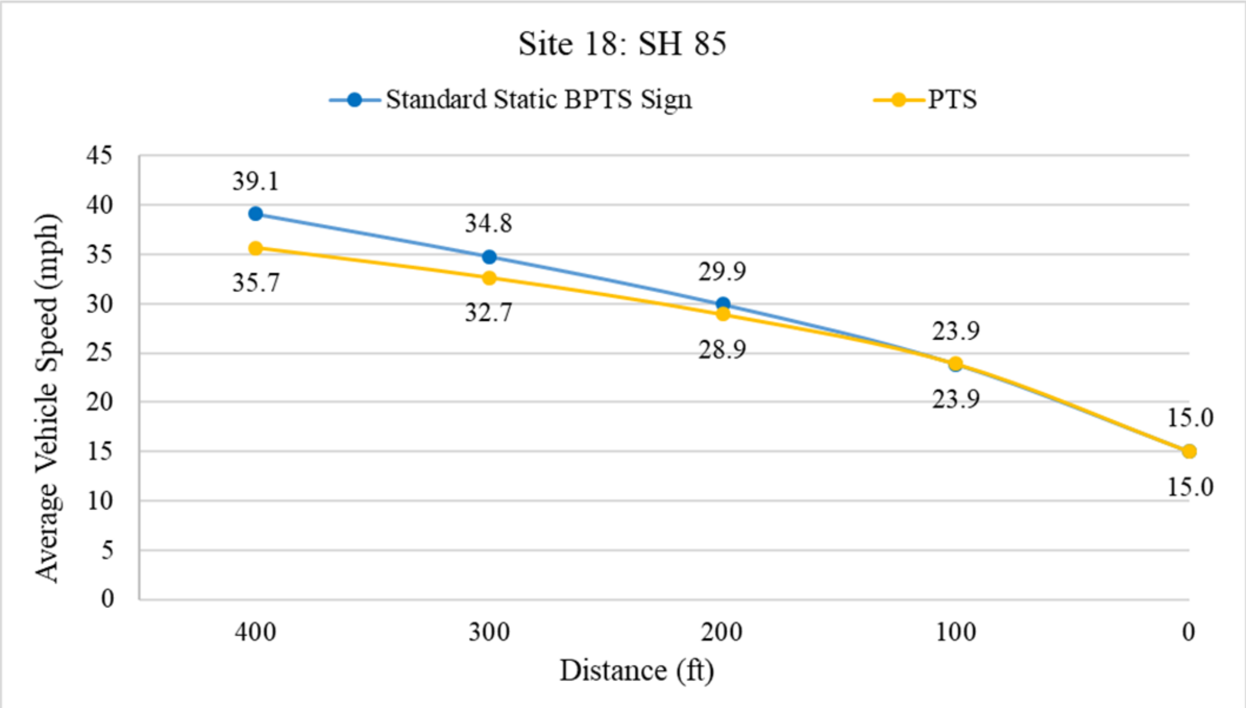


Figure 34. Site 18 Average Vehicle Speeds for Standard Static BPTS Sign and PTS.

SUMMARY

Researchers conducted a series of tests to determine if any of the treatments included in the study were associated with a reduction in vehicle speeds approaching the flagger (or the PTS). The one-way ANOVA tests compared the average speeds for each point of interest starting at 400 ft upstream of position zero (where each vehicle reached a speed of 15 mph), at increments of 100 ft. Most of the tests comparing the baseline treatment (static BPTS sign) with either a PCMS or a BPTS sign with either LED lights or a warning light found no statistically significant differences in average speeds as motorists decelerated to a stop condition. Limited data showed that drivers approaching the PTS slowed down at a distance farther away from their eventual stopping location than with the standard flagger setup. While statistically significant at 400 ft, the change in driver behavior was relatively small (less than 5 mph).

CHAPTER 5: BENEFIT-COST ANALYSIS

INTRODUCTION

In this chapter, researchers document the comparisons made of the various costs associated with the use of the different treatments evaluated in the previous chapter for flagging operations on two-lane, two-way roadways. A comparison of the costs and benefits was performed for the following:

- The standard static BPTS sign versus:
  - A BPTS sign with LED lights in the border.
  - A BPTS sign with a warning light on top.
  - A PCMS displaying a BPTS message.
  - A PCMS displaying a STOPPED TRAFFIC AHEAD message.
- The use of human flaggers (with static BPTS sign) versus a PTS.

METHODOLOGY

Typically, a benefit-cost analysis computes the incremental cost of a treatment (capital, maintenance, and operation costs) from the base condition and divides it into the computed incremental safety and operational benefits of that treatment over the base condition. For this project, however, the ability to directly measure the safety benefits of any of the treatments (i.e., a reduction in crashes) was not possible due to the limited duration of this study and the need for an extremely large sample size of projects where the base conditions and each of the treatments were deployed. In the case of comparison of human flaggers with a PTS, the use of a PTS would remove any crash risks for human flaggers present in the work zone, despite no concrete evidence on the specific safety benefits (i.e., there are no documented crash statistics for flaggers in work zones other than anecdotal evidence due to crashes being rare and random events). Therefore, the researchers focused on comparing these treatments based on capital, maintenance, and operation costs.

ANALYSIS

Comparison of Costs Associated with Static BPTS Sign, LED-Lighted BPTS Sign, and BPTS Sign with a Warning Light

In comparing the static and the added lights versions of the BPTS signs, the difference in costs would be limited to the additional costs of a warning light or the LED lights mounted to the border of a BPTS sign. Costs are given for 48-inch by 48-inch signs as described in the Texas MUTCD, Section 6F.3, Table 6F-1 (*27*). The cost was estimated for the sign and the sign stand. Transportation and maintenance were assumed to be negligible since the signs can be transported with other required work zone signs.

Static BPTS Sign

Cost = Capital Cost + Routine Maintenance + Transportation

- Capital Cost = Sign Cost + Stand Cost
  = $295 + $140
  = $435[a]
  [a] *Based on an estimate from a TxDOT vendor.*
- Maintenance = $0
  When properly stored, the service life is 3 years.
- Transportation = $0
  The sign is transported with other work zone signs.
- Service Life = Up to 3 years (based on vendor estimates)

Cost = 2 signs × $435 = $870

BPTS Sign with LED Lights

Since BPTS signs with LED lights are not available commercially, the costs were estimated based on a similarly sized LED-lighted pedestrian crossing sign that is available for purchase commercially.

Cost = Capital Cost + Routine Maintenance + Transportation

- Capital Cost (LED-Lighted Pedestrian Crossing Sign) = $1,860[a]
  [a] *Based on a solar-powered system estimate from a vendor.*
- Maintenance = $0
  When properly stored, the service life is 3 years.
- Transportation = $0
  The sign is transported with other work zone signs.

Cost = 2 signs × $1,860 = $3,720

The sign assembly has several components with seemingly different service life; however, as with other equipment, service life depends on proper care in storage and transport, as well as weather conditions and the extent of utilization.

BPTS Sign with a Warning Light

Researchers estimated the cost of a BPTS sign with a warning light.

Cost = Capital Cost + Routine Maintenance + Transportation

- Capital Cost = Sign Cost + Sign Stand Cost[a] + Warning Light[a] + Battery
  = $295 + $238 + $48 + $25 (rechargeable D-cell batteries)
  = $606
  [a] *Based on an estimate from a TxDOT vendor.*
- Maintenance = $0
  When properly stored, the service life is 3 years.

- Transportation = $0
  The sign is transported with other work zone signs.
- Service Life:
  - Sign = Up to 3 years
  - Warning Light = 10 years

Cost = 2 signs × $606 = $1,212

Considering that the static sign service life is 3 years, the comparison of costs for the three treatments is based on 3 years of utilization (see Table 8). Without knowing the direct (i.e., reduction in crashes) or surrogate safety benefits (i.e., reduction in vehicle speeds), the least expensive option is the static BPTS sign.

Table 8. Comparison of Capital and Operating Costs for BPTS Sign Treatments.

Treatment	Total Costs
BPTS static sign	$870
BPTS static sign with LEDs	$3,720
BPTS static sign with warning light	$1,212

Comparison of Costs Associated with Static BPTS Sign and PCMS

To estimate the cost of purchasing or renting a PCMS, researchers examined the TxDOT document for bid code average prices from October 2019 (*90*) and found that the average cost of purchasing a PCMS was $8,438, whereas the 3-month statewide average rental price for PCMS was stated as $55.32/day. Assuming that the PCMS is rented for 6 out of 12 months of the year, the rental cost for a year would be 6 months × 30 days/month × $55.32/day = $9,958.

The costs associated with the use of a PCMS include the capital cost or rental cost of the PCMS, training for employees, setup, and routine maintenance. The researchers estimated the hourly wages by averaging annual salaries for engineering technician I and II based on Texas Tribune Salaries (*91*) information provided for these two positions. The average of the two annual salaries resulted in a yearly salary of $36,523.50. Assuming full-time working hours (40 hours/week and 52 weeks/year), this calculation resulted in $17.56/hour. For simplicity of calculations, this amount was rounded to $18/hour.

Cost (purchase) = Capital Cost + Initial Training Cost + Routine Maintenance Cost Capital cost of equipment = $8,438

- Initial training cost = 4 hours × $18/hour × 5 employees = $360
- Routine maintenance and operation cost = ($18/hour × 1 hour/month × 12 months/year) = $216

Cost = $8,438 + $360 + $216 = $9,014

Assuming the costs associated with training, routine maintenance, and operations are the same for either renting or buying a PCMS, based on the capital and rental costs, purchasing a PCMS would result in savings after less than 6 months of utilizing it.

The researchers assumed a service life of 10 years for the PCMS (*92*), with proper routine maintenance. The cost comparison between the static BPTS sign and the PCMS is summarized in Table 9, and the comparison is provided for a decade (the service life of a PCMS). Since the service life of the static sign was assumed to be 3 years, in the span of a decade, researchers estimated the need for purchasing a couple of signs four times, costing a total of $3,484. In the case of purchasing a PCMS, the routine maintenance over a decade would cost $2,160, resulting in a total cost of $10,958 over a decade.

Table 9. Comparison of Capital and Operation Costs through a Decade for Static Sign and PCMS.

Treatment	Total Costs for a Decade
BPTS (CW3-4) static sign	$3,483
PCMS (purchase)	$10,958

Comparison of Costs Associated with Human Flagger and PTS

The researchers examined the costs associated with employing human flaggers (HFs), more specifically costs associated with wages, training, and equipment needed in the field.

Researchers estimated flagger personnel costs by averaging annual salaries for engineering technician I and II based on Texas Tribune Salaries information (*91*) for these two positions. The average of the two annual salaries resulted in a yearly salary of $36,523.50. Assuming full-time working hours (40 hours/week and 52 weeks/year), this calculation resulted in $17.56 per hour. For simplicity of calculations, this amount was rounded to $18 per hour. Given that during flagger operations a flagger is needed to direct traffic in each direction of travel, a pair of flaggers would require $36 per hour.

Assuming flaggers are new employees and have not had flagger training prior to being hired, they would need proper training to ensure they are knowledgeable on the procedures and safety measures required. The researchers found estimates for work zone flagger training from the National Safety Council (*93*) ranging from $70 to $95 for a 4-hour course.

Flaggers are required to wear a hard hat and vest to increase their visibility to vehicular traffic. Additionally, they carry a STOP/SLOW paddle to direct vehicles approaching the work zone to either stop or slowly proceed through the work zone.

Cost HF = Employee Cost (Average Hourly Wage) + Training + Equipment (Sign/Paddle, Vest, Hard Hat)

- Employee average wage = $18/hour = $4,320 monthly
- Training = training cost + employee costs for training
  = $95 + ($18/hour × 4 hours)
  = $167
- Equipment cost = paddle + hard hat + vest
  = $132 + $10 + $20
  = $162[a]
  [a] *Based on vendor estimates.*

The researchers examined the costs associated with procuring and maintaining a PTS to be used in lieu of human flaggers at work zones that require flagging operations. The breakdown of the costs included capital cost, training for personnel to set up and operate the PTS, and required routine maintenance.

The researchers examined the TxDOT document for bid code average prices from October 2019 (*90*) and found that the average cost of purchasing a PTS was $46,717.99. Additionally, based on prior research (*94*), the researchers assumed a PTS service life of 20 years.

Training is needed for employees who will be expected to learn how to set up the PTS and address any issues with the device operation. Certain companies (*95*) include on-site training and setup in the purchase price for a PTS. The training is estimated to take approximately 2 hours, so the cost associated would include employee wages and would be based on the number of employees receiving the training.

It is estimated that it will take an employee about 30 minutes each time for setup and removal of the PTS device. The cost is calculated assuming that the devices (one for each end of the work zone) are set up weekly and that routine maintenance, estimated at 1 hour/week, will be needed to ensure the device is functioning properly at all times and the batteries are fully charged.

Cost PTS = Capital Cost + Initial Training Cost + Setup Cost + Routine Maintenance Cost

- Capital cost of equipment = $46,718
- Initial training cost = 2 hours × $18/hour × 4 employees = $144
- Signal setup/removal = 0.5 hour × $18/hour × 2 employees × 12 setups per 3 months
  = $216
- Routine maintenance and operation cost = 1 hour/week × 52 weeks/year × $18/hour
  = $1,136 per year

The use of either a human flagger or a PTS largely depends on the needs of an agency and the frequency of work zones that involve flagger operation. For the sake of comparison, the researchers assumed that ether a human flagger or PTS would be needed for 3 months out of the year. Consequently, the cost for a human flagger and a PTS is estimated as:

Cost HF/2 yr = 2 employees × [2*(3 months × $4,320/month) + $167 + $162] = $52,498
Cost PTS/2 yr = $46,718 + $144 +2* $216 + 2*$1,136 = $49,566

The researchers extrapolated these costs to 2 years (3-month utilization during each year), and the final costs are summarized in Table 10, where it can be seen that after 2 years, the use of a PTS starts accruing cost savings.

Table 10. Comparison of Costs for a Human Flagger versus a PTS.

Treatment	Total Cost for 2 Years
Human Flagger	$52,498
PTS	$49,566

SUMMARY

The researchers computed the estimates for capital, maintenance, and operation costs associated with the various treatments examined in this study. The three comparisons of costs were between static signs and signs with lights (either LED lights or a warning light), static sign and PCMS, and human flagger and PTS.

In the first two sets of cost comparisons, the researchers found that the cost of purchasing and using the static BPTS signs was lower than for the static sign with lights (either LED lights or a warning light) or the PCMS.

In comparing the use of a PTS over human flaggers, the researchers noticed that for a utilization period of 3 months a year, after 2 years, the use of a PTS would result in savings. Additionally, this comparison does not account for any potential safety benefits of not having human flaggers exposed to any risks while working close to direct traffic. Unfortunately, any safety benefits are not reported, which makes it difficult for these benefits to be included in the benefit-cost analysis and thus provide a more accurate comparison of the two treatments.

CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The objective of this research project was to identify and evaluate strategies for mitigating end-of-queue crashes at flagging operations on two-lane roadways. Based on the literature review, discussions with TxDOT personnel, and outreach to TTC vendors, the research team developed a consolidated list of all potential countermeasures, which was further narrowed down based on feasibility assessment and treatment advantages to only include the following treatments:

- Add LED border lights or add a warning light to the static BPTS sign.
- Replace the static BPTS sign with a PCMS displaying either a BPTS or a STOPPED TRAFFIC AHEAD message.
- Use a PTS in lieu of the flagger at flagging operations.

Researchers collected GPS and LIDAR speed data at 18 sites across Texas for the baseline (static BPTS sign) treatment and one or more treatments from the previously mentioned list. The data were processed and analyzed using a series of one-way ANOVA tests to determine if there were any statistically significant differences in mean speeds at various distances upstream of each vehicle's position zero (position where each vehicle reached a speed of 15 mph). Most of the test results did not find any significant differences between mean speeds of the baseline treatment and the BPTS sign with LED lights, BPTS sign with a warning light, or PCMS displaying either message. In the field, the LED lights around the border of the BPTS sign and the warning light were difficult to see against the ambient lighting on a sunny day. In addition, the sign stands had flexible springs that allowed the signs to blow in the wind, potentially reducing visibility of the LED lights and warning light. Furthermore, the LED lights and warning light were meant to increase the conspicuity of the BPTS sign. Even though drivers may have noticed the BPTS sign more with LED lights or a warning light, the acquisition of information does not always result in driver behavior changes. This latter point also applies to the PCMS message tested. Drivers may see the sign, read the message, and be more cognitively aware as a result, but not change their speed. Thus, even though the mean speeds were not impacted, safety could still be improved. Researchers recommend further studies investigating ways to improve the daytime visibility of LED lights on signs. Researchers also recommend that human factors studies be conducted to further assess the effectiveness of PCMS messages in the advance warning area at flagging operations on two-lane roadways.

Due to site limitations, researchers were only able to analyze speed data from one site to compare PTS and flagger impact on mean speeds. Statistical analysis found a significant change in mean speeds at 400 ft, but the change in driver behavior was relatively small (less than 5 mph). Even so, the data showed that drivers approaching the PTS slowed down at a distance farther away from their eventual stopping location. Researchers believe that the mounting height of the PTS aided drivers in detecting and perceiving the eventual need to stop farther upstream relative to when a human flagger was used to control traffic at the work zone. While these findings are encouraging, additional studies are needed to fully understand the impact on reducing end-of-queue crashes at flagger stations.

Researchers also conducted a comparative cost analysis of the different treatments examined in this project. The cost analysis included capital costs, operation and routine maintenance costs, and transportation costs, when available. The analysis showed that the cost for purchasing and using the static BPTS signs was lower than costs for the treatments including the static signs with lights (either LED or warning) or the PCMS. However, researchers noted cost savings in just 2 years when utilizing PTSs in lieu of human flaggers.

APPENDIX: ANOVA TEST RESULTS

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	18	458	25.4	9.3
PCMS (BPTS)	29	749	25.8	17.8

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.630	1	1.630	0.112	0.740	4.057
Within Groups	656.582	45	14.591			
Total	658.213	46				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	18	554	30.77778	22.06536
PCMS (BPTS)	29	920	31.72414	33.7069

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9.946849	1	9.946849	0.339379	0.563096	4.056612
Within Groups	1318.904	45	29.30898			
Total	1328.851	46				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	13	450	34.61538	16.25641
PCMS (BPTS)	27	944	34.96296	47.03704

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.060114	1	1.060114	0.028408	0.867046	4.098172
Within Groups	1418.04	38	37.31684			
Total	1419.1	39				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	7	260	37.14286	23.47619
PCMS (BPTS)	21	770	36.66667	51.23333

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.190476	1	1.190476	0.026557	0.871808	4.225201
Within Groups	1165.524	26	44.82784			
Total	1166.714	27				

Figure 35. ANOVA Test Results for Site 1: Comparing Average Vehicle Speed for Static BPTS Sign and PCMS Displaying BPTS Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static BPTS Sign	10	254	25.4	9.822222
PCMS (STA)	11	303	27.54545	3.472727

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	24.11082	1	24.11082	3.720586	0.06882	4.38075
Within Groups	123.1273	19	6.480383			
Total	147.2381	20				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static BPTS Sign	10	328	32.8	56.17778
PCMS (STA)	11	389	35.36364	7.054545

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	34.42597	1	34.42597	1.135292	0.300003	4.38075
Within Groups	576.1455	19	30.32344			
Total	610.5714	20				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static BPTS Sign	5	192	38.4	67.8
PCMS (STA)	6	236	39.33333	15.86667

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.375758	1	2.375758	0.060998	0.810467	5.117355
Within Groups	350.5333	9	38.94815			
Total	352.9091	10				

Figure 36. ANOVA Test Results for Site 2: Comparing Average Vehicle Speed for Static BPTS Sign and PCMS Displaying STOPPED TRAFFIC AHEAD Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	33	787	23.84848	16.00758
PCMS (BPTS)	39	943	24.17949	10.5722
PCMS (STA)	20	461	23.05	12.15526

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	16.92268	2	8.461341	0.65773	0.520525	3.09887
Within Groups	1144.936	89	12.86445			
Total	1161.859	91				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	32	927	28.96875	30.54738
PCMS (BPTS)	35	1059	30.25714	19.54958
PCMS (STA)	20	559	27.95	21.73421

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	71.83232	2	35.91616	1.490147	0.231235	3.105157
Within Groups	2024.604	84	24.10243			
Total	2096.437	86				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	31	1012	32.64516	47.63656
PCMS (BPTS)	27	965	35.74074	24.04558
PCMS (STA)	13	418	32.15385	22.14103

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	177.9412	2	88.97061	2.607788	0.081056	3.131672
Within Groups	2319.974	68	34.11727			
Total	2497.915	70				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	22	806	36.63636	69.09957
PCMS (BPTS)	16	637	39.8125	30.29583
PCMS (STA)	10	355	35.5	26.27778

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	141.8883	2	70.94413	1.490403	0.23619	3.204317
Within Groups	2142.028	45	47.60063			
Total	2283.917	47				

Figure 37. ANOVA Test Results for Site 3: Comparing Average Vehicle Speed for Static BPTS Sign, PCMS Displaying BPTS Message, and PCMS Displaying STOPPED TRAFFIC AHEAD Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	17	415	24.41176	8.757353
PCMS (BPTS)	15	368	24.53333	14.55238
PCMS (STA)	10	263	26.3	27.56667

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	25.66807	2	12.83403	0.845555	0.437038	3.238096
Within Groups	591.951	39	15.17823			
Total	617.619	41				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	17	510	30	25.625
PCMS (BPTS)	15	457	30.46667	17.40952
PCMS (STA)	10	311	31.1	39.43333

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.652381	2	3.82619	0.147944	0.862961	3.238096
Within Groups	1008.633	39	25.86239			
Total	1016.286	41				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	16	543	33.9375	22.19583
PCMS (BPTS)	12	402	33.5	33.18182
PCMS (STA)	9	329	36.55556	54.02778

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	54.92136	2	27.46068	0.826134	0.446334	3.275898
Within Groups	1130.16	34	33.23999			
Total	1185.081	36				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	16	584	36.5	25.46667
PCMS (BPTS)	12	429	35.75	43.47727
PCMS (STA)	9	362	40.22222	71.94444

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	115.2215	2	57.61074	1.364227	0.269213	3.275898
Within Groups	1435.806	34	42.22958			
Total	1551.027	36				

Figure 38. ANOVA Test Results for Site 4: Comparing Average Vehicle Speed for Static BPTS Sign, PCMS Displaying BPTS Message, and PCMS Displaying STOPPED TRAFFIC AHEAD Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	31	857	27.64516	23.96989
PCMS (BPTS)	13	339	26.07692	13.74359

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	22.5256	1	22.5256	1.070197	0.306821	4.072654
Within Groups	884.0199	42	21.04809			
Total	906.5455	43				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	31	1125	36.29032	40.14624
PCMS (BPTS)	13	421	32.38462	33.58974

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	139.7178	1	139.7178	3.650562	0.062893	4.072654
Within Groups	1607.464	42	38.27295			
Total	1747.182	43				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	31	1347	43.45161	48.78925
PCMS (BPTS)	13	478	36.76923	55.69231

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	408.9922	1	408.9922	8.057125	0.006954	4.072654
Within Groups	2131.985	42	50.76155			
Total	2540.977	43				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	30	1405	46.83333	50.14368
PCMS (BPTS)	8	337	42.125	54.69643

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	140.011	1	140.011	2.743756	0.106327	4.113165
Within Groups	1837.042	36	51.02894			
Total	1977.053	37				

Figure 39. ANOVA Test Results for Site 5: Comparing Average Vehicle Speed for Static BPTS Sign and PCMS Displaying BPTS Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	19	468	24.63158	10.91228
PCMS (BPTS)	12	316	26.33333	13.69697
PCMS (STA)	12	311	25.91667	29.17424

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	24.69329	2	12.34664	0.739315	0.483851	3.231727
Within Groups	668.0044	40	16.70011			
Total	692.6977	42				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	19	575	30.26316	22.98246
PCMS (BPTS)	12	387	32.25	44.38636
PCMS (STA)	12	388	32.33333	64.06061

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	43.67819	2	21.8391	0.543734	0.584806	3.231727
Within Groups	1606.601	40	40.16502			
Total	1650.279	42				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	11	387	35.18182	15.36364
PCMS (BPTS)	7	271	38.71429	69.2381
PCMS (STA)	7	271	38.71429	134.5714

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	76.86649	2	38.43325	0.614265	0.550061	3.443357
Within Groups	1376.494	22	62.56789			
Total	1453.36	24				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	6	204	34	22
PCMS (BPTS)	3	122	40.66667	9.333333
PCMS (STA)	4	167	41.75	181.5833

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	173.5064	2	86.75321	1.288255	0.317833	4.102821
Within Groups	673.4167	10	67.34167			
Total	846.9231	12				

Figure 40. ANOVA Test Results for Site 6: Comparing Average Vehicle Speed for Static BPTS Sign, PCMS Displaying BPTS Message, and PCMS Displaying STOPPED TRAFFIC AHEAD Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	12	319	26.5833	22.8106
PCMS (BPTS)	25	627	25.08	17.91
PCMS (STA)	34	841	24.7353	15.4733

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	30.5975	2	15.2988	0.87321	0.42224	3.13167
Within Groups	1191.37	68	17.5202			
Total	1221.97	70				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	12	395	32.9167	33.3561
PCMS (BPTS)	25	790	31.6	36.75
PCMS (STA)	34	1009	29.6765	21.2558

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	111.952	2	55.976	1.95163	0.14992	3.13167
Within Groups	1950.36	68	28.6817			
Total	2062.31	70				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	12	483	40.25	71.4773
PCMS (BPTS)	25	907	36.28	41.96
PCMS (STA)	33	1164	35.2727	41.5795

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	219.65	2	109.825	2.35553	0.10265	3.13376
Within Groups	3123.84	67	46.6244			
Total	3343.49	69				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	12	524	43.6667	83.5152
PCMS (BPTS)	25	986	39.44	54.9233
PCMS (STA)	31	1214	39.1613	67.7398

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	190.744	2	95.3722	1.45214	0.24156	3.13814
Within Groups	4269.02	65	65.6772			
Total	4459.76	67				

Figure 41. ANOVA Test Results for Site 7: Comparing Average Vehicle Speed for Static BPTS Sign, PCMS Displaying BPTS Message, and PCMS Displaying STOPPED TRAFFIC AHEAD Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	9	204	22.6667	14.75
PCMS (BPTS)	10	229	22.9	3.65556

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.25789	1	0.25789	0.02905	0.86667	4.45132
Within Groups	150.9	17	8.87647			
Total	151.158	18				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	9	246	27.3333	34
PCMS (BPTS)	10	265	26.5	14.5

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.28947	1	3.28947	0.13893	0.71395	4.45132
Within Groups	402.5	17	23.6765			
Total	405.789	18				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	9	277	30.7778	43.1944
PCMS (BPTS)	9	264	29.3333	17.25

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.38889	1	9.38889	0.31066	0.58499	4.494
Within Groups	483.556	16	30.2222			
Total	492.944	17				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	9	293	32.5556	49.5278
PCMS (BPTS)	9	284	31.5556	24.0278

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.5	1	4.5	0.12236	0.73105	4.494
Within Groups	588.444	16	36.7778			
Total	592.944	17				

Figure 42. ANOVA Test Results for Site 8: Comparing Average Vehicle Speed for Static BPTS Sign and PCMS Displaying BPTS Message.

Anova: Single Factor (Distance 100 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	37	921	24.8919	11.2102
BPTS Sign with Warning Light	32	768	24	11.0323
BPTS Sign with LEDs	25	621	24.84	13.7233

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	16.0512	2	8.02558	0.67942	0.50946	3.09655
Within Groups	1074.93	91	11.8124			
Total	1090.98	93				

Anova: Single Factor (Distance 200 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	37	1114	30.1081	17.2102
BPTS Sign with Warning Light	32	938	29.3125	15.9637
BPTS Sign with LEDs	25	747	29.88	16.36

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	11.2259	2	5.61297	0.33892	0.71343	3.09655
Within Groups	1507.08	91	16.5613			
Total	1518.31	93				

Anova: Single Factor (Distance 300 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	36	1180	32.7778	25.6063
BPTS Sign with Warning Light	32	1040	32.5	26.1935
BPTS Sign with LEDs	20	649	32.45	25.4184

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.90732	2	0.95366	0.03699	0.9637	3.10384
Within Groups	2191.17	85	25.7785			
Total	2193.08	87				

Anova: Single Factor (Distance 400 ft.)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	35	1208	34.5143	39.1395
BPTS Sign with Warning Light	31	1068	34.4516	34.1892
BPTS Sign with LEDs	17	570	33.5294	22.2647

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	12.4047	2	6.20234	0.18292	0.83319	3.11077
Within Groups	2712.66	80	33.9082			
Total	2725.06	82				

Figure 43. ANOVA Test Results for Site 9: Comparing Average Vehicle Speed for Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LEDs.

Anova: Single Factor **(Distance 100 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	66	1633	24.74242	7.824942
BPTS Sign with Warning Light	35	861	24.6	17.42353
BPTS Sign with LEDs	37	884	23.89189	6.876877

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	17.846	2	8.923001	0.893234	0.411735	3.063204
Within Groups	1348.589	135	9.989547			
Total	1366.435	137				

Anova: Single Factor **(Distance 200 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	66	2000	30.30303	18.95291
BPTS Sign with Warning Light	35	1038	29.65714	22.23193
BPTS Sign with LEDs	37	1071	28.94595	13.88589

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	44.31923	2	22.15962	1.202528	0.303631	3.063204
Within Groups	2487.717	135	18.42753			
Total	2532.036	137				

Anova: Single Factor **(Distance 300 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	61	2073	33.98361	29.01639
BPTS Sign with Warning Light	32	1072	33.5	30.45161
BPTS Sign with LEDs	36	1159	32.19444	19.18968

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	73.25347	2	36.62674	1.374885	0.256636	3.0681
Within Groups	3356.622	126	26.63986			
Total	3429.876	128				

Anova: Single Factor **(Distance 400 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	56	2000	35.71429	32.20779
BPTS Sign with Warning Light	31	1112	35.87097	31.51613
BPTS Sign with LEDs	35	1210	34.57143	25.95798

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	36.35219	2	18.1761	0.600907	0.549969	3.072429
Within Groups	3599.484	119	30.24776			
Total	3635.836	121				

Figure 44. ANOVA Test Results for Site 10: Comparing Average Vehicle Speed for Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LEDs.

Anova: Single Factor **Spot Speeds**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign (can see flagger)	34	1441	42.3824	57.6373
Static (BPTS) Sign (cannot see flagger)	34	1512	44.4706	88.1961
BPTS Sign with LEDs	36	1630	45.2778	81.5778
BPTS Sign with Warning Light	40	1743	43.575	87.7378

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	161.808333	3	53.9361	0.68092	0.56513	2.66926
Within Groups	11089.4972	140	79.2107			
Total	11251.3056	143				

Figure 45. ANOVA Test Results for Site 11: Comparing Average Vehicle Speed for Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LEDs.

Anova: Single Factor **(Distance 100 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	13	305	23.4615	8.26923
BPTS Sign with Warning Light	9	204	22.6667	6.5
BPTS Sign with LEDs	9	217	24.1111	4.61111

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.42873	2	4.71436	0.70169	0.50425	3.34039
Within Groups	188.12	28	6.71856			
Total	197.548	30				

Anova: Single Factor **(Distance 200 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	13	384	29.5385	21.1026
BPTS Sign with Warning Light	9	251	27.8889	10.8611
BPTS Sign with LEDs	9	271	30.1111	7.36111

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	24.4108	2	12.2054	0.8565	0.43547	3.34039
Within Groups	399.009	28	14.2503			
Total	423.419	30				

Anova: Single Factor **(Distance 300 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	13	440	33.8462	31.8077
BPTS Sign with Warning Light	8	249	31.125	20.4107
BPTS Sign with LEDs	9	308	34.2222	14.1944

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	49.2438	2	24.6219	1.04179	0.36658	3.35413
Within Groups	638.123	27	23.6342			
Total	687.367	29				

Anova: Single Factor **(Distance 400 ft.)**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static (BPTS) Sign	13	477	36.6923	47.7308
BPTS Sign with Warning Light	8	278	34.75	22.7857
BPTS Sign with LEDs	9	338	37.5556	19.7778

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	34.8752	2	17.4376	0.52871	0.59534	3.35413
Within Groups	890.491	27	32.9812			
Total	925.367	29				

Figure 46. ANOVA Test Results for Site 12: Comparing Average Vehicle Speed for Static BPTS Sign, BPTS Sign with Warning Light, and BPTS Sign with LEDs.

Anova: Single Factor **(Distance 100 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	24	689	28.7083	15.6069
BPTS Sign with Warning Light	18	515	28.6111	57.0752

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.09722	1	0.09722	0.00293	0.95713	4.08475
Within Groups	1329.24	40	33.2309			
Total	1329.33	41				

Anova: Single Factor **(Distance 200 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	24	896	37.3333	24.7536
BPTS Sign with Warning Light	18	638	35.4444	45.6732

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	36.6984	1	36.6984	1.09077	0.30257	4.08475
Within Groups	1345.78	40	33.6444			
Total	1382.48	41				

Anova: Single Factor **(Distance 300 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	22	907	41.2273	97.6126
BPTS Sign with Warning Light	17	696	40.9412	53.8088

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.78493	1	0.78493	0.00998	0.92097	4.10546
Within Groups	2910.8	37	78.6704			
Total	2911.59	38				

Anova: Single Factor **(Distance 400 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Static (BPTS) Sign	19	890	46.8421	34.3626
BPTS Sign with Warning Light	14	612	43.7143	55.1429

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	78.859	1	78.859	1.83066	0.18584	4.15962
Within Groups	1335.38	31	43.0769			
Total	1414.24	32				

Figure 47. ANOVA Test Results for Site 13: Comparing Average Vehicle Speed for Static BPTS Sign and BPTS Sign with Warning Light.

Anova: Single Factor **Spot Speeds**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Static BPTS Sign	35	1861	53.17143	56.91092
BPTS Sign with LEDs	34	1737	51.08824	101.295

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	74.8440019	1	74.844	0.950138	0.333191	3.984049
Within Groups	5277.70672	67	78.77174			
Total	5352.55072	68				

Figure 48. ANOVA Test Results for Site 14: Comparing Average Vehicle Speed for Static BPTS Sign and BPTS Sign with LEDs.

Anova: Single Factor **(Distance 100 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Baseline	50	1193	23.86	12.6127
PTS	43	1027	23.8837	10.2004

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.01301	1	0.01301	0.00113	0.97324	3.94569
Within Groups	1046.44	91	11.4993			
Total	1046.45	92				

Anova: Single Factor **(Distance 200 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Baseline	50	1496	29.92	25.0139
PTS	43	1243	28.907	25.515

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	23.7244	1	23.7244	0.93976	0.33491	3.94569
Within Groups	2297.31	91	25.2451			
Total	2321.03	92				

Anova: Single Factor **(Distance 300 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Baseline	50	1739	34.78	33.9302
PTS	43	1404	32.6512	38.6611

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	104.771	1	104.771	2.90114	0.09193	3.94569
Within Groups	3286.35	91	36.1137			
Total	3391.12	92				

Anova: Single Factor **(Distance 400 ft.)**

SUMMARY

Groups	Count	Sum	Average	Variance
Baseline	50	1954	39.08	47.422
PTS	43	1534	35.6744	51.32

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	268.125	1	268.125	5.44737	0.0218	3.94569
Within Groups	4479.12	91	49.2211			
Total	4747.25	92				

Figure 49. ANOVA Test Results for Site 18: Comparing Average Vehicle Speed for Static BPTS Sign and PTS.

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