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16. Abstract
The purpose of this project is to explore the use of portable traffic signal technology as a means for improving the efficiency of two-lane rural maintenance operations. The research findings are based on limited field testing of portable signals in actual routine pavement maintenance work. Issues such as work zone design, driver comprehension, signal operation, and signal equipment features are discussed as they relate to this particular portable signal application.

The findings have been used to develop guidelines for the use of portable signals in maintenance operations in Texas, particularly with respect to setting up work zones and developing signal timing parameters. These recommendations are also documented in a separate implementation guide developed for field personnel. Current provisions of the *Texas Manual on Uniform Traffic Control Devices* do not fully address the technical and practical aspects of short-term application of portable signals, and proposed revisions are presented in this report. Equipment features that support short-term usage of portable signals are also discussed. Finally, future research needs in the areas of work zone speed variability, motorist information signing, short-term pavement markings, and in-zone vehicle detection are described.

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FEASIBILITY OF PORTABLE TRAFFIC SIGNALS TO REPLACE FLAGGERS IN MAINTENANCE OPERATIONS

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DISCLAIMER

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 views or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, and it is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Ginger Daniels, Texas P.E. #64560.

This document contains information about the programming of portable traffic signal control devices in rural, two-lane maintenance work zones. *The Texas Manual on Uniform Traffic Control Devices* (TMUTCD) specifies that such portable signals are subject to the same standards as permanent signal installations. This field guide should not be widely distributed until TxDOT resolves conflicting language in the TMUTCD between the requirement for engineering studies for signal installation/operation and the practical daily application of portable traffic signals in maintenance work zones. Otherwise, the proposed field setup and signal timings entered into the portable signal controllers must be appropriately determined by an engineering study (i.e., they must be approved by an engineer). Revisions to the TMUTCD will be necessary before the guidelines within this document can be fully implemented.

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CHAPTER 1. INTRODUCTION

The aging roadway system is requiring more maintenance than ever before, increasing the demands on the individual maintenance sections of the Texas Department of Transportation (TxDOT). At the same time, legislative limitations and budgetary constraints have placed pressure on TxDOT to make more efficient use of available personnel. This has created a need to focus available positions on critical skills and to find alternative means to obtain other skills and services.

While the overall size of the transportation system maintained by TxDOT has remained fairly constant over the past five years, the department's routine maintenance work force has declined by 367 employees, a 5.5 percent reduction in staffing (*1*). Rural maintenance operations within TxDOT are faced with finding ways to better utilize limited staff resources as the continued decline of the infrastructure contributes to the routine maintenance workload.

Recognizing the physical demands of flagging, the *Handbook of Safe Practices* issued by the Occupational Safety Division of TxDOT states the following: "To help prevent fatigue, flaggers *should* be rotated at a minimum of every two hours." (*2*) This expectation necessitates that all maintenance employees have interchangeable skills, which is not always practical or realistic. Alternatively, it requires the hiring of additional personnel. A third option is to seek a solution that takes advantage of available technology, such as portable traffic signals.

The purpose of this research project is to explore the use of portable traffic signal technology as a means for improving the efficiency of two-lane rural maintenance operations. Maintenance work on two-lane highways requires that traffic through the one-lane work zone be controlled using flaggers in constant radio communication. However, if portable traffic signals can be used in lieu of flaggers without a degradation of safety, then additional positions can be freed up for other critical work tasks.

Portable traffic signals have been used on several two-lane bridge construction projects throughout the state. Typically these projects have lasted a minimum of three months and had work zone lengths ranging from 400 to 1200 feet, with clear line of sight end-to-end. The valuable experience gained from these projects has contributed to the awareness of this technology and its transferability to short-term lane closures. Nonetheless, there are operational characteristics unique to daily lane closures with portable traffic signals that are not fully addressed in the *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) (*3*). Furthermore, the maintenance test sites used for this project were characterized by longer work zones and limited sight distance created by horizontal and vertical roadway features, situations that can create safety concerns.

The critical issues that will be examined and addressed in this project are as follows:

- applications of portable traffic signals in maintenance operations and their cost effectiveness;
- driver comprehension of portable traffic signals in short-term work zones within rural areas;
- work zone and signal operating parameters critical to effective use of portable signals; and
- essential equipment characteristics important to daily work zone applications.

This report present recommendations that address each of these issues. A companion document to this research report is available that provides maintenance sections with guidelines for setting up and operating portable traffic signals in rural two-lane operations.

CHAPTER 2. BACKGROUND

STUDY DESIGN

This research project is based on the testing of the portable traffic signal technology on three separate rural two-lane highway maintenance projects in the San Antonio District of TxDOT. The extent of the testing totaled twenty days over a three-month period from June 1998 through August 1998. The objectives of the field testing were as follows:

- to determine the applicability of portable traffic signals for rural maintenance operations;
- to collect data that would aid in assessing the cost effectiveness of portable traffic signals in daily maintenance operations; and
- to identify unique characteristics related to maintenance applications and recommend guidelines for work zone setup and signal operation.

The portable traffic signal equipment used for this project was the International Traffic Systems LF 1050, which consists of two self-contained trailer units (*4*). Each unit is equipped with two signal heads, a microprocessor-based controller, a radio frequency transceiver module for communication between the two units, a diesel generator that powers two industrial batteries that support the controller, and a microwave sensor to detect vehicles. The operator is required to input the minimum and maximum green times, the yellow change interval, the green extension interval, and the red clearance interval for each controller.

The equipment functioned well in the conditions under which it was tested (weather, terrain, distance between units), with minor technical difficulties associated with the microwave traffic sensors. The recommendations developed from this research project are not specific to any one product but instead are focused on the general principles of operation of this type of portable traffic signal technology. There are certain features that support portable traffic signal technology, and which are advantageous to maintenance operations; these will be addressed later in the report as enhancements to TxDOT specifications.

The trailer units were tested for this project by the San Antonio District TxDOT Maintenance Section in Bandera, Texas. The Bandera Maintenance Section is responsible for maintaining 213 centerline miles (343 km) of roadway and an area of 906 square miles (2347 square km) in Bandera County, Texas, and a small portion of Medina County, Texas. The section has a staffing level of 13 full-time employees, which equates to 16.1 miles (25.9 km) maintained per employee. Using a simple calculation from TxDOT maintenance workforce data, the average number of centerline miles of system maintained per routine maintenance employee in Texas in 1998 was 12.1 miles (19.5 km) per employee (*1*). Using the statewide average as a measure, the Bandera Maintenance Section should have 17.5 routine maintenance employees based on the length of system it maintains. This is a somewhat simplistic measure that does not account for other factors such as system condition, environmental considerations, and coverage area. It does, however, support the fact that within this particular maintenance section there was an immediate need, and considerable incentive to test this technology and find ways to incorporate it into daily work activities. As will be discussed later in the findings of this project, the attitude and leadership within the Kerrville Area Office and the Bandera Maintenance Section contributed to the success of the portable signal application on the projects where it was tested.

DATA COLLECTION

Each of the individual field test projects is described below. Selected data from field tests are presented in each case, and a detailed summary of the data collected is provided in Appendix A.

All of the work zone test sites for this project had the following similarities:

- sight distance from beginning to end of work zone was completely restricted due to hilly terrain;
- all roadways were two-lane facilities in rolling terrain with twelve foot lanes and shoulder widths of three feet or less;
- the maintenance work performed on all three sites involved asphalt pavement repair;
- there were no significant driveways or intersecting streets located within the work zones;
- stop lines were not used in advance of the signal, but a "Stop Here on Red" sign was posted at the desired stopping location in each case; and
- the time required to setup the signal trailers and begin full operation was 38 to 43 minutes, with the setup time decreasing with each successive job.

Test Site 1 - Park Road 37

The first test site is illustrated in Figure 1. Park Road 37 serves Medina Lake (between San Antonio, Texas, and Bandera, Texas) and its lakefront recreational areas, so non-local traffic is encountered on this roadway. Pertinent statistics about this roadway segment and the use of the portable traffic signals include:

Work zone length:	1100 feet
Maintenance activity:	Blade patching/level up
Total number of crew members:	7 persons
Speed limit:	40 mph
Maximum speed through work zone:	33 mph
Average speed near work area:	20 mph
Hourly volume:	184 vehicles
Signal timing:	
Maximum green time:	60 seconds
Red clearance interval:	60 seconds
Maximum wait time:	183 seconds
Number of violations:	2 (during setup only)
Maximum queue length:	9 vehicles
Average queue length:	4 vehicles

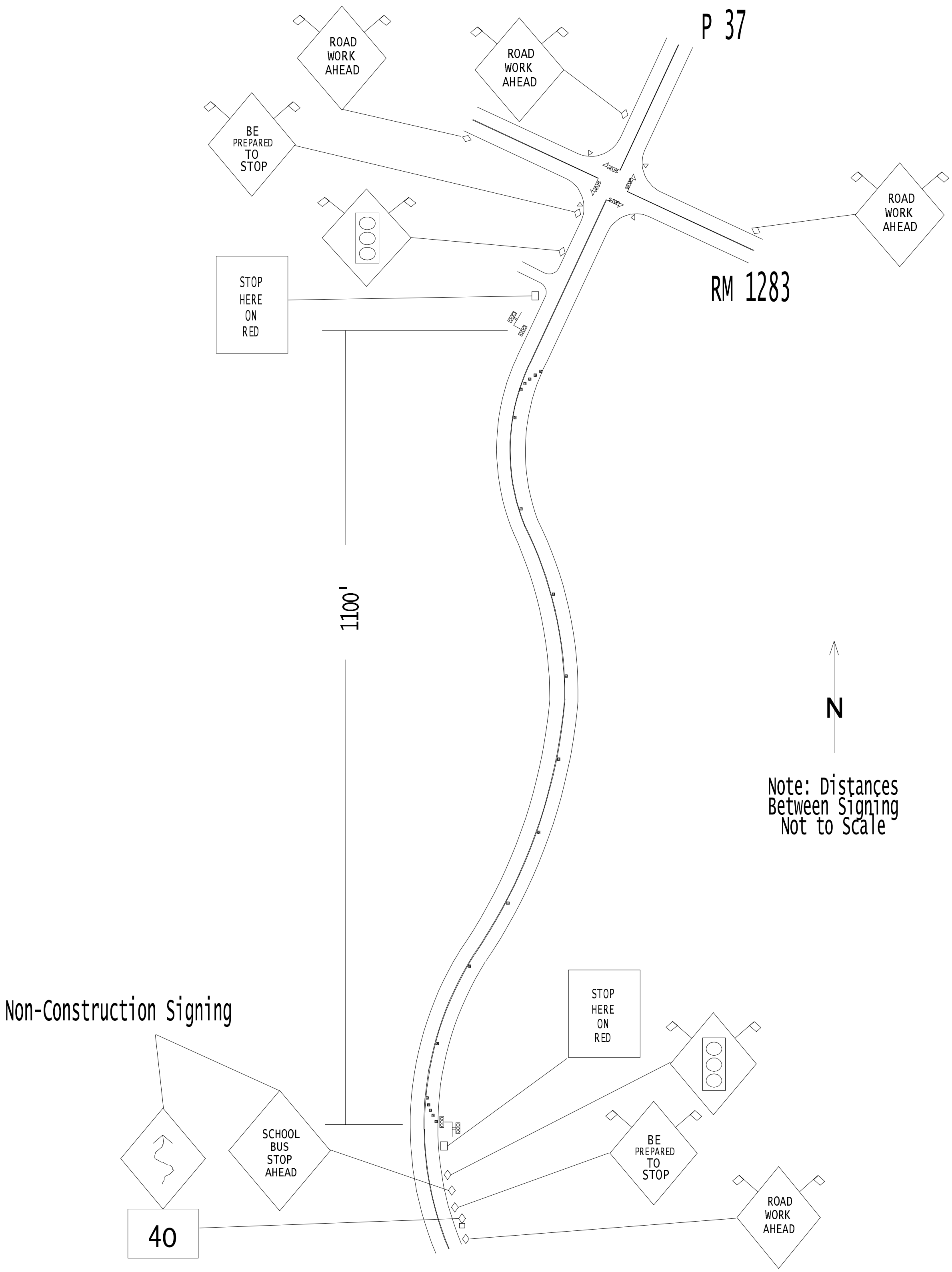


Figure 1. Park Road 37 Portable Traffic Signal Application in Bandera County, Texas.

Test Site 2 - Farm-to-Market 1283

The second test site is illustrated in Figure 2. The site is on FM 1283 in Medina County, Texas near the Bexar County line. Pertinent statistics about this roadway segment and the use of the portable traffic signals include:

ADT (FM 1283):	2800 (1996 count)
Work zone length:	1850 feet
Maintenance activity:	Blade patching/level up
Total number of crew members:	5 persons
Speed limit:	55 mph
Maximum speed through work zone:	34 mph
Average speed near work area:	25 mph
Hourly volume:	136 vehicles
Signal timing:	
Maximum green time:	40 seconds
Red clearance interval:	60 seconds
Maximum wait time:	163 seconds
Number of violations:	Observed during setup only; actual violation count not recorded
Maximum queue length:	6 vehicles
Average queue length:	3 vehicles

Test Site 3 - State Highway 16

The third and final test site was located on SH 16, and it is illustrated in Figure 3. The site is two miles west of the community of Bandera, Texas. Pertinent statistics about this roadway segment and the use of the portable traffic signals include:

ADT:	2500 (1996 count)
Work zone length:	1550 feet
Maintenance activity:	Surface replacement, base repair where needed
Total number of crew members	5 persons
Speed limit:	55 mph
Maximum speed through work zone:	40 mph
Average speed near work area:	25 mph
Hourly volume:	78 vehicles
Signal timing:	
Maximum green time:	35 seconds
Red clearance interval:	35 seconds
Maximum wait time:	108 seconds
Number of violations:	none
Maximum queue length:	3 vehicles
Average queue length:	1 vehicle

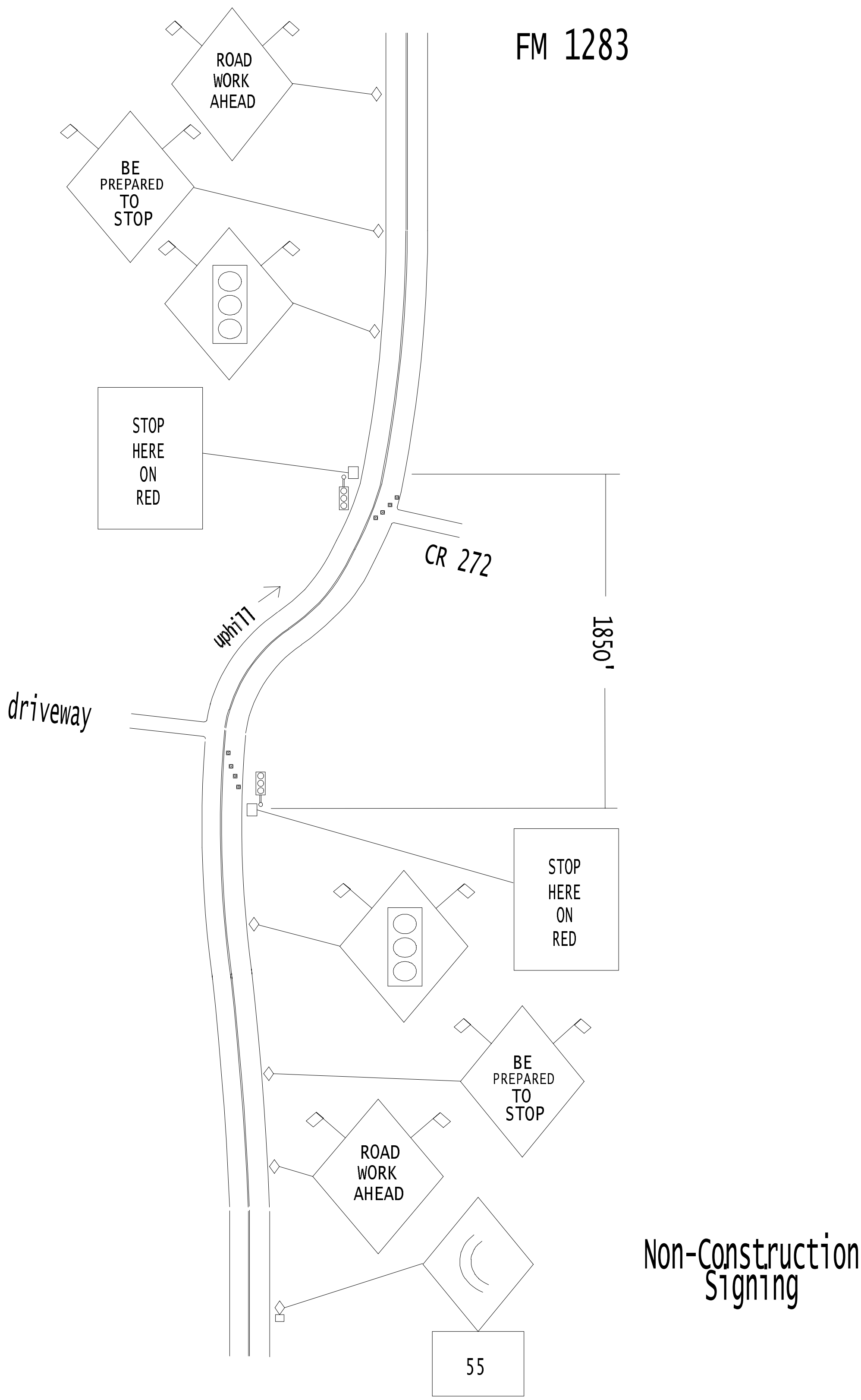


Figure 2. FM 1283 Portable Traffic Signal Application in Bandera County, Texas.

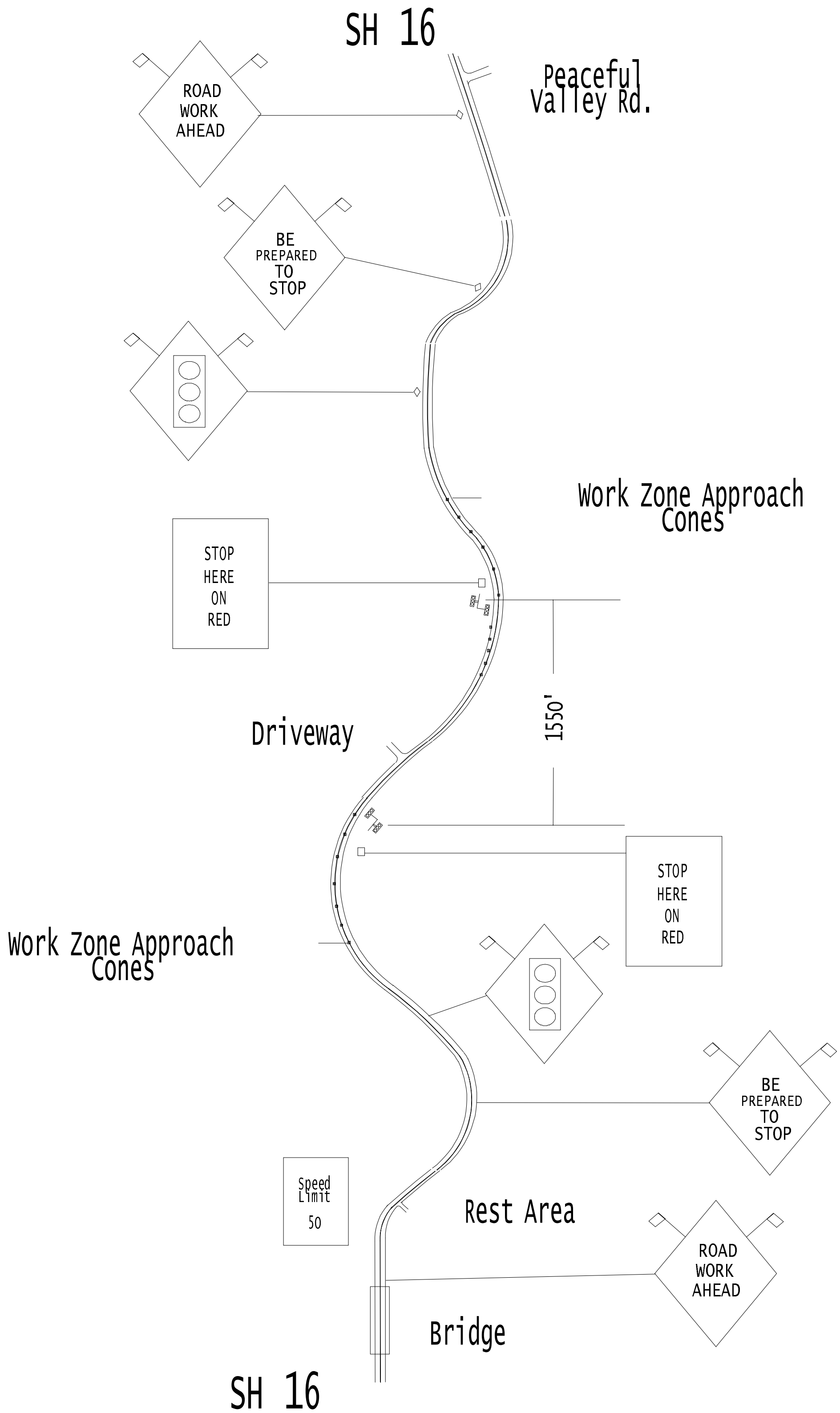


Figure 3. SH 16 Portable Traffic Signal Application in Bandera County, Texas.

ISSUES REVEALED THROUGH FIELD TESTING

The outcome of the three field tests, combined with feedback from employees within the maintenance section directly involved with the application of the equipment, revealed a number of issues to be addressed through this project:

- feasibility of portable signals for maintenance operations;
- driver comprehension and compliance;
- work zone characteristics; and
- traffic signal operating characteristics within work zones.

The last three items are interrelated and contain overlapping concepts. Each of the issues is described in this section. Those that require specific implementation recommendations are presented in depth in the following chapter.

Feasibility for Maintenance Operations

Field testing of the traffic signals proved that there is applicability for pavement repair work. The equipment was not tested for other purposes during this period, although the principles of work zone design and signal operating characteristics in short-term stationary operations are similar to that of other routine maintenance operations. The maintenance personnel were very positive about the use of the signals, particularly because it removed them from the hazardous, tiring, and stressful job of flagging. They felt an increased sense of safety within the work zone, yet still felt that they had maintained continual awareness of traffic flow near the work area.

The critical issue related to maintenance applicability is that of cost effectiveness. Given the current limitations on staffing, elimination of positions is not a reasonable basis for determining cost effectiveness. Instead, the question of cost effectiveness must be answered through increased job efficiency as displaced flaggers are reassigned to other duties.

Driver Comprehension and Compliance

One-lane, one-way work zones are often monitored and controlled by flaggers and/or a combination of flaggers and maintenance vehicles acting as lead vehicles. Due to the limited experience with portable signals in Texas, especially on rural roadways in unpopulated areas, the use of a portable traffic signal may introduce elements of driver confusion and frustration, and thus introduce risk that would not be present to the same extent under flagger-only operations. The red signal indication of a temporary traffic signal may not hold drivers as actively, especially during long wait times, as a flagger at the site. As in any work zone, violation of a flagger or portable traffic signal creates a serious safety hazard for motorists approaching from the opposite direction, as well as for workers. This situation is especially hazardous in one-lane work zones where sight distance is limited.

Temporary traffic signals used in work zones create the appearance and driver expectation of operations similar to that experienced at standard, traffic signal controlled highway intersections. This is unique, though not hazardous, in that no (crossing) conflicting traffic stream is visible, with the exception of oncoming traffic proceeding through the work zone. At common signal installations at intersections, it is possible to see both crossing and opposing traffic movements. In the case of a portable traffic signal in a construction work zone, it may not be possible to see the traffic that will be entering the one-lane, one-way work zone from the opposing direction either because of relief, roadway geometry, or distance. This situation may create a false sense of security pertaining to work zone hazard conditions. During the field tests there appeared to be some driver confusion related to flashing red operation in situations when drivers could not see opposing traffic and thus make a judgement about how to proceed. This was the only operational situation that seemed to create confusion.

The field experience did not indicate any serious problems regarding driver compliance, with the exception of several violations noted during the equipment setup period. During general operation of the signals, workers believed that drivers were less confused by the signal indications than they were with communication by flaggers. Informal surveys of the drivers queued at the signals revealed a clear understanding of the traffic signal and the approach signing.

Work Zone Characteristics

Standards for Traffic Control Devices

The TMUTCD (*3*) provides standards and guidelines for lane closures on two-lane roadways using traffic signals (Part VI, pages 6H-36 and 6H-37). The standards are specifically written for long-term work zones using traffic signals and have certain elements that are not applicable to the short-term lane closures tested in this project. Those elements include maximum work zone length, installation of semi-permanent stop lines and other pavement markings, and flashing red signal operation conditions. Although not directly stated, it is inferred from the provisions of pages 6H-36 and 6H-37 that the construction work zone has clear line of sight from end to end. A revision of the standard is needed that specifically addresses the application of portable traffic signals in short-term stationary maintenance operations during daytime hours.

Visibility of Traffic Control Devices

For any traffic control device to be effective, the device must be visible and able to convey its message with sufficient time for motorist perception and safe reaction. In the case of portable traffic signals, this means that the signal must be located so that no horizontal or vertical obstructions, in reasonable proximity to the signal, obscure the line of sight between the signal and an approaching vehicle. While this consideration is also present in a flagging operation, the height and orientation of signal heads with respect to the roadway require special attention. The height, location, and number of signal head requirements that apply to both portable and permanent traffic signals are found in Part IV, Section B of the TMUTCD (*3*).

Presence of Intersecting Streets and Driveways within the Work Zone

Streets and driveways intersecting a work zone create difficulties for portable signal operation as well as for flagging operation. The problem occurs if a vehicle approaches the work zone from an intersecting street or driveway, cannot clearly determine the current direction of travel, and enters the work zone facing oncoming traffic. The TMUTCD (*2*) states the following regarding one-lane two-way traffic control:

"Access should be controlled throughout the construction or maintenance work zone including all entering intersections within the zone. Driveways create a problem that may be monitored by flaggers."

A detailed study of intrazone access concerns was not prioritized by the sponsors of this project. Instead, the same principles used in flagging operation to address intrazone access are recommended for portable signal operations. Work zones should be planned to exclude intersections of heavily traveled streets. One technician should be stationed on the ground to monitor work zone access if minor streets or driveways cannot be avoided; the responsibility of this technician would be to hold traffic until there is certainty of the direction of travel, either by passing of a platoon of vehicles or through remote signal-monitoring capability. The notification of adjacent property owners by letter or by printed door/gate hanger would provide additional warning about the presence and duration of a one-lane two-way operation.

In addition to providing positive control over streets and driveways, flaggers at traditional one-lane work zones on two-lane highways have also served as lookouts for errant vehicles or other hazards that could penetrate the work zone. While work zone penetrations are events of low probability, their consequences can be extreme for both the motorists and the workers. One consideration that should not be ignored when using devices such as portable traffic signals in place of flaggers is that worker eyes and ears may not be focused on the roadway environment to the extent they would be if flaggers were performing traffic control. Possible means for rectifying the safety implications of not having flaggers acting as lookouts include appointing a crew member the responsibility of alerting workers to any approaching hazards (i.e., possibly the same worker regulating driveway/cross street traffic) or using work zone penetration alarms.

Work Zone Speed Considerations

The speed of traffic traveling through a work zone operated by portable traffic signals is a critical factor in determining clearance interval timings. Work zone speed has a direct impact on safety because the lowest reasonable speed through the work zone is used to compute the red clearance interval. This interval is the fixed time allotted for vehicles to pass through the work zone before opposing traffic is released. In a portable traffic signal application, the concern is not with high speeds through the work zone, but with the lowest speed that motorists will be traveling. The dilemma occurs in situations where a speed is chosen at which motorists are expected to travel, the clearance intervals are set for that chosen speed, and the actual speed of traffic is lower. The potential for the opposing traffic to receive a green indication before traffic is cleared is heightened in these situations.

Limited information exists on establishing speeds and/or the setting of advisory speeds in work zones. Page 6B-2 of Part VI of the TMUTCD *(3)* addresses speed in work zones and states the following:

2. Traffic movement should be inhibited as little as practicable.

   a. Traffic control in work and incident sites should be designed on the assumption that drivers will reduce their speeds only if they clearly perceive a need to do so. Reduced speed zoning should be avoided as much as practical.

In keeping with this concept, Section 3 of the TxDOT *Traffic Operations Manual* *(5)* advises that the regulatory speed limit within a work zone should not be reduced more than ten miles per hour below the posted speed, even in situations where traffic control devices are placed near the travel way, or where workers must work near the travel way without the protection of a positive barrier. Enforceable speed limits in the form of regulatory construction speed zones are not practical in short-term maintenance applications because they require authorization by commission minute or city ordinance in order to be legal. Advisory speed plates used in conjunction with construction signs "can often be used more appropriately than construction regulatory speed signs" *(5)*. Yet, limited information is provided on how to set advisory speed limits in work zones. There is the presumption that the same principles for regulatory signs apply to advisory signs, specifically that the conditions of the roadway will dictate a driver's speed, and that significant reductions in posted speed limit should be avoided. None of these guidelines address minimum speeds in work zones, which is the critical concern in portable traffic signal operation within one-lane work zones. Work zones controlled by portable signals are the only apparent work zone situation where minimum speeds would be of concern.

The limited test cases performed in this project provided some evidence that drivers reduced their speeds given the roadway geometrics and traffic control devices within the work zone. However, there is not sufficient data to determine the relationship between posted speed limit and actual speeds, or the variability of speeds at which motorists drive through these kinds of work zones.

Traffic Signal Operation in a Work Zone

Portable traffic signals were designed for a number of construction work zone applications, ranging from long-term installation on two-lane bridges that are reduced to one lane during construction work, to temporarily replacing permanent signals during signal-related reconstruction. In the current project, portable signals were used along rural two-lane roadways that were reduced to one-lane operation during roadway maintenance work. In all applications, the portable signals were used for no longer than eight hours. The essential function of the portable signals in these rural, one-lane maintenance zones was to replace human flagging operations. Once freed from the task of flagging, construction maintenance staff could be better utilized within the work zone.

In their function of replacing human flaggers, the portable signals use a green signal indication to replace the "proceed" hand signal, "GO" sign paddle, or "SLOW" sign paddle of a human flagger. For all of these indications, the message to motorists is that it is safe to proceed cautiously through the work zone, and that all conflicting traffic and maintenance equipment is not within the open lane of the work zone. To warn motorists that the green, or "GO," signal is terminating, portable signals use a yellow signal indication. A similar signal from a human flagger would be an outstretched palm or the fact that the flagger has turned a sign paddle to "STOP." The portable traffic signal's red indication indicates that it is no longer safe to enter the work zone. Traffic that is safely within the zone will be allowed sufficient time to clear the zone before a green signal indication is given for traffic in the opposing direction.

Human flaggers make use of a variety of devices and techniques to ensure safe traffic control coordination during flagging operations. The most common device is a hand-held radio, or walkie-talkie. By means of the radio, flaggers at each end of the work zone keep one another informed of the status of traffic proceeding through the zone. Similarly, portable traffic signals at each end of the work zone employ means of communication to ensure that they do not display conflicting signal indications. This communication varies by the length and duration of the work zone, but includes wireline options, such as hardwire conductor, and wireless options, including spread spectrum radio, microwave, or even satellite radio signals. The communications media must be checked for its ability to operate under harsh conditions, including electromagnetic interference, adverse weather (especially lightning strikes), and the impacts of rolling or mountainous terrain.

During some types of roadway maintenance work, it is necessary to temporarily halt traffic in both directions while equipment is moved or for paving applications. In a work zone managed by flaggers, each flagger would receive the message (probably by walkie-talkie) that the vehicles currently in the work zone should be allowed to proceed through, but to halt any other vehicles from entering the zone until they receive a message to resume flagging operation. With a portable traffic signal, the signals themselves can be set (either manually by a worker, or using a remote control device) to "rest in red" until the activity requiring total road closure is complete.

All activity of the portable traffic signals is controlled by carefully designed control logic that allows vehicles to enter the work zone only when it is safe. The control logic can even be monitored by an external conflict-monitoring device, known as a watchdog. The primary purpose of the control logic checks and the watchdog is to ensure that conflicting signal indications are not presented to vehicles at either end of the work zone. Both checks also ensure that vehicles that have appropriately entered the work zone have sufficient clearance time to safely proceed through and exit the one-lane work area.

Traffic Signal Control Modes of Operation

Multiple options exist for the programming of the signal controllers within the portable traffic signal devices. The two units (i.e., one at each end of the work zone) can be operated in a pretimed mode, which has a fixed duration green and clearance period for both approaching directions of traffic. Alternatively, the devices can be operated in one of several traffic actuated modes, which tend to be more responsive to real-time traffic demand at each signal. In either mode of operation, the portable traffic signals are programmed such that adequate time is available to clear vehicles once they have entered the one-lane work zone. Checks are in place in the form of a conflict monitor to ensure that conflicting indications are not presented by the signals.

Pretimed Operation In pretimed mode, the portable signals rely on a background cycle length that is composed of the time required for the green and yellow indications on each side of the work zone, and twice the clearance time plus buffer time (clearance time is usually the same for both directions). From cycle to cycle, the duration of each green indication is the same, regardless of how many vehicles are present in the queue that is stopped at the signal. Initial timing of the greens for each of the two approaches requires foreknowledge of the quantity and variability of traffic expected to pass through the work zone. Pretimed operation is appropriate for predictable traffic volumes of low to high intensity, lower traffic volumes of an intermittent nature, and as a default mode if problems are encountered with vehicle detector sensing equipment (a situation which would render actuated mode ineffective).

Traffic Actuated Operation (Red Rest) Operation of the portable traffic signals in an actuated mode implies that some form of detection technology is being used at the site to identify the presence of, and possibly keep a running count of, vehicles that approach each side of the maintenance work zone. The most conservative form of actuated control has the portable signals displaying a red indication to each side of the work zone until the detectors sense an approaching vehicle. If the clearance time has expired (i.e., any vehicles previously in the work zone have safely cleared), any vehicle approaching the signal will receive a green indication. If only one vehicle is detected, the green is displayed for the minimum green time and then the signal controller transitions to a yellow clearance interval before returning to rest in red. If more than one vehicle is in queue at the start of the green indication, detection of the multiple vehicles will result in the green indication being extended, where the upper limit of a series of extensions is the maximum green time. If the detectors sense a vehicle coming from the same direction as a vehicle that has just received the green (but the controller has already advanced back to the red rest state), the controller immediately advances to green for the approaching vehicle. This series of events would not take place if the second vehicle approached the work zone from the opposing direction, as the controllers would have to wait for the first vehicle to clear through the work zone before giving an opposing vehicle a green indication.

The signal controller begins timing the red clearance interval when the red signal indication is displayed. Essentially, the red clearance interval is the time required for a motorist to safely proceed through the work zone and have some "buffer" time between their departure from the work zone and the beginning of an opposing green indication (if a vehicle were present in queue waiting to enter the work zone from the opposing direction).

Traffic Actuated Operation (Favoring One Direction) The signals can also be set to rest in green, rather than red, for the higher volume direction of traffic, while resting in red for the opposing, lower volume direction. In this mode, the signal controller will rest in green for the higher volume approach and will only advance through yellow and red clearance to give the green to the lower volume approach when the detector senses a vehicle on that approach. If more than one vehicle is in queue on the lower volume approach, the green can be extended up to the maximum green time for that approach.

Traffic Actuated Operation (Recall to Minimum Green for Both Directions) The portable signal controllers can also be set to give at least a minimum green, yellow, and red clearance time, in succession, to each direction of traffic. This mode would operate almost like a pretimed operation, but on each side of the work zone the green could be extended longer than the minimum time if multiple vehicles were waiting on that approach. As in all other modes of actuated operation, an upper limit of green time for each side, known as the maximum green time, prevents a long queue of vehicles on one side from holding the green too long and causing unacceptable delays to traffic in the opposing direction.

Manual Operation Rather than using one of the automatic cycling modes of the signal controllers (i.e., pretimed or any of the actuated modes), the signals can also be manually operated by a member of the construction work crew. Such operation may be desirable if short-term detector problems are encountered, if highly variable volumes exceed the programmed maximum green times (and the controller has not yet been reset to handle the volume increase), or if work zone activity necessitates an unusual schedule of traffic flow interruptions. In manual mode, the controller can be advanced to green in either direction, or set to red for both directions. However, all red clearance times are observed by the controller (i.e., manually switching from green at one side to green at the other side does not switch off one green and turn on the other green right away – red clearance remains enforced). Also, in addition to the red rest mode, the controller can also be manually set to flash in red (if both ends of the work zone are in the line of sight of motorists in the opposing direction), flash in yellow (during work zone setup and take-down, while both directions of traffic remain open), and hold in red for both approaches (for temporary work across the entire roadway).

Signal System Safety and Communication

In all modes of operation the indications presented to motorists by the signals are monitored by a conflict monitor, or watchdog device. This device operates independently from the internal electronics that perform the controller timing functions, and exists solely to determine whether or not the controller logic attempts to implement settings that violate clearance times or present conflicting phase indications simultaneously. If the watchdog detects any abnormalities in the timing instructions output by the controller logic, it will customarily go to flashing red for all approaches. However, some variability exists as to how the watchdog response is programmed. For instance, if both ends of the work zone are not visible to one another, the watchdog might be set to solid red for both directions, indicating that it is unsafe to enter the work zone, if it detects any problems with the signal output of the controller.

Communication is necessary between the two controllers that control the ends of the work zone. This communication may be in the form of hardwire or wireless communication. In most cases, the portable nature of the devices necessitates wireless (i.e., radio wave) communication; however, in long-term and relatively short work zones, hardwiring the two signals together may be the most reliable means to interconnect their controllers. In all cases, the communications media must be checked for its ability to operate under harsh conditions, including electromagnetic interference, adverse weather (especially lightning strikes), and the influences of rolling or mountainous terrain.

Relationship Between Length of the Work Zone and Signal Timing

One of the most important issues affecting the operation of portable traffic signals is the maximum amount of time motorists are willing to wait at the portable signal on a red indication. In signal operations at permanent sites, the maximum wait time is some percentage of the total cycle length, where cycle lengths usually do not exceed three to four minutes. In essence, there exists a maximum wait time beyond which motorists become impatient and begin taking risks. At work zones where flaggers are present, motorist impatience can be quelled by knowledge that the flagger is holding traffic for an excessively long time either because of long vehicle clearance times or because maintenance equipment is temporarily using both travel lanes. In the case of the portable signal, there is no indication of authority (i.e., in the body of the flagger) associated with the cause of the long delay.

Motorists facing a long red at the portable signal may, therefore, judge that the signal is malfunctioning and proceed through the work zone. This can create a tremendous hazard, as the dangers present in work zones exist for workers as well as for motorists. Further, the limited space available in the one-lane work zone leaves little space cushion for error in a situation where a motorist violates the signal and is faced with a platoon coming from the opposite direction, heavy and cumbersome maintenance equipment, or workers in the lane.

Related to the maximum wait time at the signals are issues such as whether or not a line of sight is available to the other side of the work zone (i.e., stopped vehicles queued in the opposing direction), the speed at which motorists proceed through the zone, the overall length of the zone, and the phase settings of the portable signal controllers. At reasonable speeds in a work zone area (i.e., approximately 20 mph), a practical upper limit is placed on the length of the work zone based on how long motorists are willing to wait at a red indication at a portable traffic signal.

Flashing Red Operational and Safety Issues

The portable traffic signal control equipment used during this project was originally equipped with only a flashing red indication that would be displayed during equipment setup or take-down, and before or after normal work-zone signal timing operation. For long-term work activity, Part VI of the TMUTCD *(3)* requires that when a "signal is changed to a flash condition either manually or automatically, red shall be flashed to both approaches." This type of flash condition provides the safest operation of traffic, especially at night when workers/flaggers are not present. It also presumes there is a clear line of sight from one end of the work zone to the other. Motorists are required to stop at the flashing red signal, assess the traffic from the opposite approach, and determine when it is safe to proceed into a single, two-way designated (single) lane. However, the flashing red indication in the test cases was observed to create a driver perception problem in that, at a normal intersection operating in a flashing red mode, it is necessary to stop but then proceed directly if there are no conflicting vehicles in the intersection or at its approaches. The lack of a clear line of sight to the opposing traffic stream is the factor attributed to this particular driver reaction.

Temporary Closure of Both Directions Under Portable Traffic Signal Control

At intermittent times during some types of maintenance work, it is necessary to close both directions of a two-lane facility. This can occur during some paving applications, for the application of tack or prime coats, or for the reorientation of equipment. In these cases, flaggers at the site would be notified (most often by hand-held radio) that traffic is not allowed to proceed in either direction. Under a portable traffic signal application, interruption of the normal cycle is not possible unless a worker manually (or remotely, using a hand-held controlling device) sets the master signal controller into locking red rest, or hold in red, mode.

CHAPTER 3. FINDINGS AND RECOMMENDATIONS

The findings and recommendations presented in this chapter address the unresolved issues presented in the previous chapter. This chapter is divided into four sections:

- Applicability of Portable Signals to Maintenance Operations;
- Standards for Work Zone Traffic Control;
- Traffic Signal Operation in Work Zones; and
- Equipment Characteristics in Maintenance Applications.

APPLICABILITY OF PORTABLE SIGNALS TO MAINTENANCE OPERATIONS

The suitability of portable traffic signals for long-term bridge construction projects on two-lane highways has been demonstrated in Texas. Portable signal application in daily work zones has not been practiced in Texas, although this technology has been used by maintenance crews in other states for routine pavement repairs and emergency situations. The possible routine maintenance applications that have been identified are:

- pavement repair - blade patching, level-up, surface replacement, base repair;
- roadside maintenance - guardrail repair, ditch maintenance;
- bridge maintenance - rail repair, slope repair; and
- emergency situations - pavement failures, culvert washouts, rock slides.

Field testing of the equipment proved that there is applicability for pavement repair. The equipment has not been used for other purposes, although the principles of work zone design and signal operating characteristics in short-term stationary operations are similar.

The transfer of the technology from long-term construction to daily maintenance operations is technically feasible. While there may be unique conditions in maintenance work zones and the need for clear guidelines for use, the question lies in whether the expected frequency of use is enough to justify the expense. The field tests performed under this project shed light on the factors that impact cost effectiveness, but provided limited data to thoroughly analyze benefits and costs.

Cost Effectiveness

Elimination of a Full-time Position

While a simplistic approach to analyzing cost effectiveness would be to assume that two full-time positions would be eliminated as a result of the application of this equipment, the reality is that many maintenance sections are already functioning with insufficient staff and would, instead, use those displaced crew members to improve the efficiency of their operation. In the test cases, the crew found it was still important to have one individual stationed on the ground to monitor traffic operations and assist with work tasks as needed. If positions would, in fact, be eliminated by use of the technology, then it is most realistic to assume that one, and not both positions, would be eliminated.

Using the simplistic approach that assumes one position would be eliminated or reassigned to another district function, the savings accrued from the equipment would be the difference between the costs of the equipment, training, and daily operations versus the costs for one full-time employee position. Using values specific to the case study in Bandera, the savings are calculated as follows:

Savings in Year 1 = 0
Savings in Year 2 = 0 (cumulative)
Savings in Year 3 = $31,700
Savings in subsequent years = $30,000 per year average

Given that equipment costs are $65,000, the savings will not begin accruing until the third year under this scenario. According to the calculations, the equipment pays for itself in 24 months if it replaces one full-time staff position. Detailed calculations and assumptions are provided in Appendix B.

The calculations presented above rely exclusively on the premise of eliminating a full-time flagger position as the basis for determining cost savings. The maintenance section testing the equipment for this project had faced staff reductions over several years and was not able to further reduce their staffing level. In other words, the maintenance section utilized the portable signals to replace a full-time position on those days in which the equipment was used. At the frequency of use demonstrated during the testing period, which was an average of four days per month, it would take more than twenty years to realize a return on the investment (see Appendix B). Not factored into this analysis were the savings in crew efficiency due to the increase in personnel working on the specific maintenance task. Higher frequency of use, through application of the technology to more maintenance functions and shared use with neighboring maintenance sections, would obviously reduce this "return on investment" time period.

Increase in Efficiency

There are cost savings not accounted for in the above calculations that relate to the increased job efficiency resulting from use of the signals. The Bandera Maintenance Section approached the portable signal technology primarily as a means to assign flagging personnel to other critical duties, and thus to increase flexibility within the work unit. The anecdotal evidence was noted during the field tests. The reassignment of flaggers resulted in:

- increased utilization of equipment and trucks, which reduced the time to complete pavement repair jobs;
- the ability in one instance to simultaneously perform work with a small grader on a separate project - work that would not have been possible without the signals; and
- the ability to overcome otherwise low-productive days, when the crew was shorthanded, by allowing work to proceed.

Given the differences in the size and scope of the three test cases examined under this project, it is difficult to use the limited test experience to pinpoint specific savings in job efficiencies.

As a hypothetical case, it is assumed that the availability of one additional crew member provides an added six-yard dump truck for a five-day, full-depth pavement repair project. The additional truck enables the project to be completed in four days instead of five, saving the expense in employees, equipment operation, and delay to motorists for that additional day. In this hypothetical case, the savings would be approximately $1075 per day, and an average of $20,000 per year after the fourth year of use, assuming the signals were used on two pavement repair projects of similar scope on a monthly basis. Note that the signals would not pay for themselves for the first 2.8 years, accruing the average of $20,000 savings annually for each subsequent year (see Appendix B).

It is also important to recognize that portable traffic signals relieve maintenance personnel of the physical demands of flagging, such as fatigue, stress, and hazards associated with being in close proximity to moving traffic. The *Handbook of Safe Practices* issued by the Occupational Safety Division of TxDOT states the following: "To help prevent fatigue, flaggers should be rotated at a minimum of every two hours." (*2*). This expectation necessitates that all maintenance employees have interchangeable skills, which is not always practical or realistic. Alternatively, it requires the hiring of additional personnel. Portable signals address the concerns related to the physical demands of flagging, yet this particular benefit is difficult to quantify.

Frequency of Use

The savings in efficiency that can be realized through the use of portable signal technology in maintenance operations are highly dependent upon the frequency of use. The field tests revealed the following factors that can contribute to increased utilization:

- a critical need for better utilization of staff resources, primarily as a result of staffing limitations;
- a willingness to experiment with a new method of traffic control, and the leadership within the section to support it;
- a single individual within the section to whom the equipment can be assigned and who has responsibility for fully understanding its operation and for performing necessary routine maintenance;
- a commitment to consistent use - familiarity and experience with the equipment generates ideas for additional applications and increases general usage; and,
- proximity to adjacent maintenance sections who can share in its use.

Based on the cost-effectiveness calculations performed above and general observations from field testing, a reasonable guideline for frequency of use is an average of ten to twelve days per month. With this frequency of use, the signal equipment will pay for itself in approximately three years and accrue significant annual savings thereafter. Savings can be realized more quickly with more frequent use.

Summary of Findings for Maintenance Applicability

Using the field tests performed under this project as the basis of the findings, the applicability of portable traffic signals can be summarized as follows:

- Portable traffic signals are technically feasible as a replacement for flaggers in two-lane rural work zones for pavement repair projects. Although not specifically tested in other routine maintenance tasks, they do have applicability under similar work zone characteristics.

- The cost-effectiveness of portable signals in daily maintenance operations was difficult to ascertain given the limited testing experience under this research project. Anecdotal evidence from the field test cases supports the use of portable signals in maintenance operations as a means of improving crew efficiency and flexibility.

- Two different scenarios are examined in this project in an effort to establish general guidelines for use that would enhance cost effectiveness. The first scenario is the replacement of one full-time position. The second scenario is a hypothetical maintenance project where job efficiency was improved through reassignment of flaggers. In both scenarios, savings begin accruing after two years of operation and are estimated in subsequent years at approximately $20,000 to $30,000 per year.

- The primary factor contributing to cost effectiveness of portable signals to improve work efficiency (i.e., reassignment of flaggers to other work tasks) is the frequency of use. Based on the cost-effectiveness analysis, a return on investment after two years can be realized if the average use of the equipment is eight to ten days per month. Higher frequency of use to accrue savings more quickly will require creative application in a wider range of routine maintenance jobs and emergency situations, shared use with neighboring maintenance sections, and utilization of the signals on construction projects within the area.

STANDARDS FOR WORK ZONE TRAFFIC CONTROL

Proposed MUTCD Revisions

This section outlines the proposed revisions to Part VI of the TMUTCD (*3*), addressing the use of temporary, portable traffic signals for short-term stationary work. This type of work will typically involve stationary daytime maintenance activities that occupy a location from 1 to 10 hours and where a lane closure on a two-lane road necessitates the use of either flaggers or traffic signals to control traffic in both directions during a lane closure. These types of maintenance activities include blade patches, shoulder and slope repairs, guardrail repairs, and ditch maintenance. The work could also include the use of the signals during emergency situations where portable traffic signals are necessary (in lieu of flaggers) to repair rock slides, washouts, or pavement failures.

Because of the numerous limitations imposed by the existing guidelines in the TMUTCD for the use of temporary, portable traffic signals, maintenance personnel are unable to apply these guidelines for their use in short-term, stationary work activity. As mentioned in the previous section, the staff requirements for certain maintenance activities could be reduced and/or the maintenance budgets could be better utilized with the adoption of guidelines for temporary, portable traffic signals for use in short-term projects.

The current revision of Part VI of the TMUTCD (*3*) establishes the guidelines for lane closures on two-lane roadways using temporary, portable traffic signals. The guidelines address fundamental, but essential, issues such as the maximum length of the work activity area, signal display requirements, sight distance, and placement of traffic control devices in advance and in the vicinity of the work activity. The procedures for this type of lane closure are recommended for long-term projects where the work activity will occupy a location for more than three days and where it is impractical to have flaggers present during nighttime operation of the signals.

Duration of Work

To use traffic signals for controlling traffic in construction/maintenance work zones, the TMUTCD currently recommends their use only in long-term stationary work, with an emphasis on visibility (during nighttime work especially) and minimal displacement of devices. Long-term stationary work allows maintenance personnel to install a full range of traffic control devices during both daytime and nighttime work. Generally, more retroreflective and better-illuminated devices are used in long-term work zones to provide for better visibility, especially during nighttime operation of the devices when no workers may be present. Also, the devices used during long-term work zones are typically permanent and more durable so that minimal displacement occurs when workers are not present.

Traffic signals are ideal devices for long-term stationary work. The limitation for maintenance personnel, however, is the fact that no guidelines are provided in the TMUTCD for the use of traffic signals during short-term stationary work. Most maintenance and utility work is daytime, short-term duration work and the use of flaggers may be necessary to monitor traffic in some situations. It is for this reason that traffic signals could be utilized in short-term work so as to better utilize the talents of the work crew. Furthermore, for this type of work, fewer devices of a more temporary nature are typically used, simply to minimize setup and take-down time for the workers. One device that is temporary is the portable traffic signal, the same type of device that is suggested for use in long-term work zones for controlling traffic when flaggers are not present.

Maximum Length of Work Zone

The maximum length recommended between traffic signals during long-term stationary work (typically during two-lane, one-way operation) is 400 feet (*3*). The primary reason for the recommendation of this relatively short distance is due to the possibilities of a malfunction of the signals when flaggers are not present (typically at night). If a malfunction occurs, the signals would change to a flashing red condition. If a driver approaches on a flashing red, they must be able to see the opposite end of the work zone to determine if the single through lane is safe for travel.

The limitation of the suggested length with respect to short-term stationary work is the fact that most maintenance work is generally performed during the daytime and workers are always present. In the event of a malfunction, flaggers would assume traffic control responsibilities until the signals are functioning again properly. Thus, there is not as critical a need for drivers to have a line of sight to the opposite end of the work area. Therefore, the maximum length of the work area for short-term stationary work could be much greater.

Illumination

Illumination of the work zone and of the traffic control devices is required during long-term work activities because of the nighttime operation of the devices. Illumination is achieved with the use of flashing beacons, reflectors, and/or overhead illumination to improve nighttime visibility. With short-term maintenance work, illuminated devices are not necessary because the work is performed during the daytime. Illuminated devices would also be costly and time consuming to setup and take-down during short-term maintenance work.

Traffic Control Devices

As mentioned previously, the use of traffic control devices in a long-term stationary work zone is generally permanent and has a higher visibility/retroreflectivity requirement. An example would be the use of permanent pavement markings to delineate temporary changes in the passing/no passing zones on the approach to and through the work zone activity, and the use of more beacons and channelizing devices to delineate paths of travel, especially at night. In short-term maintenance work zones, it would be impractical from a time and cost perspective for work crews to modify pavement markings or to install as many channelizing devices as are used during long-term projects. Safety should still be a priority, but fewer device placements and/or modifications would be required during short-term work activity.

Flashing Operation of Traffic Signals

For long-term work activity, the TMUTCD (*3*) requires that when a "signal is changed to a flash condition either manually or automatically, red shall be flashed to both approaches." This type of flash condition provides the safest operation of traffic, especially at night when workers/flaggers are not present. Motorists are required to stop at the flashing red signal, assess the traffic from the opposite approach, and determine when it is safe to proceed into a single, two-way designated lane.

For short-term work activity, work crews could benefit by having the ability to manually program the portable traffic signals to flash either in amber or in red, depending upon the progress of work or the presence of workers. During the setup or take-down of the maintenance work area, including the placement/removal of all signs and the programming of the signal controllers, a flashing amber condition should be allowed. During these time periods, no work has actually begun or is complete, and all lanes are open for travel. If the signals are only allowed to flash red during this time, motorists could be easily misled by the flash condition and by seeing all lanes open for travel. Such a scenario establishes an erroneous expectancy for the driver the next time they approach such a traffic signal operation during maintenance activity and one or more of the lanes are temporarily closed.

Other times when all lanes are open would be ideal opportunities to manually change the signals to a flashing amber condition. These times would include extended breaks for lunch or when work crews have completed the maintenance work and are awaiting materials or instructions for their next task(s).

Flashing red would still have an important purpose during short-term maintenance work, especially during automatic changes to the signal timing due to malfunctions. When such a scenario occurs, however, work crews must be prepared to assume flagging responsibilities until the traffic signals are functioning again properly, especially if limited sight distance exists between the two traffic signals. A manual change to constant, solid or flashing red also has a purpose if work crews require the use of all lanes of travel for temporary work tasks, such as turning equipment around.

Proposed Changes for Short-Term Maintenance Work

The proposed changes for the utilization of portable, temporary traffic signals for short-term stationary maintenance work activity are addressed in Table 1 and Figure 4.

Table 1. Proposed Changes for the Use of Traffic Signals for Short-Term Stationary Maintenance Work

Condition	Existing (Pg 6H-36, Part VI, Texas MUTCD)	Proposed (Part VI, Texas MUTCD)
Work Duration	Long-Term Stationary	Short-Term Stationary
Type of Work	Day/night construction (bridge, lane)	Daytime maintenance work (pavement, ditch, roadside, bridge maintenance and emergency situations)
Length of Work Activity	Max. 400 feet	Max. 2,600 feet
Illumination	Required	Not required
Traffic Control	Permanent signing (rigid) Permanent pavement markings Adequate channeling devices Higher retroreflectivity	Temporary rigning (can be flexible) No modification to pavement markings Minimum no. of channelizing devices Retroreflectivity not critical
Flashing Operation	Red only	Amber - all lanes open Red - malfunction, manual set
Other Conditions		
Sight Distance	Required to each end	Not required to each end
Driveways/ Intersections	Not located within activity area (flag otherwise)	Not located within activity area (flag otherwise)
Stop Lines	Shall be installed	May be installed

Posted Speed (MPH)	"X" Sign Spacings (Feet)	"X" Sign Spacings (Meters)
30 or less	120	40
35	160	50
40	240	75
45	320	100
50	400	120
55	500	150

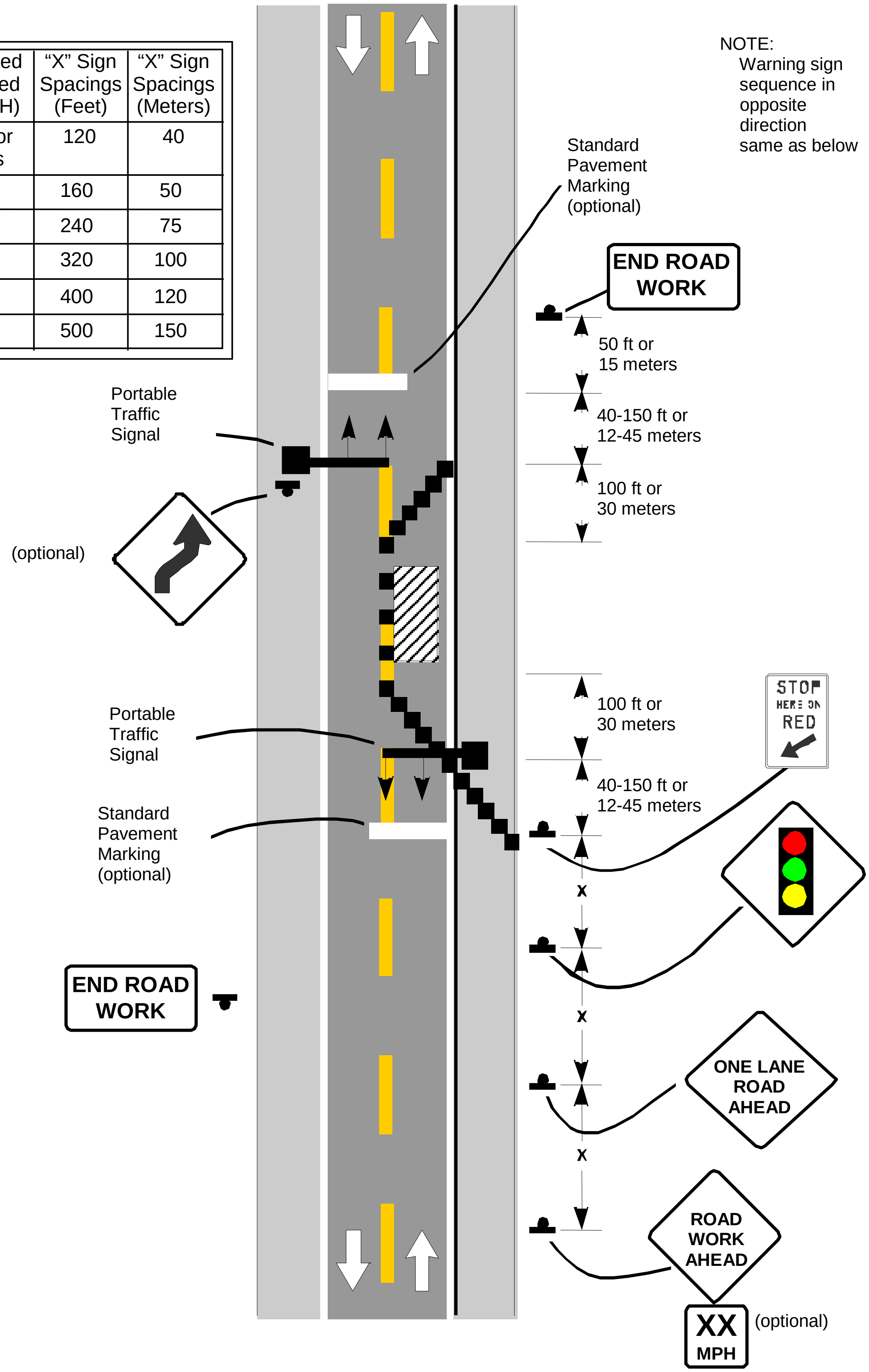


Figure 4. Proposed Changes in the Use and Placement of Traffic Control Devices for Short-Term Stationary Maintenance Work

Sight Distance Considerations

Visibility of traffic control devices is a critical factor in their effectiveness. Figure 5 and Figure 6 illustrate improper placement of portable traffic signals due to horizontal and vertical geometric limitations, respectively.

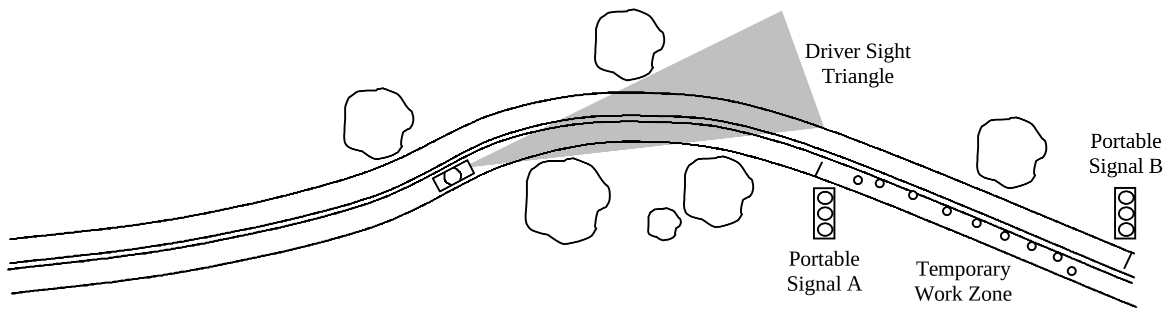


Figure 5. Driver Line of Sight Impeded by Horizontal Geometry and Roadside Objects

Figure 6. Driver Line of Sight Impeded by Vertical Geometry

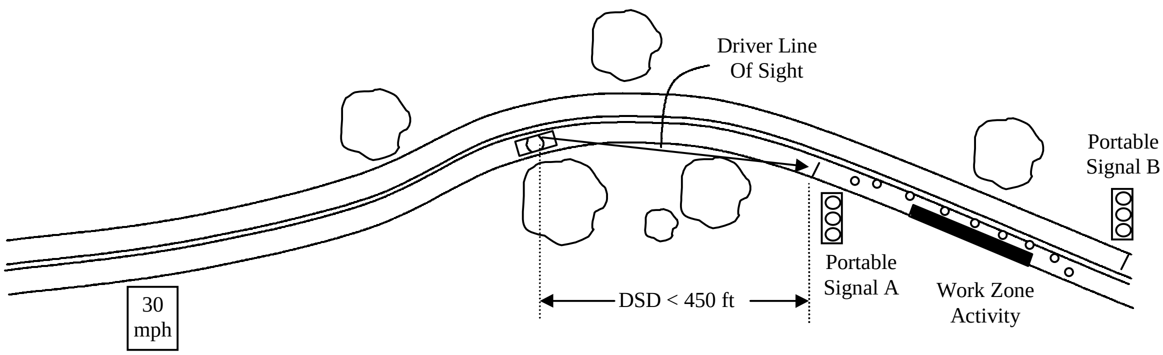
The TMUTCD *(3)* and the national MUTCD *(6)* specifies that all traffic signals have at least two signal heads per approach. If any signal heads are located above a travel lane, the bottom of such a signal head must be at least 15 feet in height, but no greater that 19 feet high. Both the presence of the work zone and the signal heads must be visible to approaching traffic. Advanced signing assists with alerting motorists to the presence of the work zone they are approaching.

Decision sight distance (DSD) is that distance required for a driver to perceive an unexpected or complex situation, arrive at a decision regarding the course of action, and execute that decision in a reasonable manner *(7)*. Such driver behavior takes considerably longer time and hence greater distance than that produced by stopping sight distance alone. Table 2 summarizes DSD requirements for a range of design speeds and conditions *(8)*. Designers should avoid locating intersections, lane drops, or horizontal alignment changes (all of which are present to some degree in the application of portable traffic signals to construction work zones) where DSD is difficult or impossible to achieve.

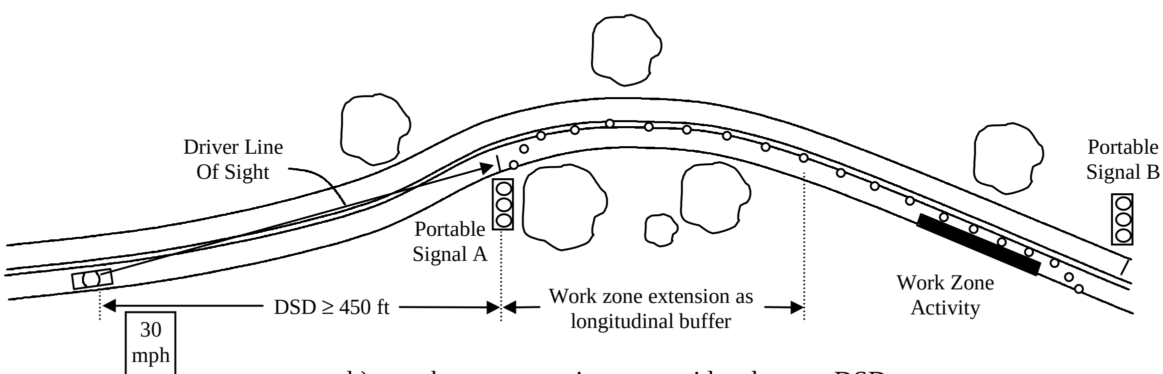
Table 2. Decision Sight Distance (*7*)

Design Speed (mph)	Decision sight distance for rural road speed/path/direction change (feet)
30	450
40	600
50	750
60	1000
70	1100

The DSD values provided in Table 2 are those necessary for drivers in environments of combined horizontal and vertical curvature in which complex conditions (such as construction work zones) must be perceived, and for which an appropriate response must be decided upon and enacted. If DSD is not available, the limits of the work zone should be extended to include the obstruction (i.e., horizontal curve, vertical curve, roadside object) that is limiting sight distance until desired DSD is available on both approaches (see Figure 7).



a). inadequate DSD (450 ft necessary at 30 mph) for safe work zone approach



b). work zone extension to provide adequate DSD

Figure 7. Example of Work Zone Extension to Obtain Decision Sight Distance

An additional restriction occurs when it is reasonable to expect a queue of vehicles to be located at the signal. In this case, it is necessary for the driver to perceive the rear (or, more specifically, the rear tail/braking lights) of the last vehicle in queue. However, the stopping sight distance required to respond to a vehicle stopped in the roadway is inherently considered in proper roadway design, and will not be discussed here.

TRAFFIC SIGNAL OPERATION IN WORK ZONES

Portable traffic signals are classified as "traffic control signals" under the provisions of the 4B-4 of the TMUTCD (*3*). As such, they are required to meet both the physical display and operational requirements of conventional traffic signals. According to the TMUTCD, a thorough engineering study of roadway and traffic conditions is required prior to the use of these devices. Therefore, consistency with the TMUTCD requires that the development of signal timing involve an experienced engineer who can assess the roadway and traffic conditions that are unique to each individual site, and make timing decisions accordingly.

The results of this research project regarding the applicability of portable traffic signals to maintenance operations indicate that the equipment should be used for routine maintenance projects an average of ten to twelve days per month. Given the organizational structure of TxDOT and the limited availability of signal engineers, especially in geographically-dispersed rural districts, it is not practical to expect that an engineering study be performed for two or more different signal applications per month.

Portable traffic signals are similar to typical traffic signals both in appearance and in the means by which they communicate with the driver. However, one might argue that portable traffic signal installations differ from standard signal installations in their purpose and function. They are used in work zone situations as devices for effectively metering traffic in a method similar to flaggers. The sequence of signal phases is never modified from project to project, only the length of time for each phase and associated clearance intervals. Throughout the state there are qualified and experienced technicians who, as part of their everyday work responsibility and function, adjust signal timing at intersections controlled by standard traffic signals without modifying the phasing.

Nevertheless, there are two concerns that prevail. First, the TMUTCD (*3*) and MUTCD (*6*) clearly state that an engineering study must be performed in conjunction with the use of portable traffic signals. Any practice in conflict with this standard exposes the responsible agency to liability. Second, there are a variety of field conditions that are difficult to capture in a single "cookbook" approach to portable signal implementation, particularly related to sight distance and work zone speed. The speed issue in particular is troublesome because it is integral to developing appropriate signal timings and clearance intervals, and little guidance is offered in Part VI of the TMUTCD (*3*) for handling speeds in one-lane work zones. These are situations in which the oversight of a professional engineer is warranted.

Considering these issues and concerns, the authors have developed conservative field implementation guidelines that minimize risk to the greatest extent possible, with safety being the primary consideration. Phase length for the red clearance interval, in particular, is based on the lowest reasonable speed through the work zone to insure the full clearance of the work zone by vehicles before the opposing green phase begins. A maximum reasonable driver wait time of four minutes has been established as a means to limit risk-taking by drivers who perceive an unreasonable length of time waiting for a green indication. The use of conservative guidelines to minimize safety risks will impact the efficiency of the operation, both in terms of the use of (long) red clearance intervals based on conservative speeds, and by limitations in work zone length.

The findings presented in this section form the basis of the guidelines recommended for portable traffic signal application and are based on conservative application and interpretation of the TMUTCD *(3)*. Along with other TMUTCD requirements, decisions regarding signal timing for individual projects must incorporate site-specific conditions and must be examined and reviewed by an engineer (as part of the required engineering study). Suggestions for further research and implementation, found later in this document, suggest means for refining existing standards to more practically apply portable traffic signals to short-term, temporary work zones.

Maximum Wait Time

From Figure 8 and Figure 9, it is possible to see the various timing components of portable traffic signals setting for work zones. Note from Figure 9 that the eastbound red signal indication is displayed for a time that is composed of clearance time plus buffer time for eastbound traffic, westbound green plus yellow time, and westbound clearance plus buffer time. Figure 10 indicates the interrelation of both work zone length and motorist speed on the maximum wait time experienced at each signal. Note that travel time through the work zone in both directions, the maximum green and corresponding yellow clearance in the opposing direction, and the buffer times must be considered when computing maximum wait time for a queue in a given direction.

Experience indicates that the maximum wait time (i.e., before driver confusion and possible violation) is approximately four minutes. A four-minute (240 second) threshold has been identified in Figure 10. However, it must be recalled that the wait time includes more factors than shown in Figure 10, which displays only the time it takes vehicles in both directions to clear the work zone. In addition, the maximum green and yellow clearance in the opposing direction, and the two buffer times must also be added when calculating the maximum wait time.

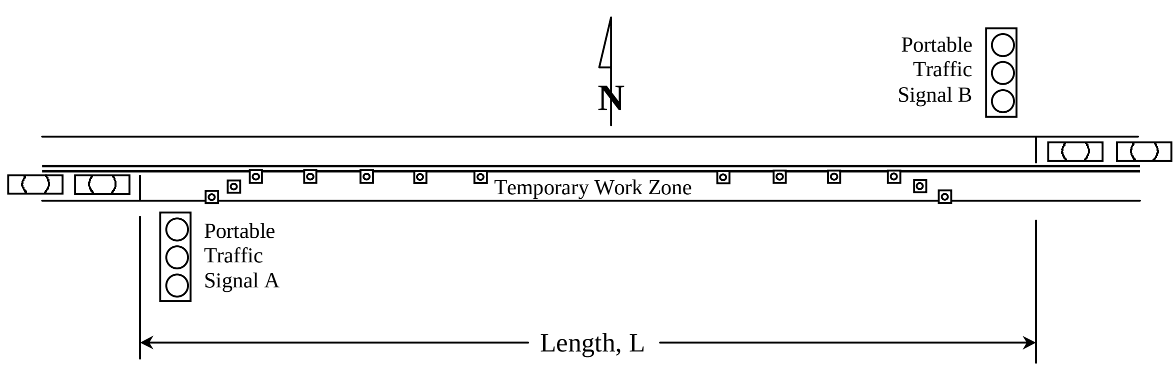


Figure 8. Portable Traffic Signal Installation for Temporary Work Zone Control

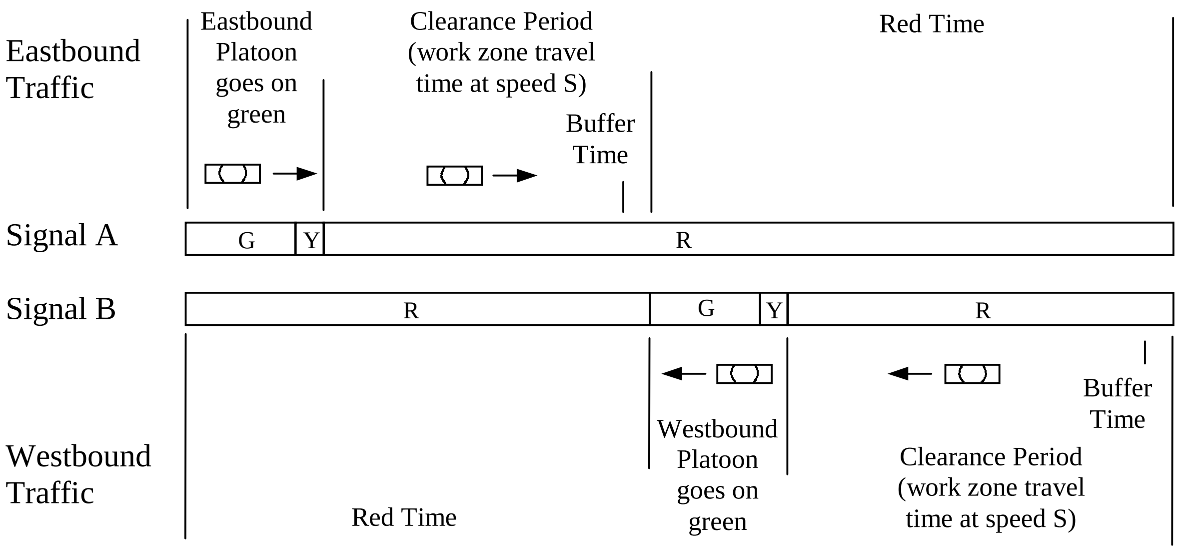


Figure 9. Complete Signal Cycle for Portable Traffic Signal Installation

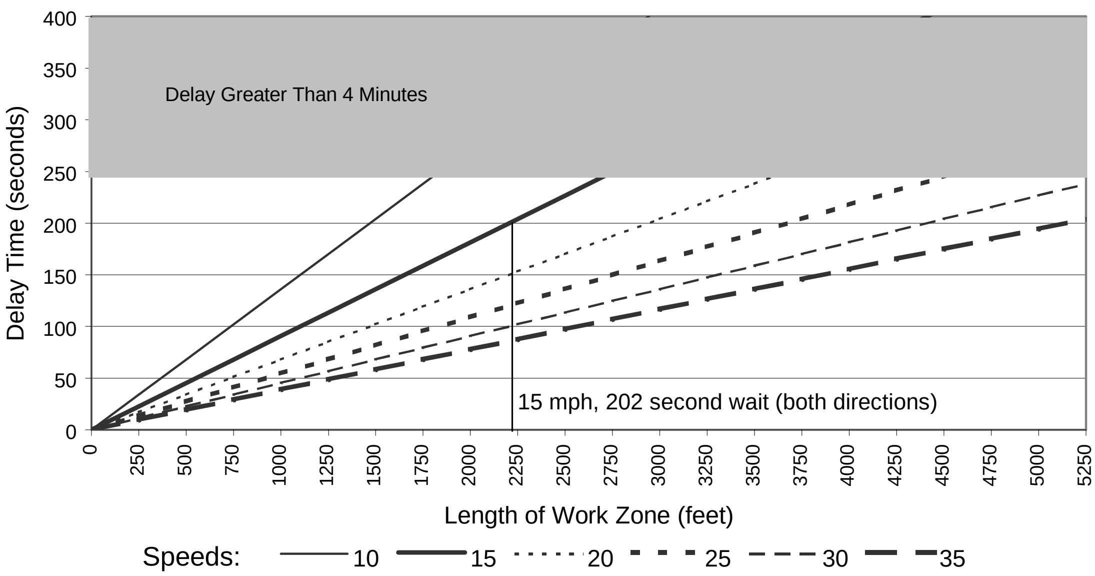


Figure 10. Impact of Speed and Length of Work Zone on Maximum Wait Time

Figure 11 is a step-by-step illustrative example of the various signal timing elements that contribute to maximum waiting time. The Figure 11 example begins where an eastbound vehicle approaches the portable traffic signal at a point in time where the signal is about to change from green to yellow, and the vehicle must stop for the ensuing red indication. In this example, assume that conservative motorists will drive through the work zone at 15 mph, that eastbound traffic has a yellow clearance time of 4 seconds, and that westbound traffic has a maximum green time of 30 seconds and a yellow clearance time of 4 seconds. This consumes 38 seconds of our maximum wait time of 240 seconds, leaving only 202 seconds for the travel time in both directions, or 101 seconds in each direction. For all practical purposes, then, the maximum length of the work zone is approximately 1100 feet in each direction (2200 feet in both directions, from Figure 10). 98 of the 101 seconds in each direction is used for travel time, and a 3 second buffer time is added. If the work zone were any longer than 1100 feet, motorists in the eastbound direction (and probably the westbound direction also) would have a wait time longer than the upper limit of 240 seconds. All timings shown in Figure 11 are for example purposes only; actual signal timing will be based on work zone characteristics, field conditions, and engineering judgement.

From Figure 11, we have the timing elements that contribute to the maximum wait time of our example problem. Equation 1 below represents a mathematical calculation for the maximum wait time for eastbound traffic. If we assume, as is usually the case, that the yellow clearance, red clearance, and buffer times are the same in both directions, Equation 1 becomes Equation 2.

$$\text{Maximum Wait Time (eastbound traffic)} = Y_e + R_e + B_e + G_{w,\,max} + Y_w + R_w + B_w \qquad (1)$$

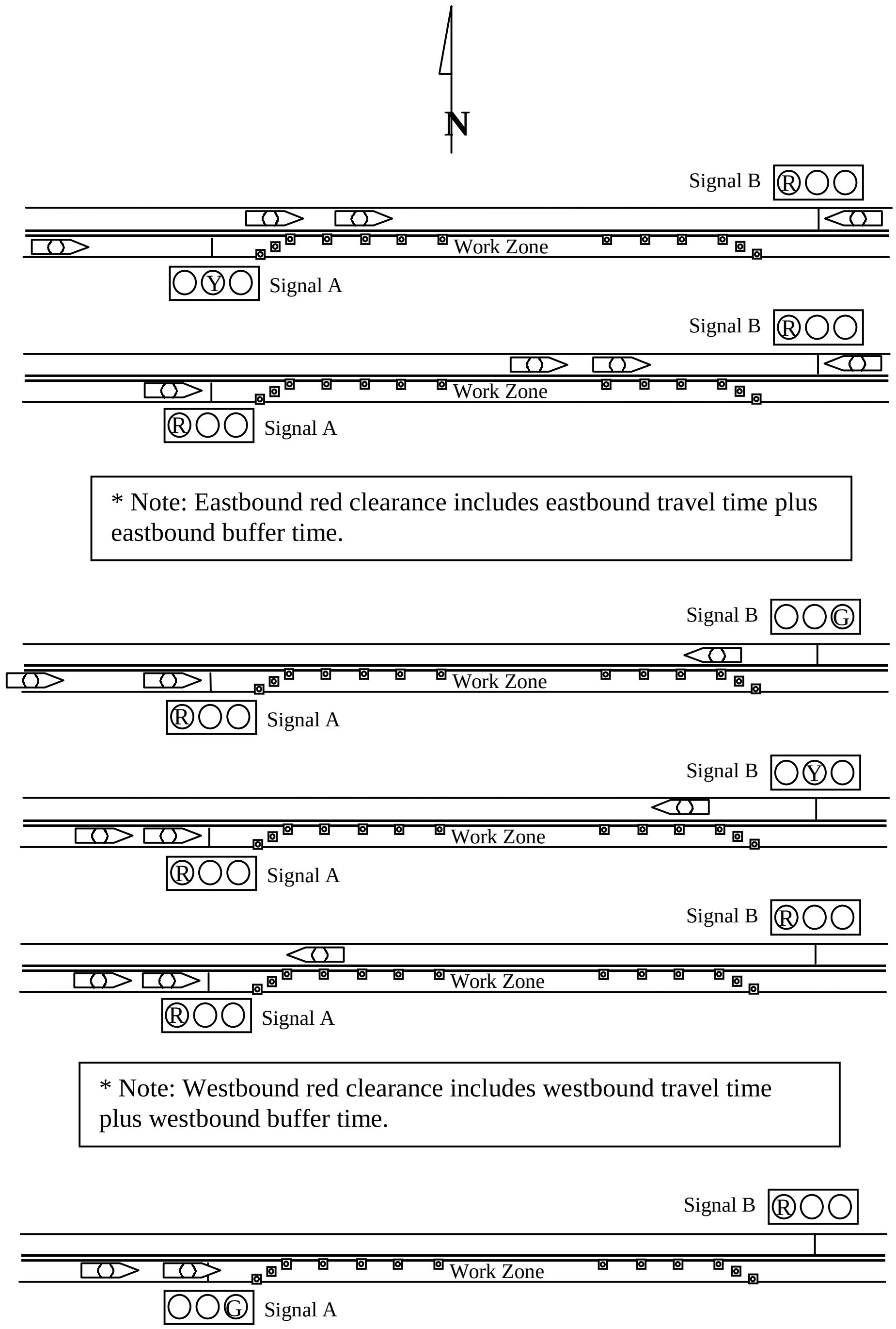
$$\text{Maximum Wait Time (each direction)} = 2Y + 2R + 2B + G_{max} \qquad (2)$$

where:
Y = yellow clearance time (applies to both directions), seconds
Y_e, Y_w = yellow clearance time in (eastbound, westbound) direction, seconds
R = red clearance time (applies to both directions), seconds
R_e, R_w = red clearance time in (eastbound, westbound) direction, seconds
B = buffer time (applies to both directions), seconds
B_e, B_w = buffer time (applies to both directions), seconds
G_{max} = maximum green time in the opposing direction, seconds
$G_{w,\,max}$ = maximum green time in the westbound direction, seconds

If the yellow clearance times, red clearance times, and/or buffer times differ for the two directions of traffic, then the average (i.e., both yellow clearance times added and then divided by 2) for each timing element must be inserted into Equation 2. Remember that the maximum wait time in each direction should be less than 240 seconds.

Note that the buffer time is not directly entered into the controller. Rather, the appropriate red clearance time and buffer times for each direction are calculated and added together. This sum is entered into the controller (for each direction) as the red clearance time.

The buffer time found in Figure 9 and Figure 11, and Equations 1 and 2 is a safety buffer that helps to guarantee that vehicles entering/departing the work zone in opposing directions are separated in time. The red clearance time that is entered into the portable signal controllers is based on the length of the work zone (from stop bar to stop bar) and the lowest reasonable (safe) speed that motorists are expected to drive through the zone. As motorists will undoubtedly drive different speeds, depending on the relative hazard they perceive in driving through the work zone (or how vigilantly they control their speed with respect to work zone speed signing), there always exists variation in work zone travel time.



Timing Element and Symbol	Example Duration, (seconds)
Eastbound Yellow, Y_e	**4**
Eastbound Red Clearance, R_e	**101**
Westbound Maximum Green Time, $G_{w,\,max}$	**30**
Westbound Yellow, Y_w	**4**
Westbound Red Clearance, R_w	**101**
Eastbound Green Time Begins	

Maximum Wait Time (Eastbound Traffic) = 240

Figure 11. Timing Elements for Wait Time Computation

Accordingly, the red clearance time entered into the portable signal controllers is based on the lowest reasonable speed expected for motorists as they drive through the zone. The buffer time should be based on engineering judgement and knowledge of motorist behavior and speed variability along the work zone roadway. Recall that the buffer time is added to the red clearance (travel time component) time for each direction, and this sum is entered into the controller as the (directional) red clearance time.

Determination of Signal Timing Parameters

The primary factors to consider when developing the timing of portable traffic signals for temporary work zone applications include:

- the length of the work zone (which may have to be separated into smaller jobs);
- the number and variability of vehicles expected to approach each side of the work zone;
- the speed of traffic approaching each side of the zone;
- the maximum amount of time motorists are willing to wait at a red traffic signal;
- the range of speeds within the work zone; and
- the amount of buffer time used to separate departing traffic from entering traffic.

After careful consideration of each of these factors and their impacts when they interact with one another, the following can be determined:

- the minimum and maximum green time for each approach;
- the extension interval for actuated operation (if used);
- the yellow clearance time for each approach;
- the red clearance time for the vehicles to travel through the zone;
- the buffer time used to time-separate opposing directions of traffic;
- the default setting (solid red, flashing red) used for temporarily stopping traffic in both directions (if necessary);
- the default setting (solid red, flashing red, flashing yellow) used while the signals are setup and taken down, while both directions of traffic are open through the work zone (if necessary); and
- the default setting (solid red, flashing red) to be used when if the equipment experiences a malfunction.

Maximum Green Time (actuated operation) or Green Time (pretimed operation) The green time that should be given for each approach is primarily determined by the number of vehicles expected during each cycle. The more vehicles, the greater the demand for green time. However, one should keep in mind that the first few vehicles at the signal will take extra time to determine that the signal is green and begin responding (i.e., stop braking and begin accelerating) to the green signal indication. Table 3 can be used to approximate the amount of green time based on how many vehicles are expected each signal cycle. One thing to keep in mind when you are computing the green time for each approach is that the total waiting time for the queues on either side of the work zone should be less than 240 seconds (i.e., four minutes) wherever possible.

Table 3. Green Phase Time Setting Per Approach

Queued Vehicles Per Cycle	Green Time *,** (sec)
<5	12
5	15
10	27
15	39
20	51
25	63
30	75
35	87
40	99

* - Based on a total lost time of 3.3 seconds and a saturation flow of 1500 passenger cars per hour green per lane.
** - Long green times may cause wait times in the opposing direction to be greater than 240 seconds, depending on the length of the work zone.

The green time settings shown in Table 3 are input as the green time for pretimed operation. In actuated operation, these values would be input as the maximum green time. If operating in pretimed mode and the green times appear to be too short (i.e., vehicles consistently remain in the queue at the onset of yellow), one should consider increasing the green time by a few seconds. Conversely, if the pretimed operation green time appears too long (i.e., the signal consistently remains green even after all vehicles in the queue have departed), green time should be reduced by a few seconds. In actuated mode, it is usually only necessary to determine whether or not the maximum time is too low (i.e., vehicles remain in queue at the onset of yellow). If there is insufficient green time, the maximum green time should be increased by a few seconds.

Minimum Green Time (actuated operation) If operating in actuated mode, it will be necessary to specify the minimum green time, or the least amount of time a green indication will be displayed to each approach. This time should be at least the time required for one or two vehicles to safely start up and proceed into the work zone. A range of 7 to 10 seconds is usually appropriate.

Extension Interval (actuated operation) If one is operating portable signals in actuated mode, it will also be necessary to specify the extension interval, or the amount of green time added to the active green phase each time another oncoming vehicle is detected. Based on the fact that motorists approaching a portable traffic signal are likely to be more conservative than motorists at a standard signalized intersection (i.e., using a saturation flow rate of 1500 passenger cars per hour green per lane), a practical extension interval is 2.4 seconds. If the signal controller only accepts integer (i.e., round number) settings, an extension interval of 3 seconds can be used. Extension intervals that are too short will not give vehicles adequate time to reach and pass through the signal; extension intervals that are too long will unnecessarily extend the green and cause higher delays to traffic in the opposing direction.

Yellow Change Interval A yellow indication is always used in normal operation to terminate a green indication and inform motorists that a change in right of way is occurring. The guidelines that exist for the duration of the yellow interval at signalized intersections are largely dependent on speed, and are also applicable to portable traffic signals. The equation used to compute the yellow change interval (6) is:

$$y = t + \frac{v}{2a + 2Gg}$$

where:
y = length of the yellow interval, to the nearest 0.1 second
t = driver perception/reaction time, recommended as 1.0 second
v = velocity of approaching vehicle, in feet/second
a = deceleration rate, recommended as 10 feet/second^2
G = acceleration due to gravity, 32 feet/second^2
g = grade of approach, decimal format (0.02 for 2%, downhill is negative)

Different combinations of speed and grade produce the values shown in Table 4.

Table 4. Yellow Change Intervals for Various Speed and Grade Combinations

85th Percentile Speed (mph)	Grade of Approach								
	Uphill				Level	Downhill			
	+4%	+3%	+2%	+1%	0	-1%	-2%	-3%	-4%
25	2.7	2.7	2.8	2.8	2.9	2.9	3.0	3.1	3.2
35	3.3	3.4	3.5	3.5	3.6	3.6	3.8	3.9	4.0
45	4.0	4.1	4.2	4.2	4.4	4.5	4.6	4.7	4.8

Red Clearance Interval Portable traffic signals make use of the red clearance interval, or “all red” period to allow vehicles that have entered the work zone under a green or yellow indication to safely pass through and exit the one-lane work zone. A red indication is displayed to traffic at both ends of the work zone. The primary determining factors in the duration of the red clearance interval are the speeds at which motorists will drive through the one lane work zone and the amount of buffer time between the departure of vehicles that have traveled through the zone and the start of green for opposing direction traffic (at the same end of the work zone). As faster vehicles will pass through the work zone more quickly than slower vehicles, it is necessary for safe operation to design the duration of the red clearance around the slowest reasonable speed that motorists will use in the work zone.

It is important to note that the basic and common means of computing a one-lane work zone red clearance time as the length of the zone divided by the lowest, reasonable speed that motorists will use in driving through the zone does not explicitly include several important considerations. Among these considerations are the impacts of start-up lost time (i.e., time elapsing for the first motorist in the queue to perceive that the signal is green and begin responding by accelerating the vehicle) and the time required to accelerate the vehicle up to the speed the motorist will use in driving through the work zone. However, both of these actions occur during the minimum green time and/or yellow change interval (i.e., before the red clearance interval begins timing), and it is generally safe to assume that a vehicle entering the work zone during the yellow change interval (i.e., just prior to the onset of the red clearance interval) is traveling at the nominal speed of the platoon that is released from the signal and is proceeding through the work zone. If for any reason either or both of the minimum green time or yellow change interval are programmed to be very short (i.e., less than at least the values given in the sections above for prevailing conditions), some amount of the start-up lost time and acceleration time must be considered for their impacts on necessary red clearance time.

The speed used to compute the red clearance interval will depend on a number of factors, including the location and length of the work zone, any work zone speed reduction and/or warning signing, the operating (i.e., non-work zone) and posted speeds on the facility, and the duration and nature of work in the construction/maintenance work zone. The following equation uses work zone travel speed and work zone length to compute work zone travel time. Table 5 contains values computed using this equation for different combinations of work zone speed and length. Note that the values in Table 5 are for travel time at the given speed only; they do not include any buffer time.

$$TT = \frac{L}{1.4667 \times v}$$

where: TT = travel time, rounded up to the nearest 0.1 or 0.01 second
L = work zone length, feet
v = lowest reasonable work zone travel speed, miles per hour (mph)

Table 5. Work Zone Travel Time for Various Speeds and Work Zone Lengths

Lowest Reasonable Speed (mph)	Work Zone Travel Time (sec) by Work Zone Length (feet)									
	250	500	750	1000	1250	1500	1750	2000	2250	2500
15	11.4	22.7	34.1	45.4	56.7	68.1	79.4	90.8	102.1	113.4
20	8.6	17.1	25.6	34.1	42.6	51.1	59.6	68.1	76.6	85.1
25	6.9	13.7	20.5	27.3	34.1	40.9	47.7	54.5	61.3	68.1
30	5.7	11.4	17.1	22.7	28.4	34.1	39.7	45.4	51.1	56.7
35	4.9	9.8	14.6	19.5	24.3	29.2	34.1	38.9	43.8	48.6
40	4.3	8.6	12.8	17.1	21.3	25.6	29.8	34.1	38.3	42.6
45	3.8	7.6	11.4	15.2	18.9	22.7	26.5	30.3	34.1	37.8

Where appropriate minimum green times and yellow change intervals are used, the red clearance interval will be equal to the work zone travel time plus the buffer time:

Red Clearance Interval = Work Zone Travel Time + Buffer Time

Buffer Time Buffer time is a safety time cushion that helps to guarantee that vehicles entering/departing the work zone in opposing directions are separated in time. The red clearance time that is entered into the portable signal controllers is based on the length of the work zone (from stop bar to stop bar) and the safe speed that motorists are expected to drive through the zone. As motorists will undoubtedly drive different speeds, depending on the relative hazard they perceive in driving through the work zone (or how vigilantly they control their speed with respect to work zone speed signing), there always exists variation in work zone travel time.

It is in the interest of safety that the red clearance time entered into the portable signal controllers be based on the lowest reasonable speed expected for motorists as they drive through the zone. However, it is likely that a very slow motorist (i.e., slower than the speed used to compute the red clearance time), or a motorist that pauses or stops in the work zone due to a perceived or actual conflict with work zone maintenance equipment, will travel through the work zone. Since it will take this motorist longer than the red clearance time to safely travel through the work zone, a buffer time is entered into the controller so that departing traffic is safely separated in time from traffic that will enter the work zone from the opposing direction. The buffer time should be based on engineering judgement and knowledge of motorist behavior and speed variability along the work zone roadway. Recall that the buffer time is added to the red clearance time for each direction, and this sum is entered into the controller as the (directional) red clearance time.

Flashing Red/Flashing Yellow Operation

In portable traffic signal use for long work zones, it may not be possible to see the signal and waiting traffic at the other end of the work zone, or the traffic that is currently (and appropriately) driving through the work zone in the approaching direction. In this circumstance, there exists no way for the motorist at a flashing red (which can be used in short work zones where opposing direction motorists can see one another) to perceive whether or not the right of way is clear and passage is safe. This confusion could lead to driver error and a serious hazard condition, even though lanes in both directions may, in fact, remain open (i.e., while the work zone is being assembled or dismantled). For longer work zones, it appears more appropriate to use flashing red only when there exists an equipment malfunction, similar to permanent signal installations which go into flash when a malfunction occurs. Even in this instance, a solid red should be considered if the conflict monitor can default to solid red operation. During any malfunction, it is necessary for maintenance workers to immediately begin acting as flaggers, because motorists may not know how to correctly respond to the sudden initiation of flashing red operation or an extremely long solid red indication.

A flashing yellow indication may be more appropriate than flashing red in the temporary work zone signal installation when both lanes of traffic remain open (i.e., during equipment setup and take-down, or during worker breaks). The flashing yellow would appropriately indicate that caution should be exercised in the work zone, but also indicates that the lanes in both traffic directions remain open. It is emphasized that the flashing yellow mode **only** be used when both lanes (i.e., both directions) of traffic remain safely open. During equipment malfunctions, the flashing red or solid red indication is appropriate, to be supported by flaggers who assume traffic control responsibility in the work zone until the equipment can be repaired and restore to normal (i.e., not flashing red or continuous solid red) operation.

In all modes of operation, the indications presented to motorists by the signals are monitored by a conflict monitor, or watchdog device. This device operates independently from the internal electronics that perform the controller timing functions and exists solely to determine whether or not the controller logic attempts to implement settings that violate clearance times or present conflicting phase indications simultaneously. If the watchdog detects any abnormalities in the timing instructions output by the controller logic, it will customarily go to flashing red for all approaches. However, some variability exists into how the watchdog response is programmed. For instance, if both ends of the work zone are visible to one another, the watchdog may be set to flash in red if it detects any problems with the signal output of the controller. If both ends of the work zone are not visible to one another, it may be preferable to display a solid red rather than a flashing red indication during equipment malfunction. Choice of the appropriate conflict mode (i.e., solid red or flashing red) will depend on site characteristics and engineering judgement.

EQUIPMENT CHARACTERISTICS IN MAINTENANCE APPLICATIONS

Current TxDOT specifications were developed anticipating use of portable signals for long-term construction projects as opposed to maintenance operations. The discussion that follows addresses equipment features which have been identified as potential updates to TxDOT specifications.

Remote Operation of Signals from Work Area

The equipment used in the field tests did not have the capability for remote operation. Instead, the supplier provided a light at the back of each signal head that was illumined when the signal was displaying a red indication. This enabled the workers to judge the traffic stream in relation to the red light indication and determine when breaks in the traffic stream were available. While this mechanism worked sufficiently in these three applications, there may be situations where the trailers are not visible from the work area.

The ability to utilize the "dead time" between traffic platoons in the work zone was identified by employees as one of the most valuable assets of the portable signals. For this reason, the inclusion of remote operating capability is recommended for future purchases of portable signals that are targeted for maintenance applications. Some desirable features of such a remote control monitoring and control device include an indication:

- of which direction traffic is currently proceeding through the work zone;
- that the master controller has received a request for locking red rest operation;
- when the vehicles in the work zone have cleared the zone;
- when locking red rest operation is initiated by the signal controller;
- that a request from the remote has been issued to return to normal operation;
- when normal operation has been returned;
- of active signal indications at both signals at all times (including locking red rest and flashing indication);
- as to how long each phase has been active (and its total duration);
- if the conflict monitor has been activated; and
- if fuel is running low in the generator's fuel reservoir at either signal.

At virtually all rural two-lane work zone sites similar to those examined in this project, there is no access to a permanent power supply. For short-term work zones, this is usually not problematic in that maintenance staff is available to monitor the equipment and refill the fuel supply, if necessary. Some portable traffic signals are even equipped with built-in generators, supplanting the need for external generators. Alternatives to diesel or gasoline-powered generators include battery power and combinations of battery power and solar energy cells. Depending on the power requirements of the signal lights and controller equipment, battery power or a combination of solar energy and battery power may not be able to effectively accommodate longer term (i.e., overnight) work zone use of portable traffic signals. However, for short-term application (i.e., less than eight hours) the use of battery-operated signals and/or solar powered signals appears reasonable. In fact, such portable signals have the potential to be lighter, more maneuverable, and simpler to maintain than those equipped with generators.

Another means of affecting the power requirements and/or electrical supply needs of a portable traffic signal is by lowering the overall power demand of the signal controller and signal lights. One technology that is quickly becoming very popular for signal lights is light-emitting diodes (LEDs) that replace the incandescent bulbs currently used in most signal installations. LEDs can provide similar performance to bulbs in terms of light output and visibility, especially when designed with appropriate lens covers. The Institute of Transportation Engineers is currently reviewing LEDs as a replacement/alternative technology to bulbs for signal lights, and a specification is expected some time in 1999. Once this specification is released, LEDs will become more widespread. Their application to portable signals will reduce power requirements for signal lights by up to 80 percent, and open new opportunities for portable signal trailer and energy system design.

One feature that was discussed by project researchers for improving motorist information of wait time at portable traffic signals was a countdown clock on the trailer unit displaying remaining motorist wait time for each direction. Supporting this suggestion is the fact that motorists who are aware of their wait time will be much less anxious and uncertain about signal control, and more likely to obey the displayed indications (especially the red indication). Arguments against the use of a countdown clock for wait time surround the fact that motorist expectation of green time may lead to early starts or quick acceleration when the green indication begins. This is very undesirable given that for portable traffic signals in work zones, the opposing direction of traffic has just cleared the open lane of the work zone. Also, if the signals were to malfunction and go into a flashing red or solid red mode, it is unclear how to effectively remove/alter the countdown clock without causing motorist confusion. Similarly, if workers must put the signal into an all-red mode while work zone equipment is being turned around (or for other work zone activity requiring the temporary closure of both lanes), the countdown clock would have to be halted or blanked out completely, again causing motorist confusion.

RECOMMENDATIONS FOR FURTHER RESEARCH

Work Zone Speed Issues

The speed that motorists use to drive through work zones controlled by portable traffic signals has a direct influence on safety, as the speed is used to compute the red clearance interval (i.e., the fixed time allotted for vehicles to pass through the work zone, before opposing traffic is released). Pages 6H-36 and 6H-37 of Part VI of the TMUTCD (*3*) describe work zone setup requirements for the use of portable traffic signals in work zones. Figure TA-12 of the TMUTCD, shown on page 6H-37, shows that speed within the work zone is uncontrolled, unless the optional advisory speed construction warning plate (CW13-1 or SCW13-1) is used. Even using the optional speed warning plate, speeds would only be controlled by advisory warning, rather than by regulation, which is more enforceable. Furthermore, the fact that the speed plate is optional (not used in most cases) means that drivers can select virtually any speed to proceed through the work zone, limited only by the posted speed limit on the facility.

The broad range of possible speeds that motorists will judge to be reasonable and prudent in proceeding through the work zone produces a broad range of red clearance time requirements for the portable traffic signal devices. However, only a single red clearance time can be programmed into the signal controllers. Also, these devices possess no practical means (and no technology exits or has been adapted) for detecting vehicles within the work zone and determining when the work zone has been cleared. Thus, red clearance intervals must always be programmed for the lowest reasonable speed that motorists will use in the work zone, where even the lowest speed must be estimated/predicted by an engineering study. In reality, programming red clearance times for the lowest reasonable speed means that in most cases, the efficiency of the signals is reduced. Vehicles waiting to enter the zone can receive the green only after the red clearance has expired for a platoon of vehicles that (at any speed greater than the lowest reasonable speed) has already safely passed through the work zone.

Research into the relationship between posted speed limit and the speed motorists use to drive through rural, one-lane work zones controlled by portable traffic signals, and the variability of speeds in these work zones, may give more insight and guidance in the setting of clearance time requirements.

Motorist Signing and Wait Time Expectation

Motorist dynamic signing that indicates (by countdown clock) how much time remains before the platoon at a portable traffic signal receives a green signal indication may be one means of providing information to motorists about signal operation. Similar information could also be made available by a static sign that informs motorists what the approximate maximum wait time will be, based on the work zone characteristics and signal settings used at each site. Further research into the application of such dynamic or static signing for portable signal operations would indicate whether this type of information was correctly understood by motorists. Such research could also indicate whether the information, especially if dynamic, was abused by motorists to over-anticipate the onset of a green signal indication.

Application of Stop Bars in Short-Term Portable Traffic Signal Applications

Part VI of the TMUTCD *(3)* requires that a stop bar be used in the work zone setup for one-lane work zones controlled by portable traffic signals. This requirement applies to work zones of long (i.e., multiple day) duration. Historically, the stop bar has taken the form of white thermal tape or white paint. However, the sites reviewed in this project, and the short-term work zone applications for portable signals researched during this investigation, were of only a short-term duration (i.e., one day, usually less than eight hours). The paint or thermal tape used in longer terms work zones would be very costly to use for a work zone that exists for a single day. Further, the time required to apply and remove such materials would apply additional limits to the amount of activity devoted to the work zone function in a one-day setup.

Some forms of portable or other temporary stop bar products exist, but have not historically been included in TxDOT specifications because of poor performance under higher speed conditions. The devices were either torn apart or pulled up from the pavement as high speed or heavy vehicles crossed over them. A low-cost, desirably portable, stop bar capable of quick installation and removal, and exhibiting uniform acceptable performance for a range of speeds, needs to be researched and developed. Such a product would be applicable for short term portable signal applications, similar to those reviewed in this project, and for other temporary applications where a stop bar control device is necessary.

Sensor Technology Research

Several portable detection technologies exist that can be used to allowed actuated traffic signal control with portable traffic signals. Suitable detectors include infrared devices, microwave devices, and video detection devices. The optimal technology will depend on site location factors and duration of the application. Those portable traffic signals that can be operated in actuated mode have one of these (or other applicable) technologies mounted on the portable signal trailer and aimed to sense vehicles approaching that end of the work zone. Further research might identify which detection technology is best suited for portable signal application, or which detector is optimal for a given set of site and weather characteristics. Long-term research into detection technologies may reveal a means of detecting whether or not vehicles are within the work zone. Such detection would be extremely useful in improving the efficiency and safety of portable signals (and work zones in general) controlling traffic through work zones. Vehicles would only be released from one direction after the work zone vehicle sensor verifies that all vehicles have cleared from the opposing direction (i.e., a check on effective red clearance). Such functionality, contained in a portable form, is beyond the range of current detection technologies, especially for longer work zones.

Training Video for Portable Traffic Signal Operation

One means of training TxDOT staff in the safe setup, programming, and use of portable traffic signals for work zone traffic control is the use of video. Due to the practicality of this approach to training, signal manufacturers and retailers may even contribute, cooperatively with TxDOT, to producing such a training tool. A variety of technologies and formats are available, including VHS, CD-ROM, and DVD.

GLOSSARY OF TERMS

A variety of terms pertaining to work zone setup and requirements can be found in Part VI, Section 6C of the TMUTCD *(3)*. The following glossary pertaining to traffic signal terminology contains terms from several sources , including references *(7)* and *(9)*.

Cycle Length, or Cycle – Time elapsed between the start of successive green indications for same-direction traffic. The cycle length is fixed, or constant, in pretimed operation and variable in actuated operation.

Minimum Green Time - The shortest green time of a phase. If a time setting control is designated as minimum green, the green time shall not be less than that setting. For a fully-actuated controller, minimum green is the first timed portion of the green interval. It is usually set (i.e., for permanent signal installations) considering the number of waiting vehicles between the detector and stop line, though this definition may not be applicable (depending on sensing equipment) for portable signals.

Maximum Green Time - In actuated controllers, the longest time for which a green indication will be displayed (and the longest the green indication can be extended) in the presence of a call on an opposing phase.

Pretimed Operation - Operation of traffic signals with predetermined fixed cycle length, fixed interval duration, and fixed interval sequence.

Actuated Operation - Operation of traffic control signals in accordance with the varying demands of traffic as registered with the controller by traffic detectors.

Red Rest - Display of the red indication for all signal phases after the expiration of all clearance intervals.

Extension Interval - For a fully actuated controller, that portion of the green interval in which timing resets with each subsequent vehicle actuation, thus extending the green interval.

Yellow Change Interval - Signal interval following the green display for each phase which indicates a change in right-of-way assignment is occurring. Longer yellow change intervals are used with higher approach speeds.

Red Clearance Interval - Interval following the yellow portion of each phase. Red clearance at standard intersections is designed around intersection width and vehicle speeds. In the case of portable traffic signals, the red clearance is the time required to safely travel through the work zone.

Buffer Time - A signal phasing period designed as a safety cushion to separate departing and approaching traffic movements through the one-lane work zone. The tail end of the red clearance period is referred to as the buffer time, especially when this time has been specifically designed and incorporated for safety.

Detector - A sensing device used with actuated control that is able to identify when a vehicle is approaching or stopped at an intersection. Detectors using a variety of sensing technologies are available. Most intersections use in-pavement loop detectors, whereas portable signals commonly use either microwave, infrared, or video detection.

Gap Out - If no vehicles pass the detector during the vehicle (i.e., green) interval, the signal will gap out. In other words, the green time counts down to zero, and the signal changes to yellow, and then to red.

REFERENCES

1. *Public Information Office.* Texas Department of Transportation, Austin, Texas, February 1, 1999.

2. *Handbook of Safe Practices.* Texas Department of Transportation, Occupational Safety Division. 1997.

3. *Texas Manual on Uniform Traffic Control Devices.* Texas Department of Transportation, Austin, Texas, 1980 (Revision 6, January 1996).

4. *Operating Manual LF 1050 LF 4000.* International Traffic Systems, Inc., Lakeland Heights, Florida, 1992.

5. *Traffic Operations Manual*, Procedures for Establishing Speed Zones, Texas Department of Transportation, August 1996.

6. *Manual on Uniform Traffic Control Devices.* United States Department of Transportation, Federal Highway Administration, 1988.

7. *Traffic Engineering Handbook, Fourth Edition*. Institute of Transportation Engineers, Prentice Hall, 1992.

8. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highways and Transportation Officials, 1990.

9. Robert L. Gordon, et al. *Traffic Control Systems Handbook*. United States Department of Transportation, Federal Highway Administration, 1996.

APPENDIX A: DATA AND OBSERVATIONS FROM FIELD TESTS

Project and date	**PR 37** 6/16/98
Physical conditions	
Terrain	Hilly
Weather conditions	partly cloudy, hot
Work Zone Characteristics	
Length of WZ	1000 feet
Duration of WZ	9:00 am to 3:30 pm
Actual speeds through WZ	32.7 mph max; 19.8 mph near equip and wrkrs
Existing traffic control devices	None
Sight distance	Limited from end to end of work zone
Pavement width	2-12' lanes
Shoulder width	<1 ft. each side
Speed limit	40 mph
Number of driveways and locations	None
Number of intersecting roadways and locations	None
Special characteristices of TCP	No stop lines.
Maintenance Activity	
Type of maintenance work	Blade patching/level up. 10 areas, both full Width and half width
Equipment used	Maintainer, pneumatic, broom, flatweel, 3 dumps, 1 pick-up, distributor
Number of crew members	7 persons
Time required to setup signals	2-person operation: 29 minutes actual; 43 min After work zone prepared
Fuel consumption	2 gallons/24 hours
Other operating expenses	
Notification process	None
Signal equipment problems	Difficulty with sensor on master
Amount of employee time spent monitoring equip	Approx. 2 hrs; assist. Provided by supplier
Comments/concerns from crew on site	Overall, positive response from crew concerns: liability; need way to know Signal display at any time in order to coordinate movement of equipment Within travel lane
Traffic Operations	
Driver compliance (# movements on red)	During 2.5 hours, 2 violators observed at Master. Both were immediately after setup
ADT and hourly volumes through the work zone	30-minute volume: 92 vehicles
Phase settings for master and slave controllers	Max-60 sec; min-10; ext-5; yel-3; red clear-60
Vehicular conflicts and reason	Conflict occurred as equipment at work area extended into travel lane, stopping traffic at mid-WZ. Opposing green time was used by these vehicles exiting the work zone.
Stopped delay	Maximum wait time: 3 min, 3 sec; or 183 sec Maximum queue length: 9, mean: 4
Drivers' general perceptions	No problem with visibility of signal; all noticed advance warning signs, esp. "signal ahead" and "be prepared to stop."
Comments/Observations	>Training will be important to allay liability concerns >Tetup guidelines need to address sight distance requirements >Crews need mechanism to know direction of traffic (indications were added to back of signal ahead subsequent to this project) >Max. WZ length will depend on reasonable motorist waiting time >Static signing for max wait time would help >On-demand scenario does not work as well with minimal traffic, like one or two veh. >Cross street traffic was not evaluated this day. Signals were used on same roadway different day with this situation present. >Watch for power lines – interfere w/communications? >Proximity to intersections - signing, comprehension >Driveways inside work zones

Project and date	FM 1283 7/8/98
Physical conditions	
Terrain	Hilly
Weather conditions	Clear, hot, dry
Work Zone Characteristics	
Length of WZ	1850 feet
Duration of WZ	9:30 am to 3:00 pm
Actual speeds through WZ	34 mph max; 25 near equip and wrkrs
Existing traffic control devices	Curve advisory sign for 55 mph
Sight distance	Limited from end to end of work zone
Pavement width	2-12' lanes
Shoulder width	<1' each side
Speed limit	55 mph
Number of driveways and locations	1
Number of intersecting roadways and locations	1
Special characteristices of TCP	No stop lines; limited cones within wz
Maintenance Activity	
Type of maintenance work	Blade patching/level up.
Equipment used	Maintainer, pneumatic, broom, flatweel, dumps, 1 pick-up, distributor
Number of crew members	5 persons
Time required to setup signals	2-persons; 21 min actual, 40 min after wz ready
Fuel consumption	2 gallons/24 hours
Other operating expenses	
Notification process	None
Signal equipment problems	None
Amount of employee time spent monitoring equip	Approx. 35 minutes
Comments/concerns from crew on site	Positive response from crew; signal indication on back assisted with coordination of work with traffic flow; suggested flashing yellow operation during setup to address violations
Traffic Operations	
Driver compliance (# movements on red)	Many red violations during setup, most waved on by flaggers
ADT and hourly volumes through the work zone	30-minute volume: 68 vehicles
Phase settings for master and slave controllers	Max-40 sec; min-10; ext-10; yel-3; red clear-60
Vehicular conflicts and reason	No observed conflicts.
Stopped delay	Max wait time: 2 min. 43 sec, or 163 seconds max. queue length: 6; mean: 2.5
Drivers' general perceptions	Signing was clear and appropriate; driver comprehension good.
Comments/Observations	>Speed through work zone; how would drivers know to reduce speed with a green indication? >Coning still needed throughout the work zone; driver does not know which lane to use without them >Training in what signal settings mean, esp. impact on operation of long ext. interval >Crew suggestion about flashing yellow operation during setup

Project and date	**SH 16** - 4 miles north of Bandera 8/13/98
Physical conditions	
Terrain	Curving road, not hilly
Weather conditions	Clear and hot
Work Zone Characteristics	
Length of WZ	1500 feet
Duration of WZ	9:30 am to 3:00 pm
Actual speeds through WZ	40 mph max; avg. 25 mph near equip. and wrkrs
Existing traffic control devices	Curve advisory sign for 50 mph
Sight distance	Limited from end to end of work zone
Pavement width	2-12' lanes
Shoulder width	<3' each side
Speed limit	55 mph
Number of driveways and locations	1 w/in zone at south end
Number of intersecting roadways and locations	0
Special characteristices of TCP	No stop lines; limited cones within wz but used on approach
Maintenance Activity	
Type of maintenance work	Surface replacement; excavation of base if needed (not needed after viewing)
Equipment used	Backhoe, loader, pneumatic, sweeper, grader, 2 dumps (10 and 6-yd); 2 pickups
Number of crew members	4 workers, 1 mechanic, 1 supervisor
Time required to setup signals	38 minutes from setup to full oper.; 24 from setup to yellow flash, 14 minutes to running
Fuel consumption	2 gallons/24 hours
Other operating expenses	
Notification process	None
Signal equipment problems	See below
Amount of employee time spent monitoring equip	20 minutes
Comments/concerns from crew on site	Continued positive feedback; signal indication could be more visible - white strobe? yel flash on setup works best (but not in compliance with MUTCD); mechanic is the lead operator of the signals; (others a little intimidated)
Traffic Operations	
Driver compliance (# movements on red)	No observed violations (operator attributes to location and type of driver)
ADT and hourly volumes through the work zone	30 minute volume: 39 vehicles
Phase settings for master and slave controllers	Max-35 sec; min-10; ext-10; yel-3; red clr-35 sec
Vehicular conflicts and reason	Potential conflicts w/driveway; one vehicle exited in proper direction; second with assistance Lack of cones actually helped in this situation - actual work area was further north
Stopped delay	Max wait time: 1 minute, 48 sec; or 108 sec Max queue length: 3*; mean: 1.4
Drivers' general perceptions	Signing clear; driver comprehension good; no indication of driver agitation, except as noted below*
Comments/Observations	>Use of equipment allowed another small grader job to proceed at different location *> Need guidelines on placement of stop line & sign; sensor has been adjusted such that small vehicles too far back are not detected. 7 “Bubba” steps is the rule for sign placement. One instance: sensor did not detect vehicle and waited 2.5 min > Clearance time is being set by driving the zone at 15-20 mph and noting time to do so >Contacted Todd 8/14 about conflict with TMUTCD (yellow flash) >May need to suggest minimum skill set necessary to operate and maintain equipment

APPENDIX B: VALUES USED IN COST EFFECTIVENESS CALCULATIONS

Costs = (capital cost + initial training cost) + (routine maintenance cost + set-up cost)

Capital cost of equipment = $65,000[1]

Average employee cost = $16.61 per hour[2]

Initial training costs = $332[3]
4 hours X $16.61/hour X 5 employees

Routine maintenance and operation cost = $1,064 per year
(1 hr./week X 52 weeks/year X $16.61/hr.) + $200 in parts, supplies, fuel/year[4]
*increases at a rate of 10% per year as equipment ages

Additional costs for set-up and removal of signals[5] = $1,595
0.5 hour X $16.61/hour X 4 employees = $45.50/set-up X 48 set-ups/year

<u>Scenario 1 – Elimination of one FTE (full-time equivalent)</u>

Year 1	Costs	($65,000 + $332) + ($1,064 + $1,595) = $67,991
	Savings	$16.61 X 2080 = $34,550
	Difference	- $33,441
	Benefit	0 for first year
Year 2	Costs	(($1,064 X 1.1) + $1,595) = $2,765
	Savings	$16.61 X 2080 = $34,550
	Difference	$31,785
	Benefit	0 for second year (cumulative) [$31,785 - $33,441 = -$1,656]
Year 3	Costs	(($1170 X 1.1) + $1,595) = $2,882
	Savings	$16.61 X 2080 = $34,550
	Difference	$31,668
	Benefit	$30,012 for second year (cumulative) [$31,668 - $1,656 = $30,012]

[1] Equipment costs based on purchase amount for signals used in field tests. This equipment did not include the maintenance-oriented features suggested in this study.

[2] $16.61/hour is the average employee rate charged for damage claims. Due to low turnover, the Bandera maintenance section employs predominately Maintenance Technician II positions, which are paid at a higher rate than a Maintenance Technician I.

[3] Assumes that the purchase contract includes four hours of training support provided by supplier.

[4] Maintenance and operation costs are dependent upon frequency of use; in this example, the assumption was made that the portable signals were in operation on a routine basis.

[5] The additional time associated with set-up and removal of the portable signal equipment over that required for a flagging operation was determined from field tests and employee feedback to be 30 minutes per usage. The fact that other work set-up activities could occur simultaneously was factored into this value.

Year 4+	Costs	(($1,287 X 1.1) + $1,595) = $3,011
	Savings	$16.61 X 2080 = $34,550
	Difference	$31,539
	Benefit	$31,539 for fourth year; savings would accrue each year thereafter for the life of the equipment, with the amount slightly decreasing each year as the equipment ages and maintenance costs increase

Number of years to recoup initial expenses

y = Number of years to realize return on investment
or the year at which accumulated costs equal accumulated benefits

$$65332 + (1064(1.1)^{y} + 1595y) = 34550y$$

y = 2.02 years

Cost savings from eliminating one FTE during time period signals in actual use

Frequency of use = 4 days/month = 48 days per year

Savings for one FTE for these days = $6,378

$16.61/hour X 8 hours/day X 48 days/year

y = Number of years to realize return on investment
or the year at which accumulated costs equal accumulated benefits

$$65332 + (1064(1.1)^{y} + 1595y) = 6378y$$

y = 14.5 years

<u>Scenario 2 – Improvement in Job Efficiency</u>

5-day project reduced to 4-day project

Efficiency Savings from reduction in project length by one day

Savings in personnel:

5 employees X 8 hours/day X $16.61/hour = $664.40

Savings in equipment

$150/day

Efficiency savings = $814.40

Motorist delay savings from reduction in project length by one day:

Assume 35 cycles per hour, 3 vehicles per cycle queued for 100 seconds, and 6 hours of operation = 17.5 vehicle-hours of delay for one work day

Delay savings = $262.15

(17.5 veh-hrs. X $14.98/veh-hr. motorist cost)

Savings for one day: $814.40 + $262.15 = $1076.55

Using $1075/day in total savings:
($1075 X 2 days/month X 12 months/year) = $25,800 per year in efficiency savings[6]

Year 1	Costs	($65,000 + $332) + ($1,064 + $1,595) = $67,991
	Savings	$25,800
	Difference	- $42,191
	Benefit	0 for first year
Year 2	Costs	(($1,064 X 1.1) + $1,595) = $2,765
	Savings	$25,800
	Difference	$23,035
	Benefit	0 for second year (cumulative) [$23,035 - $42,991 = -$19,956]
Year 3	Costs	(($1,170 X 1.1) + $1,595) = $2,882
	Savings	$25,800
	Difference	$22,918
	Benefit	$2,962 for third year (cumulative) [$22,918 - $19,956 = $2,962]
Year 4+	Costs	(($1,287 X (1.1) + $1,595) = $3,011
	Savings	$25,800
	Difference	$22,789
	Benefit	$22,789 for fourth year; savings would accrue each year thereafter for the life of the equipment, with the amount slightly decreasing each year as the equipment ages and maintenance costs increase

Number of years to recoup initial expenses
y = Number of years to realize return on investment
or the year at which accumulated costs equal accumulated benefits

$$65332 + (1064(1.1)^{y} + 1595y) = 25800y$$

y = 2.8 years

[6] Two days of savings per month would assume two separate four-day projects, or eight days of work per month where signals are used