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16. Abstract

The purpose of this project is to summarize the results of the research project, *Feasibility of Portable Traffic Signals to Replace Flaggers in Maintenance Operations.* The purpose of the research project was 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 traffic 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 discussed.

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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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IMPLEMENTATION RECOMMENDATIONS

1. **Cost Effectiveness** The portable traffic signals evaluated in this research study have technical applicability in routine maintenance operations, particularly pavement repair projects. The cost effectiveness of portable signals in daily maintenance operations was difficult to ascertain with a high degree of precision given the limited testing experience under this research study. Anecdotal evidence from the field tests supports the use of portable signals in maintenance operations as a means of improving crew efficiency and flexibility, which are two qualities that were difficult to measure under this study. Based on a cost-effectiveness analysis using two hypothetical situations, a return on investment after two years can be realized if the average use of the equipment is eight to ten days per month. The primary factor contributing to cost effectiveness is the frequency of use. Higher frequency of use (and more rapid accrual of savings) 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.

2. **Items Related to the TMUTCD** Two items related to the Texas Manual on Uniform Traffic Control Devices (*1*) are identified for proposed revisions.

   2.1 *New provisions for short-term stationary work zone using portable traffic signals* The TMUTCD (*1*) provides standards and guidelines for lane closures on two-lane roadways using traffic signals (sections 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 study. Those elements include maximum work zone length, installation of semi-permanent stop lines and other pavement markings, and flashing red conditions. Although not directly stated, it is inferred from the provisions of 6H-36 and 6H-37 that the construction work zone has clear line of sight from end-to-end, which was not a condition in any of the test sites. Revisions to the standards are presented in this report that specifically address the application of portable traffic signals in short-term stationary maintenance operations.

   2.2 *Conflict between language in the TMUTCD and practical field application of portable signals* Portable traffic signals are classified as "traffic control signals" under the provisions of the 4B-4 of the TMUTCD (*1*). 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 their use. Therefore, consistency with the TMUTCD would require 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. Given the organizational structure of the Texas Department of Transportation and the limited availability of signal engineers, especially in geographically dispersed rural districts, it is not practical to expect an engineering study to be performed for two or more different signal applications per month.

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. Nevertheless, the TMUTCD clearly states that an engineering study must be performed for any traffic signal application, including portable traffic signals, and any practice in conflict with this standard exposes the responsible agency to liability concerns.

3. **Implementation Guide** A guidebook written for field personnel is provided as a separate deliverable. Its purpose is to serve as a supplement to the equipment operator's manual and provide guidelines for the application of portable traffic signals in short-term, routine maintenance projects on rural two-lane highways. Using the findings of the research study as its basis, the document provides guidelines on the types of maintenance projects best suited for portable traffic signals, procedures for setting up work zones, and the steps for determining signal timings for setting the controllers. The implementation guide will serve as a useful tool for field personnel in the application of this technology.

4. **Equipment Features** The TxDOT specification for portable traffic signals should be updated to incorporate a remote operating feature (i.e., most likely in the form of a handset) into the equipment requirements. During the test cases, 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 monitoring and operating capability is recommended for future purchases of portable signals that are targeted for maintenance applications.

5. **Future Research** Work zone speed and its relationship to portable traffic signal clearance time settings should be further investigated. Such future research should recommend practices (including the using of work zone speed control singing) to improve clearance setting procedures. Additional work zone signing, either static or dynamic, should also be investigated to inform motorists approaching or queued at portable signals what their total or current wait time is. Such signing has the potential to improve motorist compliance and comprehension of portable signal function. Future research should also be made into developing a low-cost, portable stop bar that can be easily installed and removed. Such a device would improve the work zone setup and traffic control for short-term, portable traffic signals, and it could be used in other temporary control applications. Also, there exists no clear guide to the correct usage of detectors for portable traffic signals. Research could reveal what type of detection is optimal for each combination of site characteristics and weather conditions; longer term research might identify cost-effective means of detecting vehicles within the length of the work zone. Finally, the development of a training video or multimedia tool (i.e., CD-ROM or DVD) is recommended for training maintenance staff in the safe and effective use of portable traffic signals.

CHAPTER 1. RESEARCH PROBLEM AND PROJECT OBJECTIVES

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 find alternative means to obtain other skills and services.

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 study 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 a number of 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) (*1*). Furthermore, the maintenance test sites used for this study 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 examined and addressed in this study 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.

Recommendations are presented that address each of these issues. All findings are documented in Research Report 3926-1 (*3*), and an additional companion document, Implementation Guide 3926-3 (*4*), is available that provides maintenance sections with guidelines for setting up and operating portable traffic signals in rural two-lane operations.

CHAPTER 2. RESEARCH TASKS AND PROCEDURES

The basic research tasks for this project, as refined during a meeting with TxDOT on September 26, 1997, are listed as follows:

- Task 1: Identify applicable operating conditions.
- Task 2: Identify applicable maintenance activities.
- Task 3: Determine efficiency and effectiveness relative to conventional techniques.
- Task 4: Develop instruction manual for use by field crews.
- Task 5: Prepare and submit final report.

Study results are based on the testing of the portable traffic signal technology on three separate rural two-lane highway maintenance projects in the TxDOT San Antonio District. The extent of the testing totaled 20 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 set up and signal operation.

The portable traffic signal equipment used for this study 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 which 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 time, 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. It should be noted that 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 technology. There are certain features that support portable traffic signal technology and which are advantageous to maintenance operations; these are highlighted in the research implementation recommendations as possible changes to TxDOT specifications.

The trailer units were tested for this project by the TxDOT Maintenance Section in Bandera, Texas. Three different work zones were evaluated using portable signals in place of flaggers.

All of the work zone test sites for this study 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 12-foot lanes and shoulder widths of 3 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;
- the time required to set up the signal trailers and begin full operation was 38 to 43 minutes, with the set up time decreasing with each successive job; and
- average speeds through the work zone were 20 to 25 mph. Maximum speeds were 33 to 40 mph.

Using the results of the field tests and input provided by the maintenance personnel involved in the testing, the researchers investigated a number of issues, developed recommendations, and prepared an implementation guide to be used by field personnel. The full documentation of data collection, findings, and recommendations can be found in Research Report 3926-1 (*3*).

CHAPTER 3. SUMMARY OF RESEARCH FINDINGS

FEASIBILITY FOR MAINTENANCE OPERATIONS

Field testing of the equipment 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 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.

The cost effectiveness of portable signals in daily maintenance operations was difficult to ascertain given the limited testing experience under this research study. 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.

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.

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.

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, frustration, and 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 in the opposite direction and for workers. This situation is especially hazardous in the one-lane work zones where sight distance is limited.

Temporary traffic signals for use in work zones create the appearance and driver expectation of operations similar to that experienced at standard, traffic signal controlled intersections. This is deceptive, 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, either because of relief, roadway geometry, or distance, to see the traffic that will be entering the one-lane, one-way work zone from the opposing direction. 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 set-up 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 (*1*) provides standards and guidelines for lane closures on two-lane roadways using traffic signals (sections 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 study. Those elements include maximum work zone length, installation of semi-permanent stop lines and other pavement markings, and flashing red conditions. Although not directly stated, it is inferred from the provisions of 6H-36 and 6H-37 that the construction work zone has clear line of sight through the entire work zone.

Revisions to the standards are needed that specifically address the application of portable traffic signals in short-term stationary maintenance operations. The revisions are provided in Table 1 and shown on Figure 1.

Visibility of Traffic Control Devices

In order 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 of the signal heads require special attention. The TMUTCD (*1*) 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.

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 signing (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

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.

Table 2 summarizes decision sight distance (DSD) requirements for a range of design speeds and conditions (*7*). 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.

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

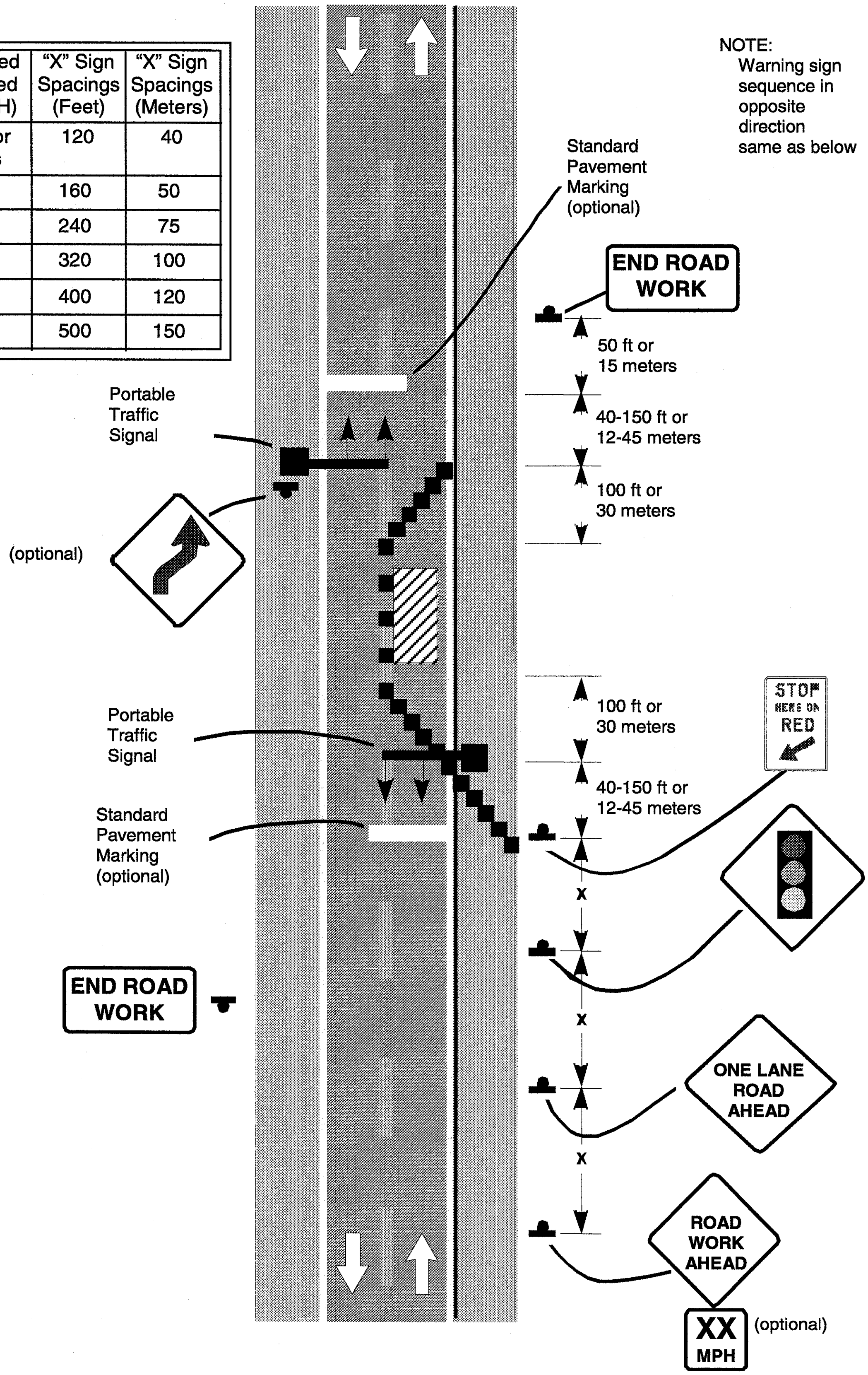
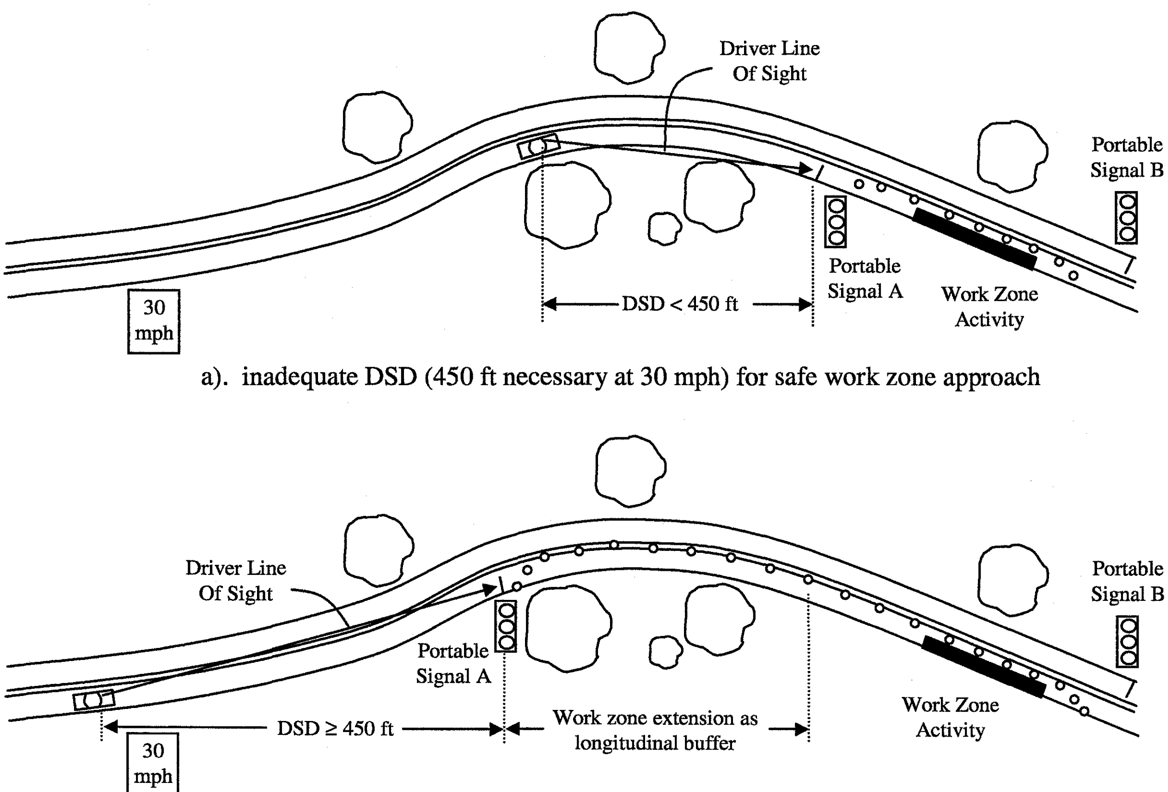


Figure 1. Proposed Changes in the Use and Placement of Traffic Control Devices for Short-Term Stationary Maintenance Work.

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 2).



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

b). work zone extension to provide adequate DSD

Figure 2. Example of Work Zone Extension to Obtain Decision Sight Distance.

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 (*1*) 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 study. 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 motorists and 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 setting advisory speeds in work zones. Regarding speeds in work zones, the TMUTCD (*1*) states that "traffic movement should be inhibited as little as practicable," and "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."

Minimum speeds in work zones, which is the critical concern in portable traffic signal operation within one-lane work zones, are not addressed. 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 study 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 are classified as "traffic control signals" under the provisions of the 4B-4 of the TMUTCD (*1*). 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 study regarding the applicability of portable traffic signals to maintenance operations indicate that the equipment should be used for routine maintenance projects an average of 10 to 12 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 (*1*) 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 (*1*) 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 research findings form the basis of the guidelines recommended for portable traffic signal application that are documented in the implementation guide (*4*). These guidelines are based on conservative application and interpretation of the TMUTCD (*1*). 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.

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 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.

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, long-term and relatively short work zones may see hardwiring the two signals together as 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 impacts 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. Motorists facing a long red at the portable signal may judge that the signal is malfunctioning and proceed along their way through the work zone. This can create a tremendous hazard, as the dangers present in work zones exist for workers as well as 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 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.

From Figure 3 and Figure 4, it is possible to see the various timing components of portable traffic signals setting for work zones. Note from Figure 4 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 5 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 5. However, it must be recalled that the wait time includes more factors than shown in Figure 5, 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.

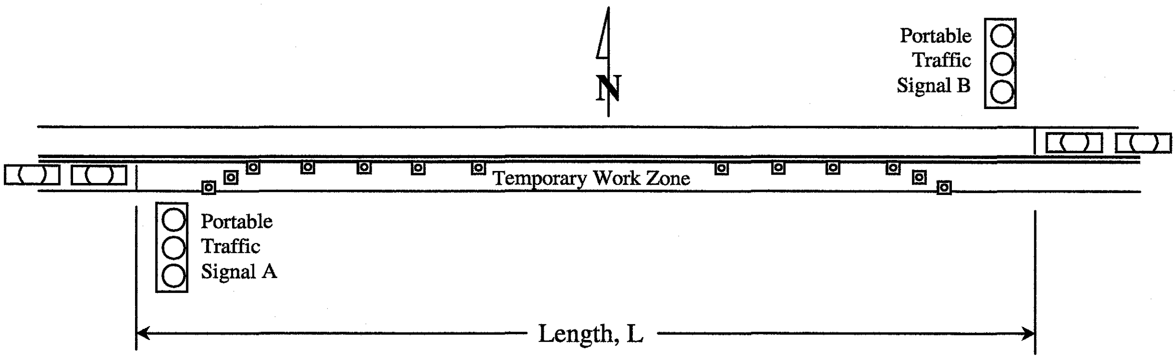


Figure 3. Portable Traffic Signal Installation for Temporary Work Zone Control.

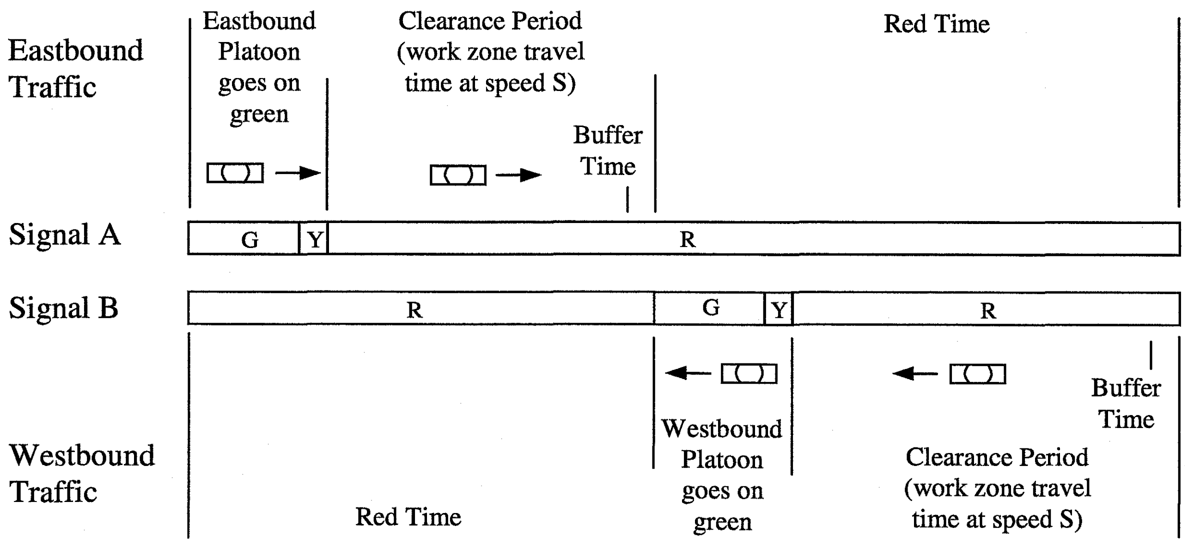


Figure 4. Complete Signal Cycle for Portable Traffic Signal Installation.

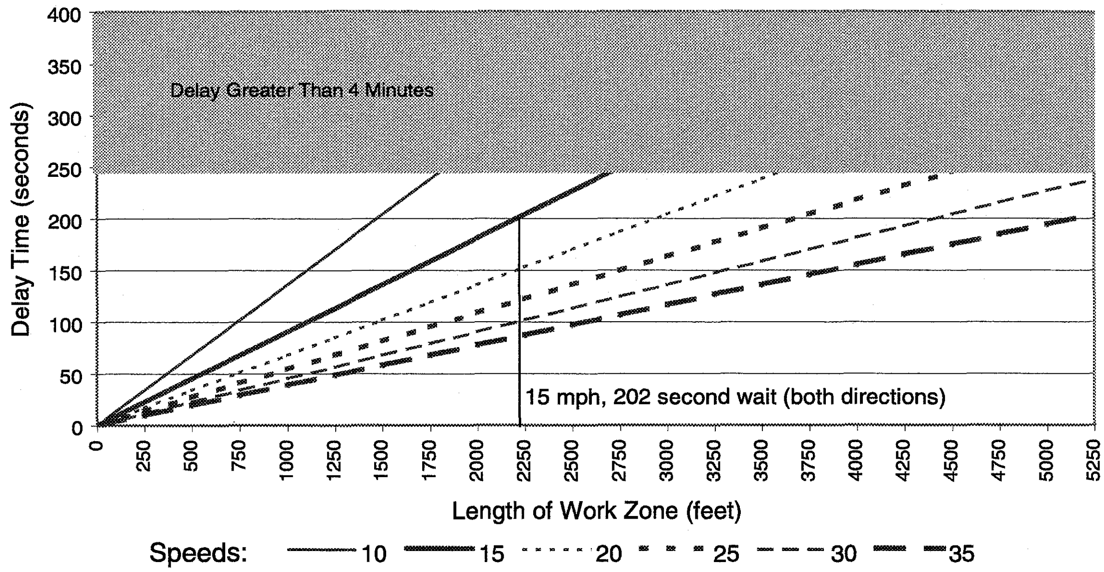


Figure 5. Impact of Speed and Length of Work Zone on Maximum Wait Time.

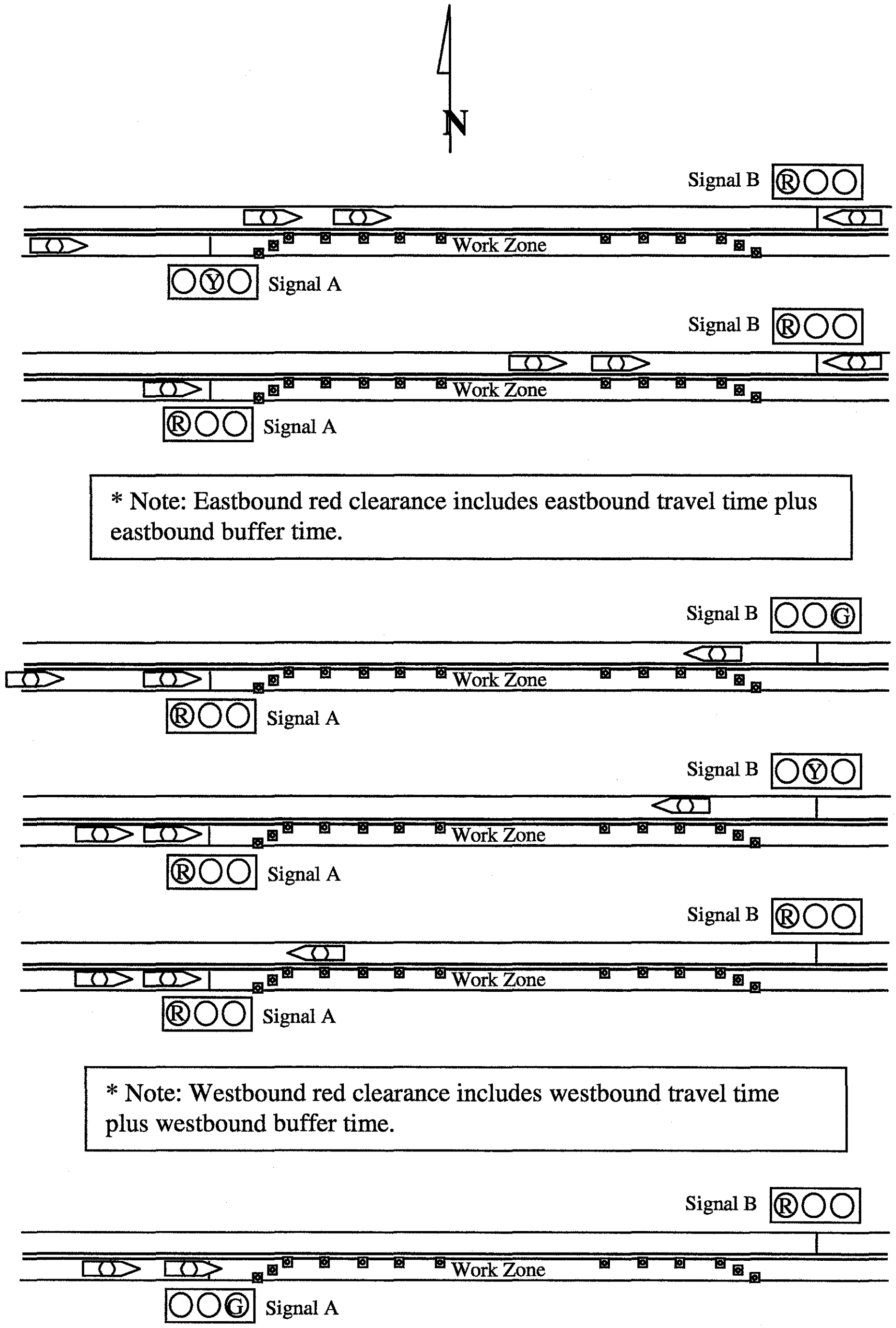
Figure 6 is a step-by-step illustrative example of the various signal timing elements that contribute to maximum waiting time. The Figure 6 example begins where an eastbound vehicle approaches the portable traffic signal at a point in time where the signal is about to change from green to yellow, and 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 four seconds, and that westbound traffic has a maximum green time of 30 seconds and a yellow clearance time of four 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 5). Ninety-eight of the 101 seconds in each direction is used for travel time, and a three-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 6 are for example purposes only; actual signal timing will be based on work zone characteristics, field conditions, and engineering judgement.

From Figure 6, we have the timing elements that contribute to the maximum wait time of our example problem. Equation 1 represents a mathematical calculation for the maximum wait time for eastbound traffic.

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

where:

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



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 6. Timing Elements for Wait Time Computation.

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:

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

Where:
- Y = yellow clearance time (applies to both directions), seconds
- R = red clearance time (applies to both directions), seconds
- B = buffer time (applies to both directions), seconds
- G_{max} = maximum green time in the opposing 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 two) 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 (based on travel time) time and buffer time 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 4 and Figure 6, 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.

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 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 set up 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. 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.

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.

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 seven to 10 seconds is usually appropriate.

Extension Interval (Actuated Operation)

If 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. An extension interval of three seconds can be used if the signal controller only accepts integer (i.e., round number) settings.

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

Table 4. Yellow Change Intervals for Various Speed and Grade Combinations (*8*).

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.

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 normal (i.e., non-work zone) speeds and speed limit on the facility, and the duration and nature of work in the construction/maintenance work zone. Table 5 contains values for travel time based on speed and work zone length. Note that the values in Table 5 are for travel time at the given speed only; they do not include any buffer time.

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:

$$\text{Red Clearance Interval} = \text{Work Zone Travel Time} + \text{Buffer Time}$$

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. 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 (i.e., for longer work zones), 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 (since 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.

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.

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);
- of 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.

Other equipment features that warrant consideration are as follows:

- alternatives to diesel or gasoline-powered generators, such as battery power and combinations of battery power and solar energy cells;
- light-emitting diodes (LEDs) that replace the incandescent bulbs currently used in most signal installations; and
- equipment features that promote flexibility and portability for short-term applications (i.e., weight and maneuverability).

CHAPTER 4. 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 (*1*) 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 (and 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 (*1*) 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 study, 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 long term 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 study, 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 allow 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 through the use of video. This particular medium was identified by field personnel as one of the more valuable approaches to promoting implementation. 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.

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