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16. Abstract

This report describes the methodology and results of analyses performed to identify and evaluate alternative methods to control traffic entering a lane closure on a two-lane, two-way road from low-volume access points. Researchers documented the state-of-the-practice regarding temporary traffic control at lane closures on two-lane, two-way roads in Texas, and examined existing and innovative devices and strategies that could be used to control traffic entering from low-volume access points. Researchers also compared the benefits and costs of various temporary traffic control alternatives for low-volume access points. Motorist surveys and field studies were conducted to assess motorist understanding and the operational and safety effectiveness of two innovative devices to control traffic at low-volume access points. The findings from these tasks and studies were used to develop guidelines regarding the appropriate traffic control for low-volume access points within a lane closure on a two-lane, two-way road.

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DISCLAIMER

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

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER 1:
INTRODUCTION

STATEMENT OF THE PROBLEM

When a lane is closed on a two-lane, two-way road for construction or maintenance activities provisions must be made to alternate one-way movement of the two original travel lanes through the work area. Typically, flaggers are positioned at each end of the lane closure to control the flow of traffic. Pilot cars may also be used to direct traffic through the work zone, as well as regulate the speed of vehicles. Unfortunately, this type of temporary traffic control requires two to three workers. In addition, since flaggers are positioned on the edge of high speed roads in the transition area where traffic is moved out of its normal path, crashes involving flaggers can result in serious injury or death to the flagger.

More recently, automated flagger assistance devices (AFADs) and temporary traffic control signals (TTCSs) are being utilized to control traffic during temporary one-way operations. AFADs are designed to be remotely operated by a flagger positioned off the roadway, thereby reducing the flagger's exposure to traffic. In contrast, TTCSs replace flaggers, allowing them to conduct other work.

Quite often there are low-volume access points, such as residential driveways or county roads, within the temporary one-lane section of roadway. There is the potential for motorists entering the roadway from these access points to misunderstand the direction of traffic, enter the roadway going in the wrong direction, and collide with a vehicle travelling through the work zone. While these access points should be monitored, existing methods are not always feasible based on conditions such as work duration, traffic volume, time of day, and cost of the method. So, Texas A&M Transportation Institute (TTI) researchers were asked to identify and evaluate alternative methods to control traffic entering a lane closure on a two-lane, two-way road from low-volume access points.

CONTENTS OF THIS REPORT

This report describes the methodology and results of analyses conducted to: (1) identify and evaluate traffic control technologies and strategies that could be used to control traffic entering from low-volume access points and (2) develop guidelines regarding the appropriate traffic control for low-volume access points within a lane closure on a two-lane, two-way road. Chapter 2 documents the state-of-the-practice regarding temporary traffic control at lane closures on two-lane, two-way roads in Texas. Chapter 3 examines existing and innovative strategies and devices that could be used to control traffic entering from low-volume access points. Chapter 4 and Chapter 5 detail the experimental design and findings from the motorist surveys and field studies, respectively. Chapter 6 compares the benefits and costs of various temporary traffic control alternatives for low-volume access points. Chapter 7 contains a summary of all the findings and guidelines regarding appropriate traffic control for low-volume access points within a lane closure on a two-lane, two-way road.

CHAPTER 2:
STATE-OF-THE-PRACTICE

INTRODUCTION

In order to determine the state-of-the-practice regarding temporary traffic control at lane closures on two-lane, two-way roads in Texas, researchers reviewed Texas standards and previous literature. In addition, researchers also conducted telephone discussions with key Texas Department of Transportation (TxDOT) personnel. The following sections describe the findings of these activities.

TEXAS STANDARDS AND PREVIOUS LITERATURE

The *2011 Texas Manual on Uniform Traffic Control Devices* (MUTCD) (*1*) provides guidance on the temporary traffic control that can be used when traffic in opposite directions must use a single lane for a limited distance. The Texas MUTCD states that movements from each end shall be coordinated and that access should be controlled throughout the one-lane section. The Texas MUTCD acknowledges that driveways create a problem that should be monitored, and that closures of all entering intersections within the work zone should be considered. Provisions for alternate control for one-way movement through the single lane section include flagger control, stop or yield control, or TTCSs at each end of the work zone. A pilot vehicle may also be used.

Flagger Control

According to the Texas MUTCD, when flagger control is used, traffic should be regulated by a flagger at each end of a constricted section of roadway. Only if the one-lane section is short enough to allow one flagger to see from one end of the zone to the other may traffic be controlled by a single flagger. In such a case, the flagger should be stationed on the shoulder opposite the construction or work space, or in a position where good visibility and traffic control can be maintained at all times. Flaggers may also be used to control traffic entering from intersecting roadways or driveways. All flaggers should be able to communicate with each other to ensure coordination among movements (*1*).

Flagger control is typically used for short duration operations (work that occupies a location up to 1 hour) and short-term stationary operations (daytime work that occupies a location for more than 1 hour within a single daylight period). Flagger control may also be used at night as long as the flagger station is illuminated.

Since flaggers are positioned on the edge of high speed roads in the work zone transition area (where traffic is moved out of its normal path), crashes involving flaggers often result in serious injury to the flagger. Recently, AFADs were approved by TxDOT (*1*). AFADs are portable traffic control systems designed to be remotely operated by a flagger positioned off the roadway; thereby reducing the flagger's exposure to vehicular traffic. However, it is important to remember that AFADs must be operated by a flagger who has been trained on the operation of the device, and the flagger operating the AFAD cannot leave the device unattended at any time while the device is being used.

Stop or Yield Control

As an alternate to flagger control, STOP or YIELD signs may be used to control traffic on low-volume roads at one-lane, two-way work zones when motorists are able to see the other end of the one-lane section and have sufficient visibility of approaching vehicles (*1*). For projects in urban areas, the work space should be no longer than one half a city block. In rural areas, this type of temporary traffic control may be used on roadways with less than 2000 annual daily traffic (ADT) and the work space should be no longer than 400 ft (*2*).

Temporary Traffic Control Signals

TTCSs can also be used to control the movement of vehicles through a one-lane section, and do not require the presence of flagger control. TTCSs must meet the physical display and operational requirements of a conventional traffic control signal. Adequate means, such as interconnection, shall be provided to prevent conflicting signal indications, such as green and green, at opposite ends of the section. Adequate red clearance interval durations must be provided to clear the one-lane section of conflicting vehicles before opposing traffic is allowed to proceed (*1*).

The Texas MUTCD indicates that TTCSs are preferable to flaggers for long-term projects and other activities that would require flagging at night (*1*). TxDOT standards also state that for long-term, one-lane, two-way control (work that occupies a location more than three days), TTCSs should be used if the volume and length criteria described above for stop and yield control cannot be met (*2*).

A previous TTI study (*3*) found conservative estimates of the savings achieved by using portable traffic control signals (TTCSs on portable supports) ranged from $9 to $14 an hour, and that the signals would pay for themselves after 1600 hours of service. Initially, portable traffic control signals (PTCSs) used a fixed-time (or pre-timed) strategy to assign right-of-way among the two directions of traffic. Previous research (*3*) regarding this approach showed that at sites with low traffic demand, motorist delay increased when PTCSs were used in place of flaggers. One of advantage of flaggers is that they can react quicker to isolated random vehicle arrivals and gaps in the traffic stream in a manner that minimizes vehicle stops and delays. However, when traffic demands were greater, flaggers were not found to have as distinct an advantage over fixed-time signals.

PTCSs were originally used on two-lane bridge construction projects, so the work zone length was relatively short (400 to 1200 ft) (*4*). Now, PTCSs are being used on construction and maintenance projects that are considerably longer (5280 ft). As noted in a previous TTI study (*4*), streets and driveways intersecting the lane closure can create difficulties for PTCS operation, as well as for flagging operations. A detailed study of intrazone access concerns was not completed as part of this TTI study. Instead, the following principles used during flagging operations to address intrazone access were recommended for PTCS operations.

- The length of the lane closure should be designed to exclude intersections of heavily traveled cross streets.
- If minor streets or driveways must be located within the lane closure, a worker should be stationed at the access point to hold traffic until the direction of travel of the main street traffic is clear.

Pilot Vehicle

A pilot vehicle may be used to guide a queue of vehicles and regulate the speed of vehicles through the one-lane section. However, according to the Texas MUTCD, when a pilot vehicle is used a flagger must be stationed on the approach to the activity area to control vehicular traffic until the pilot vehicle is available (*1*).

STATE-OF-THE-PRACTICE IN TEXAS

In order to determine the state-of-the practice regarding temporary traffic control at lane closures on two-lane, two-way roadways, in the fall of 2011 researchers conducted telephone interviews with TxDOT personnel familiar with these types of work zone activities. The interview took approximately 10 to 15 minutes to complete. The research team conducted a total of 23 interviews. Table 1 lists the 23 districts and area offices that participated.

Table 1. TxDOT District and Area Offices Interviewed.

District	Area Office
Abilene	Big Spring
Amarillo	Pampa
Atlanta	Mount Pleasant
Austin	Burnet
Beaumont	Beaumont
Brownwood	Brownwood
Bryan	Bryan
Childress	Childress
Corpus Christi	Sinton
Dallas	Corsicana
El Paso	Alpine
Fort Worth	Weatherford
Houston	Fort Bend
Laredo	Laredo
Lubbock	Brownfield
Odessa	Odessa and Midland
Pharr	Hebbronville
San Angelo	San Angelo
San Antonio	New Braunfels
Tyler	Jacksonville
Waco	Gatesville
Wichita	Wichita Falls
Yoakum	Yoakum

The research team developed an interview guide to ensure that key topics were covered consistently from person to person. The topics discussed were divided into three sections: (1) temporary traffic control on the main road, (2) temporary traffic control at the access points, and (3) innovative technologies or strategies used to control traffic at access points. Topics discussed in each section during the telephone interviews included:

1) Temporary traffic control on main road
    - What types of temporary traffic control does your agency use to direct traffic on the main road at lane closures on two-lane, two-way roadways? Which one(s) does your agency use the majority of the time?
    - What are the main factors that influence the selection of the temporary traffic control on the main road? What are the top three factors that influence the selection of the temporary traffic control on the main road?
    - Does your agency have policies and/or practices regarding what temporary traffic control to use on the main road at lane closures on two-lane, two-way roads?
2) Temporary traffic control at access points
    - What types of temporary traffic control does your agency use at access points within a lane closure on two-lane, two-way roadways? Which one(s) does your agency use the majority of the time?
    - What are the main factors that influence the selection of the temporary traffic control at access points within a lane closure on two-lane, two-way roadways? What are the top three factors that influence the selection of the temporary traffic control at the access points?
    - Does your agency have policies and/or practices regarding what temporary traffic control to use at access points within a lane closure on two-lane, two-way roads?
    - What are the difficulties with controlling traffic at access points within lane closures on two-lane, two-way roads?
3) Innovative technologies and strategies
    - Do you know of any innovative technologies or strategies that could be used to control traffic at access points within a lane closure on two-lane, two-way roadways? If so, could you please describe the technology/strategy and how it was used? Has your agency used this technology/strategy?

It should be noted that when discussing factors that influence the selection of temporary traffic control on the main road and at access points within a lane closure, the researchers had a list of potential factors that could be considered on the interview guide. If a certain factor was not mentioned by TxDOT personnel, the researcher would prompt the individual to ensure that all potential factors were addressed. The list of factors considered for the main road consisted of the following: work zone duration, work zone length, main road demand, cost of temporary traffic control, availability of temporary traffic control, number of access points with the lane closure, and access point demand. Factors to be considered on the access road were the same as above but with the addition of type of temporary traffic control on the main road. TxDOT personnel could also mention additional factors during the interview.

Temporary Traffic Control on Main Road

As shown in Table 2, all the TxDOT personnel contacted stated they use flagger control on the main road at lane closures on two-lane, two-way roadways. Also, the majority of personnel contacted use a pilot vehicle to guide traffic and regulate speed through the one-lane section. Since AFADs are fairly new to TxDOT, it is not surprising that only 13 percent stated that they currently used AFADs in conjunction with flaggers. More than half of the personnel contacted use PTCSs instead of flaggers. A few districts also reported using yield control on the main road. Overall, flagger control in conjunction with a pilot vehicle was the most widely used temporary traffic control at lane closures on two-lane, two-way roads.

Table 2. Types of Temporary Traffic Control Used on Main Road.

Type of Temporary Traffic Control	Percent of Respondents[a] (n=23)
Flaggers	100%
Flaggers with pilot vehicle	96%
Flaggers with AFADs	13%
PTCSs	61%
Yield	8%

[a] The sum across rows does not equal 100 percent due to multiple responses per respondent.

Table 3 shows the factors that influence the selection of the temporary traffic control on the main road. Overall, work zone duration, work zone length, and main road demand were the top three factors that impacted the selection of the temporary traffic control on the main road. Work duration refers to the length of time the work activity will take to complete. For short duration operations (i.e., less than one daytime hour), flagger control is typically used. Flaggers are also used for short-term operations (i.e., daytime work that occupies a location for more than one hour but less than a single daylight period). However, most personnel stated that as the duration increased (i.e., several hours to all day) they typically added a pilot vehicle. Flaggers in conjunction with a pilot vehicle are also used for daytime operations that may take several days to complete but do not require temporary traffic control overnight. AFADs are also used in conjunction with flaggers for short duration and short-term operations. PTCSs are most often used when the work activity requires the main road temporary traffic control to be active both during the day and at night (i.e., intermediate-term and long-term operations). However, in an effort to improve flagger safety and work crew productivity, it is becoming more common for PTCSs to be used with work activities that only last one day.

Table 3. Percent of Respondents Choosing Each Factor that Influences the Selection of Temporary Traffic Control on the Main Road.

Type of Temporary Traffic Control	Factors that Influence Selection of TTC on Main Road[a]					
	Work Zone Duration	Work Zone Length	Main Road Demand	Number of Access Points	Availability of TTC	Access Point Demand
Flaggers (n=23)	100%	87%	87%	83%	13%	48%
Flaggers with pilot vehicle (n=22)	77%	86%	64%	45%	9%	0%
PTCSs (n=14)	86%	57%	71%	14%	29%	7%
AFADs (n=3)	100%	100%	33%	33%	67%	0%
Overall (n=62)	89%	81%	73%	40%	18%	19%

[a] The sum across columns does not equal 100 percent due to multiple responses per respondent.

Work zone length refers to the distance from the beginning to the end of the temporary traffic control zone. All of the types of main road temporary traffic control shown in Table 3 are used for work zones that are "short" in length (typically less than a mile). When sight distance becomes an issue pilot vehicles are typically added or PTCSs are used. Obviously, the available sight distance varies widely across the state due to terrain changes (i.e., gentle rolling of the plains and piney woods to flat in west Texas).

Main road demand represents the traffic volume on the main road. While the main road demand was considered a primary factor in the selection of the temporary traffic control on the main road, most individuals stated that they used knowledge of the area and engineering judgment with respect to this factor. Flagger control is used on both high and low volume facilities; however, pilot vehicles are typically added as the volume increases. PTCS are also used across a range of traffic volumes.

The number of access points and access point demand influenced the decision to use flagger control more than other types of temporary traffic control. Based on further discussion, this influence was impacted by the need to have additional flaggers at the access points. Some individuals mentioned that if there were too many access points they would add a pilot vehicle.

Not surprisingly, availability highly influenced the decision to use AFADs and to some extent the use of PTCSs. The research team also asked whether the cost of the temporary traffic control impacted their decisions. The majority of personnel stated that cost does not influence the selection decision because it is integrated into the overall construction/maintenance project cost or was already owned by TxDOT. The only other factor repeatedly mentioned by respondents was whether or not flaggers would have limited sight distance and/or communication issues due to the terrain (i.e., horizontal and vertical curvature). If either of these factors were determined to be a concern, pilot vehicles were typically added.

Finally, each individual was asked what policies and/or practices their office used regarding what temporary traffic control to use on the main road at lane closures on two-lane, two-way roadways. The policies mentioned included the Texas MUTCD (*1*) and the TxDOT Traffic Control Plan Standards (*2*).

Temporary Traffic Control at Access Points

When asked what type of temporary traffic control was used at access points within a lane closure on a two-lane, two-way road, flagger control was selected by all personnel. In addition, almost one-quarter of the respondents (22 percent) stated that they also used barricades and cones to close low-volume access points. TxDOT personnel also visit property owners and residents to notify them of the changes in traffic control and what they should do when exiting their driveway.

As in the previous section, each contact was asked what main factors influenced their selection of the type of temporary traffic control to use at the access points. Table 4 contains the factors that influence the use of flagger control at access points. The top factor was access point demand or the traffic volume coming from the access point (74 percent). Most individuals stated that they used knowledge of the area and engineering judgment to determine if a flagger was needed at each access point on a case-by-case basis. While some of the TxDOT personnel reported that their district used certain traffic volume criteria to determine when a flagger was needed, the thresholds varied widely.

Table 4. Factors that Influence the Use of Flagger Control at Access Points (n=23).

Factors	Percent of Respondents[a]
Access point demand	74%
Main road demand	48%
Number of access points	43%
Work zone duration	35%
Work zone length	35%
Site distance	13%
Availability of flaggers	9%
Type of location	9%
Safety	9%
Type of temporary traffic control on main road	4%
Type of work	4%
Type of traffic	4%

[a] The sum across rows does not equal 100 percent due to multiple responses per respondent.

The next most mentioned factor was the main road demand (48 percent). About one-third of these respondents stated that if the volume was high on the main road they would consider using flaggers at all access point locations. Conversely, 17 percent of the respondents stated that if the main road demand was low, they may not use flaggers at access points (i.e., self-controlled). Another one-third of the respondents reiterated that each access point had to be considered on a case-by-case basis. One respondent did mention that if the main road demand was over 15,000 vehicles per day (vpd) and there were concerns with the number of access points and/or access point demand, they consider completely closing the main road and providing a detour via another route.

Forty-three percent of the respondents also indicated that the number of access points within the lane closure was an influential factor. Of those, 70 percent stated that they try to use a flagger at all access points, but again each access point must be considered on a case-by-case basis. Some respondents explained that they try to minimize the number of access posts within the lane closure by reducing the work zone length.

About one-third of the respondents indicated that the work zone length and duration influenced the decision to use a flagger at an access point. When access points are located in a shorter length work zone, the flaggers at the ends of the temporary traffic control on the main road may be able to see the vehicles arrive at the access points and signal them when to proceed. In contrast, longer work zones limit that ability of the flagger to view access point vehicles and vice versa. Instead of stationing a flagger at each access point, sometimes a pilot vehicle is added to direct traffic from access points. As the pilot vehicle travels through the work zone, the driver looks for vehicles that need to enter the main roadway from access points, uses hand signals to identify which way the motorist needs to proceed, and directs them when to proceed. Of course, personnel visit with property owners prior to the work beginning to discuss the procedures being implemented. For shorter term operations, most personnel indicated that they consider using flaggers at all access points, but again this would need to be determined on a case-by-case basis.

Each individual was asked what policies and/or practices their office used regarding what temporary traffic control to use at access points within lane closures on two-lane, two-way roadways. Again, the policies mentioned included the Texas MUTCD (*1*) and the TxDOT Traffic Control Plan Standards (*2*). However, 43 percent of the respondents noted the lack of direction regarding the type of temporary traffic control to use at access points and when it should be used, but realized again that each case is site specific.

Finally, researchers asked each individual if they had experienced any difficulties with controlling traffic at access points within lane closures on two-lane, two-way roadways. The following is a list of comments and the percentage of respondents that reported them:

- Distracted motorists and motorist inattention (43 percent).
- Manpower; hard to cover all access points (22 percent).
- Lack of an indication of what action motorists need to do at access points (9 percent).
- Access points that are located too close to traffic signals, resulting in vehicles getting backed up at access point (4 percent).
- Motorists exiting from the access point and coming into the work zone area the wrong way (4 percent).

Innovative Technologies and Strategies

In the final section, researchers asked TxDOT personnel if they knew of any innovative technologies or strategies that could be used to control traffic at access points within a lane closure on two-lane, two-way roadways. The majority of the personnel contacted (91 percent) replied no. Only two individuals provided comments with regard to innovative technologies or strategies.

- One suggested that the pilot vehicle driver control an AFAD located at the access point. As the pilot vehicle passed the access point, the driver could remotely raise the gate arm, and vehicles located at the access point could then join the vehicle queue behind the pilot vehicle. The pilot vehicle could also remotely lower the gate arm or it could be done automatically with sensing technology.
- Another individual suggested using temporary traffic control signs or a signal of some type that indicated to motorists when they could proceed and the direction they should proceed (i.e., right or left).

Both individuals stated the strategy would need to indicate when the motorist at the access point should stop, when to proceed, the direction to proceed, and who had the right of way. However, neither individual had ever heard of or used such technologies.

CHAPTER 3:
STRATEGIES AND DEVICES FOR LOW-VOLUME ACCESS POINT CONTROL

INTRODUCTION

Some traditional single lane temporary traffic control methods can also be used at access points. In addition, discussions with PTCS manufacturers and the TxDOT project working group revealed that experimental products to control traffic at low-volume access points within lane closures on two-lane, two-way roads are being developed. Overall, researchers identified and explored four innovative device concepts. The following sections describe these devices and strategies, as well as the researchers' recommendations regarding further study.

EXISTING STRATEGIES AND DEVICES

As discussed previously, provisions for alternate control for one-way movement through the single lane section include flagger control, stop or yield control, or PTCSs at each end of the work zone. Of these methods, a flagger or a PTCS could also be used to control traffic entering the single lane section from a low-volume access point.

Flagger Control

Flaggers can be placed at low-volume access points; however, as mentioned previously, there are safety and productivity concerns with this method. The practicality of having a flagger stationed at a low-volume access point all day when very few vehicles are expected is debatable. Most TxDOT personnel interviewed stated that they used knowledge of the area and engineering judgment to determine if a flagger is needed at each access point on a case-by-case basis. The use of flaggers for work that requires a lane closure but no active work overnight (e.g., concrete curing) is also undesirable. Based on the TxDOT interview results and discussions with the TxDOT project working group, researchers discovered an overall desire to utilize devices instead of flaggers to control traffic on the main road and at access points.

Portable Traffic Control Signals

Based on discussions with the TxDOT project working group, PTCSs are sometimes used at access points. When this occurs, PTCSs are also used at each end of the lane closure on the main road. Currently, PTCSs used in Texas display steady circular red, yellow, and green indications. Thus, directional information (i.e., right or left turns allowed) cannot be conveyed to drivers at the access point. So, when the access point PTCS displays the steady green circular indication (proceed), the other two PTCSs on the main road must display steady circular red indications (stop). The access point traffic is then free to travel in either direction. One concern with this setup is the potential increase in traffic delay on the main road, especially as the work zone length and main road volume increases. Currently, vehicle actuation is not typically used with PTCSs so even when there are no vehicles at the access point it would be serviced; yielding longer delays on the main road. Even if vehicle actuation was used, this setup encounters further coordination and delay issues if there are multiple low-volume access points. Another potential solution would be to purchase PTCSs that provide directional information for use at access points. However, TxDOT desired a lower cost solution that would work in conjunction with PTCSs on the main road.

INNOVATIVE DEVICES

Based on the TxDOT's desire to utilize lower cost devices instead of a flagger or PTCS to control traffic entering the single lane section from a low-volume access point, researchers investigated several innovative devices.

Push Button Device

The first innovative technology uses equipment similar to an electronic gate-opener at the access point. When a vehicle needs to exit the access point, the motorist pushes a button on the equipment. The equipment then sends a wireless signal to the flagger station, which notifies the flagger that a vehicle needs to exit the access point, but does not indicate the direction the motorist wants to go. Thus, traffic in both directions on the major road must be stopped. The vehicle at the access point is then allowed to enter the lane closure and travel in either direction. To date, the application of this innovative technology has been limited to residential driveways located within the lane closure. This innovative technology can also be used with PTCSs.

TTI researchers reviewed the operation of this device and identified several concerns. First, if the equipment at the access point is fixed (cannot be moved), this may negatively impact work activities dependent upon its location. Power would also be needed. Based on discussions with the vendor, it was unclear whether the motorist at the access point received confirmation that the flagger or PTCS has been notified of their presence. It was also unclear how the motorist at the access point was told when to enter the lane closure. An option would be to include two-way communication. That way, the motorist and flagger could verbally communicate (i.e., need to leave, desired direction, when to proceed, etc.). This would also remove the need to stop both directions of traffic, which could increase the main road delay. However, including two-way communication may require a Federal Communications Commission (FCC) license to operate the system. Obviously, flaggers can confirm that the access point vehicle has cleared the closure. However, if PTCSs are used, adequate all-red time must be provided to allow the access point vehicle to clear the lane closure in either direction. Currently, there is no equipment used to verify that the vehicle has cleared the lane closure. If there is more than one access point within the lane closure, coordination among the equipment and signals would be needed to ensure that motorists from multiple driveways are not entering the lane closure at the same time and traveling in opposite directions. Overall, TTI researchers felt that this type of technology would only be feasible when there is one residential driveway (i.e., small number of familiar motorists), and TxDOT personnel met with the residents to explain the upcoming temporary traffic control situation and technology.

Modified Stop Sign Device

In 2009, Randy Bowers of TxDOT developed the device concept illustrated in Figure 1 to control traffic from residential driveways within a lane closure on a two-lane, two-way road where PTCSs control the main road traffic. This portable device is comprised of two signs. The top sign is diamond shaped with an orange background (i.e., a construction warning sign). In the middle of the top sign there is an octagonal stop sign face (white legend on a red background) surrounded by red light-emitting diodes (LEDs). A yellow LED arrow is located on each side of the stop sign face (one pointing to the left and one pointing to the right). The red LEDs surrounding the stop sign face would be illuminated during the all-red phase of the PTCSs controlling traffic on the major road. Flashing yellow LED arrows, timed in conjunction with the PTCS steady circular green indications, would be illuminated to show the motorist at the access point the direction of travel in which they may proceed. A change to a steady yellow LED arrow, timed in conjunction with the PTCS steady circular yellow indication, would signify that the device was about to change to a stop condition. The bottom sign is a rectangular regulatory sign (black legend on a white background) that states ONE WAY ACCESS PERMITTED IN DIRECTION OF FLASHING YELLOW ARROW.

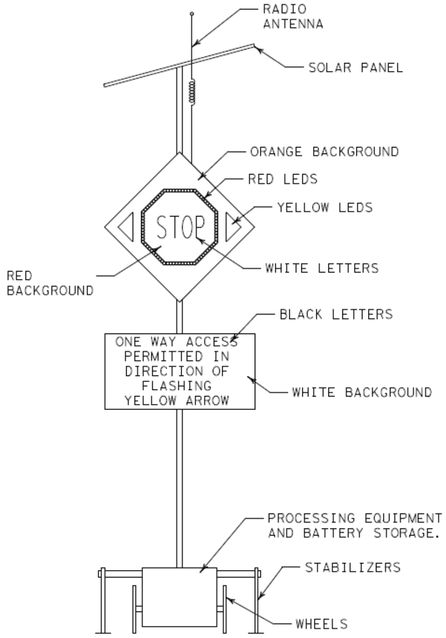


Figure 1. Modified Stop Sign Device.

TTI researchers evaluated this device regarding Texas MUTCD requirements and identified several concerns (*1*). The top sign is not actually a stop sign since it is embedded into another sign. Instead the top sign looks more like a stop ahead sign (W3-1). So there was some question as to the legality of the stop part of the sign, as well as how motorists would interpret the sign. The flashing yellow arrows used to indicate the direction a motorist may proceed are not standard arrow displays. In addition, the bottom regulatory sign may be interpreted as indicating the way the motorist should go (correct) or the way the major road traffic is coming from (not correct). Researchers also saw the opportunity for access point vehicles to become entrapped within the lane closure dependent upon how the device operated relative to the PTCSs.

Hybrid Device

Randy Bowers also developed the device concept illustrated in Figure 2 to control traffic from low-volume access points within a lane closure on a two-lane, two-way road where PTCSs control traffic on the major road.. This device is a hybrid of a PTCS and an AFAD. This concept is a similar application to the one illustrated in Figure 1 but replaces the stop sign face with a steady circular red indication (12 inch) and utilizes standard flashing yellow arrow indications (8 inch) for the directional information. The following phase sequence repeats and is coordinated with the PTCSs on the main road: the stop phase, the proceed phase in one direction (e.g., right), the transition phase in the same direction (e.g., right), the stop phase, the proceed phase in the other direction (e.g., left), the transition phase in the same direction (e.g., left), and the stop phase. In the stop phase, the steady circular red indication is illuminated to inform drivers to remain stopped. In the proceed phase, the yellow arrow indication flashes in the direction that motorists can travel (either left or right). A steady yellow arrow indication is provided as a change interval between the flashing yellow arrow and steady circular red indications. In addition to the ONE WAY ACCESS PERMITTED IN DIRECTION OF FLASHING YELLOW ARROW regulatory sign, a NO TURN ON RED sign (R10-11) is displayed to restrict turns during the stop phase.

Figure 2. Hybrid Signal Device.

TTI researchers also had concerns regarding this device's design. Since this hybrid device merge designs from existing temporary traffic control devices there is some potential for motorist misunderstanding of the device. While this design does use standard traffic signal indications, the signal head order is not standard (i.e., steady circular red signal in the middle). TTI researchers also questioned whether the flashing yellow arrows indicate to access point motorists that they must yield the right-of-way to vehicles on the major road. Flashing yellow arrow indications have been studied extensively for permissive left turns, but not in this type of application. The need for both regulatory signs, as well as motorist understanding of these signs with such a signal head, was also unknown.

To address some concerns expressed by the Federal Highway Administration (FHWA) regarding the device in Figure 2, TTI researchers developed the modified hybrid device design shown in Figure 3. The two flashing yellow arrow indications were now located below the steady circular red indication, and all indications were 12 inches in diameter. The modified hybrid device would operate in the same manner as the original hybrid device in Figure 2. In addition, a NO TURN ON RED sign would most likely be needed. While questions regarding actual operation and motorist understanding still existed, TTI researchers and TxDOT believed this design had promise.

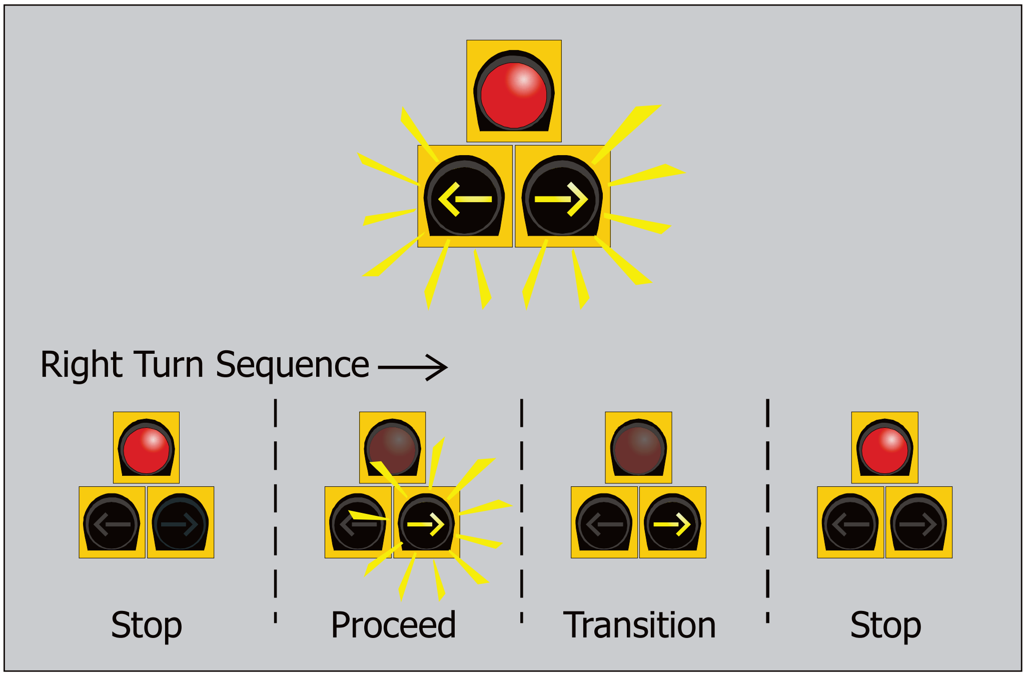


Figure 3. Modified Hybrid Device.

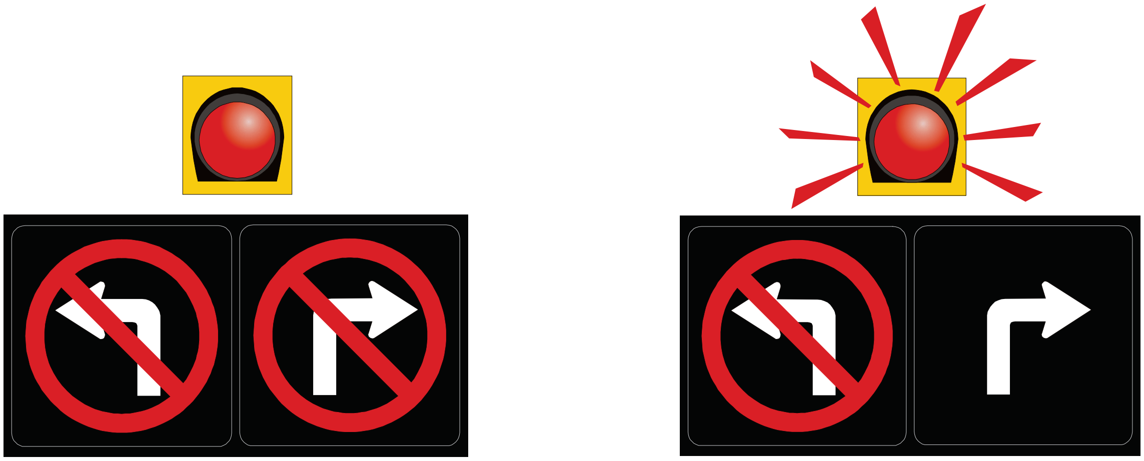
Researchers considered the use of dual steady red arrow indications (right and left) in one signal lens instead of the steady circular red indication. However, researchers determined that while technology exists to produce a dual arrow signal indication, the limited application of such indications made development cost prohibitive.

Researchers also considered using various combinations of steady circular red, flashing/steady red arrow, flashing/steady yellow arrow, and steady green arrow indications in a three row signal indication configuration. However, to reduce cost and potential confusion with standard signals, the TxDOT working group preferred a two row design.

Blank-Out Sign Device

TTI researchers also developed the initial concept for the device in Figure 4. This device is comprised of a circular red indication and two internally illuminated blank-out signs that display movement prohibition signs (R3-1 and R3-2). In the stop phase, this device would display a steady circular red indication to indicate that motorists should stop and remain stopped until otherwise indicated, and both movement prohibition signs would be illuminated to prohibit left and right turns. When a vehicle is allowed to proceed to the left, the circular red indication would flash and the red circle/slash would not display over the left arrow; allowing traffic to turn to the left only after coming to a complete stop. The circle/slash on the sign with the right arrow would be displayed; prohibiting right turns. When right turns are allowed, the circular red indication would flash, the red circle/slash would not display over the right arrow, and the red circle/slash would display over the left arrow. Off-the-shelf blank-out signs would need to be altered such that the white arrows and red circles/slashes could be illuminated separately.

According to the Texas MUTCD (*1*), if a black background is used the legend color should match the background color of the standard sign, such as white for regulatory. Of course, newer technology provides the capability to display an exact duplicate of the standard static signs (i.e., white background, black arrow, and red circle/slash). However, such technologies (i.e., full-matrix and full-color) are more expensive.



a) Stop – No Turns Allowed **b) Proceed – Right Turns Allowed**

Figure 4. Blank-Out Sign Device.

SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDY

While some traditional temporary traffic control methods can be used to control traffic entering a lane closure on a two-lane, two-way road from low-volume access points, TxDOT was interested in evaluating innovative devices in an effort to improve safety and reduce costs. Overall, TTI researchers and TxDOT believed that the modified hybrid device and the blank-out sign device showed the most promise. Thus, TTI researchers recommended the conduct of:

- Motorist surveys to determine motorists' understanding of these two devices.
- Field studies to assess the operational and safety effectiveness of these two devices.

These studies are described in the following chapters.

CHAPTER 4:
MOTORIST SURVEY

INTRODUCTION

Before building actual prototypes of the modified hybrid and blank-out sign devices, researchers conducted an initial assessment of motorist understanding of these devices using laptop-based surveys. The following sections describe the experimental design, data analysis, and results of the motorist surveys.

EXPERIMENTAL DESIGN

The following sections document the treatments used, participants solicited, and protocol followed for the motorist surveys.

Treatments

Figure 3 and Figure 4 show the two devices evaluated in the motorist surveys. Researchers evaluated the modified hybrid device with and without the NO TURN ON RED sign (R10-11) shown in Figure 5 to assess the need for including the supplemental sign to control the turn movements during the stop phase. The ONE WAY ACCESS PERMITTED IN DIRECTION OF FLASHING YELLOW ARROW regulatory sign was not used.

Figure 5. No Turn on Red Sign (*1*).

As previously discussed, the initial design of the second device included blank-out sign technology to display movement prohibition signs (i.e., black background, white arrow, and red circle/slash). However, newer technology provides the capability to display an exact duplicate of the standard static signs (i.e., white background, black arrow, and red circle/slash). So, in the motorist surveys researchers evaluated both versions (white arrow with black background and black arrow with white background) to determine if color impacted comprehension.

Table 5 shows the video sequences researchers created on a laptop computer to evaluate motorist comprehension of the modified hybrid and blank-out sign devices. Figure 6 shows screenshots from four of the videos (i.e., one for each treatment type). Researchers created the devices in these screenshots in a software program using preexisting graphics of other traffic control devices.

Table 5. Treatment Video Sequences.

Device	Phase 1	Phase 2	Phase 3	Sample Size
Modified hybrid	Flashing left arrow	Steady left arrow	Steady circular red	8
Modified hybrid	Flashing right arrow	Steady right arrow	Steady circular red	8
Modified hybrid	Steady circular red	Flashing left arrow	Steady left arrow	8
Modified hybrid	Steady circular red	Flashing right arrow	Steady right arrow	8
Modified hybrid with R10-11 sign	Flashing left arrow	Steady circular red	NA	24
Modified hybrid with R10-11 sign	Flashing right arrow	Steady circular red	NA	24
Modified hybrid with R10-11 sign	Steady circular red	Flashing left arrow	NA	24
Modified hybrid with R10-11 sign	Steady circular red	Flashing right arrow	NA	24
Blank-out sign black background	Left turn allowed	No turns allowed	NA	24
Blank-out sign black background	Right turn allowed	No turns allowed	NA	24
Blank-out sign black background	No turns allowed	Left turn allowed	NA	24
Blank-out sign black background	No turns allowed	Right turn allowed	NA	24
Blank-out sign white background	Left turn allowed	No turns allowed	NA	8
Blank-out sign white background	Right turn allowed	No turns allowed	NA	8
Blank-out sign white background	No turns allowed	Left turn allowed	NA	8
Blank-out sign white background	No turns allowed	Right turn allowed	NA	8

NA = Not Applicable

a) Modified Hybrid Device.

b) Modified Hybrid Device with R10-11 Sign.

c) Blank-Out Sign Device with Black Background.

d) Blank-Out Sign Device with White Background.

Figure 6. Screenshots from Select Videos.

Participants

In the fall of 2012, researchers conducted motorist surveys at Department of Public Safety (DPS) Driver License Offices in Bryan, San Angelo, and Tyler, Texas. A total of 320 participants were surveyed. Participants were required to be at least 18 years old, have a current Texas driver license, and could not be color blind. Researchers based the demographic sample on the age and gender of the Texas driving population (*5*), and the education data from the U.S. Census Bureau (*6*). Table 6 summarizes the demographic distribution obtained for both devices, as well as the Texas based demographics. Overall, it is believed that the results obtained in this study represent Texas drivers reasonably well.

Table 6. Participant Demographics.

Sample	Gender		Age Group		Education	
	Male	**Female**	**18-54**	**55+**	**High School Diploma or Less**	**Some College (≥ 2 years) or More**
Modified Hybrid Device (n=128)	49%	51%	71%	29%	50%	50%
Blank-Out Sign Device (n=128)	48%	52%	66%	34%	45%	55%
2010 Texas Data (*5,6*)	50%	50%	71%	29%	46%	54%

Protocol

Each participant only viewed one video sequence on a laptop computer. While each phase was shown, researchers asked the participant what the device was telling them to do. Researchers asked more specific follow-up questions as needed to determine:

- Whether or not the participant would turn onto the main road.
- Which direction the participant would or would not turn.
- Whether or not the participant would come to a complete stop before turning onto the main road.
- Whether or not the participant would yield to the vehicles traveling on the main road.
- Which direction the participant thought the vehicles on the main road were going.
- Whether the participant would stop and then turn onto the main road or would remain stopped until otherwise indicated.

DATA ANALYSIS

Researchers entered all data collected into spreadsheets, categorized participant answers to all questions, and computed percentages to assess motorist comprehension of the devices evaluated. Researchers analyzed all data by phase (i.e., proceed, transition, and stop).

With respect to comprehension, a device was considered acceptable for use when 85 percent of the total survey participants correctly interpreted the meaning of the device (*7*). When the comprehension level was less than 85 percent, researchers used a confidence interval test with a 5 percent significance level (alpha=0.05) to determine if the comprehension percentage was statistically different from the 85 percent criterion. If 0.85 fell within the boundaries of the confidence interval, then the level of comprehension for the tested device was not statistically different from 85 percent.

Researchers then used the Bernoulli model to determine whether the device impacted the proportion of motorists that chose an answer category. This model compared two proportions of independent random samples for an answer category. The null hypothesis was that the two proportions were equal; while the alternative hypothesis was that the two proportions were not equal. The null hypothesis was rejected if the test statistic, Z, was greater than 1.96. This value was selected using a level of significance of alpha equal to 0.05 (i.e., a 95 percent level of confidence). Rejection of the null hypothesis indicated that there was a statistically significant difference in comprehension levels between the treatments. Since this model can only be used to assess two proportions at a time, researchers had to conduct multiple comparisons when more than two treatments were compared. In these instances, the individual level of significance of alpha was equal to 0.02 (i.e., a 98 percent level of confidence) and the test statistic, Z, had to be greater than 2.33 to reject the null hypothesis. Thus, keeping the overall level of significance of alpha equal to 0.05 (i.e., a 95 percent level of confidence).

RESULTS

Researchers initially conducted surveys in Bryan, Texas, to determine motorist understanding of:

- The transition phase used with the modified hybrid device (i.e., steady yellow arrow) (n=32).
- Impact of the background color on motorist understanding of the blank-out sign device (n=64).

For the modified hybrid device, 50 percent of the participants thought the flashing and steady yellow arrows had the same meaning. In addition, 75 percent of those participants who thought there was a difference between the flashing and steady yellow arrows just thought the flashing yellow arrow was either more conspicuous (25 percent) or indicated the need for more caution (50 percent). Since motorists did not understand the intended meaning of the steady yellow arrow (i.e., changing from proceed to stop condition, so prepare to stop), researchers decided not to include the transition phase in further evaluations. These data were consistent with previous research (*8*).

As expected, researchers found that the blank-out sign background/arrow color (i.e., black/white and white/black) did not impact comprehension. Therefore, researchers only used the black background and white arrow combination in further evaluations. The final dataset for the blank-out sign device included all data collected (i.e., both color combinations).

Table 7 contains the results for the proceed phase for the modified hybrid device with and without the R10-11 sign and the blank-out sign device. Looking at the answers to the first four questions in this table, all three treatments exceeded the 85 percent criterion for understanding. In other words, all three treatments adequately conveyed to motorists that they could turn onto the main road, which direction they were allowed to turn, which direction vehicles on the main road were traveling, and the need to yield to vehicles on the main road. However, in two cases (i.e., which direction they could turn and which direction vehicles on the main road were traveling) the blank-out sign device resulted in significantly different results than the modified hybrid device with the R10-11 sign; showing improved understanding for the blank-out sign device.

The last question in Table 7 addressed the need to come to a complete stop before turning onto the main road. Researchers found that this action was adequately conveyed through the flashing circular red indication in the blank-out sign device (97 percent). For the modified hybrid device, the flashing yellow arrow indications used only require motorists to cautiously enter the intersection and yield the right-of-way appropriately. While motorists may come to a complete stop before turning, if the situation dictated it, they are not required to. So, the mixed responses to this question for modified hybrid device were not surprising. Overall, researchers considered both answers (i.e., yes and no) to be correct.

Table 8 contains the results for the stop phase for the modified hybrid device with and without the R10-11 sign and the blank-out sign device. Unlike for the proceed phase, there were several instances for the stop phase where the comprehension of the modified hybrid device without the R10-11 sign was below the 85 percent criterion. Only 68 percent of the participants thought they could not turn onto the main road during the stop condition. Further investigation showed that 16 percent thought they could still turn right and another 16 percent thought they could still turn both directions even though a steady circular red indication was displayed. In addition, only 34 percent of the participants stated they would stop and remain stopped until otherwise indicated by the device. This low percentage is concerning since vehicles cannot be turning onto the main road from an access point during the stop phase. The addition of the R10-11 sign increased the percentage of participants that would remain stopped to 94 percent. In all cases, the lower comprehension percentages for the modified hybrid device without the R10-11 sign were significantly different from the comprehension percentages for the modified hybrid device with the R10-11 sign; showing improved understanding with the addition of the R10-11 sign. The blank-out sign device was also found to be better understood than the modified hybrid device without the R10-11 sign during the stop phase.

Table 7. Motorist Survey Proceed Phase Results.

Question	Modified Hybrid Device		Blank-Out Sign Device (n=128)
	Without R10-11 Sign (n=32)	With R10-11 Sign (n=96)	
Can you turn onto the main road?			
- Yes	100%	100%	100%
- No	0%	0%	0%
- Unsure	0%	0%	0%
Which direction can you turn?			
- Correct direction	97%	94%[a]	100%
- Incorrect direction	3%	6%	0%
- Unsure	0%	0%	0%
Which direction do you think vehicles on the main road are going?			
- Correct direction	94%	90%[b]	99%
- Incorrect direction	6%	10%	1%
- Unsure	0%	0%	0%
Do you need to yield to vehicles on the main road?			
- Yes	97%	98%	100%
- No	0%	2%	0%
- Unsure	3%	0%	0%
Do you have to come to a complete stop before turning?			
- Yes	69%	81%	97%
- No	31%	19%	3%
- Unsure	0%	0%	0%

[a] Statistically different from the blank-out sign device (Z=2.87).
[b] Statistically different from the blank-out sign device (Z=3.30).

Table 8. Motorist Survey Stop Phase Results.

Question	Modified Hybrid Device		Blank-Out Sign Device (n=128)
	Without R10-11 Sign (n=32)	With R10-11 Sign (n=96)	
Can you turn onto the main road?			
- Yes	32%	4%	0%
- No	68%[b]	96%	100%
- Unsure	0%	0%	0%
Which direction can't you turn?			
- Right	0%	0%	0%
- Left	16%	2%	0%
- Right and left	68%[c]	95%[d]	100%
- Unsure	0%	0%	0%
- Neither	16%	3%	0%
Which direction can you turn?			
- Right	16%	2%	0%
- Left	0%	0%	0%
- Right and left	16%	3%	0%
- Unsure	0%	0%	0%
- Neither	68%[c]	95%[d]	100%
Would you stop and then turn onto the main road or would you remain stopped until otherwise indicated?			
- Remain stopped	34%[e]	94%	98%
- Stop and then go	56%	6%	2%
- Both [a]	10%	0%	0%

Underlined text indicates response levels statistically less than 85 percent.

[a] Participants would stop and then go for a right turn, but would remain stopped until otherwise indicated for a left turn.

[b] Statistically different from the modified hybrid device with R10-11 sign (Z=4.25) and the blank-out sign device (Z=6.53).

[c] Statistically different from the modified hybrid device with R10-11 sign (Z=3.97) and the blank-out sign device (Z=6.53).

[d] Statistically different from the blank-out sign device (Z=2.61).

[e] Statistically different from the modified hybrid device with R10-11 sign (Z=7.13) and the blank-out sign device (Z=8.97)

Both the modified hybrid device with the R10-11 sign and the blank-out sign device exceeded the 85 percent criterion for understanding during the stop phase. However, the blank-out sign device was found to be significantly different than the modified hybrid device with the R10-11 sign with respect to which direction motorists could and could not turn (100 percent versus 95 percent, respectively), showing improved understanding of the blank-out sign device.

SUMMARY

In the fall of 2012, researchers conducted laptop-based motorist surveys at DPS Driver License Offices in Texas to determine motorists' understanding of the modified hybrid and blank-out sign devices. While both of the devices appear to be adequately understood by motorists when displaying messages to proceed in a certain direction, the modified hybrid device was not as well understood as the blank-out sign device under the stop condition. More specifically, under the stop condition the modified hybrid device without a R10-11 sign yielded comprehension levels less than the standard criterion. Adding a R10-11 sign to the modified hybrid device did improve comprehension levels such that they exceeded the standard criterion. However, comprehension levels for the modified hybrid device with a R10-11 sign for both phases (proceed and stop) were still less than those for the blank-out sign device (and in several cases significantly less).

CHAPTER 5:
FIELD STUDY

INTRODUCTION

Even though the motorist survey findings showed that the blank-out sign device was better understood than the modified hybrid device, TxDOT wanted to further study both devices. So, researchers worked with a PTCS manufacturer to build one prototype of each device that would work in conjunction with PTCSs. In the summer of 2013, researchers conducted a field study to assess the operational and safety effectiveness of the two devices. The following sections describe the prototype devices, experimental design, data analysis, and results of the field study.

PROTOTYPE DEVICES

Figure 7 shows the prototype modified hybrid device in the stop phase, while Figure 8 shows this prototype allowing left turns. The modified hybrid device was comprised of a 12-inch steady circular red indication and two 12-inch yellow arrow indications. As discussed previously, in the stop phase, the steady circular red indication is illuminated to inform drivers to remain stopped. In the proceed phase, the yellow arrow indication flashes in the direction that motorists can travel (either left or right). Although motorists did not appear to understand the difference between the steady and flashing yellow arrow indications in the motorist survey, TTI researchers and the TxDOT project working group agreed that the steady yellow arrow indication should be used to transition from the proceed phase to the stop phase (like with red/yellow AFADs and traffic signals). Therefore, in the field the following phasing was used for the modified hybrid device: the stop phase, the proceed phase in one direction (e.g., right), the transition phase in the same direction (e.g., right), the stop phase, the proceed phase in the other direction (e.g., left), the transition phase in the same direction (e.g., left), and the stop phase. The distance from the bottom of the yellow arrow indications to the pavement was 7 ft. A NO TURN ON RED sign (24 inches by 30 inches) was mounted on a separate sign support adjacent to the modified hybrid device.

Figure 7. Modified Hybrid Device in the Stop Phase.

Figure 8. Modified Hybrid Device Allowing Left Turns.

Figure 9 shows that the prototype blank-out sign device was made up of a 12-inch circular red indication and two internally illuminated movement prohibition signs (each 24 inches by 24 inches) that were altered such that the white arrows and red circles/slashes could be illuminated separately. As discussed previously, in the stop phase (Figure 10), the blank-out sign device displays a steady circular red indication and both movement prohibition signs (white arrows and circles/slashes are illuminated). When a vehicle is allowed to proceed to the left (Figure 11), the circular red indication will flash and the red circle/slash will not display over the left arrow. The circle/slash on the sign with the right arrow will be displayed; prohibiting right turns. When right turns are allowed, the circular red indication will flash, the red circle/slash will not display over the right arrow, and the red circle/slash will display over the left arrow. The distance from the bottom of the internally illuminated signs to the pavement was 7 ft. The distance from the top of the internally illuminated signs to the bottom of the circular red indication was 12 inches.

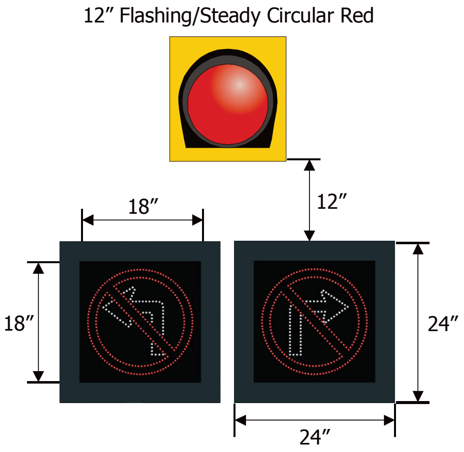


Figure 9. Blank-Out Sign Device Dimensions.

Figure 10. Blank-Out Sign Device in the Stop Phase.

Figure 11. Blank-Out Sign Device Allowing a Left Turn.

Both prototype devices were designed to work in synchronization with PTCSs placed at each end of a lane closure on a two-lane, two-way road. For demonstration, a north/south two-lane, two-way road with one access point will be considered. At the same time the PTCS on the south end of the lane closure displayed a steady circular green indication for northbound traffic to proceed, the prototype device in use displayed the appropriate indication that would allow traffic at the access point to turn in the northbound direction only. When the PTCS at the south end displayed a steady circular red indication to stop northbound traffic, the prototype device in use continued to allow northbound traffic to turn. This permitted traffic from the access point to turn before, during, or after the main road queue; thus, providing more opportunities to service access point vehicles and reduce the probability of access point vehicles not being able to join the end of the main road queue. The all-red duration was adjusted appropriately to account for the extended proceed phase at the access point.

In order for a prototype device to work with the PTCSs as described above, all three devices were programmed using a hand-held control pad. The programming process required the following information: the expected or observed speed through the work zone, the length of the work zone, the travel time between each PTCSs on the main road and the access point, the number of access points (only one in the field study), and the expected queues on the main road, as well as at the access point.

Since both prototype devices were newly designed traffic control devices, before deploying on an actual roadway TxDOT submitted a request to FHWA to experiment with the prototype devices. FHWA approved this request on June 27, 2013.

EXPERIMENTAL DESIGN

The following sections document the field study location and protocol followed for the field study.

Location

The field study site was near the city of Cleburne, Texas, at the intersection of Farm-to-Market (FM) Road 916 and County Road (CR) 418 (Figure 12). This intersection was in a rural area and the FM road was a two-lane, two-way road. The TxDOT maintenance crew had to close one lane to complete an overlay on FM 916. The 2011 approximate average annual daily traffic (AADT) on FM 916 was 1450 vpd and the speed limit was 60 mph. The length of the lane closure on FM 916 (measured from PTCS to PTCS) was approximately 4500 ft. CR 418 was approximately 700 ft from the west end of the lane closure and approximately 3800 ft from the east end of the lane closure. So, drivers on CR 418 at FM 916 could see the west end of the lane closure, but not the east end. These drivers could also see the work activity.

Figure 12. Study Site with Access Point.

The field study occurred over two days; one prototype device controlled the access point traffic each day. Since both prototype devices informed drivers when to stop and when to proceed, researchers and TxDOT personnel decided the stop sign located at the intersection should be covered while a prototype device was deployed. This removed any conflict that the driver may have experienced if they were to see a prototype device and a stop sign. Based on TxDOT recommendations, the prototype devices were placed at the intersection across the main road in front of oncoming accessing point motorists to ensure that drivers could view the full device.

Controlled Field Study

Researchers conducted a controlled field study at the site to assess motorist understanding of the two prototype devices in an actual work zone setting. For the controlled field study, participants were recruited from the local area. Participants were required to be at least 18 years old, have a current Texas driver license, meet minimum levels of acceptable vision (i.e., 20/40 visual acuity and could not be color blind), be able to speak and read English, and agree to be audiotaped (for documentation purposes). A total of 16 participants (eight per device) were recruited for this study. The recruited participants ranged in age from 18 to 65 and included both male and female drivers.

Two state-owned 2009 Ford Explorers were used. Each vehicle contained a small video camera mounted on the dashboard to capture the forward road scene. In addition to capturing video of the road, the video camera documented the discussion between the driver (i.e., participant) and researcher for later review and reduction.

Observation Phase

Each participant began with the observation phase. In this phase, the participant drove one of the state-owned vehicles to the work zone site. A researcher rode with the participant in the front passenger seat. At the work zone, the participant was given instructions to enter the lane closure and then the access point. The participant was then instructed to turn around at a predetermined location and then exit the access point to the left or right when directed by the traffic control device (half of the participants provided each direction). During the observation phase, the researcher documented the actions and comments of the participants as they approached and reacted to one of the prototype devices. If a driver attempted to make an incorrect maneuver, the researcher in the vehicle stopped them.

Survey Phase

After the observation phase, each participant was directed back to the access point and asked to park in a predetermined location where the participant could view the same prototype device, while not impeding other traffic. The participant was then asked a series of questions while viewing the device cycle through its various phases. Survey questions included:

- Can you turn onto the main road?
- Which direction(s) can you turn?
- Which direction(s) can’t you turn?
- Do you have to come to a complete stop before turning?
- Do you need to yield to the vehicles traveling on the main road?

- Which direction do you think the vehicles on the main road are going?
- Would you stop and then turn onto the main road or would you remain stopped until otherwise indicated?
- Do you have any other comments about the device you viewed?

Upon completion of the survey phase, the participant was instructed to return to the check-in site.

Non-Controlled Field Study

Drivers not involved in the controlled field study were also observed at the access point. Thus, this portion of the study focused on drivers that had no prior knowledge of the device or its operation and were encountering the device on their own. For each vehicle arrival, a researcher located off the roadway noted the device phase and the driver's reaction. If a driver made an incorrect maneuver, workers on-site were notified and the vehicle was stopped.

DATA ANALYSIS

Researchers entered all the data collected from the controlled and non-controlled field studies into spreadsheets, categorized by prototype device. Researchers organized the controlled study observation data by participant and device phase (i.e., stop and proceed), and then reviewed each participant's comments and actions to determine if they understood the device phases seen. Researchers also noted the order in which each participant saw the various device phases.

Due to potential interference, researchers removed observation data for two participants (one per device). These participants approached the prototype device while another vehicle was already stopped on the country road at the intersection. Researchers agreed that these data should not be considered as the participants may have been influenced by the actions of the driver in front of them, as opposed to only what the prototype device was telling them.

Researchers also reviewed the controlled study survey responses for each phase for each device to determine if participants understood each device. As with the laptop-based motorist survey, researchers considered a device to be acceptable for use if 85 percent of the total survey participants correctly interpreted the meaning of the device. When the comprehension level was less than 85 percent, researchers used a confidence interval test with a 5 percent significance level (alpha=0.05) to determine if the comprehension percentage was statistically different from the 85 percent criterion. If 0.85 fell within the boundaries of the confidence interval, then the level of comprehension for the tested device was not statistically different from 85 percent.

Researchers reduced the non-controlled study vehicle data to assess compliance with the prototype devices. The average number of vehicles arriving per hour at the access point was also computed.

RESULTS

The following sections detail the field study findings (controlled and non-controlled) for both prototype devices.

Controlled Field Study

The controlled field study included the observation and survey phases.

Observation Data

All of the participants (100 percent) reacted correctly to the blank-out sign device – turning in the appropriate direction when allowed. In contrast, for the modified hybrid device 43 percent of the participants (three out of seven) had to be stopped from making the wrong turn by the researcher in the vehicle. Two of these participants attempted to make a right turn when the modified hybrid device was displaying a flashing yellow left arrow (i.e., only left turns allowed). The other participant attempted to make a left turn when the modified hybrid device was displaying a flashing yellow right arrow (i.e., only right turns allowed). All of the remaining participants (57 percent) correctly reacted to the modified hybrid device.

Survey Data

Table 9 shows the survey results for the proceed phase for both devices. More than 85 percent of the participants understood that for both devices they could turn onto the main road in the direction shown. Only one participant (12 percent) initially thought he/she could not proceed even though the blank-out sign device was displaying a left arrow without a circle/slash. The reason provided dealt with the flashing red circular indication, not the internally illuminated signs. Once this participant saw the blank-out sign device cycle through the stop phase and display a right arrow without a circle/slash, he/she understood they could proceed in the direction of the arrow without a circle/slash.

Table 9. Field Study Proceed Phase Results.

Question	Modified Hybrid Device (n=8)	Blank-Out Sign Device (n=8)
Can you turn onto the main road?		
- Yes	100%	88%
- No	0%	12%
- Unsure	0%	0%
Which direction can you turn?		
- Correct direction	100%	88%
- Incorrect direction	0%	12%
- Unsure	0%	0%
Do you need to yield to vehicles on the main road?		
- Yes	100%	100%
- No	0%	0%
- Unsure	0%	0%
Which direction do you think vehicles on the main road are going?		
- Correct direction	100%	88%
- Incorrect direction	0%	12%
- Unsure	0%	0%
Do you have to come to a complete stop before turning?		
- Yes	37%	100%
- No	63%	0%
- Unsure	0%	0%

All of the participants for both devices (100 percent) understood that they must yield to the main road traffic, and all but one participant (88 percent) understood which direction the main road traffic was going. All of the participants that saw the blank-out sign device (100 percent) also understood that they should come to a complete stop before turning. As expected, the answers to whether or not a complete stop was needed before turning for the modified hybrid device were mixed. However, as with the motorist survey, researchers considered both answers to be correct.

Table 10 shows the survey results for the stop phase for both devices. For both devices, all of the participants (100 percent) understood they could not turn onto the main road. Participant comments regarding the modified hybrid device verified that the NO TURN ON RED sign indicated that no turns were allowed when the steady circular red indication was illuminated. Participant comments regarding the blank-out sign device confirmed that the red circle/slashes clearly indicated that no turns were allowed. Two participants (one for each device [12 percent]) did believe that they could stop and then go (like at a stop sign) instead of remaining stopped until otherwise indicated. One participant commented that they would stop and go if the red light remained on for too long and no one else was around. The other participant stated they would remain stopped during the day because of the presence of workers and higher traffic volumes on the main road, but at night, would most likely stop and go.

Table 10. Field Study Stop Phase Results.

Question	Modified Hybrid Device (n=8)	Blank-Out Sign Device (n=8)
Can you turn onto the main road?		
- Yes	0%	0%
- No	100%	100%
- Unsure	0%	0%
Which direction can't you turn?		
- Right	0%	0%
- Left	0%	0%
- Right and left	100%	100%
- Unsure	0%	0%
Would you stop and then turn onto the main road or would you remain stopped until otherwise indicated?		
- Remain stopped	88%	88%
- Stop and then go	12%	0%
- Both[a]	0%	12%

[a] Participant would remain stopped until otherwise indicated during the day, but would stop and then go at night.

Researchers also reviewed the closing comments made by the participants for indications of issues with the two devices. Seventy-five percent of the participants (six out of eight) indicated confusion with some aspect of the modified hybrid device. These aspects included:

- The device does not look like a traffic signal – One participant commented that since the device did not look like a standard signal, it was confusing and he/she thought the device was for the workers not motorists.
- The device displays – One participant mentioned that the device was confusing when the circular red indication was not illuminated (i.e., the proceed phase).

Several participants commented that the device did not indicate which direction they could go clearly. Although, one participant, while admitting that they were initially confused, said that they were able to understand the device after seeing all the phases and having time to think about what action to take.

- The height of the device – One participant commented that the device was too low, and that it should be the same height as PTCSs.
- The length of the stop phase – In some cases, due to the initial programming, the stop phase was too short or longer than planned. As these issues arose, they were addressed in the field, but obviously impacted comprehension.
- The covered stop sign at the intersection – As indicated previously, researchers covered the stop sign at the intersection since the prototype devices were designed to convey the desired stop condition and did not want the stop sign to suggest a conflicting message to motorists. However, the covered stop sign itself became a source of confusion, as motorists questioned the need to stop at all. The location of the covered stop sign and prototype device may have also contributed to the confusion, as the prototype device was located across the main road in front of oncoming access point motorists while the stop sign was located on the near side of the road.

In contrast to the modified hybrid device, only 25 percent of the participants who saw the blank-out sign device (two out of eight) indicated some type of confusion with the device. But these participants noted that with experience and education the device would be easily understood.

Non-Controlled Field Study Data

While the modified hybrid device was deployed, 39 vehicles not involved with the controlled field study arrived at the intersection; averaging 7 vehicles per hour (vph). Of these drivers, 13 percent (five) made incorrect maneuvers and thus were considered non-compliant. Three drivers turned the opposite direction indicated by the modified hybrid device, while two drivers turned when the device was in the stop phase. These vehicles were intercepted by workers and allowed to proceed when it was safe to do so. Other than the non-compliant vehicles, there were four drivers (10 percent) that asked workers what action they were expected to take.

The day the blank-out sign was deployed only 13 non-controlled vehicles were observed; about 4 vph. Lower traffic volumes and a shorter data collection period contributed to the lower number of observed vehicles. Of the drivers observed, 23 percent (three) did not comply with the device. However, 15 percent of the non-compliance (two occurrences) was attributed to the timing of the blank-out sign device. As discussed previously, the blank-out sign device should have been programmed to hold the proceed phase until after the main road queue had time to pass the access point; allowing access point vehicles to join the end of the queue. However, this did not occur initially, so the access point vehicles were stopped while the main road queue was traveling by. Instead of waiting, two vehicles turned on red to join the end of the queue. After this timing issue was fixed, no further non-compliance of this type occurred.

SUMMARY

Researchers worked with a manufacturer to build one prototype modified hybrid device and one prototype blank-out sign that would work in conjunction with PTCSs. Researchers then conducted controlled and non-controlled field studies to assess the operational and safety effectiveness of the two prototype devices. The controlled field study utilized recruited participants from the local area and included observation and survey portions. The non-controlled field study focused on all other drivers trying to enter the lane closure from the access point controlled by one of the two prototype devices.

Based on the controlled field study participants' answers to the survey questions, it appeared that the modified hybrid device was well understood. However, the closing comments revealed insight into potential issues with various aspects of the modified hybrid device. In addition, only 57 percent of the controlled field study participants correctly followed the instructions provided by the modified hybrid device when they first encountered it. The remaining controlled field study participants (43 percent) had to be stopped from making the wrong turn by a researcher. In the non-controlled field study, 13 percent of the drivers made incorrect maneuvers and had to be intercepted by workers. An additional 10 percent of the drivers stopped to ask workers what action to take. Overall, the data suggested that the flashing yellow arrow indications used with the modified hybrid device were not well understood.

In contrast, 100 percent of the controlled field study participants correctly reacted to the blank-out sign. While some potential confusion was noted by these participants during the survey phase, all participants noted that with experience and education the blank-out sign device would be easily understood. In addition, most of the non-controlled study driver compliance issues were due to the programming of the blank-out sign with the PTCSs on the main road (i.e., drivers not being allowed to proceed at the end of the main road vehicle queue). Overall, the data suggested that the use of the circle/slashes over the directional arrows on the blank-out sign device adequately informed motorists when they could and could not turn.

CHAPTER 6:
BENEFIT/COST COMPARISON

INTRODUCTION

In addition to the studies discussed in previous chapters, researchers conducted an analysis to compare the benefits and costs of various temporary traffic control alternatives for low-volume access points within lane closures on two-lane, two-way roads. The analysis included relative agency costs (e.g., equipment or labor), potential user costs (e.g., increases in delay), and potential benefits (e.g., reductions in user delay). Safety impacts could not be quantified for the analysis, since crash modification factors were unavailable for the work zone scenarios of interest. However, safety must be considered as part of the decision process.

TEMPORARY TRAFFIC CONTROL METHODS

Table 11 summarizes the temporary traffic control methods considered. Based on current practice, the main road temporary traffic control was either flaggers or PTCSs (the same control was used at both ends). The access point temporary traffic control was a flagger, PTCS, modified hybrid device, or blank-out sign device. While all four of the access point temporary traffic control methods were used with PTCSs on the main road, only a flagger was used at the access point when flaggers were used on the main road. These scenarios were based on current practice and TxDOT's desire to utilize technology in place of flaggers.

Table 11. Temporary Traffic Control Methods To Be Evaluated.

Main Road	Access Point
Flagger	Flagger
PTCS	Flagger
PTCS	PTCS
PTCS	Modified Hybrid Device
PTCS	Blank-Out Sign Device

A flagger at the access point would be in communication with the flagger on each end of the main road. Typical practice is for the flagger at the access point to allow vehicles to enter the main road in the appropriate direction after the last vehicle in the main road traffic platoon. Since standard PTCSs only display steady circular red, yellow, and green indications, current practice requires all the main road traffic to stop before servicing the access point traffic. The access point vehicles are then allowed to proceed in either direction (clearance time is based on the longest distance from the access point to the end of the work zone on the main road). Based on discussions with TxDOT, vehicle detection is not typically used at the access point; thus, the access point must be serviced during each cycle whether or not a vehicle is present. This strategy can obviously lead to increased delay on the main road. If detection is used, the access point is only serviced when a vehicle is detected, which should reduce the main road delay. Of course, if multiple driveways are present each driveway must be serviced separately; resulting in increased delay on the main road and at the access points. The prototype devices were designed to be smaller devices that provide directional information and could be placed at intersecting low-volume roadways or driveways. These devices would service the access point in conjunction with the main road PTCSs.

Based on the average low bid unit prices available on the TxDOT website (*9*), a flagger is paid about $20 per hour. Based on the TxDOT state contract for PTCSs, a pair of PTCSs cost approximately $70,000. So, the cost of one extra PTCS at an access point was estimated to be $35,000. Based on manufacturer information, each PTCS has a service life of 20 years. The modified hybrid and blank-out sign devices are estimated to cost about $10,000 and $20,000, respectively. Both prototype devices are expected to have a service life of at least 10 years. It was assumed that all of the temporary traffic control devices considered had relatively low maintenance costs and similar salvage costs, so these items were not included in the following computations.

For a typical 6-hour day, such as for a short-term maintenance operation, a flagger at an access point would cost $120. Assuming the need to control access point traffic at least once a week for similar work (e.g., four times a month), a PTCS, modified hybrid device, and blank-out sign device would pay for themselves in 6 years, 2 years, and 4 years, respectively.

For a 48-hour continuous work period, such as concrete paving, a flagger at an access point would cost $960. Assuming the need to control access point traffic at least once a month for similar work, a PTCS, modified hybrid device, and blank-out sign device would pay for themselves in 3 years, 1 year, and 2 years, respectively. Of course, this does not consider the safety implications of having a flagger to control access point traffic overnight when no active work is occurring but the lane closure is needed for the concrete to cure.

While these two scenarios represent expected common applications, if an access point control device was readily available it would most likely be used for a variety of work durations over the course of a month. It is important to note for the two scenarios provided, all three access point traffic control devices paid for themselves well within their expected service life.

DELAY ANALYSIS

Initial agency cost to purchase temporary traffic control devices is not the only consideration. As discussed previously, how the devices operate in the field impacts the delay to the main road and access point traffic. The following sections document the delay simulation approach, delay simulation results, delay models, and delay model results.

Delay Simulation Approach

Researchers used VISSIM microscopic simulation to model all the configurations of traffic control methods. Then, the simulation outputs were used to calibrate analytical equations to estimate the delay for vehicles from the main road, access point, as well as the entire work zone. The structure of the analytical equations was carefully developed based upon the combination of the Highway Capacity Manual (HCM) delay analysis approach, empirical observation from the simulation results, and the operational characteristics of the traffic control methods.

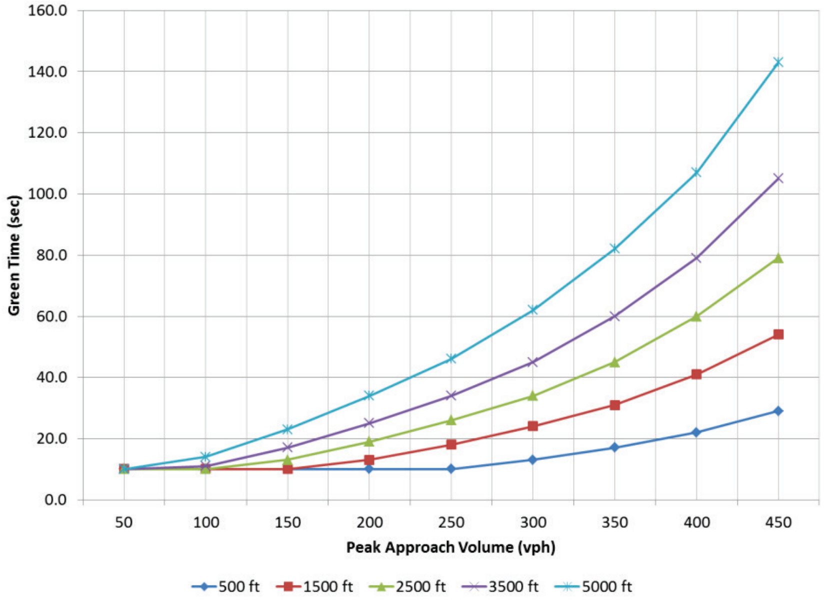
When flaggers controlled the access point traffic, vehicles were allowed to enter the main road in the appropriate direction after the last vehicle in the main road traffic platoon. This procedure represents current practice. When PTCSs were used to direct the access point traffic, it was assumed that there was no detection at the access point. Therefore, an all red period was presented for the main road traffic while the access point traffic was allowed to travel in either direction. When the prototype devices were used to control the access point traffic, vehicles were allowed to enter the main road in the appropriate direction before, within, and after the main road traffic platoon, when they can safely do so.

In the case of an all flagger operation (main road and access point), the traffic control was modeled using actuated operation on main road to replicate the operational responsiveness to arriving traffic patterns expected under flagger operation. The detection on the main street was set up using a stop bar detector and an advanced detector. The stop bar detector monitors the traffic waiting at the flagger location while the advance detector monitors the headway arriving at the approach. In this manner, the service of main road traffic is based on a combination of the waiting queue as well as arriving headway as typically operated when using flaggers. The traffic control at the access point was also programmed using delay overlap to withhold the service until the queue from the major approach was cleared from the access point.

When the main road was controlled by PTCSs, the traffic control was modeled using a fixed time signal controller. When PTCSs are used to control traffic on the main road and access point, a three-phase fixed-time operation is programmed for the signal control. The green times on all phases can be adjusted to respond to expected demand on each approach. When PTCSs are used on the main road and a flagger or a prototype device was used at the access point, a two-phase fixed-time operation was used for controlling the signal. In the case of a flagger, additional delay overlap was programmed to withhold the beginning of the service time at the access point until the queue from the main road was cleared. For the prototype devices, a trailing overlap was programmed in the model to extend additional service time in the direction of traffic flow after the green on the main road was terminated.

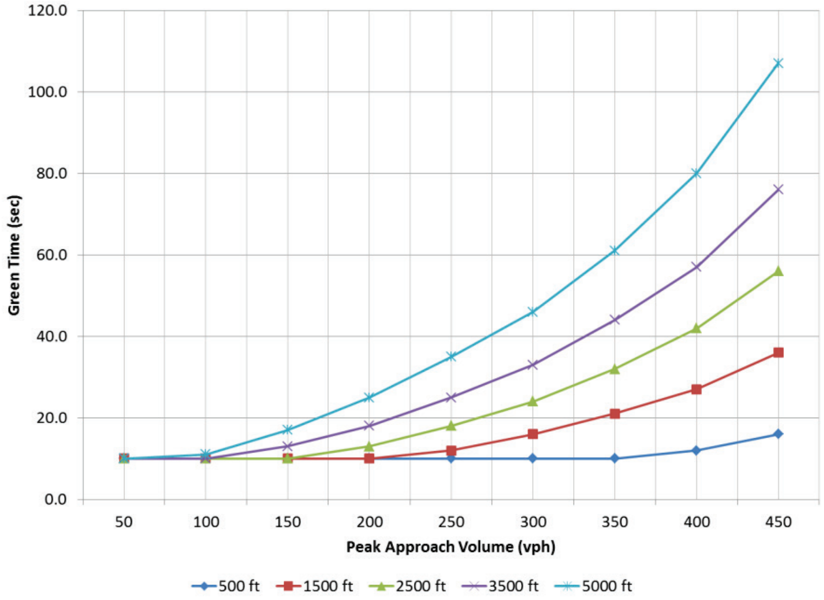
The researchers utilized HCM signal analysis to determine the minimum green time needed to avoid queue overflows when PTCSs were used. Figure 13 provides the recommended green time when all the approaches are controlled by PTCSs. Figure 14 provides a similar threshold for PTCSs on the major approaches when either flagger or prototype device is used to control an access point. As seen in these graphs, the required green time is increased with longer work zones. Based on these findings, researchers choose the following green time settings for the PTCSs:

- 30 seconds for work zone lengths less than or equal to 2500 ft.
- 45 seconds for work zone lengths greater than 2500 ft but less than or equal to 3500 ft.
- 60 seconds for work zone lengths greater than 3500 ft.
- 10 seconds for the access point.



Work zone travel speed = 55 mph; Access point green time = 10 seconds

Figure 13. Recommended Green Time on Major Approach When PTCSs Control All Approaches.



Work zone travel speed = 55 mph; Access point controlled by flagger or prototype device

Figure 14. Recommended Green Time on Major Approach When PTCSs Control Major Approaches Only.

The observation from the simulation results confirmed that the queue was unable to clear within a cycle when the green time settings were lower than the recommended values for certain volume combinations. Therefore, the simulation outputs from scenarios that resulted in queue overflows were excluded from subsequent delay modeling.

The access point was assumed to be located in the middle of the lane closure with a single-lane approach. To simplify the modeling process, it was assumed that there is an equal split for turning movements from an access point. This assumption produces conservative delay numbers for access point vehicles because the vehicles from an access point that desire to turn in the direction against the traffic flow can potentially block the vehicles behind for a long duration. However, the impact of the total delay should be minimal because typical volume range at access points is relatively low compared to main road volumes.

Table 12 lists the range of model parameters evaluated in the simulation. On another recent TxDOT project (0-6407), TTI researchers collected data at 20 work zones on two-lane, two-way roads in the Bryan, Lufkin, Paris, and San Antonio Districts. The typical 2009 AADT volume ranged from 220 to 5100 vehicles per day (vpd) with the majority of these sites (55 percent) having less than 2000 vpd. Based on these characteristics, the research team decided to model roadways with 200 to 6000 vpd. These AADT volumes were converted to hourly volumes for the purpose of this analysis. Based on the extreme case of a 70/30 directional split on the main road, an AADT of 6000 vpd, and an AADT-to-peak-hour conversion factor of 0.10, the highest hourly volume on the main road is calculated as $6000 \times 0.7 \times 0.1 = 420$ vph. Similarly, the lower range of hourly volume based on the AADT of 200 vpd would be equivalent to 6 vph ($200 \times 0.3 \times 0.1$). Since the value of 6 vph was too low to produce significant delay numbers, the researchers set the lowest approach volume rate at 60 vph (2000 vpd) for the simulation analysis. A 50/50 directional split was also used. The specific traffic volume values for the six scenarios utilized are in Table 13.

On the same previous TxDOT project the length of the lane closures ranged from approximately 300 ft to 1 mile, with three-quarters of the sites less than 2500 ft in length. Based on this information, researchers choose the following work zone lengths for the simulation: 500 ft, 1500 ft, 2500 ft, 3500 ft, and 5000 ft.

Table 12. Simulation Parameters.

Parameters	Range
Annual average daily traffic (vpd)	2000-6000
Main road approach volume (vph)	60-420
Main road opposing volume (vph)	60-420
Short-term work zone capacity (vph)	1450
Work zone length (ft)	500, 1500, 2500, 3500, 5000
Work zone travel speed (mph)	55
Access point volume (vph)	20
Turning split for access point vehicles (%/%)	50/50
Critical gap for access point vehicles (sec)	6.5

vpd = vehicle per day; vph = vehicles per hour; min = minutes; mph = miles per hour; ft = feet; veh = vehicles; sec = seconds

Table 13. Traffic Volume Parameters.

Scenario	Major Approach 1 (vph)	Major Approach 2 (vph)	Access Point Approach (vph)
1	100	100	20
2	200	200	20
3	300	300	20
4	140	60	20
5	280	120	20
6	420	180	20

The short-term work zone capacity was used to model the flow rate at which the traffic can be released from a queue. Sarasau et al. (2004) (*10*) conducted a study on capacity of short-term work zone lane closures. The value of 1467 passenger cars per hour per lane (pcphpl) was suggested as a starting point for estimation of short-term work zone capacity. For simplicity, a value of 1,450 pcphpl was chosen in this study.

While many two-lane, two-way roads in Texas have a speed limit of 70 mph, it is expected that motorists will slow down in lane closures on these roadways. Thus, the research team chose a work zone travel speed of 55 mph. The researchers decreased this assumed travel speed by 5 mph to calculate the design travel time that was used to determine all red time required for clearing the traffic between two major approaches.

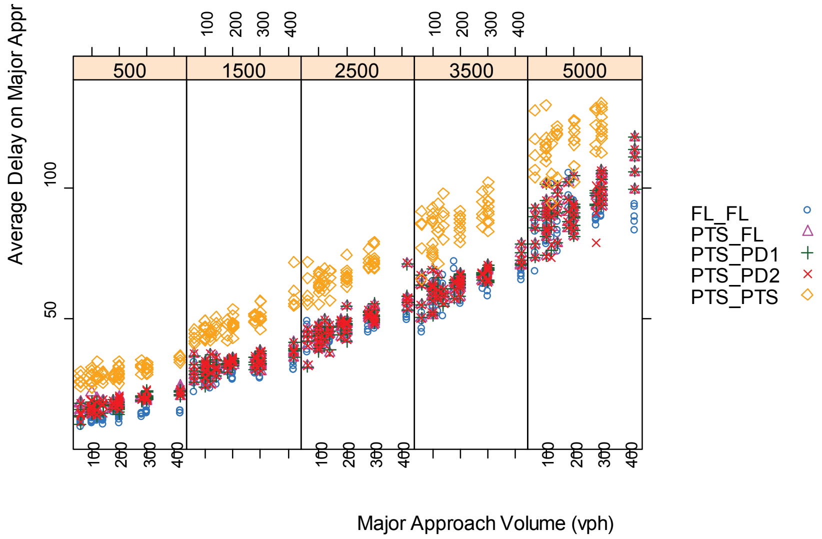
Based on discussions with the project panel, the access point volume is expected to be generally very low and thus 20 vehicles was considered in this analysis. The turning split of vehicles of access point can have an impact on a one-lane approach. A balanced split of 50/50 was the most conservative case because left-turning and right-turning vehicles can alternately block each other while waiting on the approach.

For the prototype device control at the access point, the vehicles from the access point could turn in the direction of the traffic flow when the gaps within the traffic stream were larger than its critical gap. The critical gap was defined as the minimum time interval between the front bumpers of two successive vehicles in the major traffic stream that will allow the entry of one minor-street vehicle. According to HCM 2000 (*11*), the base critical gaps for right turn and left turn from a minor street are 6.2 and 7.1 seconds, respectively. In the case of the traffic from an access point, it was reasonable to assume that there was no practical distinction between the left- and right-turn traffic because both would need to slow down and watch for the permissible direction of the traffic flow. Based on these data, researchers decided to use an average critical gap value of 6.5 seconds. In the simulation, researchers refined the safety distance parameters of the VISSIM conflict area such that it reflected proper yielding operation of vehicles from an access point.

Overall, researchers created a total of 150 scenarios covering the five traffic control configurations, six traffic volume patterns, and five work zone lengths. The simulation of 60 minutes for each scenario is a typical practice for traffic analysis. To properly capture the stochastic nature of the traffic pattern, researchers ran each scenario for 60 minutes five separate times. In the end, the simulation evaluation produced a total of 750 simulation runs for delay modeling and analysis.

Delay Simulation Results

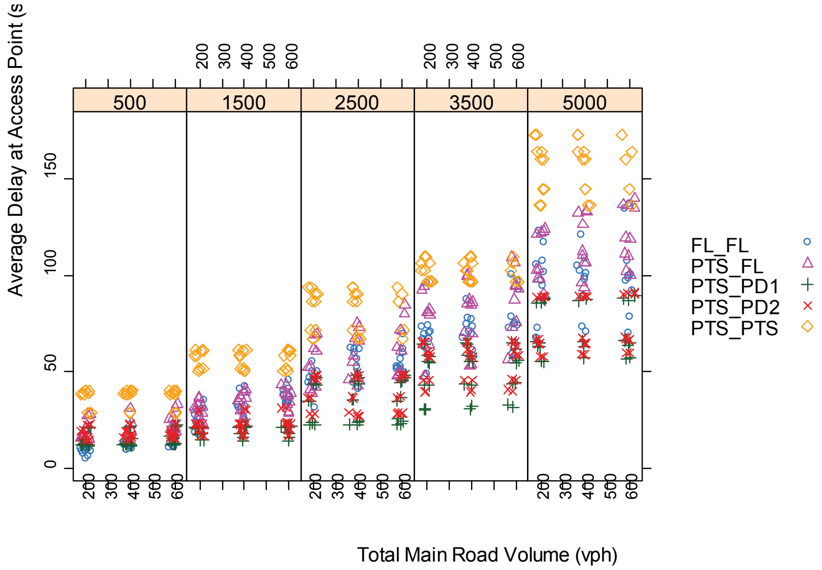
Figure 15 shows the observed delay on major approaches is strongly influenced by the length of the work zone and the traffic volume. In general, the delay on the major approaches is the lowest when all approaches are controlled by flaggers regardless of the length of the work zone. The delay produced when PTCSs are used for the main road and either a flagger or prototype device is used at the access point was similar for any given scenario. As expected, the highest delay scenario is noted when PTCSs are used for both the main road and the access point; as it is least responsive to traffic conditions (i.e., no detection was used).



FL = Flagger; PTS = Portable Traffic Signal; PD1 = Modified Hybrid Device; PD2 = Blank-Out Sign Device

Figure 15. Observed Delay on Major Approaches by Work Zone Length and Major Approach Volume.

Figure 16 shows the observed delay at the access point from the simulation varied by the length of the work zones. As expected, the delay magnitude increases with the length of the work zone but not the main road traffic volume. The largest delay at an access point occurs when all approaches are controlled by PTCSs. The two prototype devices generally produced less delay than the other three scenarios.



FL = Flagger; PTS = Portable Traffic Signal; PD1 = Modified Hybrid Device; PD2 = Blank-Out Sign Device

Figure 16. Observed Delay at Access Point by Work Zone Length and Total Main Road Volume.

Delay Models

The results from the simulation models were analyzed and calibrated to provide the easy-to-use delay models that are sensitive to work zone characteristics, traffic patterns, and traffic control methods. Researchers evaluated several model forms based on the goodness-of-fit statistics and sensible interpretation of the model coefficients. The researchers calibrated the models separately for the delay on major approaches and the delay at access point.

Major Approach Delay Model

The delay on the major approach can be estimated using the following equations:

$$d_m = d_1^{0.9474} e^{0.3503 - 0.075 I_{PTS-PD2} - 0.0853 I_{PTS-FL} - 0.8039_{PTS-PD1} - 0.0934_{PTS-PTS}} \tag{1}$$

$$d_1 = \begin{cases} \dfrac{0.5C\left(1-q/C\right)^2}{1-\left(q/C\right)^2}; \text{ if the control is all flaggers} \\ \dfrac{0.5C\left(1-g/C\right)^2}{1-\min\left(1,X\right)\left(g/C\right)}; \text{ if otherwise} \end{cases} \tag{2}$$

$$X = \frac{q/s}{g/C} \tag{3}$$

where

q = approach volume (vph).

s = saturation flow rate (vph).

g = green time for PTCS control (sec).

C = cycle length for PTCS control (sec).

$I_{PTS-PD2}$ = 1 if the control is PTCSs on the main road and the blank-out sign (PD2) at the access point; 0 if otherwise.

I_{PTS-FL} = 1 if the control is PTCSs on the main road and a flagger at the access point; 0 if otherwise.

$I_{PTS-PD1}$ = 1 if the control is PTCSs on the main road and the modified hybrid device (PD1) at the access point; 0 if otherwise.

$I_{PTS-PTS}$ = 1 if the control is PTCSs on the main road and access point; 0 if otherwise.

If the work zone is controlled by all flaggers, the value of C is estimated as:

$$C_{FL} = \frac{0.85L}{0.85 - \sum_i \frac{q_{m,i}}{s}} \tag{4}$$

$$L = 6 + \frac{2\ell_{wz}}{1.47v} \tag{5}$$

where

ℓ_{wz} = work zone length (ft).

v = work zone travel speed (mph).

$q_{m,i}$ = volume from major approach i (vph).

Access Point Delay Model

If the access point is controlled by a PTCS, the delay at the access point can be estimated as:

$$d_{AP} = \frac{0.5C\left(1 - q/C\right)^2}{1 - \left(q/C\right)^2} \tag{6}$$

If the access point is controlled by either a flagger or one of the prototype devices, the delay at the access point can be estimated as:

$$d_{AP} = t_{wz}^{1.1841} e^{\left(-0.5094 - 0.3488 I_{PTS-PD2} - 0.4615 I_{PTS-PD1} + 0.0086 q_m / t_p + 0.2814 t_p / t_{wz}\right)} \tag{7}$$

where

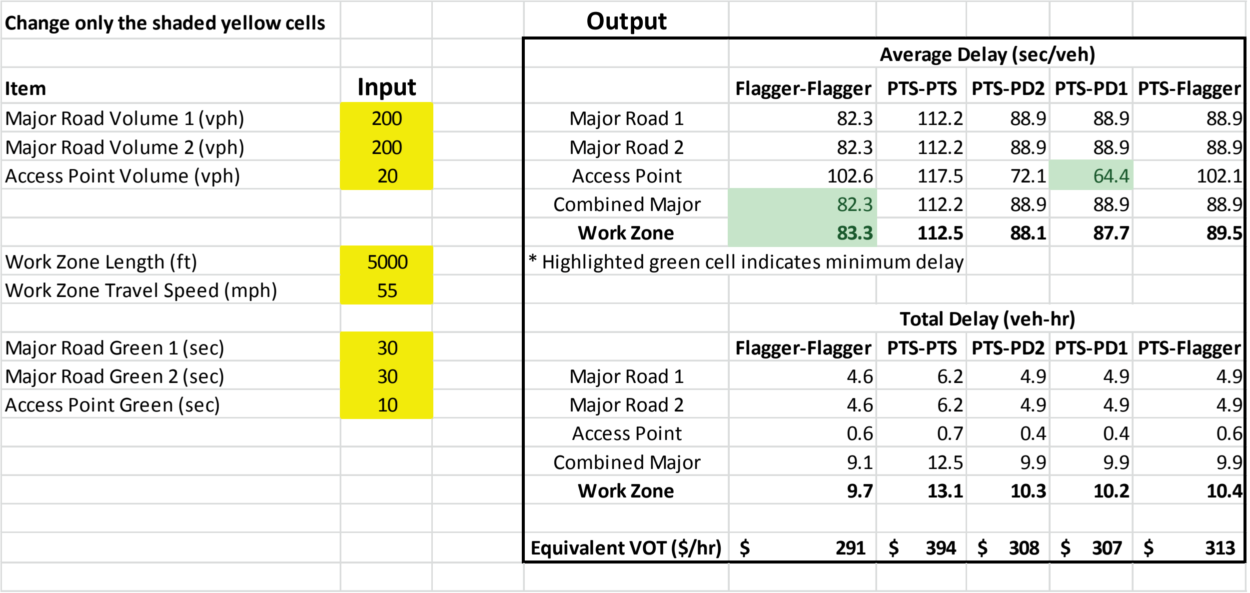
q_m = summation of volume from both major approaches (vph).

t_{wz} = work zone travel time = $\ell_{wz} / 1.47v$ (sec).

t_p = main street green time (sec) if the main road is controlled by PTCSs; $0.5C_{FL} - t_{wz}$ if the main road is controlled by flaggers.

Model Validation

Researchers implemented the calibrated models in a spreadsheet to facilitate model usage. Figure 17 contains a screenshot of the delay calculator. The analyst will only need to enter the volumes, work zone length, travel speed, and green time settings (yellow shaded cells in Figure 17) to produce the delay comparison across the five traffic control configurations.



Change only the shaded yellow cells	
Item	Input
Major Road Volume 1 (vph)	200
Major Road Volume 2 (vph)	200
Access Point Volume (vph)	20
Work Zone Length (ft)	5000
Work Zone Travel Speed (mph)	55
Major Road Green 1 (sec)	30
Major Road Green 2 (sec)	30
Access Point Green (sec)	10

Output

	Average Delay (sec/veh)				
	Flagger-Flagger	**PTS-PTS**	**PTS-PD2**	**PTS-PD1**	**PTS-Flagger**
Major Road 1	82.3	112.2	88.9	88.9	88.9
Major Road 2	82.3	112.2	88.9	88.9	88.9
Access Point	102.6	117.5	72.1	64.4	102.1
Combined Major	82.3	112.2	88.9	88.9	88.9
Work Zone	**83.3**	**112.5**	**88.1**	**87.7**	**89.5**

* Highlighted green cell indicates minimum delay

	Total Delay (veh-hr)				
	Flagger-Flagger	**PTS-PTS**	**PTS-PD2**	**PTS-PD1**	**PTS-Flagger**
Major Road 1	4.6	6.2	4.9	4.9	4.9
Major Road 2	4.6	6.2	4.9	4.9	4.9
Access Point	0.6	0.7	0.4	0.4	0.6
Combined Major	9.1	12.5	9.9	9.9	9.9
Work Zone	**9.7**	**13.1**	**10.3**	**10.2**	**10.4**
Equivalent VOT ($/hr)	**$ 291**	**$ 394**	**$ 308**	**$ 307**	**$ 313**

PTS = Portable Traffic Signal; PD1 = Modified Hybrid Device; PD2 = Blank-Out Sign Device

Figure 17. Spreadsheet-Based Delay Calculator.

Figure 18 and Figure 19 show the delay values computed from the models versus the values observed from the simulation on the major approaches and at the access point, respectively. The solid diagonal line represents the ideal case where the model estimates and observed values are equal.

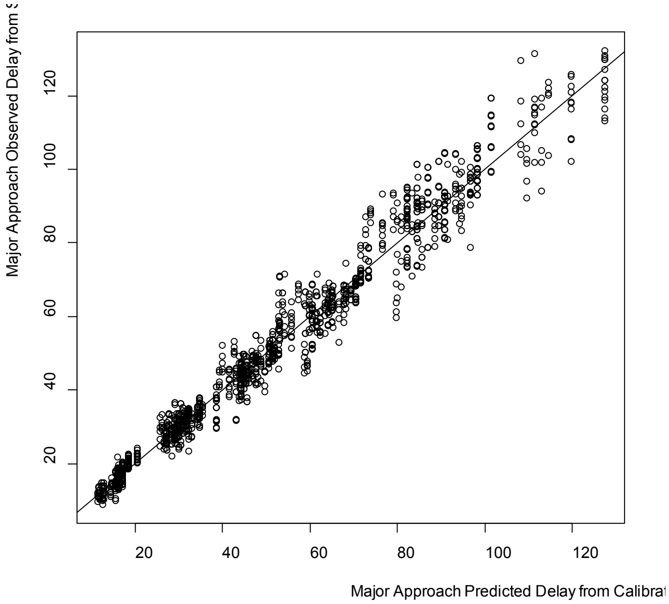


Figure 18. Simulated Delays versus Model Estimates on Major Approaches.

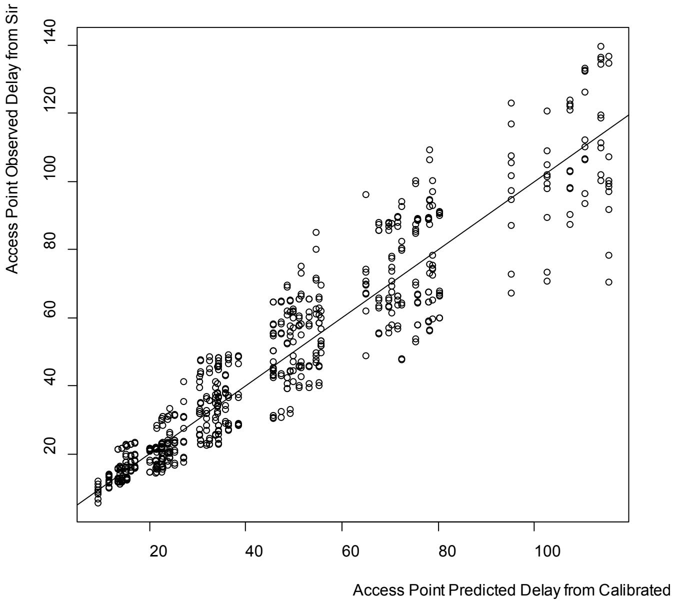


Figure 19. Simulated Delays versus Model Estimates at Access Point.

Delay Model Results

Using the delay models, researchers calculated the access point and work zone delay for the scenario where PTCSs control the main road and either a flagger, PTCS, or prototype device control the access point using the following parameters:

- Main road volume (50/50 split) = 100, 200, 300, and 400 vph.
- Access point volume = 20 vph.
- Work zone length = 1000, 2000, 3000, 4000, and 5000 ft.
- Work zone speed limit = 55 mph.
- Major road approach green time (each direction) = 30 seconds.
- Access point green time (10 seconds).

While the two prototype devices operated slightly differently in the simulation program, for all practical purposes their contribution to the overall work zone delay was very small and quite similar. So, for this effort researchers did not consider them separately.

The baseline condition was PTCSs on the main road and a flagger at the access point. As Figure 20 shows the access point delay is relatively small per hour of work and ranges from 0.13 to 0.57 veh-hr.

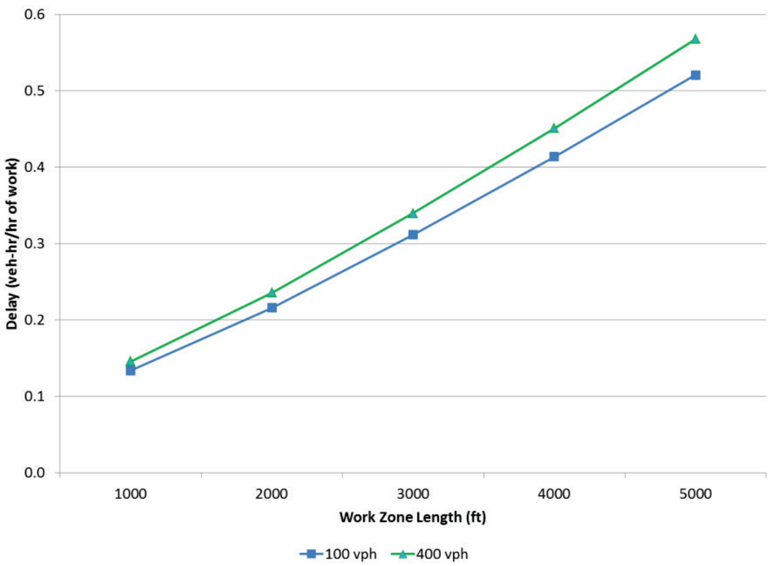


Figure 20. PTCS-Flagger Access Point Delay.

Table 14 shows the difference in the access point delay when a PTCS or a prototype device is used in lieu of a flagger at the access point. When a PTCS is used at the access point the delay increases (user cost). Assuming a value of time of $30 per hour, these delay increases cost users between $2.56 and $4.45 more per hour compared to using a flagger at the access point. Conversely, when a prototype device is used at the access point the delay decreases (user benefit); yielding a reduction in user costs by $1.18 to $5.01 per hour.

Table 15 shows the difference in the work zone delay when a PTCS or a prototype device is used in lieu of a flagger at the access point. Since the prototype devices are designed to work in conjunction with the PTCSs on the main road, the main road traffic does not experience any additional delay. So, the decrease in the work zone delay is the same as the decrease in the access point delay. Conversely, the use of a PTCS increases the work zone delay; negatively impacting both the main road and access point traffic. Overall, the increases in delay when using a PTCS at the access point costs users between $12.04 and $80.30 more per hour compared to using a flagger at the access point.

Table 14. Difference in Access Point Delay from PTCS-Flagger (Base Condition).

Total Main Road Volume (vph)	Work Zone Length (ft)	PTS-PTS (veh-hr/hr)	PTS-PD (veh-hr/hr)
100	1000	0.13	-0.04
	2000	0.15	-0.06
	3000	0.15	-0.09
	4000	0.14	-0.12
	5000	0.13	-0.15
200	1000	0.13	-0.04
	2000	0.14	-0.07
	3000	0.14	-0.09
	4000	0.13	-0.13
	5000	0.12	-0.16
300	1000	0.13	-0.04
	2000	0.14	-0.07
	3000	0.13	-0.10
	4000	0.12	-0.13
	5000	0.10	-0.16
400	1000	0.12	-0.04
	2000	0.13	-0.07
	3000	0.12	-0.10
	4000	0.10	-0.13
	5000	0.09	-0.17

PTS = Portable Traffic Signal; PD = Prototype Device

SUMMARY AND CONCLUSIONS

The selection of the appropriate traffic control method includes an assessment of a device's benefits compared to its costs. Researchers confirmed that the current practice of using portable signals to control both the main road and access point traffic (without vehicle detection) increases delay for the main road and the access point traffic. Conversely, researchers found that the prototype devices decrease delay at the access point. In addition, since the prototype devices provide directional information (which way to turn and which way not to turn), these devices can work in conjunction with the main road PTCSs, and thus do not impact the main road delay. Researchers also determined that it would take 1 to 4 years for the prototype devices to pay for themselves, dependent upon use and type of device. While safety impacts could not be quantified for this analysis, worker and motorist safety must be considered when determining the most appropriate traffic control method for low-volume access points, as well as the main road.

Table 15. Difference in Work Zone Delay from PTCS-Flagger (Base Condition).

Total Main Road Volume (vph)	Work Zone Length (ft)	PTS-PTS (veh-hr/hr)	PTS-PD (veh-hr/hr)
100	1000	0.40	-0.04
	2000	0.52	-0.06
	3000	0.61	-0.09
	4000	0.69	-0.12
	5000	0.78	-0.15
200	1000	0.67	-0.04
	2000	0.88	-0.07
	3000	1.06	-0.09
	4000	1.24	-0.13
	5000	1.41	-0.16
300	1000	0.95	-0.04
	2000	1.25	-0.07
	3000	1.53	-0.10
	4000	1.79	-0.13
	5000	2.05	-0.16
400	1000	1.23	-0.04
	2000	1.63	-0.07
	3000	1.99	-0.10
	4000	2.34	-0.13
	5000	2.68	-0.17

PTS = Portable Traffic Signal; PD = Prototype Device

CHAPTER 7:
SUMMARY, RECOMMENDATIONS, AND GUIDELINES

The objectives of this research project were to: (1) identify and evaluate traffic control technologies and strategies that could be used to control traffic entering from low-volume access points and (2) develop guidelines regarding the appropriate traffic control for low-volume access points within a lane closure on a two-lane, two-way road. To do this, researchers examined the state-of-the-practice regarding temporary traffic control at lane closures on two-lane, two-way roads in Texas, and identified existing and innovative strategies and devices that could be used to control traffic entering from low-volume access points. Based on this information, TxDOT and TTI decided to further investigate two innovative devices: modified hybrid device and blank-out sign device. Researchers conducted motorist surveys and field studies to assess motorist understanding of and the operational and safety effectiveness of these two devices. Researchers also compared the benefits and costs of various temporary traffic control alternatives for low-volume access points, including the two innovative devices. Overall, the findings from these tasks and studies were used to develop guidelines regarding the appropriate traffic control for low-volume access points within a lane closure on a two-lane, two-way road.

SUMMARY

State-of-the-Practice

When a lane is closed on a two-lane, two-way road for construction or maintenance activities provisions must be made to alternate one-way movement of the two original travel lanes through the work area. Quite often there are low-volume access points, such as residential driveways or county roads, within the temporary one-lane section of roadway. While these access points should be monitored, existing methods are not always feasible based on conditions such as work duration, traffic volume, time of day, and cost of the method. So, researchers identified and explored the potential of four innovative device concepts. Based on this review, researchers and TxDOT believed that the following two innovative devices showed the most promise: modified hybrid device and blank-out sign device.

Motorist Survey

Before building actual prototypes of the modified hybrid and blank-out sign devices, researchers conducted an initial assessment of motorist understanding of these devices using laptop-based surveys. While both of the devices appear to be adequately understood by motorists when displaying messages to proceed in a certain direction, the modified hybrid device was not as well understood as the blank-out sign device under the stop condition. More specifically, under the stop condition the modified hybrid device without an R10-11 sign yielded comprehension levels less than the standard criterion. Adding an R10-11 sign to the modified hybrid device did improve comprehension levels such that they exceeded the standard criterion. However, comprehension levels for the modified hybrid device with an R10-11 sign for both phases (proceed and stop) were still less than those for the blank-out sign device (and in several cases significantly less). Overall, the motorist survey findings implied that the blank-out sign device was better understood than the modified hybrid device.

Field Study

Even though the motorist survey findings showed that the blank-out sign device was better understood than the modified hybrid device, TxDOT wanted to evaluate both devices in the field. So, researchers worked with a manufacturer to build one prototype modified hybrid device and one prototype blank-out sign that would work in conjunction with PTCSs on the main road. Researchers then conducted controlled and non-controlled field studies to assess the operational and safety effectiveness of the two prototype devices. The controlled field study utilized recruited participants from the local area and included observation and survey portions. The non-controlled field study focused on all other drivers trying to enter the lane closure from the access point controlled by one of the two prototype devices.

Based on the controlled field study participants' answers to the survey questions, it appeared that the modified hybrid device was well understood. However, the closing comments revealed insight into potential issues with various aspects of the modified hybrid device. In addition, only 57 percent of the controlled field study participants correctly followed the instructions provided by the modified hybrid device when they first encountered it. The remaining controlled field study participants (43 percent) had to be stopped from making the wrong turn by a researcher. In the non-controlled field study, 13 percent of the drivers made incorrect maneuvers and had to be intercepted by workers. An additional 10 percent of the drivers stopped to ask workers what action to take. Overall, the field study findings suggested that the flashing yellow arrow indications used with the modified hybrid device were not well understood.

In contrast, 100 percent of the controlled field study participants correctly reacted to the blank-out sign. While some potential confusion was noted by these participants during the survey phase, all participants noted that with experience and education the blank-out sign device would be easily understood. In addition, most of the non-controlled study driver compliance issues were due to the programming of the blank-out sign with the PTCSs on the main road (i.e., drivers not being allowed to proceed at the end of the main road vehicle queue). Overall, the field study findings suggested that the use of the circle/slashes over the directional arrows on the blank-out sign device adequately informed motorists when they could and could not turn.

Benefit/Cost Comparison

Researchers confirmed that the current practice of using portable signals to control both the main road and access point traffic (without vehicle detection) increases delay for the main road and the access point traffic. Conversely, researchers found that the prototype devices decrease delay at the access point. In addition, since the prototype devices provide directional information (which way to turn and which way not to turn), these devices can work in conjunction with the main road PTCSs and thus do not impact the main road delay. Researchers also determined that it would take 1 to 4 years for the prototype devices to pay for themselves, dependent upon use and type of device. While safety impacts could not be quantified for this analysis, worker and motorist safety must be considered when determining the most appropriate traffic control method for low-volume access points, as well as the main road.

RECOMMENDATIONS AND GUIDELINES

To ensure the safety of the motoring public and workers, all access points within a work zone lane closure on a two-lane, two-way road should be monitored. At a minimum, engineering judgment should be used to determine if a flagger is needed at a low-volume access point. TxDOT should also continue to visit property owners and residents to notify them of the temporary changes in traffic control and the appropriate actions to take when they exit their driveway.

While PTCSs may be used to control traffic at low-volume access points, their current design (i.e., no directional indications and no vehicle detection) will lead to increased work zone delay. Implementing vehicle detection so that the access point is only serviced when needed, should reduce the main road delay. However, since directional information cannot be currently conveyed with existing PTCS equipment, the main road must still be stopped to allow for access point traffic to travel in either direction. It should be noted that multiple low-volume access points within the lane closure further complicates this situation and can increase total work zone delay (main road and access point).

The two prototype devices created as part of this research project work in conjunction with the PTCSs on the main road, such that drivers from the low-volume access point can enter the main road in the designated direction before, within, or after the main road platoon. This synchronized system reduces the total work zone delay and allows for multiple low-volume access points to be serviced at the same time. However, some operational and safety concerns were identified with the two prototype devices. Overall, researchers do <u>not</u> recommend the use of the modified hybrid design. Researchers do however recommend that TxDOT further experiment in the field with the blank-out sign device. The following operational issues should be addressed in additional evaluations:

- Where should the blank-out sign device be located? – In the motorist surveys, researchers positioned the device on the near side of the intersection to the right of the low-volume access point road (similar to where a stop sign would be located). However, the geometry of the intersection and the highly directional nature of the internally illuminated LED signs may result in the blank-out sign not being seen by motorists. In the field study, researchers positioned the device on the far side of the intersection in front of oncoming access point traffic. However, dependent upon the lane closed (near or far) and the location of the work activity the blank-out sign could be blocked from motorists' view or in the way of the work activity.
- Should the existing stop sign be covered or removed for the duration of the work activity? – During the field study, researchers covered the existing stop sign located at the intersection of the low-volume access point and the main road since the

blank-out device informed drivers when to stop and when to proceed and did not want drivers to see a conflicting message. However, the covered stop sign appeared to confuse some participants in the controlled field study. This may also be influenced by the position of the blank-out sign device (see previous bullet point).

- Ensure appropriate coordination with the PTCSs on the main road – The system should be programmed such that access point vehicles can turn before, within, and after the main road traffic platoon. The programming process requires the following information: the expected or observed speed through the work zone, the length of the work zone, the travel time between each PTCS on the main road and the access point, the number of access points, and the expected queues on the main road, as well as at the access point. As needed, the all-red duration should be adjusted appropriately to account for the extended proceed phase at the access point.

CHAPTER 8:
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