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16. ABSTRACT

This research study evaluated methods of traffic control for mitigating wrong way movements from low volume access points in work zones that use reversible control. A literature review was conducted to identify traffic control systems that could address this problem. The most relevant devices found were a type of traffic control system known as a Driveway Assistance Device (DAD). A commercial DAD was selected for testing that was made by Superior Traffic Services (STS) of Missoula, Montana. A test plan along with a test protocol was developed and testing was conducted. Testing was conducted in two groups using a total of 11 volunteer test drivers. Of the 11 test drives, two drivers entered the intersection when a red signal was displayed by the DAD. Some driver anxiety was observed about unknown wait times, so it was recommended that the onboard Changeable Message Sign (CMS) be used to display wait times. Testing with the onboard CMS was not conducted due to impacts from the COVID-19 pandemic and other reasons. In addition to testing of existing equipment, new concepts were synthesized. These new concepts included using machine vision to ensure that all vehicles that entered the work zone exited before the traffic direction is reversed and adding micro radio transmitters to a Traffic Control System (TCS) in order to provide directions to motorists. A proposal was also generated for modifications that can be made to existing DADs that included adding a gate arm and adding an intrusion detection system.

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Managing Low Volume Access Points in Work Zones

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Executive Summary

Problem, Need, and Purpose of Research

Reversible control occurs when two opposing directions of traffic are required to share one lane. Lane sharing is generally accomplished by stationing controllers at each end of the work zone to direct traffic about when it is their turn to go. Traffic flows in one direction for a time while vehicles wanting to go the other direction are asked to wait. After some time, the lane is cleared of vehicles and the direction of traffic flow is reversed. A difficulty occurs when there is a low volume access point, such as side roads and driveways, in the work zone. If a vehicle enters the traffic lane from a low volume access point while going against the current traffic flow, significant disruptions to operations can occur and safety becomes a significant concern. There is a desire to reduce the possibility of vehicles going against traffic flow by using state-of-the-art technology. The main purpose of this work was to consider methods of controlling vehicle traffic entering from low volume access points and to test one commercial product suited to the task.

Background

Caltrans wishes to address wrong way movements within work zones that use reversible control and that have low volume access points. Caltrans Standard Plan T13 outlines a typical work zone with reversible control and can serve as a guide to workers when deploying such a work zone. The T13 plan may require modification to accommodate any new equipment, such as some of the more recent and advanced technologies, if implemented.

Overview of the Work and Methodology

This research study consisted of two phases; the work performed in both phases are included in this report. The first phase of study included conducting a literature review, collecting information about systems and techniques used by others, presenting the information, assisting in the selection of the equipment to study further, developing a test plan, and proposing new concepts. The second phase included procuring commercial equipment, developing the testing protocol, performing testing, analyzing results, considering costs, and making recommendations.

As part of phase one, a literature review of Traffic Control Systems (TCS) was conducted and a presentation based on the literature review was given along with possible concepts for new equipment. Some commercial equipment

designed specifically for controlling low volume access points in closures using reversing control were identified. These TCS are known as Driveway Assistance Devices (DADs) and are available from several manufacturers. A DAD is a portable device with arrows on it that show which direction traffic can currently turn (if any). Based on a comparison of the available commercial equipment, a DAD made by Superior Traffic Services (STS) was selected for further testing in phase 2, and a draft test plan was generated. A proposal for new modifications to commercial equipment like that of STS was also generated.

As part of phase two, the equipment from STS identified in phase one was rented. The testing protocol was generated, and Institutional Review Board (IRB) approval was received to recruit volunteer test drivers. Testing was conducted on the efficacy of the STS equipment as well as various operational considerations. Costs of using the equipment versus a human flagger were also compared.

Major Results and Recommendations

In this research, DAD equipment from STS that was capable of being controlled via remote control was tested. DAD's are often controlled by a Portable Traffic Signal (PTS), but for this testing, a human controlled the equipment via remote control (no PTS was used). Out of 11 test drivers (split into two separate tests), only two improperly entered the intersection and made a turn when the DAD had a red arrow in the direction they turned. It was noted that many drivers seemed to be anxious about the unknown wait time and/or whether the DAD had detected them. Some drivers would slowly roll forward after initially stopping but did not enter the intersection. Based on these results, a new IRB approval was generated to use the DAD with its built-in, small CMS sign to inform drivers of expected wait time. The CMS sign may also be actuated by approaching vehicles. Work was completed to make the DAD capable of this feature, but testing is needed to see how drivers will react. Testing was not conducted due to shelter in place requirements of the COVID-19 pandemic. However, such testing can be part of a future study.

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List of Acronyms and Abbreviations

Acronym	Definition
AFAD	Automated Flagger Assistance Device
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
AI	Artificial Intelligence
Caltrans	California Department of Transportation
CAMUTCD	California Manual on Uniform Traffic Control Device
CMS	Changeable Message Sign
COTS	Commercial Off-The-Shelf
COZEEP	Construction Zone Enhanced Enforcement Program
CPI	Consumer Price Index
CVC	California Vehicle Code
DAD	Driveway Assistance Device
DMS	Driveway Management Signal
DMU	Driveway Management Unit
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
FHWA	Federal Highway Administration
HAR	Highway Advisory Radio
IRB	Institutional Review Board
LED	Light Emitting Diodes

Acronym	Definition
MAZEED	Maintenance Zone Enhanced Enforcement Program
MUTCD	Manual on Uniform Traffic Control Device
MUWE	Median Usual Weekly Earnings
OSHA	Occupational Safety and Health Administration
PCMS	Portable Changeable Message Sign
PTS	Portable Traffic Signal
STS	Superior Traffic Services
TCD	Traffic Control Device
TCS	Traffic Control Systems
VSL	Value of a Statistical Life
WSDOT	Washington State Department of Transportation

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CHAPTER 1:

Introduction

Problem

The California Department of Transportation (Caltrans) is charged with supervising and maintaining California's diverse network of highways and freeways. There are over 50,000 lane miles in Caltrans' care [1]. When a highway or freeway requires maintenance, a temporary work zone is established, and lane closures may be needed.

Many different types of lane closures exist, each with their own challenges and unique situations. Caltrans has many standard plans available to help design a closure. Standard Plan T13 [2] involves traffic taking turns when sharing one lane, and T12 [3] applies to multi-lane roads but does not require traffic to take turns. The specific type of closure prompting this research is called a "lane closure with reversible control" as outlined in Caltrans Standard Plan T13 [2]. For convenience, the closure found in the T13 [2] will hereafter be referred to as a Reversing Control (RC) lane closure. With an RC lane closure, traffic is controlled such that two opposing directions of traffic share one lane. Sharing one lane is generally accomplished by stationing controllers (i.e. human flaggers or other machines) at each end of the work zone to direct traffic and tell drivers when it is their turn to go. Traffic flows in one direction for a time while vehicles wanting to go the other direction are asked to wait. After some time, the lane is cleared of vehicles and roles are reversed: the direction of traffic that was flowing is now asked to wait and the previously waiting direction proceeds. A comprehensive review of RC lane closure operations was given in [4]. If an errant driver fails to wait when asked, it creates a situation where vehicles may end up in a head on collision. Frequently, the RC lane closure only has two end points as discussed above, but controlling traffic is complicated if there are intersections or low volume side roads within the work zone. An example of a typical RC lane closure with a low volume side road and a potential vehicle conflict is shown in Figure 1.1. When a driver approaches the RC lane closure from a side road, their entry must be coordinated with the controllers at the main endpoints of the work zone to avoid conflicts. Directing traffic entering from side roads in an RC lane closure is the focus of this research effort.

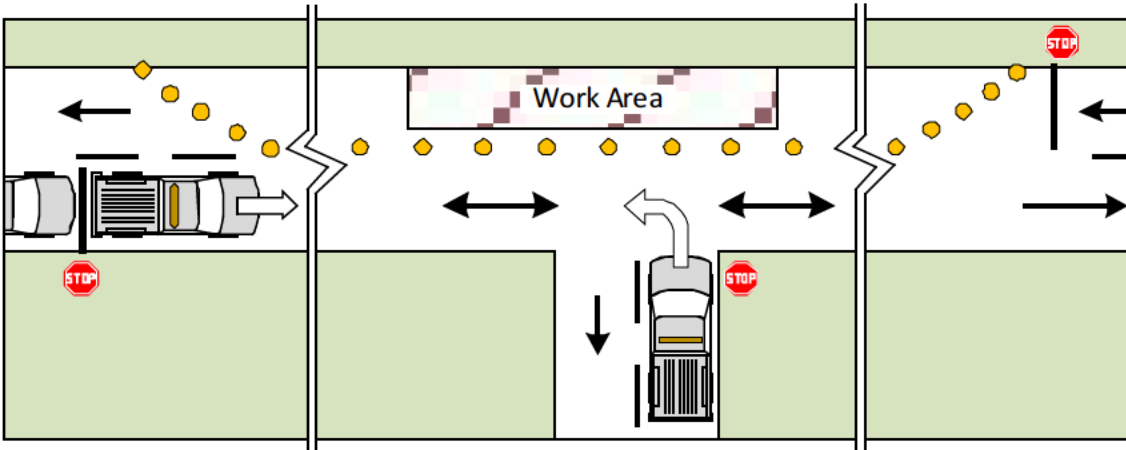


Figure 1.1 Lane Closure with Potential Vehicle Conflict

Objectives

The main purpose of this work was to consider methods of controlling vehicle traffic entering from one or more low volume access points in a work zone that uses reversible control. As part of this, modifications to the Standard Plan T13 were proposed to allow new equipment and a commercial device was tested. It is expected that having more tools that Caltrans and its contractors can use with low volume access points will contribute to improved safety among other benefits.

Scope

The focus of this work will be on low volume access points, such as driveways, within the RC lane closure work zone. This research study incorporated a number of discrete tasks. The first phase (first 6 tasks) were focused on reviewing and selecting available options to address the need; the second phase (second 5 tasks) focused on testing a commercial product to address the need. The 11 total tasks were:

- Task 1: Forming a Project Panel and General Project Management
- Task 2: Literature Review and Assessment of Available Technology
- Task 3: Presentation of State of Art and Available Technology to the Panel
- Task 4: Developing a Test Plan for an Existing Product
- Task 5: Creating a Proposal for Developing a Concept for New Equipment
- Task 6: Research Documentation and Reporting (for Phase 1)
- Task 7: Procurement of a Commercial Product

- Task 8: Development of the Test Protocol
- Task 9: Performing Testing of a Commercial Product in a Closed Facility
- Task 10: Test Results and Cost Analysis
- Task 11: Research Documentation and Reporting (for Phase 1 and 2)

Background

Caltrans wishes to address wrong way movements within work zones that use RC lane closures and that have low volume access points. Caltrans Standard Plan T13 [2] outlines a typical work zone with RC lane closures and can serve as a guide to workers when deploying into this type of work zone. In order to apply new technology to this application, T13 [2] may need to be modified. A research study panel consisting of the stakeholders has been formed as part of Task 1, and AHMCT researchers have been working with the panel over the course of this research study.

Research Methodology

The methodology of this research included reviewing existing literature for a wide variety of ways to control traffic. Some of the ways to control traffic considered were automated equipment based, some relied on human flaggers, while some types were designed to assist flaggers; as a group these will all be referred to as Traffic Control Systems (TCS). The most applicable TCS were considered further, and commercial systems were compared to help decide which equipment to use for further testing. New concepts were also synthesized as were potential modifications to existing equipment. A test plan was generated for the selected equipment, and a proposal was made for one or more of the concepts presented. The equipment selected for testing and the test plan was developed through collaboration with the research study panel consisting of Caltrans stakeholders. Test protocols for conducting testing using human volunteer drivers were generated and approved by the Institutional Review Board (IRB). Data was collected about the efficacy of the selected commercial equipment as well as various operational considerations.

Overview of Research Results

The main focus of this work was to review possible Traffic Control Systems for controlling low volume access points, select a commercial system for testing, and testing of the commercial system. A presentation of various TCS that could be applied with and without modification was made. The most applicable type of TCS were devices intended to be placed at low volume access points with lighted arrows that tell drivers which direction (if any) they can turn. These

devices are available from several manufacturers [5], [6], [7] and there are some variations [4]. The term DAD (Driveway Assistance Device) is used by several manufacturers [5], [6], and in reports [4]; this work will adopt the term DAD for all of these types of devices except where it is desired to point out some specific difference.

After comparison of the various DAD's, equipment made by STS was selected for testing. A test plan was created, and testing was conducted using the STS equipment. Testing consisted of 11 drivers split into two groups. Results showed that two of the 11 drivers entered the intersection and made a turn when the DAD showed a red arrow in that direction. It seemed that drivers were anxious about how long they would be required to wait or if the DAD had detected them or was working. Some drivers would slowly roll forward after initially stopping but did not enter the intersection. A new protocol was developed to use the DAD with its built-in, small CMS sign to inform drivers of expected wait time. Work was completed to make the DAD capable of this feature, but additional testing is needed to see how drivers will react.

CHAPTER 2:

Literature Review and Assessment of Technology

Literature

To assess the current state of practice for RC lane closures, standard plans and guidance documents used by workers were considered from several different Departments of Transportation (DOTs). It should be noted that these standard plans are applied with good engineering judgement and are not intended to be indiscriminately applied. The standard plan used by Caltrans includes guidance on intersections and as mentioned previously, is known as T13 [2]. Other state DOTs also have plans for RC lane closure situations that address intersections, such as Kansas [8], Missouri [9], Washington [10], and Wyoming [11]. Beyond the United States of America, relevant plans were also found for Ireland [12] where the RC lane closure is known as “Shuttle Working.” The UK also has guidance that says a human “stop/go” operator must control traffic on side roads if there is a pilot car in use [13] and that a give/take system can be used on short closures [14]. Of the plans and guidance considered, many only discussed flaggers and/or pilot cars. Placing human flaggers at low volume access points is not ideal, however, because there may be only a few cars per day and workers could be more productive performing other tasks. Pilot cars can be used, but these typically work in addition to some form of entry control. When Oregon partnered with FHWA to survey work zones throughout Oregon, it was noted that pilot cars did not work well in areas with many side roads and long distance closures [15].

The traveling public’s understanding of how to react when encountering a work zone is critical and drivers need to be given clear guidance. To gauge the public sentiment regarding work zones, drivers in Oregon were asked about their experiences [16]. Some things learned from the Oregon study were that drivers wanted better direction/guidance and that nighttime visibility was sometimes poor [16]. Other studies have also said that drivers would like more information in work zones [17]. When solving the problem of directing traffic entering from side road access points in an RC lane closure, the above concerns should be considered.

TCS include both Traffic Control Devices (TCD) as well as human control methods. The main line access points in a RC lane closure are typically controlled by human flaggers, but there are various TCDs as well. The TCDs vary from devices designed to assist human flaggers to fully autonomous temporary

traffic lights. Some types of TCDs are event-driven, meaning that they react to the presence of vehicles autonomously or in some cases upon operator input. Event-driven TCDs include red/yellow and stop/slow Automated Flagging Assistance Devices (AFAD) as defined in the Federal Highway Administration (FHWA) Manual on Uniform Traffic Control Devices (MUTCD) [18] as well as vehicle actuated Portable Traffic Signals (PTS), gates [19], projection signs [20], and radar actuated Portable Changeable Message Signs (PCMS). Many TCDs are applied to control the main work zone entrance points, but it may be possible to use them on low volume side roads.

AFADs have been looked at by several studies applied to the main access points of a work zone. Red/yellow AFADs have mandatory gate arms while stop/slow AFAD's have optional gate arms, and the MUTCD (Section 6E.04) requires both types to be operated by a flagger in visual range [18]. Since these systems are not commonly seen by drivers, some confusion may be expected. To reduce driver confusion, different instructional signs have been studied with stop/slow and red/yellow AFADs, and a gate arm was recommended for stop/slow systems [21]. One study conducted field tests of stop/slow and red/yellow AFADs [22] while using the best performing signs found in previous work [21]. The findings were that human flaggers had perfect compliance, while AFAD systems with gate arms had lower errant driver rates than those without arms [22]. In another study, red/yellow AFADs were compared against flaggers as well as PTS systems [23]. The results showed flaggers and AFADs performing similarly, while PTS systems had a much higher errant driver rate [23]. A vehicle carried AFAD and CMS system along with a horn designed to stop errant drivers has also been field tested to compare with human flaggers; the results found a similar errant driver rate for both [24]. Research in AFADs in Australia found good compliance for most systems, but driver confusion was noted [25]. Unlike the stationary AFADs discussed above, Minnesota DOT developed a mobile AFAD that can be remotely positioned using a controller [26]. It was developed primarily to follow a moving work zone.

A PTS can also be used to direct work zone traffic. These are portable versions of traffic lights commonly seen in intersections, and unlike AFADs, they can operate autonomously. In the UK, multi-phase traffic lights are suggested as a possible option when side roads exist in the work zone if the work zone is short enough [14]. Portable traffic lights also exist that can be remotely actuated from a pilot vehicle [27]. One study comparing a PTS system with or without a flagger present to human flaggers alone found that human flaggers had a lower errant driver rate; however, for this study if a flagger waived a vehicle through a red light, it was counted as running a red light [28]. Another study looked at using a PTS system with a pilot car and compared it to a PTS system with a flagger present and a pilot car [29]. If the flagger waved a vehicle through a red light, it was considered an errant driver, and for both cases, a similar errant driver rate was reported.

Beyond AFAD and PTS systems, other devices have been considered for traffic control at work zone entry points. A portable boom gate is used in Australia to control traffic where one operator can control multiple devices [19]. Towable gates also exist that may be possible to use in controlling traffic at work zone entrance points [30]. To stop vehicles at a major tunnel entrance, Australia has also deployed a system where a stop sign is projected onto a water curtain that is generated on demand [20]. Other types of projection systems also exist, such as those used to control indoor traffic [31], and there are headlights that can project warnings to drivers [32]. In an attempt to remove humans from dangerous situations, a concept for a robotic flagger that moves in and out of traffic lanes has been proposed [33], and self-deploying traffic barrels operated under remote control have been developed [34]. There also exists a drone vehicle that supports a type of CMS that can be remotely controlled or configured to autonomously follow a lead vehicle [35].

Several studies have looked at calming traffic with active devices reacting to the presence of vehicles. One such study used warning messages on a radar actuated CMS [36], they found that warning drivers who are speeding and displaying the minimum fine did not significantly slow drivers better than other messages. Though not active, it has also been found that the presence of a CMS even when off may affect traffic [37]. Systems designed to attract drivers' attention have also been tested, it was found that placing a speed actuated horn before a speed trailer was more effective than a speed trailer alone [38].

To give workers an early warning about dangerous vehicles, some systems have been designed to detect vehicles intruding on their work area. Some of these detection systems may be adaptable to warn of vehicles errantly entering a work zone from a low volume side road. Several intrusion detection systems were reviewed in one study [39], they found that a system operated by compressed gas was the loudest while others had visual and haptic warnings as well as audible components. Radar tracking systems also exist that try to warn workers in the likely path of a vehicle by using small vibrating boxes worn by the workers [40]. Though not exactly an intrusion system, the "Egress Warning System" used in Ohio detects vehicles passing certain access points and displays a warning to drivers on a large screen [41].

Other forms of TCDs exist that are not event driven; in other words, these devices do not react to the presence of a vehicle. Non-event driven systems take the form of humanoid work zone dummies, portable traffic lights operated by a timer, static signs, road markings, cones, informational systems, and lights. Work zone dummies designed to look like humans with various levels of realism are used or are available for use in other countries to warn drivers of a work zone [42], [43], and have been used in the USA in the past [44]. Tall humanoid "robots" are also used in place of traffic lights to catch people's attention. These include the 14 foot tall system used in India [45] and the robot controllers of

Kinshasa [46]. Unlike the previous systems designed to draw attention, Washington, DC roadways that regularly change traffic direction are controlled by static “one-way” signs with a posted schedule [47].

To make crosswalks more conspicuous, self-illuminating pavement markings have been tried [48] as well as lights which project the outline of the crosswalk [49], [50]. In a similar vein, lights have been imbedded in the ground at the entrance to crosswalks in order to catch the attention of pedestrians as they look down while walking [51]. Some have attempted to paint illusions on roadways that look like 3D objects. One study reported small gains after painting the road with 3D looking lines in addition to a warning to look for pedestrians [52]. Others have tried painting crosswalks to look 3D [53] or even painted 3D children in the street [54], but no quantitative data on performance has been found for these examples.

On the informational side, a prototype portable sign has been developed to provide real-time wait times to drivers at road closures [55]. Commercial systems, such as the Highway Advisory Radio (HAR), can also be used to disseminate information. Users in Florida thought HAR was important for emergencies [56], and Washington State DOT (WSDOT) found that portable HAR worked well in work zones [17]. In Japan, lights and signs are used frequently to provide warnings and information to drivers, but one study found that adding more Light Emitting Diodes (LEDs) to night work zones did not necessarily improve visibility, while shorter messages on signs were better than longer ones [57].

Of all the equipment and methods reviewed, the family of devices tested in [58] was the only system specifically intended for low volume access points in the RC lane closure. These are portable devices with a method of telling drivers in which direction they are currently allowed to go (if any). In [58] two variations of the device, called the “Modified Hybrid Device” and the “Blank-out Sign Device,” were tested in a virtual environment as well as in the field. During the uncontrolled field study, the “Modified Hybrid Device” was tested with 39 vehicles and had a 13% errant driver rate with an additional 10% of drivers asking for guidance [58]. The “Blank-out Sign Device” was tested with 13 vehicles and had three errant drivers (23%), but two of them were attributed to a technical issue [58]. A variation of this traffic control system device is commercially available from multiple manufactures and is known as a Driveway Assistance Device (DAD) [5], [6]. A version of a DAD made by STS is also known as a Driveway Management Signal (DMS) [7] or a Driveway Management Unit (DMU). Various configurations of DAD exist or have been deployed [4], but DAD-type systems are still not regularly used.

CHAPTER 3:

Presentation of State of the Art and Available Technology

Presentation High Level Summary

Many different Traffic Control Systems (TCS) were considered during the literature review, including equipment-based devices and human-based. Many of the traffic control systems included were not originally designed for the problem of the RC lane closure with low volume access points but may still be usable in some form. After reviewing the literature, the information learned was distilled into a presentation format and presented to the research study panel. Some highlights from the presentation will be given here (using the most up to date information) along with additional information and results that were generated after the presentation.

The TCS covered in the presentation included many different techniques. Some of the TCS, such as Portable Traffic Signals (PTS) and human flaggers (Figure 3.1 and Figure 3.2 respectively), are commonly seen by drivers.

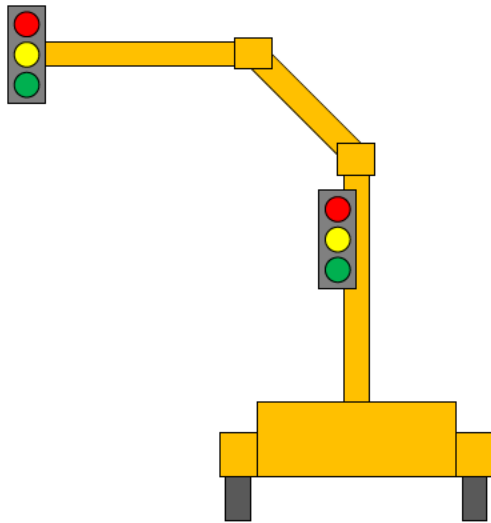


Figure 3.1 Typical Portable Traffic Signal (PTS)



Figure 3.2 Example Human Flagger

Less common TCS covered in the presentation included various types of Automated Flagger Assistance Devices (AFADs) as defined in the MUTCD [18]. An AFAD system is a device intended to improve safety by allowing a human flagger to control traffic through the AFAD while the human operator stands in a safer location than where a flagger would normally stand. An example of a red/yellow AFAD system is shown in Figure 3.3. Portable gates work under a similar concept to the AFAD by allowing a human to control traffic from a remote location as shown in Figure 3.4. One particular brand portable gate is the Portaboom that is used in Australia [19].

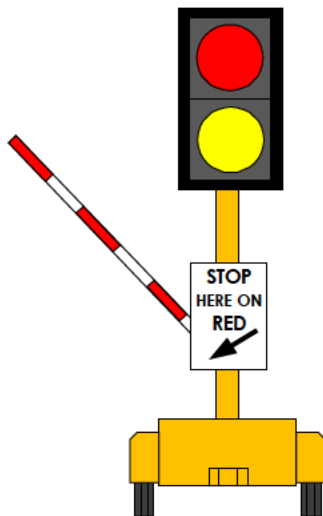


Figure 3.3 Typical Red/Yellow AFAD

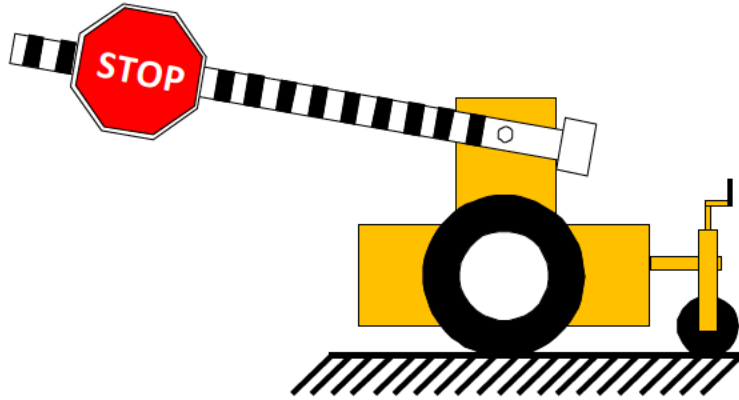


Figure 3.4 Generic Portable Gate

The only type of TCS presented that was specifically for the problem of low volume access points in an RC lane closure is the family of devices known as a Driveway Assistance Device (DAD) [5], [6] (or similar [7]) as shown in Figure 3.5. This is a passive TCS (as defined later in the report) that sits near the intersection of the low volume access point and the main line roadway. A DAD has an array of lights intended to direct drivers, and it can tell drivers to stop as well as to tell them in which direction they are currently allowed to go. After the presentation, DAD type products were considered further, which will be discussed in more detail later in this report. Various configurations of DADs are known to have been deployed [4], but this type of device is still not used regularly.

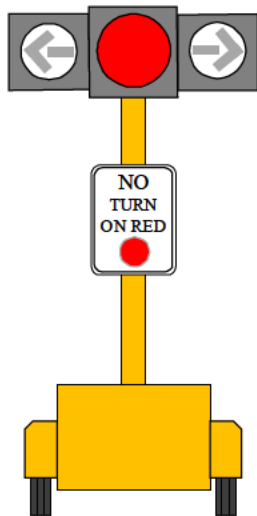


Figure 3.5 Example DAD System

Many other TCS were considered in the presentation but will not be discussed in this summary, including large traffic control robots [45], Australia's water projection stop sign [20], and glowing crosswalks [48]. Many of the TCS included in the literature review were also not included in further analysis as they were deemed less applicable to the current study.

Considering only the traffic control systems that seemed to be most applicable and common, a summary was generated as shown in Figure 3.6. The traffic control systems included in Figure 3.6 are possible to use in the configurations shown but are not necessarily approved for each configuration. Work zones of the type defined in Caltrans T13 [2] and Caltrans T12 [3] standard plans are both considered in Figure 3.6. It is clear from Figure 3.6 that there are significant differences between the T13 [2] scenario and the T12 scenario [3]. A more in-depth comparison of T13 [2], T12 [3] and T11 [59] are included in Appendix E.

To aid in the process of considering the large range of TCS options shown in Figure 3.6 and in the literature, a classification system was employed to provide organization. To this end, two methods of classification were discussed. The first method is based on the attributes of the TCS and is detailed below. The second method of classification was more academic and based on machine learning. Details of the machine learning method will not be discussed here, but a detailed discussion of this method was published as a TRB conference paper [60].

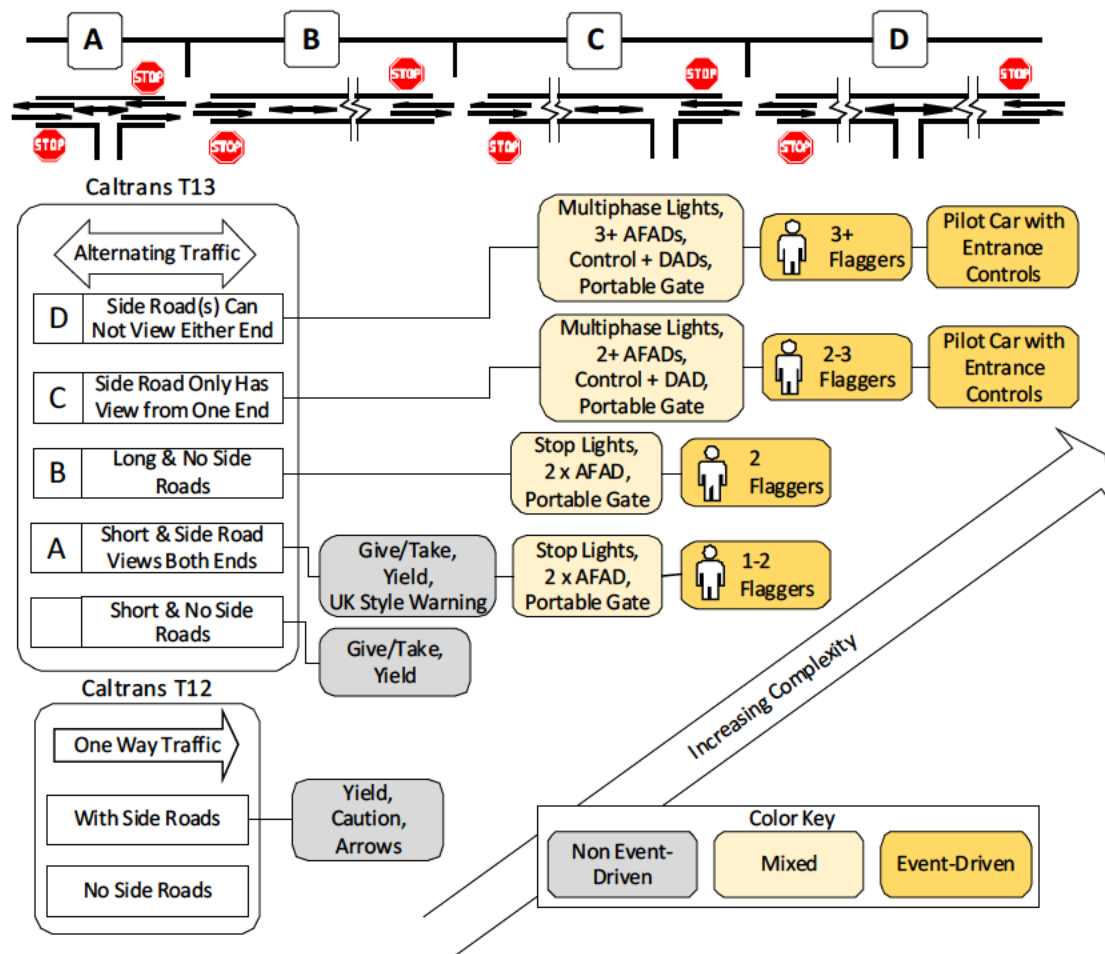


Figure 3.6 Partial Summary of Existing Methods

The first method of classification developed is based on attributes of the Traffic Control Systems (TCS) and is shown in Figure 3.7. For this classification, TCS discussed in the literature review are divided into event driven and non-event driven categories. Event driven was defined as reacting to the presence of vehicles, and non-event driven was defined as not reacting to vehicles. The event driven and non-event driven categories were further divided into active and passive. An active system is defined as one that physically blocks vehicles in some manner (like a gate arm) and passive is informational (like a stop light). The result of the classification can be thought of as a type of organization scheme in which systems with similar attributes are combined. This result allows for a quick understanding generally how each TCS works and to quickly assess possible options. For example, if it is decided that a TCS must react to traffic, only devices in the event driven category need to be considered, and the types of TCS available can be quickly identified. For TCS, such as a DAD, it is noted that even though it may not be event driven, it may be interacting with an event driven TCS, such as a vehicle actuated traffic signal.

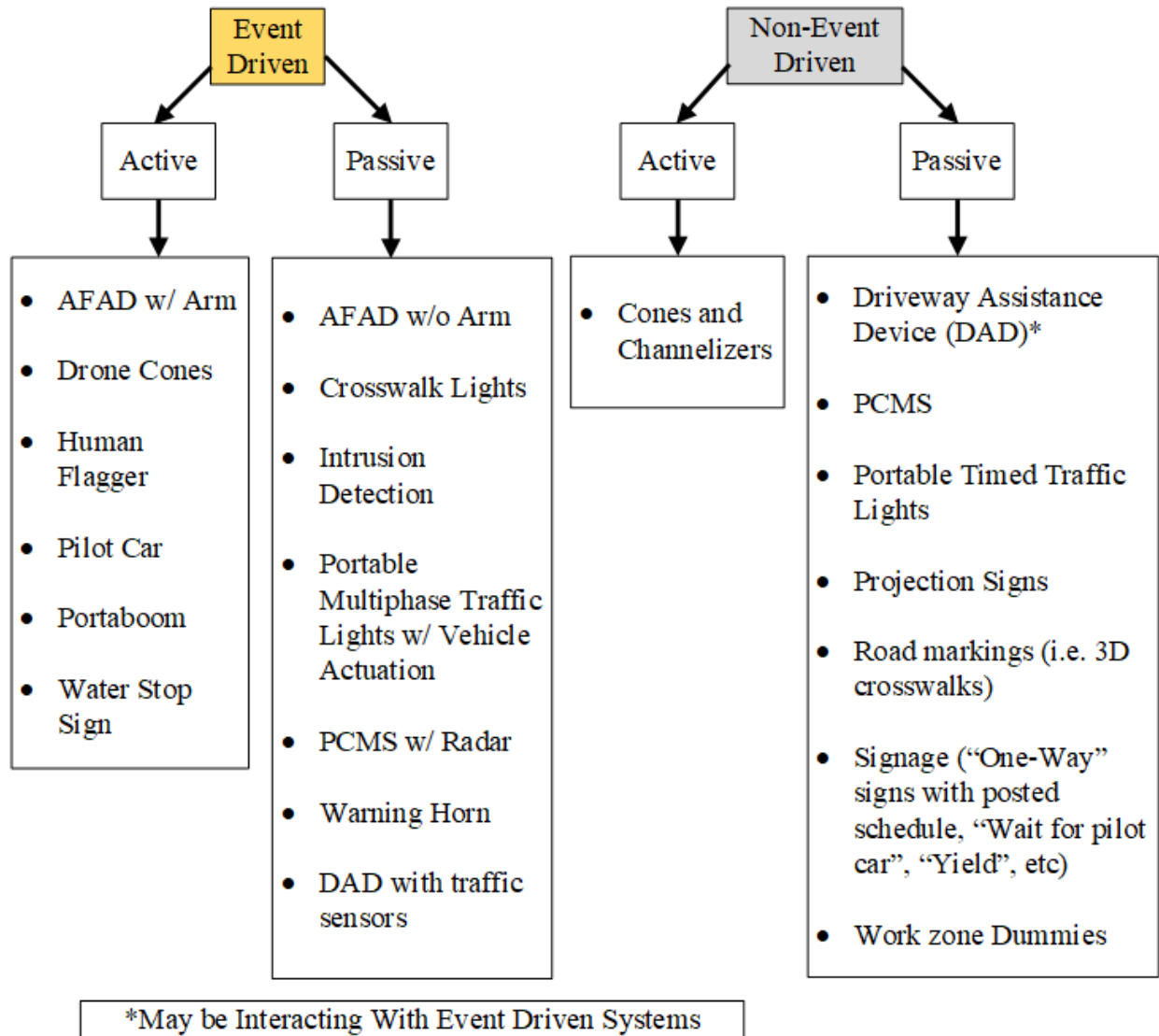


Figure 3.7 Proposed Traffic Control System Classification

Several concepts were also synthesized that could be considered for future development. The concepts mainly focused on increasing compliance and improving safety. The concepts included a variety of items such as:

1. Modifying a DAD to include a gate arm and considering a different arrangement of lights. A version of this concept is shown in Figure 3.8.
2. Adding a Wi-Fi portal to transmit user information to motorists stopped at the TCS. A version of this concept is shown in Figure 3.9.
3. Using an unlicensed micro AM or FM radio to provide information to motorists stopped at the new TCS (like a smaller HAR system). A version of this concept is shown in Figure 3.10.

4. Adding computer vision to track vehicles at the control points of the work zone to ensure that all vehicles that entered also exited. A version of this concept is shown in Figure 3.11.
5. Adding an alert system for the flaggers to inform them of traffic at the DAD when there is no line of sight.

The idea behind Concept 1 presented above was to modify a DAD, thus making an active TCS as previously discussed. The idea behind Concepts 2 and 3 presented above was to add new equipment to an existing TCS to provide information to drivers about what to do when encountering a potentially new-to-them TCS. Concepts 2 and 3 would broadcast information a short distance to vehicles in the immediate vicinity and potentially allow more information to be delivered than static signs could convey. Concept 2 would allow drivers who were stopped at the TCS to connect to a Wi-Fi network being broadcast by the equipment to obtain directions on what to do. The directions could potentially take many forms, such as images, webpages, video, and more. For Concept 2, all the information could be stored locally, and no internet connection would be needed. Concept 3 is similar to Concept 2, except that it would use a micro AM or FM radio station [61], [62] to broadcast information that drivers could receive on their standard car radio similar to a HAR system [56].

Concept 4 would require developing the most equipment. The idea behind concept 4 would be to check every vehicle exiting the work zone against those that entered the work zone using machine vision to identify each vehicle's license plate. This system was designed to mimic how human flaggers operate when they radio each other information about the last vehicle to enter the work zone. With a system like Concept 4, a TCS would not allow traffic to change directions until it could verify that the work zone was clear rather than assuming vehicles had cleared the work zone after some amount of time. An example output from a machine vision program is shown in Figure 3.12, which identifies several vehicles as well as the license plate on the closest vehicle.

Concept 5 is to add a camera or other sensors at the DAD site and a monitoring system such as display or other sensors to inform flaggers of traffic at the DAD site. This design is useful when there is no or a difficult line of sight for the flagger to observe traffic at the DAD location. This concept is included in some STS equipment and therefore is not discussed further here since it is not a new concept.

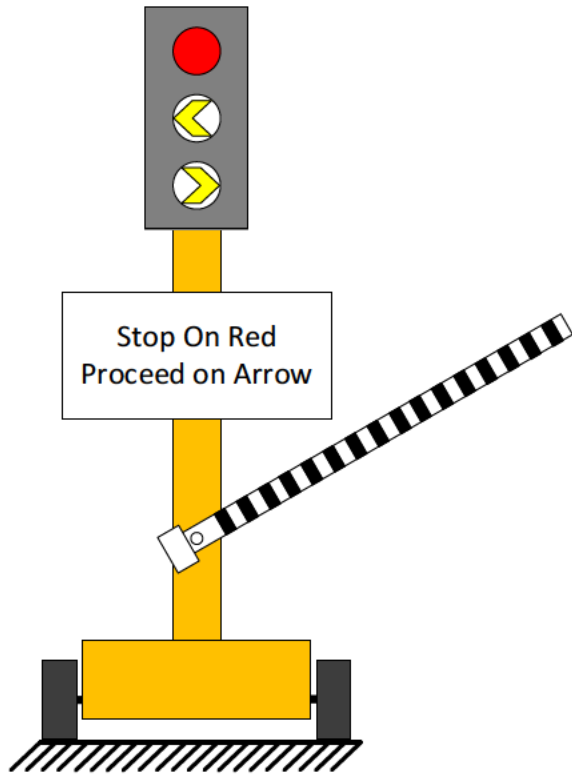


Figure 3.8 DAD with Gate Arm Addition

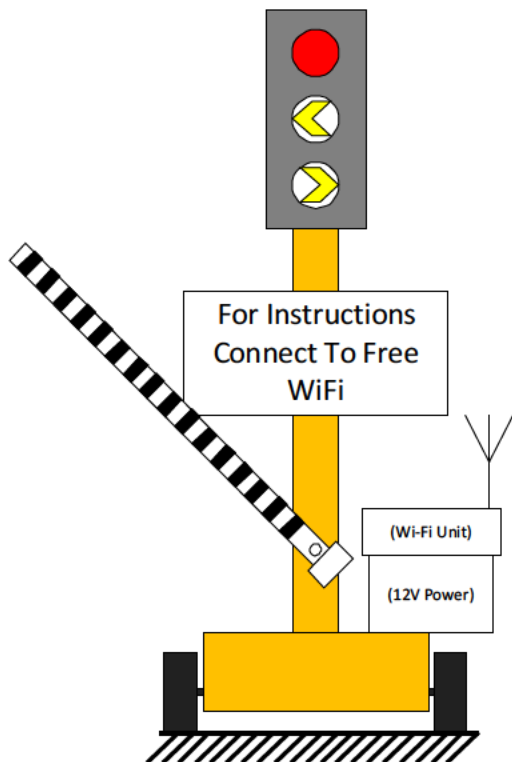


Figure 3.9 DAD with Gate and Wi-Fi Information

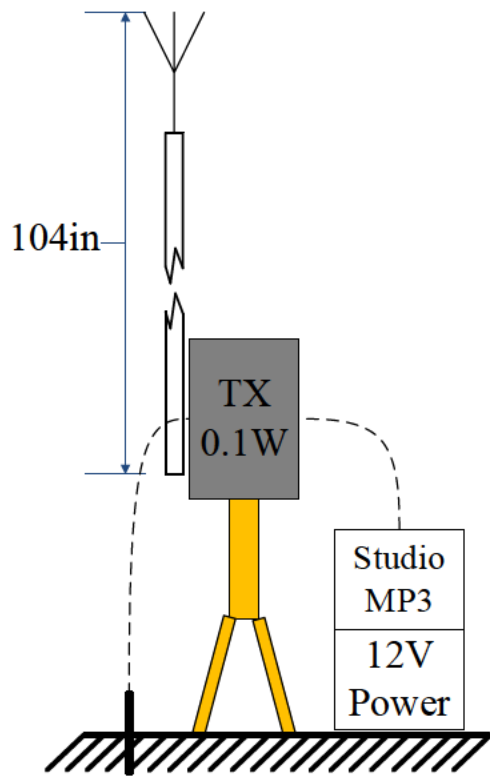


Figure 3.10 Micro Radio Transmitter

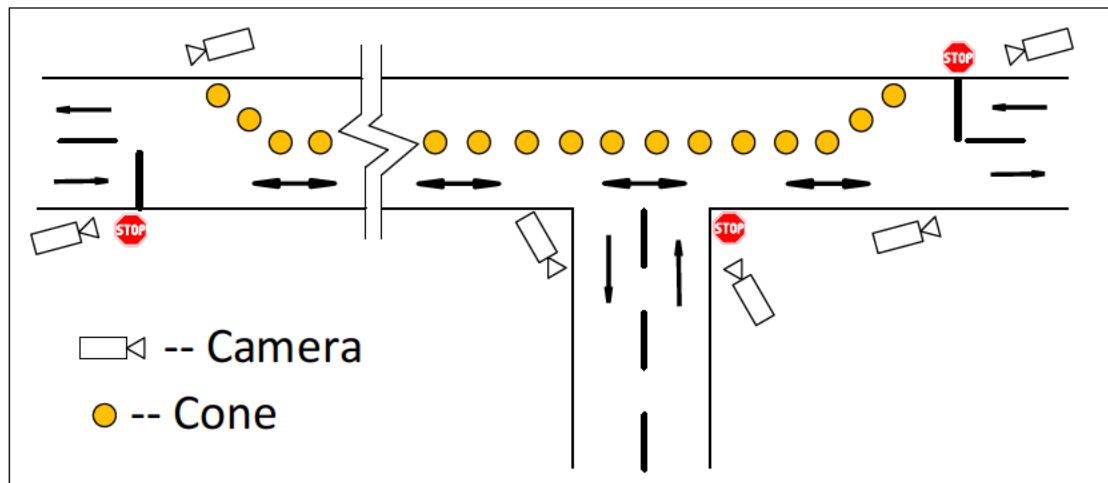


Figure 3.11 Machine Vision Workspace Management

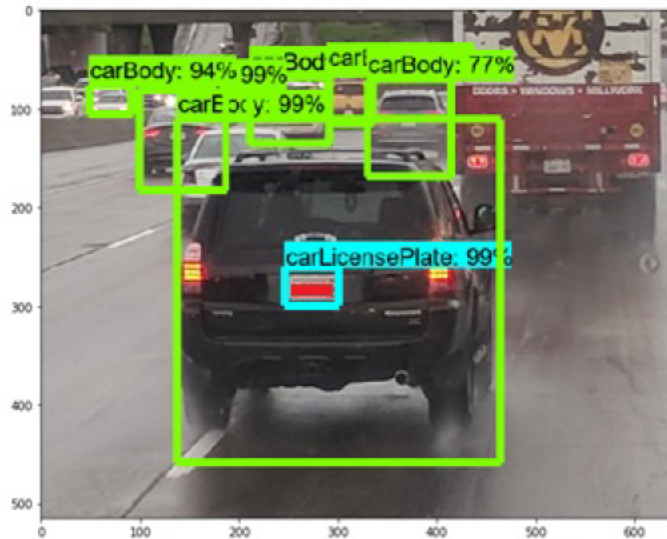


Figure 3.12 Sample Machine Vision Output (License Plate Manually Censored)

Selection of Equipment

Given the results of the literature and presentation, and based on the experience of the researchers, several recommendations for possible options to consider with and without modification were generated as shown in Table 3.1. The main equipment that could be considered without modification were the various types of DAD systems. It may also be possible to use an AFAD if the human flagger controlling the AFAD directs the traffic direction or clears the work zone traffic and then allows side road traffic to enter going either direction. Some possible commercial equipment and their vendors are shown in Appendix A. Equipment modifications proposed in Table 3.1 include anti-collision sensors for the AFAD gate arm, a camera to allow remote viewing of the AFAD, a CMS sign providing real time information to motorists similar to [55], combining the Construction Zone Enhanced Enforcement Program (COZEEP)/Maintenance Zone Enhanced Enforcement Program (MAZEEP) with the AFAD or DAD, and a DAD-type system with a gate arm added similar to an AFAD.

Table 3.1 Proposed Methods of Traffic Control

Equipment to Consider Without Modification	Equipment to Consider with Modification
Automated Flagger Assistance Device (AFAD) with gate arm as seen in Figure 3.3	AFAD with the gate arm modified to include anti-collision sensors
Driveway Assistance Device (DAD) as seen in Figure 3.5 (or Driveway Management Signal)	AFAD with a remotely viewable camera to overcome the FHWA line of sight rules

Equipment to Consider Without Modification	Equipment to Consider with Modification
	CMS to provide advisory information and/or display real-time information from a pilot car mounted GPS system similar to [55].
	AFAD or DAD integrated with COZEEP/MAZEEP
	DAD with gate arm added



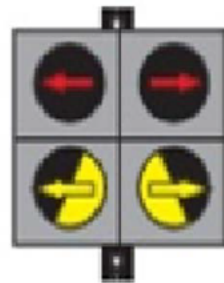
Comparison of Commercial Driveway Equipment

It was desired to test a commercial off the shelf (COTS) solution for traffic control. To facilitate selection of a COTS solution, a comparison was created for the various DAD systems from Horizon Signal [5], JTI [6], and Superior Traffic Systems [7]. It was also decided by the research study panel to not pursue solutions that involve a pilot car as scenarios with pilot cars are already well served by current standard plans.

To compare the COTS solutions for traffic control, AHMCT worked with Caltrans and contacted three manufactures to collect details about specific questions. Publicly available information on their websites was also reviewed and used [5],[6],[7]. A condensed version of this information is given in Table 3.2, and an extended version can be found in Appendix B.

Table 3.2 Comparison of COTS DAD type Equipment

	JTI Traffic [6]	Horizon Signal [5]	Superior Traffic Systems (STS) [7]
System Operation	Designed to work with JTI Portable Traffic Signal (PTS). DAD has no sensors. The PTS has a remote control.	Designed to work with Horizon PTS. DAD has no sensors. The PTS also has a remote control.	Designed to work with STS PTS or as a standalone unit. DAD has sensors (video and radar). Remote control for PTS or DAD.
All clear mode	Possible with custom engineering.	Possible with custom engineering.	Can be configured for this.
MUTCD Compliant	MUTCD has authorized studies.	In process of getting MUTCD approval.	Not currently.

	JTI Traffic [6]	Horizon Signal [5]	Superior Traffic Systems (STS) [7]
Shape of Signal on DAD	<p>DAD has a horizontal signal (Figure 3.13); it can be changed to vertical.</p>  <p>Figure 3.13 JTI Signal Head</p>	<p>DAD has a horizontal signal (Figure 3.14); it can be changed to vertical.</p>  <p>Figure 3.14 Horizon Signal Head</p>	<p>DAD setup as shown in Figure 3.15, but it can be changed to vertical.</p>  <p>Figure 3.15 STS Signal Head</p>
Live Webcam	Yes, with remote monitor service (data charges may apply).	No, but can provide power for a device.	Included standard. Also doubles as video detection for traffic.
Power Source	DAD has battery bank with solar charging option.	DAD has battery bank with solar charging option.	DAD has battery bank with solar charging option.
DAD Versions	DAD has 4 styles: wheeled base (cart), towable, barrier mount, and truck mount.	DAD has 2 styles: cart and trailer unit with more batteries and a larger solar panel.	DAD has 2 styles: square base and new larger trailer unit.
Safety Backup	No standard intrusion alarm solution.	Can add audible alarm to DAD trailer.	No warning for vehicle ignoring red signal.
Transport Options	DAD carts can be trailer transported. DAD trailers tandem towed.	DAD carts can be trailer transported. DAD trailers cannot be tandem towed.	DAD carts can be trailer transported. DAD trailers will have tandem towing.
DAD CMS Interface	Does not have CMS interface.	Does not have CMS interface.	Has CMS interface. A small CMS can be mounted on the DAD.

	JTI Traffic [6]	Horizon Signal [5]	Superior Traffic Systems (STS) [7]
Remote Monitoring Capability	Location, run time, battery status, and system logs.	Location, run time, battery status, and system logs.	Location, run time, battery status, and system logs (standard feature).
Acquisition options	Purchase or rent	Purchase or rent.	Typically rent only (all-inclusive price).

NOTE: This information was compiled with the help of Caltrans and from data provided by the manufacturers [5],[6],[7].

All three options compared in Table 3.2 are intended for a similar task; managing vehicles entering work zones from low volume access points. Referring to Table 3.2, each option has its own feature set and relative strengths that will be briefly summarized here. At the time the data was collected, none of the devices in Table 3.2 were MUTCD compliant (Horizon and JTI systems were either in the process or had studies on their devices). The Horizon DAD and the JTI DAD have similar arrangements of lights with one solid red round light and one arrow in each direction, while the STS unit has a set of four arrows to direct traffic. JTI has an optional webcam system that allows for live remote viewing of traffic while STS has this standard. All three companies have solar charging ability and the batteries were advertised to last at least 10 days or more. Of the three options, only the Horizon Signal DAD has an intrusion detection alarm available. One key differentiation between the three devices is the ability to be operated as a standalone device. Of the three devices, only the STS version was reported to have the ability to operate standalone without any custom work or modifications. All three devices can operate in conjunction with an appropriate portable traffic signal on the main line.

After careful consideration, it was decided that the STS unit should be used for testing as it seemed to provide more flexibility with its standalone operation mode. It is noted that operating the STS equipment in standalone operation rather than autonomously may increase operating costs for certain configurations.

Lighting Configuration

The STS version of a DAD could be configured with different arrangements of lights. The Caltrans research study panel considered several options, including vertical arrangements, but the final three candidates considered included Options A, B, and C shown in Figure 3.16.

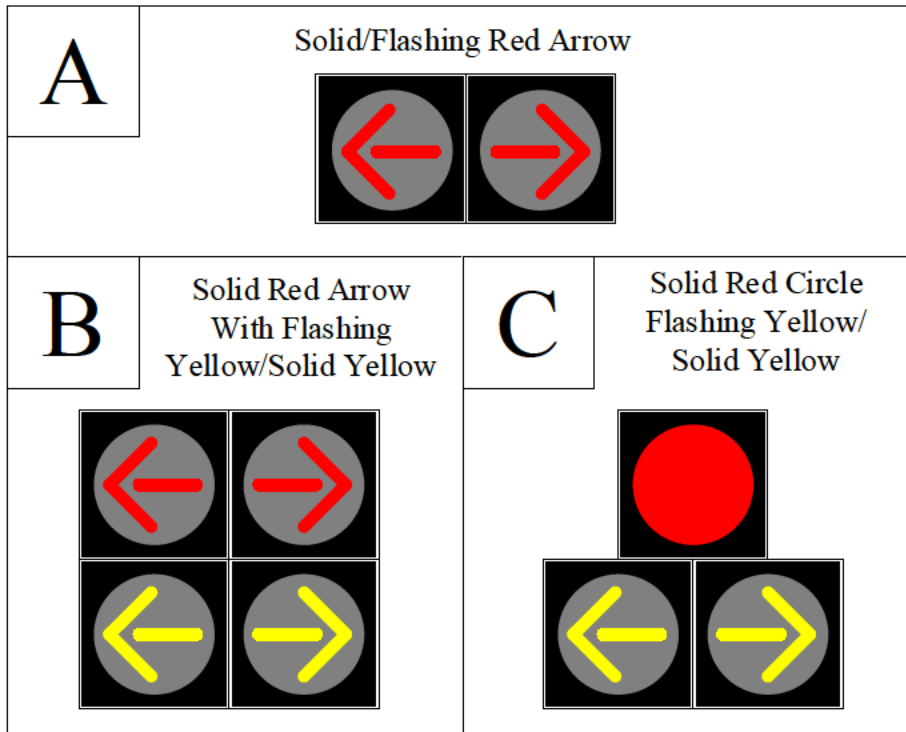


Figure 3.16 Possible Lighting Options (B based on STS [7], C as in [58])

Considering Figure 3.16, each arrangement of lights would operate in a slightly different manner. Option A is the simplest arrangement consisting of only two light sections. This option would function as follows: when traffic is fully stopped both red arrows would be solid, when traffic is allowed to proceed in a certain direction, one of the arrows would flash red to allow movement in that direction and the other arrow would remain solid. An example of Option A with a right turn allowed signal is shown in Figure 3.17. Option B from Figure 3.16 represents a four arrow signal head from STS [7] and would function by making both arrows solid red when traffic is fully stopped. However, when traffic can proceed, Option B would blink a yellow arrow in the direction of travel, and the solid red in that direction would turn off. An example of Option B with a right turn allowed signal is shown in Figure 3.17. Option C from Figure 3.16 is like the design used in research study [58] that was not recommended in the conclusion of that study. In this option, a solid red light indicates a full stop of traffic. When traffic is allowed to proceed in some direction, the red light would turn off and the yellow arrow would blink in the direction of travel currently allowed. An example of Option C with a right turn allowed signal is shown in Figure 3.17. For the options that use a blinking yellow arrow, a short duration of solid yellow arrow can be added before going back to red (similar to a standard stoplight).

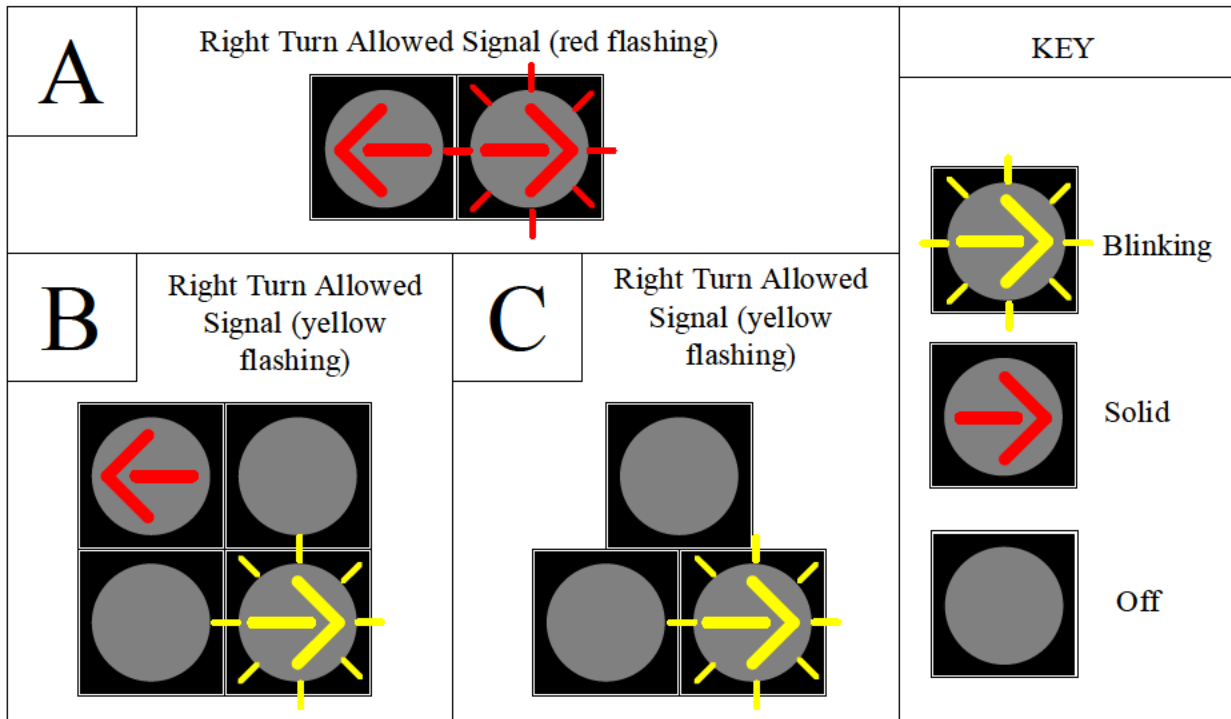


Figure 3.17 Example Right Turn Allowed Signal (B based on STS [7], C as in [58])

After some discussion with the Caltrans research study panel and in consultation with the CA MUTCD Section 4, it was decided that Option B or C would be acceptable for testing under the rules of the CA MUTCD. The panel selected Option B to test as Option C is known to have issues as described in [58]. Several instructional signs will accompany the signal when in use. The instructional signs and the wording they use will be discussed in Chapter 6.

CHAPTER 4:

Developing a Test Plan for an Existing Product

To test existing commercial products, a test plan was developed. The test plan was initially developed before the test protocol, which will be discussed in Chapter 7. When the protocol was developed, the test plan had to evolve in order to help facilitate the IRB approval process needed to work with human volunteer drivers. Originally it was planned to use the images and videos gathered as a deliverable. However, while working on the protocol for IRB, it became clear that in order to protect the identity of the test drivers, the videos had to be destroyed at the end of the research. Images taken when the test drivers were not present are included in the report. Another change was related to the post-testing interviews with the signal operators. When Caltrans operated the signal, their operator was not a test volunteer taking part in the study nor a member of the research team; as such, they could not be interviewed as originally planned. The intended questions were mostly irrelevant when a researcher operated the signal. As such, this part was removed from the protocol and that part of the test plan could not be completed.

Testing Metrics and Layout

The test plan considered typical metrics and methods used to test traffic control equipment. The primary metric of interest is compliance [24], [25], [28], [58], [63] (details about compliance applied to this problem will be given in Chapter 8). Other metrics, such as relative stop position [25], [24], can also be considered. Beyond quantitative measures, post-experience interviews can also be conducted with drivers similar those done for early DAD type systems [58], and for studies on AFAD's [63], [24].

The test plan covers two basic placements of the equipment that can be tested, and a copy of the test plan is provided in Appendix C. The basic configuration of the test after updating it to reflect the changes in the test protocol is shown in Figure 4.1 (not drawn to scale). Note that the boxes representing Test Location #1 and Test Location #2 are just general areas where the trailer will be placed and do not represent the actual size or outline of the trailer.

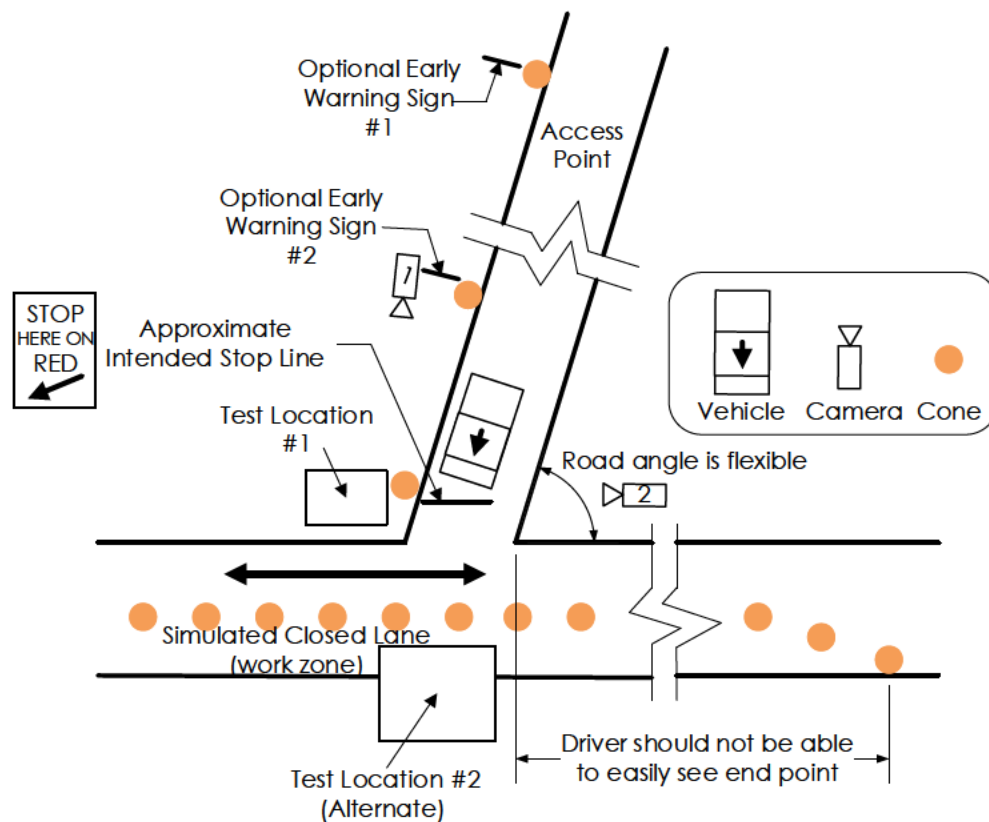


Figure 4.1 General Configuration of Test Layout (not drawn to scale)

Proposed Modifications to T13

Caltrans Standard Plan T13, as it is currently designed, does not include provisions for the use of a DAD-type device on a side road or driveway. To enable the use of the equipment on low volume access points, modifications are suggested as shown in Figure 4.2. The main change to T13 is the addition of an icon depicting a driveway signal along with a new note that a DAD is optional. Further changes may be warranted to show that the DAD device can be placed across the intersection, or to clarify the use of pilot cars with the DAD, but this scenario was not tested as part of this research.

CHAPTER 5:

Proposal for Developing a Concept for New Equipment

Proposal Motivation

Commercial Traffic Control Systems (TCS) were found that are designed specifically for the problem of low volume access points in work zones. The test of one such commercial TCS will be discussed later in this work, but there was also a desire for custom modifications to solve what seem to be limitations of the current devices. The concept being proposed consists of two separate systems, and either one can be developed independently. The two proposed systems include:

- A gate arm with sensors to stop the gate from closing on vehicles
- A multi-sensor intrusion detection system

The full details of the two concepts being proposed are given in Appendix D, but a brief overview will be given here. Potential application of equipment to T11 and T12 are also considered and included in Appendix E.

Proposal Overview

The two systems being proposed (a gate arm and intrusion detection) are shown in a schematic view in Figure 5.1. As discussed, the two systems are independent, and one can be developed and operated without the other.

The first system included in the proposal is a gate arm added to a DAD (or similar device). Gate arms on AFADs have been shown to increase driver compliance [22], and it is anticipated they would have a positive impact on DAD compliance as well. The gate arm system would only be usable when the DAD is positioned at the corner of the intersection. The gate arm would not be usable when the DAD is placed across the street from the access point as is sometimes done. In the corner configuration, the arm will lower when vehicles are requested to stop. The proposed arm will be connected to sensors that will not allow the arm to close on vehicles.

The second system included is a radar and/or Artificial Intelligence (AI)-powered intrusion detection system. This system is designed to detect vehicles entering the work zone when the stop signal is given and warn the human flaggers who are controlling the work zone remotely. If an intrusion is detected, the system would transmit a wireless message to a relay station near the human

flagger. The relay station would then convert the message to a form that could be understood by a mobile device such as a tablet. In this way, the flaggers in control of the main line would be warned if a vehicle entered the work zone when it should not. To make this system operate, two cameras are recommended so that it can be effective at the intersection corner as well as across the street.

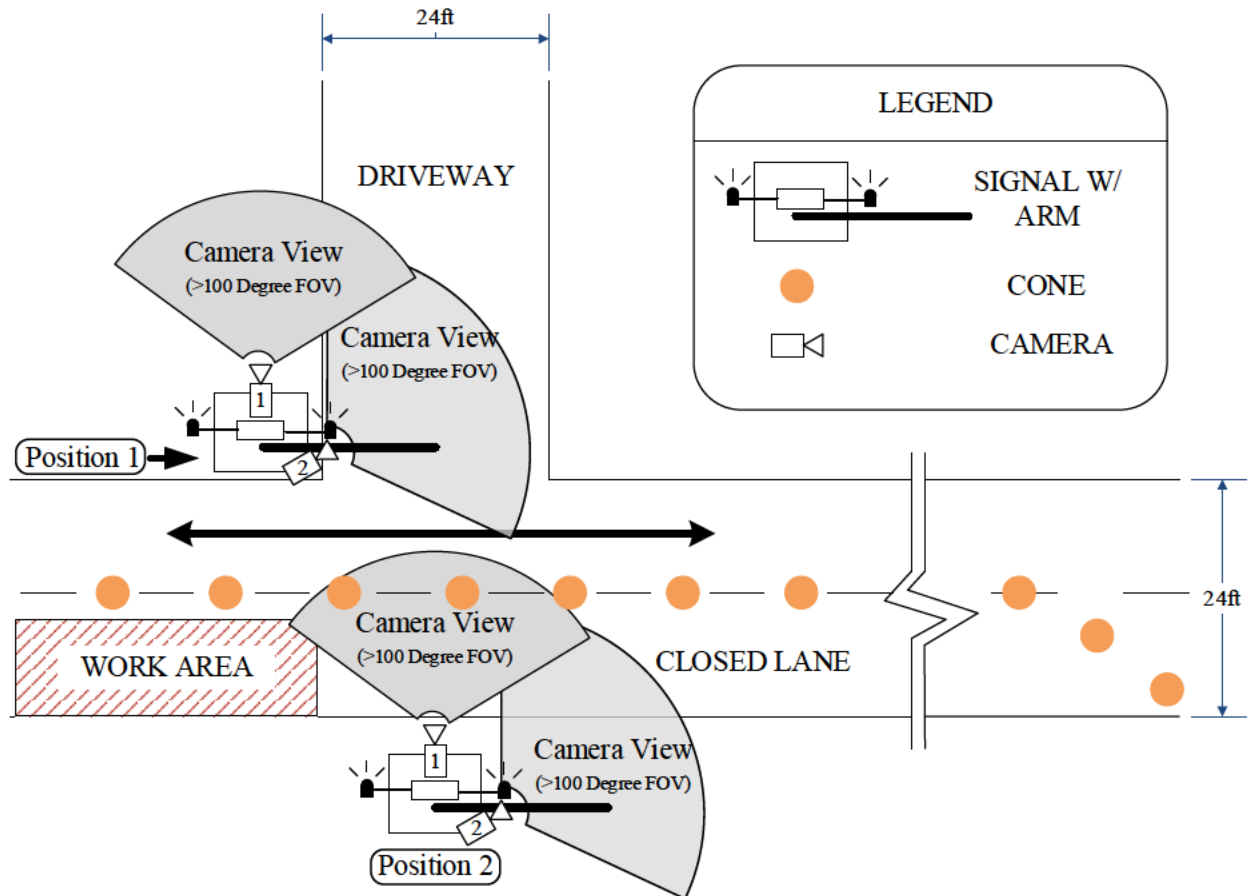


Figure 5.1 Proposed Combined System in Two Positions

It is anticipated that the combination of the two systems will supplement each other. The gate arm is an active system that tries to increase driver compliance by actively blocking vehicles. The intrusion detection system is a passive system that is intended to mitigate the effects of a vehicle violating the direction of the TCS. Development of the gate arm system is primarily a mechanical and electrical design effort. The intrusion detection system is primarily an electrical and software effort.

CHAPTER 6:

Procurement of a Commercial Product

This chapter contains a brief overview of the equipment acquired for testing along with some details about how it operates. The DAD made by STS was rented for testing, and it is noted that STS does not normally sell their equipment.

The Equipment

The signs used with the trailer during testing are shown in Figure 6.1. The signs are all 24 inches wide and the “STOP HERE ON RED” sign is a Caltrans standard R10-6 sign. The other two signs were custom made and intended to provide guidance to drivers who may not have seen this type of signal before. Versions of a “NO TURN ON RED” sign have been used on DADs before, and the “Yield” sign is very similar to what New Jersey has used [4]. The signs were selected after considering several variations as discussed in Appendix F. Questions were asked of the drivers if the selected signs or device were confusing as well as if they had suggestions for re-wording any of the signs.



Figure 6.1 Stop Here on Red Sign (left), Yield, and No Turn Signs (right)

The trailer has a small programmable changeable message sign (CMS) board attached that can be used to provide information to drivers. The built in

CMS can be programmed to display different messages, but to change the message displayed, a service center must be called. Figure 6.2 shows the DAD made by STS with a right turn allowed signal. Note that the CMS shown displaying “wait time” was not used during testing.

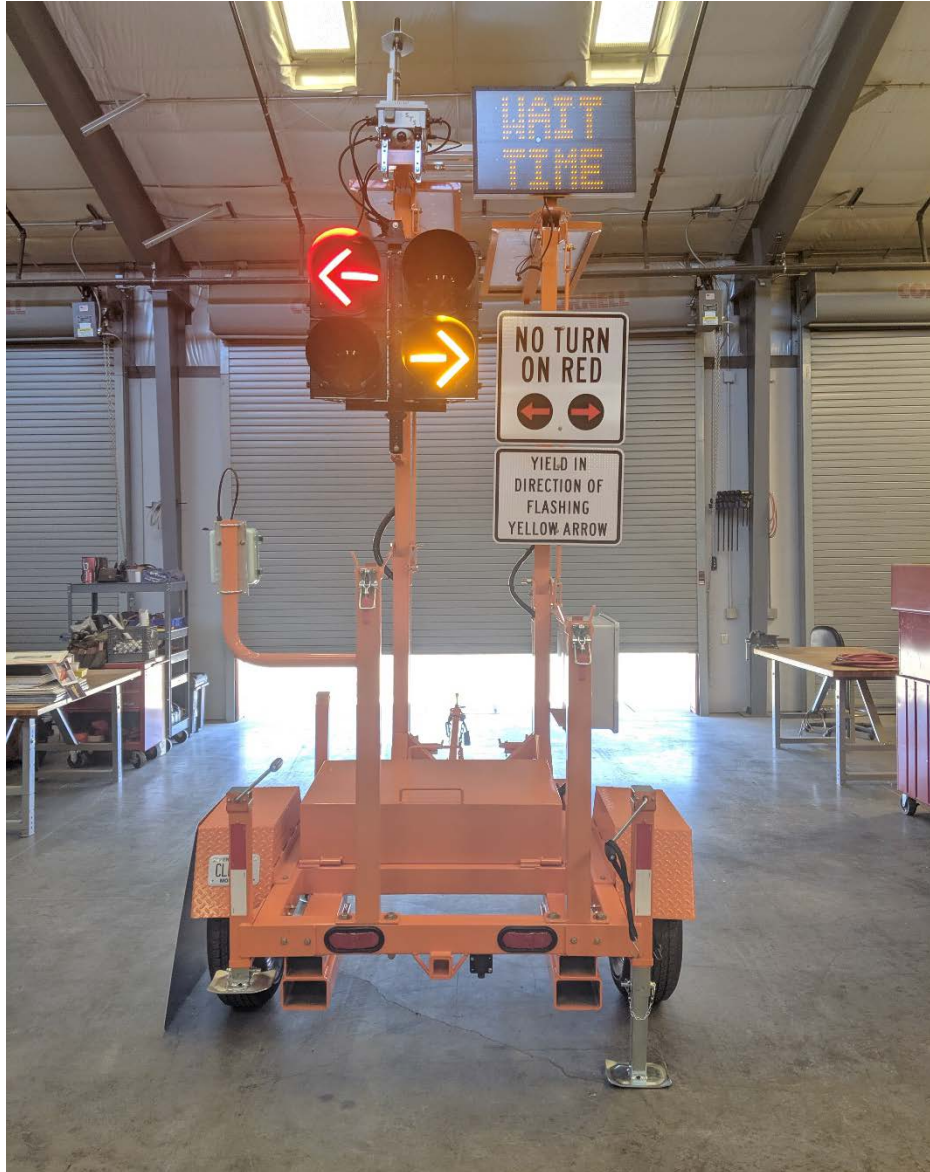


Figure 6.2 STS Signal Setup and Operating

A view of the STS equipment setup and operation at an intersection is shown in Figure 6.3. This view was taken from approximately 50 feet from the DAD with the arrow lights showing red in both directions, indicating a vehicle should stop. In the testing described in Chapter 8, a “STOP HERE” sign was placed approximately 30 ft. in front of the signal. It is noted that because there are

hoods on the signal lights, stopping too close will make it difficult or impossible to see the lights, depending on how the DAD is oriented.



Figure 6.3 Typical Driver View from Approximately 50 ft.

The trailer is designed to be towed and placed into position in the field. There are four jacks to provide stabilization. Once the jacks are in place, there are two towers that tilt into position. Both towers have solar panels on the top that can charge the batteries or run the signal if there is enough sunlight. There are two cameras on the trailer as well. One camera is mounted near the top of one of the towers and gives a view of approaching traffic. This camera records data in the cloud and can be viewed remotely over the internet if the trailer is placed in a location that has data available. To give an idea of the scale of the trailer, it is shown next to a full-size SUV in Figure 6.4.



Figure 6.4 View of STS equipment with Towing SUV

The DAD made by STS can be controlled by a PTS in use on the main roadway or by a human flagger using either a handheld remote or via a web-based “virtual remote.” A view of the handheld remote in a protective cover is shown in Figure 6.5. The action of each button on the remote control can be customized by contacting STS. When a button is pressed and held, the remote vibrates. Testing revealed that the signal works best by pressing the buttons and waiting until the vibration is felt.



Figure 6.5 Handheld Remote

Remote Monitoring and Controlling

If the DAD made by STS is used in a location where wireless data is available, a website-type interface can be used to access the system remotely. Once a user logs into the system, there are several options. Three of these options will be discussed here:

- Virtual Remote
- Location
- Real-Time Status

The real-time status section allows the user to check the current state of the lights, battery voltages, temperatures, power consumption, and the camera view. There is also an indicator showing when a vehicle is detected (vehicle detection can use the on-board camera or the radar system). Some items, such as the battery voltage, have a graph showing trends over time.

The Virtual Remote operates like the physical handheld remote. The buttons can be customized by contacting STS. Our configuration had four options: stop, off, flash left, and flash right. When a button is pressed, an indicator will acknowledge the command. If the user is watching the Real-Time Status page

while using the virtual remote, they can see the current state of the lights change to match the command (after some period of lag).

The Location option uses the DAD's onboard GPS system to report its current location. Then an aerial view is shown with the current location of the trailer marked.

A view of the Real-Time Status page open in one browser window with the virtual remote in a second browser window is shown in Figure 6.6. As discussed, the current state of the lights can be seen along with the system logs as well as other information such as temperatures, voltages, and camera view.

The image shows two browser windows. The main window displays the 'Real-Time Status' page for 'CA - UC Davis - DMU Research Project'. It features a control panel on the left with 'Flash Left Arrow' and 'Flash Right Arrow' buttons, each showing a 90% battery level and 0.0W power. A central area shows a live camera feed from 'LTC53-Cam1' at '2020/06/04 18:47:33'. To the right of the camera feed is a table of system metrics for 'LTC53 (E)'. Below the camera feed is a 'System Log' showing various status messages. A secondary window titled 'STS Remote Control' is open on the right, showing a table of buttons and their functions, including 'STOP', 'OFF', 'Flash Left', and 'Flash Right'.

Name	LTC53 (E)		
Volt	13.0V	8.7V	
Links	Internal 100		
Temp	138.6 F	94.4 F	91.0 F
Power	Cam1	Cam2	Fan
Counts	Std: 888	47	27
	Left: 0	0	0
GPS	Fix, Drift: Unknown MCU Range: 1 m		
Speed	Cur: 0 MPH, Thresh: 15 MPH Radar Sensitivity: 50%, Lockout: 5		

Button	Function
STOP	All Signals Red
OFF	All Signal Off
Flash Left	Flash Left Arrow
Flash Right	Flash Right Arrow

System Log

- [2020-06-04 18:46:04 PDT] Starting All Lamps Off Mode
- [2020-06-04 18:45:34 PDT] Starting 1-Way Mode for Phase 1
- [2020-03-16 14:52:51 PDT] Starting All Off Mode
- [2020-03-16 14:52:43 PDT] handleHandheldCmd: Starting All Stop Mode
- [2020-03-16 14:52:20 PDT] One Way Phase 2

Figure 6.6 Remote Monitoring Example

CHAPTER 7:

Development of the Test Protocol

The test protocol was modified in several rounds improve the overall testing and re-approved by the IRB. The last modification was to address the usage of the Changeable Message Sign (CMS) and to agree on a wording for the CMS. An edited and formatted version of the most recent protocol is included in Appendix G. Some considerations about its development are discussed in this chapter.

Access Point

The length of the low volume access point road or driveway could vary greatly depending on the real-world application. For this testing, it was decided that the access point should be long enough to support the use of an optional early warning sign. The two optional early warning signs are shown in Figure 4.1 as Sign #1 and Sign #2. From the CAMUTCD (Section 2C.05) a roadway with a speed limit of 25 mph (not in heavy traffic) should have a warning sign placed 100 ft. before the signal (Sign #2). The CAMUTCD specification may not exactly match the intended application since this equipment may be used even for short driveways. However, to accommodate the optional sign during testing, a roadway length of at least 200 ft. was needed. To limit a test driver's ability to see the DAD in operation before the test started, a staging area was also included.

Cameras

Rather than use three cameras as originally planned, two cameras were used as shown in the updated test plan image in Chapter 4. In order to protect the identity of the test drivers at the direction of the IRB, the cameras were positioned such that the test drivers would not be readily in their view. Camera 1 was used to capture the rear of the vehicle as well as the state of the DAD. Camera 2 captured the side of the vehicle roughly across from the intended stop location. This camera was adjusted to capture the lower portion of the car from roughly the base of the windows down.

Changeable Message Sign

After the first two rounds of testing (more details will be given in Chapter 8), it was decided that future testing should also include the use of the CMS. Consulting with project panel, it was decided the CMS should display "XX min

delay" where XX is an appropriate length of time in minutes. The changeable message sign can also be actuated by the presence of a vehicle (i.e. light up when a vehicle is detected).

Driver Questions

To help make recommendations regarding improvement of the equipment's efficacy, test drivers were asked a series of questions. The questions took the shape of an anonymous questionnaire that was filled out immediately after encountering the DAD in the testing. The questions and the information synthesized from the questions will be discussed in Chapter 9. An updated version of the questions with additional test driver demographics that is recommended to be used in future testing is also included in Appendix H.

IRB Exemption

Since this testing involved human subjects, it had to be reviewed and approved by the IRB. This is UC Davis policy. Some of the items reviewed included the test protocol (inclusion and exclusion criteria, questions asked, safety, risks, general procedures, protections of personal information, etc.) as well as the consent documents and wording of public facing signs. As part of the inclusion/exclusion criteria, this testing could only accept licensed test drivers who could safely operate a motor vehicle and could not include protected groups, specifically individuals unable to consent, those who were under 18, pregnant women, and prisoners. Ultimately, this study was found to be exempt research in accordance with IRB regulations as long as it was conducted as described in the documents submitted.

CHAPTER 8:

Testing of a Commercial Product in a Closed Facility

Testing Location

As per the test plan and the test protocol, the simulated work zone had a “T” type of intersection. The work zone was setup as described in the test plan and the test protocol. If there was a discrepancy between plan and protocol, the protocol was used. The first two tests were conducted with the DAD near the corner of the intersection (Test Location #1 from the test plan in Chapter 4). An annotated aerial image of the actual test location is shown in Figure 8.1.

As discussed in the test plan, the intersection was designed such that vehicles approaching the intended stop line did not have a clear view of the work zone or its end points. To make the intersection blind to the test drivers (i.e., they would not be able to easily see the endpoints) a combination of work zone length, fencing, and parked vehicles was used. A view from a vehicle approaching the signal while showing an all red indication is shown in Figure 8.2.

While test vehicles were being operated by the volunteer test drivers, the test location was closed to vehicle access (other than those that were part of the test). Human flaggers were stationed at all the access points to ensure no vehicles or pedestrians entered testing location. The roads used were generally packed gravel, which is not significantly different than what may be encountered in a real work zone.



Figure 8.1 Test Site Setup

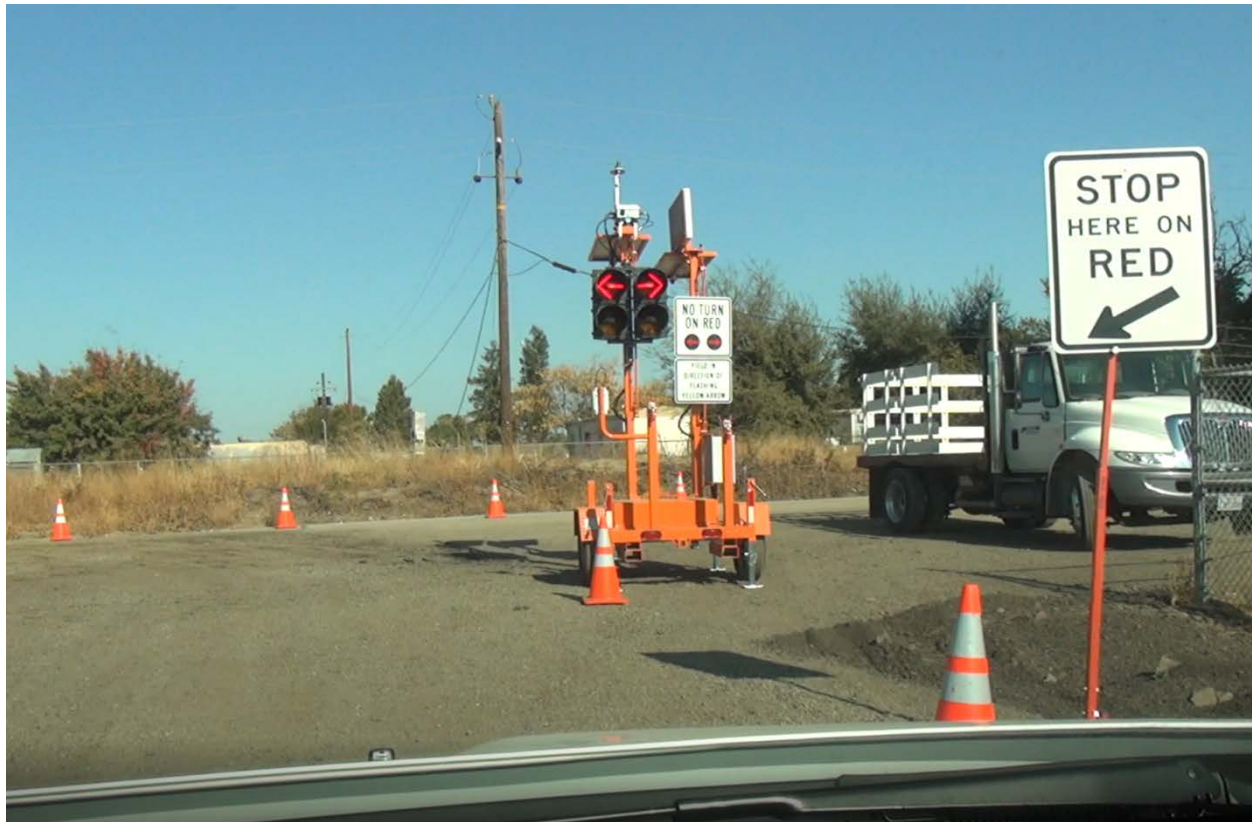


Figure 8.2 View of Test Setup at the Intersection

Compliance Metric

As discussed in the test plan, one key metric is compliance with California Vehicle Code (CVC) section 21453(c). This code deals specifically with arrow signals and states that, “A driver... shall stop at a clearly marked limit line, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection...” [64]. The setup of test included a sign that said, “STOP HERE ON RED”; however, this only provided guidance to drivers, but it was not a “limit line” as defined in CVC 377 (i.e., a white line at least 12 inches wide), nor was a crosswalk. As such it was decided that the appropriate metric to use for later analysis of the data (Chapter 9) would be to count as non-compliant any vehicle that entered the intersection while the signal prohibited this move. In other words, if a vehicle was judged to have entered the intersection (based on review of the videos), it was counted as non-compliant, and a vehicle that rolled forward beyond the “STOP HERE ON RED” sign, but did not enter the intersection, was not counted.

Compliance Testing

Testing was preformed using volunteer test drivers who were recruited via advertising at UC Davis campus in accordance with the approved IRB protocols. Testing was conducted in two rounds in November 2019 and January 2020. It was not possible to conduct testing in December due to the IRB protocol needing to be updated and the holidays making recruitment of test volunteers difficult.

As discussed, the DAD made by STS that was tested in this work can be controlled by a PTS or by a human flagger. For the testing completed in this work, the DAD was operated by a human acting as a flagger. In the November 2019 testing, one of the researchers operated the DAD while also operating as a flagger at one endpoint. In the January 2020 testing, the DAD was operated by a Caltrans employee whose only task was to perform the operation. The first test group was instructed “at the intersection make a left turn” while the second test group was instructed “at the intersection your intended destination is to the left” (the wording was changed based on recommendation by the project panel). In all cases, the vehicle was shown a red signal as they approached, and the signal stayed red for approximately two minutes after they stopped. After approximately two minutes, the signal changed to allow a left turn movement. Figure 8.3 shows a view with a Caltrans vehicle containing the operator off the edge of the roadway with the DAD in the background. The operator in Figure 8.3 is controlling the DAD using the handheld remote.



Figure 8.3 View of Test Setup with Caltrans Operator in Foreground

The vehicle driven for the test was provided to the volunteer test drivers by the researchers. For both test groups, a Chevrolet Volt was used. The car was rented "just-as" with no modifications made for the testing. The volunteer test drivers were alone as they drove through the work zone, and there was no data collection from the car. Test drivers adjusted the mirrors and the seat however they felt best for their driving style.

CHAPTER 9:

Test Results and Cost Analysis

The equipment was tested as discussed in Chapter 8. The data collected is analyzed in this chapter to ascertain the performance of the equipment as well as to make recommendations for potential improvements. The sample size of the testing is relatively small, but some interesting trends were uncovered, and modifications were made to the test plan and protocol to support more testing in the future.

Data Extraction

Data from the videos was extracted by manually viewing the video recordings. As discussed previously, two cameras were used such that a view was available from the back of the vehicle as well as the side near where the vehicle was intended to stop. In some cases, the vehicles may have stopped beyond the field of view of the side camera; however, the back camera could still be used. To aid in the data analysis, the two camera views were synchronized on specific motion. This eliminated the need for an accurate time stamp in the video. The video data was used to judge compliance as well as to check stopped position of the vehicles. Rather than extract the approximate distance from the “STOP HERE ON RED” sign to the vehicles initial stopping point, the vehicles were just checked to make sure they did stop in the vicinity of the “STOP HERE ON RED” sign.

Data from the survey given to the volunteer test drivers was summarized/paraphrased and results were analyzed using the well-known process of thematic analysis [65]. The responses were read for each question, and the themes were extracted. Generalized comments related to some of the questions were also considered as a method for explaining the results. As per IRB rules, the driver’s identities must be protected. As such the all exact comments collected during the survey are not included in the report.

Compliance Results

The first round of testing happened in November 2019 when six test drivers were able attend testing on the same day. One of the six test drivers entered the intersection and made her/his turn while the signal was still showing a red. All the test drivers initially stopped near the “STOP HERE ON RED” sign. The initial stop suggests that the signal was conspicuous enough to make people notice it and

act. Several of the test drivers did roll forward after stopping, suggesting they were anxious about how long they needed to wait.

The second round of testing happened in January 2020 when five test drivers were able to volunteer for testing. All of the five test drivers initially stopped near the "STOP HERE ON RED" sign. One test driver went through the signal while it was still red after waiting for a while. This test driver also made a right turn instead of a left as directed. Several test drivers stopped and then rolled forward a short distance. Two noteworthy reactions included a test driver who moved forward then backed up, and a different test driver who slowly rolled forward nearly a full car length, but did not make the turn before the signal changed.

The main difference between Test #1 and Test #2 was that Test #1 included a standard early warning sign displayed 100 ft. before the DAD. An example of the early warning sign is shown in Figure 9.1. In both tests, the CMS sign on the trailer was not used. As discussed previously, for both tests, only test drivers who made the turn onto the crossroad while the signal was red were counted as running the red light (regardless of if they stopped first or not). The results of the testing are shown in Table 9.1. The compliance observed (with and without the early warning sign) was compared using the statistical test known as Fisher's Exact Test [66]. For this dataset, no statistical evidence was found to show that compliance depended on the existence of early warning sign. The lack of statistical evidence does not mean the warning sign will never make a difference, and results may change with a larger sample size. More details about the statistical test are given in Appendix I. Considering that all drivers initially stopped when no turn was allowed (i.e. red arrows), and that there was no statistical evidence of a difference between the tests, the early warning sign may not be required.



Figure 9.1 Standard Early Warning Sign (CA MUTCD W3-4)

Table 9.1 Summary Contingency Table Showing All Results of Driver Testing

	With Early Warning Sign	Without Early Warning Sign
Compliant	5	4

	With Early Warning Sign	Without Early Warning Sign
(Waited for Signal)		
Non-Compliant (Ran Red Light)	1	1

Survey Responses

The survey responses from both test groups were summarized/paraphrased, then thematic coding was applied and the results were aggregated. Thematic coding involves reading each response and categorizing it based on common themes. In some cases, the main theme is positive while there are still some issues raised. More details about the responses and suggestions based on the test data are discussed in the next section. The questions asked, the themes, and their counts are all displayed in Figure 9.2 and Figure 9.3. For purposes of this analysis, questions four and 11-13 are not plotted as they capture helpful information but do not directly measure performance.

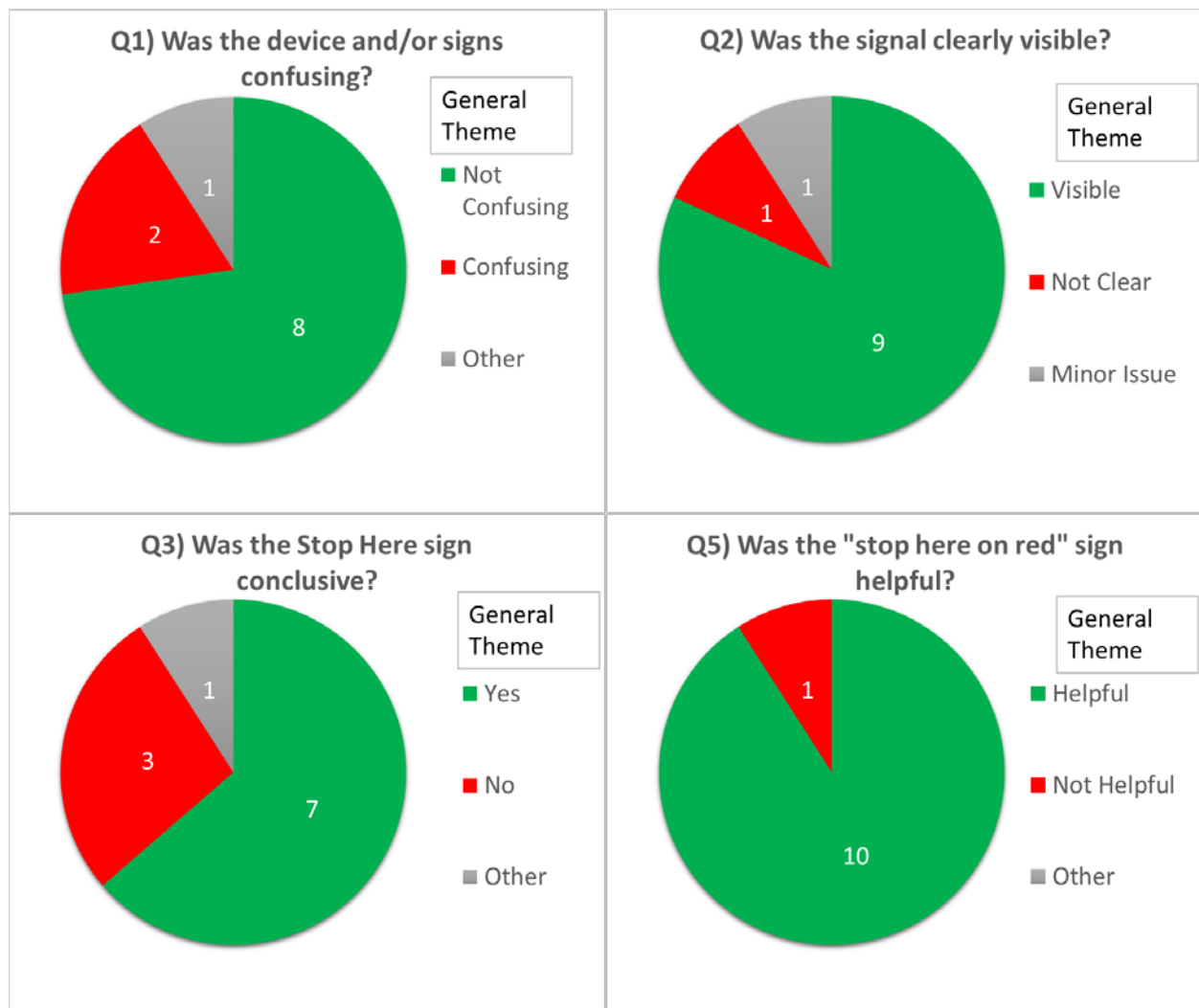


Figure 9.2 Results of Theme Analysis Applied to Survey Questions Part 1

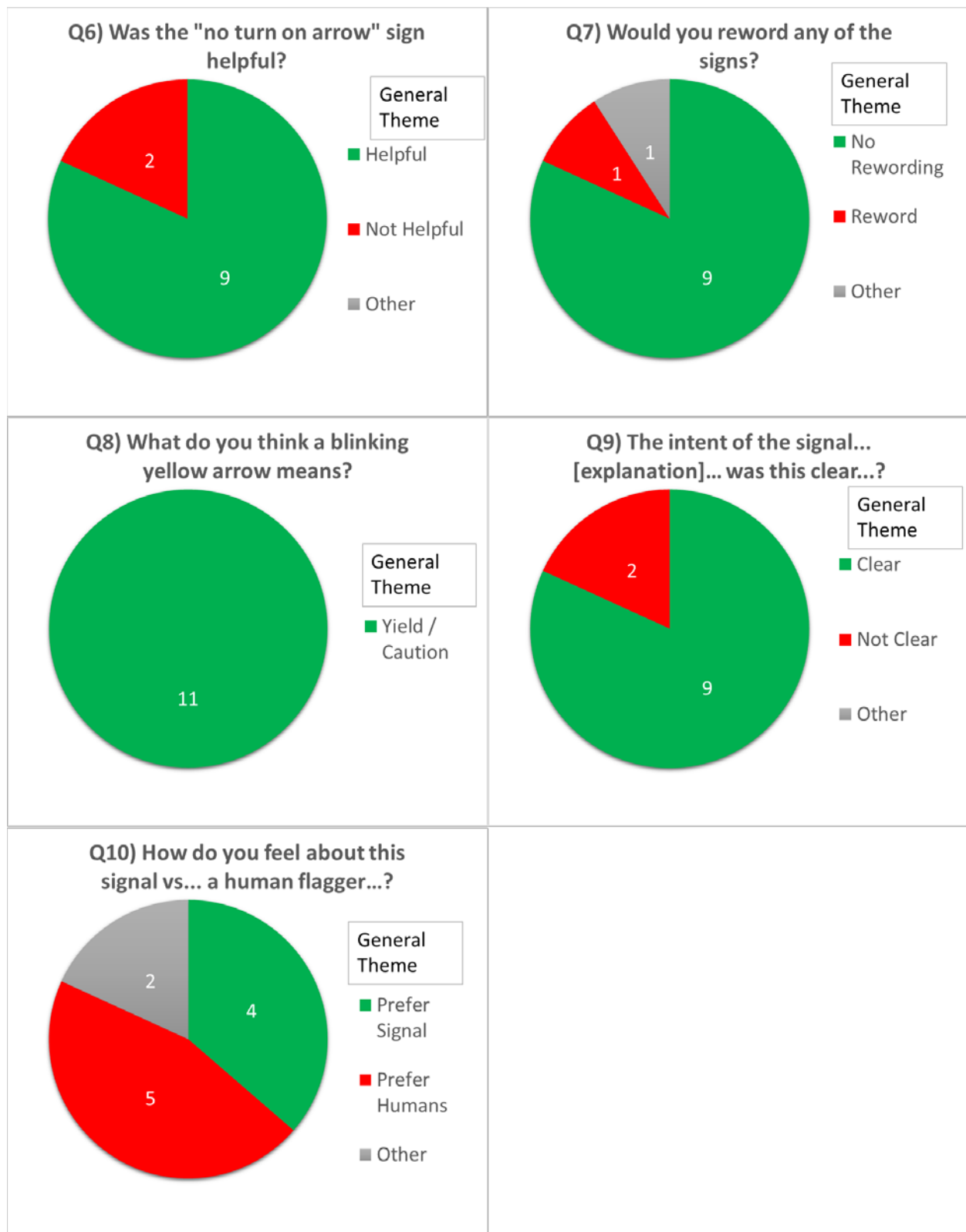


Figure 9.3 Results of Theme Analysis Applied to Survey Questions Part 2

Question 4, which was not included in Figure 9.3, revealed that two of the test drivers had previously seen a signal used in a manner similar to the DAD signal used in this test.

Discussion and Suggested Modifications

From observations of the test drivers' behavior (i.e. rolling forward after stopping, moving forward then backing up, etc.), it seemed that the test drivers were anxious about stopping at the signal for an unknown amount of time without clear indication that the signal was working or had recognized their presence. To generate recommendations for improving performance, the survey response themes (discussed above), combined with the paraphrased/summarized survey comments (Appendix J), are used. Some of the responses and questions will be discussed here, others can be seen in Appendix J. The questions are the same that were included in Figure 9.2 and Figure 9.3. It is noted that some comments reoccur in multiple questions. This does not necessarily mean multiple people had the same issue. It could be one individual providing the same or similar comment to multiple questions.

Question one asked, "Was the device and/or signs confusing?" Four of those who indicated no confusion had issues with the wait time. One participant indicated confusion after waiting so long and one was confused where to stop (with the stop line being far from the signal). Based on this, it seems an indication of some sort to inform drivers of approximate wait times would be helpful. This could be achieved with the STS's onboard CMS sign.

Question two asked, "Was the signal clearly visible?" Many responses had no visibility problems. The lack of issues reported seems to support the observation that every vehicle did initially stop. Some said it was visible but there were still issues including that there were too many signs, and that there was some glare. One comment noted that the no turn on red sign was not very visible. As will be seen in question three, removing the early warning sign may help with this issue.

Question three asked, "Was the Stop Here sign conclusive?" This question had the second most negative responses. The main issues reported were that the "stop here" sign was easy to overlook, there were redundant signs, confusing because a worker was seen holding a slow sign (possibly referring to the person with the stop/slow paddle closing the road behind the driver), and too far from the signal. Some were also generally positive but noted they were unsure if they were detected or unsure exactly where to stop. The first three issues/comments may be addressed by reducing the number of visible signs. One potential sign that may be considered for removal is the early warning sign since it did not seem to influence compliance (discussed previously). It may also be possible to move the early warning sign further from the DAD. Either of these cases should be tested for effect before implemented as standard. In a normal work zone, it is not expected that a human flagger would be visible, so this issue

is not addressed. It is anticipated that by having fewer signs it may be clear where to stop and the issue of vehicle detection will be addressed later.

Question 5 asked, "Was the 'stop here on red' sign helpful?" Question 6 asked, "Was the 'no turn on arrow' sign helpful?" For question five, there was one indication that the sign was unneeded, and one response that was ok with the sign but that indicated a desire for a stop line. For Question six, two participants indicated the red arrows were enough on their own and as such the sign was not needed. From these responses it seems that these two questions did not generate any significant changes needed.

Question seven asked, "Would you reword any of the signs (explain)?" Most comments indicated no rewording was required. One comment indicated that no rewording was needed, but that something about wait time would be helpful, another said no rewording was needed but that the stop here sign could be more prominent, and one noted the yield in direction of yellow sign took a little time to understand. Based on these responses it seems that the signs closest to the equipment are acceptable. A solution that would cover the wait time comment was already identified in question one.

Question eight asked, "What do you think a blinking yellow arrow means?" Question nine asked, "The intent of the signal is to tell you which direction you are allowed to turn. The idea is that you can turn only in the direction that the yellow arrow is blinking or solid. You must stop and wait for any direction that shows a red arrow. Was this clear to you when you saw the signal?" All individuals surveyed understood the meaning of the blinking yellow light. For question nine, the issues reported included that one person did not see the light change so decided to go after some time, and one person did not think the signal was part of the test. From these comments, it seems that adding a wait time indication may be helpful (like question one).

Question ten asked, "How do you feel about this signal vs having a human flagger provide directions?" This question got the most mixed responses. It seemed that people generally prefer human interaction. However, even some who preferred humans said the signal would also be acceptable or could be more practical in the long run. It is anticipated that with time and exposure to DADs or similar type systems, individuals' preferences may change.

As a step toward addressing the issues discussed, modifications to the testing protocol were developed. It was decided to use the DAD's onboard CMS to display wait times with the wording "XX Min Delay", where XX is the correct time in minutes. Furthermore, there is an option to make CMS actuated by the presence of a vehicle approaching the DAD (i.e. make the CMS light up when a vehicle approaches). The STS equipment programming was updated and the main controller replaced to incorporate these features. Approval from the IRB was granted for these modifications and equipment was upgraded by mid-

March 2020. Unfortunately, testing of the new upgrades and protocol could not be conducted due to shelter in place requirements of the COVID-19 pandemic.

More details of potential future testing with the CMS sign will be presented in the Future Work section of Chapter 10. It is anticipated that eliminating or moving the optional early warning sign, providing a wait time indication, and using the optional vehicle actuation on the CMS will increase the amount of positive survey responses. This hypothesis needs to be tested.

Operational Considerations

Several practical operational considerations beyond compliance were tested. Setup time, setup complexity, runtime, and operating range were considered.

Setup Time and Effort

The setup time for the DAD was considered to compare the system rented against a human flagger who has relatively simple setup. After familiarization and use of the equipment, its setup time was measured. The trailer took approximately four minutes to connect to the towing vehicle and approximately seven minutes to position in the field and setup. The seven-minute setup time was obtained with two individuals present and included the time it takes to set the four stabilizing outriggers and tilt the two towers into position but did not include travel time. Setup with one individual should not be significantly slower. This time (especially the setup time) may change depending on conditions in the field and experience of the operator.

Setup complexity goes beyond time considerations and considers other items such as how difficult is the task, etc. The STS trailer has two main towers that tip into position once the jacks are placed. The tower with the signal head mounted to it takes significantly more force to tip into place than the other tower. Using a spring scale, the force required to tip the tower with the signal head into position was approximately 110 lbs. with a peak force of 125 lbs. Care should be taken when raising and lowering the towers into position.

Local Handheld Remote Control

The operating distance of the handheld remote control was tested in relatively flat conditions with minimal obstructions. The remote was found to still control the trailer at 1,500 ft. The signal at this point seemed like it was near its limit and no testing beyond this distance was tried. The test location near AHMCT is shown in Figure 9.4 with the red stars indicating the DAD location and the remote control with a distance of 1,500 ft. between. It is noted that the internet-based control of the signal can be used from a distance much further if internet service is available.



Figure 9.4 Remote Control Distance Test

Internet Remote Control

Remote monitoring and controlling capability (as discussed in Chapter 6) was tested using an iPad Pro 10.5 as well as a laptop PC running Windows 10. Both systems could access and control the signal without any issues. The DAD was commanded to change the state of the lights via the internet remote control while watching the real-time dashboard state and the camera. The distance between the operator and the DAD was approximately 19 straight line miles. There was lag time observed from the perspective of the operator/flagger. In the operator's perspective, the time it took from pressing the flash left button until the dashboard indicated a change in the status of the lights was about 17 seconds.

Runtime

The runtime of the signal can vary depending on the amount of sun available for the solar panels to charge the batteries. After the signal was initially delivered, it was kept at an indoor storage location with some natural sunlight from overhead skylights. The system was left running with main controller, cameras, radios, and internet abilities always on; the signal lights were in various states (blinking, solid on, and off). The system ran for approximately 34 days. At the 34-day mark, the system was still running but the battery voltage was low and needed to be recharged. This type of scenario is very unlikely, and in real usage conditions (outside with the sun), it is anticipated that the system should have a longer runtime.

Cost Analysis

Flagging in a construction work zone exposes employees to traffic hazards. There have been 40.9 deaths for every 100 thousand full time equivalent persons working as flaggers or crossing guards; a rate 40 times higher than the average for all road construction jobs [67]. The Occupational Safety and Health Administration (OSHA) was searched with the keyword “flagger” to find deaths reported from January 2017 through 2019 [68], results tabulated showed that flaggers have been killed while on the job in work zones in many parts of the USA: Arkansas, Vermont, Indiana, Oregon, Colorado, Illinois, Iowa, Pennsylvania, and Maryland. The total number of flaggers killed in collisions that involved the general public was 11. References for the individual fatalities tabulated are included in Appendix K. Note that these represent all flagging operations and do not differentiate between government employees and private contractors. The most recent fatality for CA that was found in the OSHA database was in 2015 in Ventura where a flagger was killed².

Beyond pure economics, the loss of life while on the job in a hazardous occupation can be devastating to families, coworkers, and friends. Caltrans has adopted a “Toward Zero Deaths” goal to improve safety for employees and the travelling public, which is reflected in research efforts to improve work zone safety. To direct limited resources to where the most value (i.e., safety) is returned, an analysis must be conducted using established parameters and values. The results of the analysis help drive appropriate decision-making. To quantify the economic part of the loss, the Value of a Statistical Life (VSL) methodology as reported by the US DOT from 2016 is used. For 2016, the US DOT reported the VSL as \$9.6 Million (using 2015 as the base year) and noted that this

² [OSHA Last CA Flagger Fatality](https://www.osha.gov/pls/imis/establishment.inspection_detail?id=1103168.015)
(https://www.osha.gov/pls/imis/establishment.inspection_detail?id=1103168.015)

number must be revised when using it in the future years. The revision is done by using an equation which accounts for inflation and real income [69].

$$VSL_t = VSL_0 \frac{P_t}{P_0} \left(\frac{I_t}{I_0} \right)^\varepsilon \quad \text{Equation 2}$$

In Equation 2 subscript (0) indicates values for the base year and subscript (t) indicates values for the updated year. The price index (P_t) comes from the Consumer Price Index for All Urban Consumers Current Series (CPI). The real income (I_t) comes from the Median Usual Weekly Earnings (MUWE) in unadjusted (1982-84) dollars. The income elasticity of the VSL (ε) is taken as 1 [69].

The relevant values needed to update the VSL are given in Table 9.2 using 2016 as the base year. Based on these numbers, the VSL for the first quarter of 2020 is \$11.0 Million. Using the 11 flagger fatalities discussed previously, the purely economic value of the loss was \$121 million dollars (in VSL 2020 dollars). Assuming the fatality rate is average over the 36 months considered, this is approximately a \$3.4 million-dollar loss per month. As mentioned, this economic value does not consider externalities beyond pure economics suffered by family, friends, and coworkers.

Table 9.2 Values to Calculate VSL 2020 and Result

Metric	Value 2016	Value 2020	% Change
Price Index (P) from CPI-U	240.007 [70] (2016 Average)	258.255 [70] (Q1 2020 Average)	7.6%
Real Income (I) from MUWE	\$347 [71] (2016 Average)	\$370 [71] (Q1 2020)	6.6%
VSL	\$9.6 Million [69]	\$11.0 Million	14.7%

In addition to the national data about flagger fatalities, CA data was considered where available. A dataset of 497,518 traffic collision report narratives from partway through 2015 to approximately mid-2018 was searched for incidents involving flaggers. Of these cases, 160 contained the keyword "flagger", and six of these (3.75%) included flaggers being hit or near misses. A summary of the six cases: two cases involved a flagger that was hit, one case involved a flaggers sign hitting a car while the car was being signaled to stop (some dispute about how this happened), and three cases were near misses. For the near misses, all involved a vehicle crash of some sort. In one near miss, the flagger ran for the shoulder, in the second, the vehicle slammed on the breaks to avoid the flagger, and in the last, the vehicle almost hit the flagger. This dataset only contained cases where a vehicle collision was involved and there may be many more cases of near misses or job-related injuries not

captured here. Quantifying the value of these incidents is difficult, and beyond the scope of this report.

A significant benefit of using equipment to control live traffic is that it generally allows operators to stay out of traffic lanes, thus removing the operator (or the flagger) from the dangers posed by working near active traffic. The equipment under test in this study is made by STS [7] and can be controlled locally via a remote or through the internet if a data connection is available. As such, this equipment can allow the flagger/operator to stay safely away from the active traffic lanes while operating it.

Other monetary considerations beyond safety also exist and can be both direct and indirect costs. The DAD under consideration can be controlled by a PTS on the main line where it is assumed to add no extra daily cost to operate, or it can be operated by a flagger. If a flagger is operating any equipment, labor expenses will be incurred. The number of personnel required to control the low volume access point using a DAD can vary depending on if it is operated by a PTS, an existing flagger on the main line, or by a dedicated operator. If a dedicated operator is used, there is no change in the number of personnel versus a human flagger. If a PTS or an existing flagger is used to control the DAD, then there is expected to be less personnel needed. The setup can be done like a light trailer or arrow board. The equipment is towed into the desired position, the stabilizers set, and the masts rotated into position. The setup can be done by one individual, but the effort to rotate the masts into position is rather high and care should be taken.

The expenses associated with controlling the traffic at the low volume access point vary depending on how the STS equipment is used. If the STS equipment is operated remotely by one of the flaggers already on the main line, the cost of operation may be reduced versus using dedicated personnel. Table 9.3 compares the costs for three cases at one low volume access point: a human flagger, a DAD under local control (i.e., a dedicated operator), and a DAD under remote control by an existing mainline flagger. The values shown in the table represent the estimated additional personnel, equipment, and costs per low volume access point beyond whatever already exists for the main line.

Table 9.3 Cost Comparison for Controlling a Low Volume Access Point

Additional Personnel, Equipment & Costs per Intersection	Case 1: Human Flagger	Case 2: DAD w/ Local Control (Dedicated Operator)	Case 3: DAD Remotely Controlled by Existing Flagger
Local Flaggers/Operators	1	1	0
Communication Radio's	1	1	0

Additional Personnel, Equipment & Costs per Intersection	Case 1: Human Flagger	Case 2: DAD w/ Local Control (Dedicated Operator)	Case 3: DAD Remotely Controlled by Existing Flagger
Stop Paddle	1	0	0
Safety Equipment Set (vest/hat/glasses/etc.)	1	1	0
Flagger Daily Cost	\$452.56 (\$56.57/hour) [72]	\$452.56 (\$56.57/hour) [72]	\$0
Estimated DAD Equipment Rental Cost	\$0	\$600- \$1,500/month ³	\$600- \$1,500/month ³
Assumed Setup/Takedown Costs	\$0	\$135.20 ⁴	\$135.20 ⁴

As seen in Table 9.3, the primary cost difference is the equipment rental rate and the human flagger daily cost. For Case 3, it is assumed that when the equipment is operated by an existing human flagger, none of the flaggers cost is allocated to the low volume intersection. Other differences between cases may exist that are not shown in the table such as shade structures for flaggers, additional traffic cones, etc.

To compare the typically anticipated operating costs, a theoretical scenario is considered. The equipment is assumed to be rented for one month with a 50% utilization (i.e., two weeks of use). Of the two weeks used, it is assumed that the job is active five days a week for a total of 10 working days). Furthermore, it is assumed that two jobs are completed, meaning the setup/takedown fee is incurred twice. The rental price is taken as the median value (i.e., \$1,050). Under these assumptions, the three cases referenced in Table 9.3 are compared. The results of the comparison are shown in Figure 9.5, and the DAD being remotely controlled is the cheapest option. It is noted that this comparison considers only the operating cost and ignores any costs associated with risks (injury and/or death).

³ As per personal communication with STS, rent depends on quantity, duration, location, etc.

⁴ Setup cost for DAD assumed same as setup cost for light tower in 2018 dollars [73].

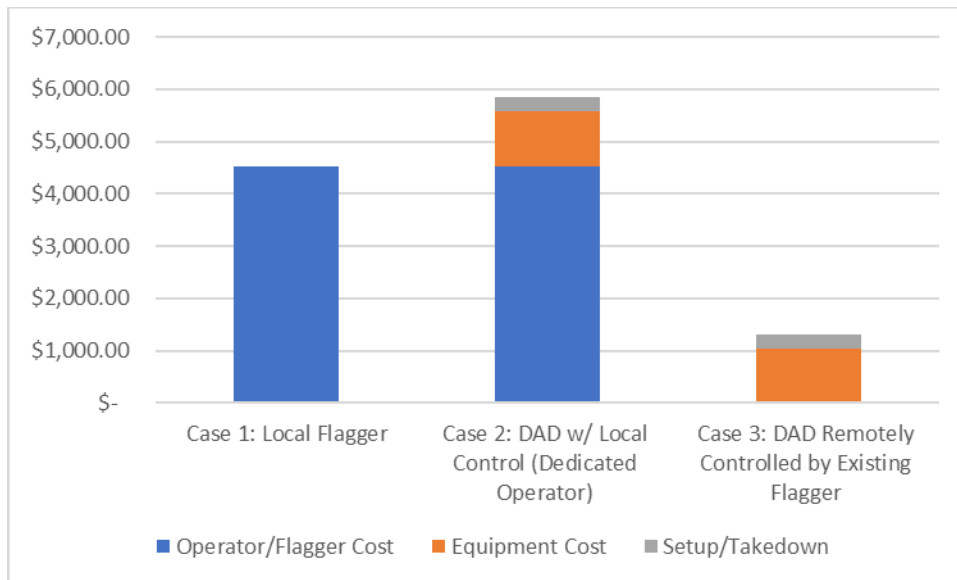


Figure 9.5 Control Cost Comparison for Three Cases on a Monthly Basis

CHAPTER 10:

Conclusions and Future Research

This report covered Phase One and Phase Two of the Managing Low Volume Access Points in Work Zones research study. The focus was considering possible Traffic Control Systems for controlling low volume access points, selecting a commercial system for testing, and testing the commercial system.

This research study was broken down into 11 separate tasks generally described as:

- Forming a project panel and general project management (Task 1)
- Comprehensive literature review of existing TCS (Task 2)
- Distillation and presentation of the available TCS, synthesis of concepts, comparison of the most relevant commercial systems, and selection of commercial TCS for testing (Task 3)
- Development of a test plan for the selected TCS (Task 4)
- Proposal for research to develop a concept for new equipment (Task 5)
- Research documentation for Phase 1 (Task 6)
- Procurement of equipment (Task 7)
- Development of a test protocol (Task 8)
- Testing of equipment (Task 9)
- Analyzing results and costs (Task 10)
- Generating the final report for both phases (Task 11)

The comprehensive literature review from Task 2 was undertaken to see what TCS may be applicable to the stated problem. The literature and systems considered covered items used in the USA as well as items used in other countries and conceptual ideas that have been made public. As part of Task 3, the results of the literature search were considered, and commercial equipment was selected for further evaluation. New concepts were also presented as well as potential modifications that would be made to existing systems. A test plan was generated in Task 4 for the commercial equipment, and Task 5 created a proposal for research to develop a new system. The proposal included a gate arm modification to an existing system and an intrusion detection system based on machine vision. Tasks 7-9 were to procure the commercial equipment to test, develop the test protocol, and test the equipment. The protocol was reviewed

by the UC Davis IRB, and the research was determined to be exempt as long as conducted as described when reviewed. The equipment was rented from STS for testing, and testing was conducted using volunteer test drivers. The tests were conducted on the UC Davis campus in two groups. As part of Task 10, the test data was analyzed, and costs were considered. For costs, it was determined that labor is a significant part of the expense. Using equipment to control the traffic at the low volume access point could be cheaper or more expensive than a human flagger depending on labor costs and allocation of expenses.

Discussion

Tests of the equipment rented from STS showed that its function as a traffic control device was generally understood by the test drivers and they were mostly able to follow the DAD's indications in a safe manner consistent with the desired actions. There seemed to be some signs of driver anxiety related to the duration of wait as discussed in Chapter 9. A potential solution to these issues was generated, and IRB approval was received along with equipment upgrades. The proposed solution was to use the small CMS sign that is mounted to the DAD trailer in order to display the approximate wait time. The wording decided was "XX Min Delay" where XX would be filled in with an appropriate time in minutes. Work was also done with STS to make the CMS sign vehicle actuated so that it lights up when a vehicle approaches by using radar built into the STS driveway equipment. In this way, drivers would know that the DAD was operating and that there was a delay time. Unfortunately, research schedule limits did not allow testing of the proposed solution. Future testing, as described below, is recommended to test the CMS and to increase the sample size of the test. As also discussed in Chapter 9, a significant number of test drivers said they preferred a human flagger to a signal; although many of them also said a signal would be okay or perhaps more practical. It is anticipated that people would become familiar with signals over time and this preference may change.

Recommendations

The ability to control the equipment from a vehicle or other remote location without having a human flagger stand in a traffic lane is anticipated to increase safety. Most test drivers understood the intention of the signal. Possible driver anxiety about wait time was discovered, and the use of the CMS to alleviate possible driver anxiety about wait times should be considered. Testing based on the updated protocol (i.e., using the CMS sign) is recommended to confirm the driving public's understanding of the system and determine the optimal configuration for safety and efficiency.

Future Research

As discussed, modifications to the operating protocol of the STS equipment (i.e., using the CMS sign that is mounted to the trailer potentially with vehicle actuation) were suggested. To test the effect of this modified protocol, IRB approval was received. Future testing to see how this modified protocol affects the results is needed. Testing is also needed with the signal placed in the alternate position shown in the test plan (i.e., across the intersection). To conclude, the following items need more research:

- Testing with the CMS sign active to display the wait time (vehicle actuation optional but recommended).
- Testing of remote viewing and controlling capability in which the DAD is operated outside of the controller's direct line of sight.
- Testing with additional test drivers to broaden the statistical base.
- Testing with the DAD in the alternate position (i.e., across the intersection).
- Optionally conducting one or more of the above tests with a queue of test drivers rather than one. In this scenario, the front test driver would be waiting for a right turn, while the second test driver would be waiting for a left turn. The question to answer would be: what happens if the DAD shows a left turn but the front test driver (waiting for a right turn) does not go? Will the test driver waiting for the left turn try to drive around? A potential solution to this issue, assuming only one low volume access point, would be to clear the work zone main line and allow cars to make turns in both directions.
- Optionally conduct testing where drivers are told their destination is to the left, but when they approach the DAD a right arrow is shown.

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Appendix A:

Partial List of Vendors with Relevant Commercial Equipment

A partial list of possible vendors with commercially available equipment was created based on the recommendations of Table 3.1. For AFAD equipment with a gate arm there are several manufactures that have been identified as seen in Table A.1.

Table A.1 Commercially available equipment usable without modification

AFAD equipment with arm	AFAD equipment without arm	Driveway equipment
Intellistrobe [red/yellow] (www.intellistrobe.com)	ROSA (https://www.remoteperspectivesafetyattendant.com/)	Horizon DAD (http://horizonsignal.com/driveway-assistance-device/)
Autoflagger 76-x [stop/slow] and 54 [red/yellow] (www.autoflagger.com/)		JTI Traffic Sentinel Driveway Assistance Device (http://www.jtitraffic.com/our-products/portable-traffic-signals/sentinel-dad/)
RFC 2.4 [red/yellow] (www.northamericatrafic.com/flagging-devices/rcf-2-4/)		Superior Traffic Systems (STS) PEDESTAL (https://superiortrafficservices.com/our-devices/)
AF 100 [red/yellow] (www.noflaggers.com/index.html)		
Robo Flagger (http://www.securstop.com/index.html)		

Table A.2 identified other equipment that would be possible to use with modifications. There are several portable gate options, one of which is used for

highway maintenance in Australia, and one AFAD type device from Europe which may not match AFAD requirements in the USA.

Table A.2 Commercially available equipment usable if modified

AFAD without arm	Portable gates
RoboSign [European style] (https://starttraffic.uk/robosign-remote-control-stop-go)	Portaboom [used in Australia] (www.trafficaccess.com.au/portaboom)
	Battery Operated Barrier (https://batteryoperatedbarrier.com/)

Table A.3 contains a list of commercially available Changeable Message Signs (CMS). Based on the proposed CMS usage as seen in Table 3.1, the CMS must be able to be updated in real-time using an external source. To meet the real-time update requirement, these signs may need to be modified or specified to have specific options.

Table A.3 Commercially available changeable message signs

Brands
WANCO (https://www.wanco.com/products/variable-message-signs/)
Ver-Mac (https://www.ver-mac.com/en/products/series/serie/message-signs/1)
National Signal (www.nationalsignalinc.net/)
Addco (http://www.addco.com/Product/DH1000)
American Signal (http://amsig.com/products/full-size-portable-message-signs/)
Solar Tech (http://solartechnology.com/products/message-boards/)

Appendix B: Extended Comparison Matrix

Table B-1 contained in this appendix is the full comparison matrix of the commercial DAD type equipment found. A table similar to this was presented to the panel when making decisions about which equipment to test.

Table B.1 Commercial DAD Equipment Comparison

	JTI Traffic Sentinel Driveway Assistance Device (DAD) [2]	Horizon Signal Driveway Assistance Device (DAD) [1]	Superior Traffic Systems (STS) Driveway Management Signal (DMS) PEDESTAL [3]
System Operation	<p>The JTI Sentinel DAD is set up to work with their Portable Traffic Signal (PTS). The PTS can be set up for timed signal control or for sensor actuation control (video and radar).</p> <p>The Sentinel DAD is controlled by the PTS and has no sensors.</p> <p>The PTS also has a remote control so that the flagger can operate the signal if need be.</p> <p>Standalone DAD operation would require custom engineering and is not available at this time.</p>	<p>The Horizon DAD is set up to work with their Portable Traffic Signal (PTS). The PTS can be set up for timed signal control or for sensor actuation control (video and radar).</p> <p>The Horizon DAD is controlled by the PTS and has no sensors.</p> <p>The PTS also has a remote control so that a human flagger can operate the signal if need be.</p> <p>Standalone DAD operation would require custom engineering.</p>	<p>The STS Pedestal DAD is set up to work with the STS Portable Traffic Signal (PTS) or as a standalone unit.</p> <p>When paired with the PTS, the Pedestal DAD is controlled by the PTS. The PTS can be set up for timed signal control or sensor actuation (video and radar).</p> <p>For standalone operation, the Pedestal DAD uses sensors (video and radar) for control.</p> <p>The remote control has control of the PTS when paired with the Pedestal DAD. The remote control has control of the Pedestal DAD when it is</p>

	JTI Traffic Sentinel Driveway Assistance Device (DAD) [2]	Horizon Signal Driveway Assistance Device (DAD) [1]	Superior Traffic Systems (STS) Driveway Management Signal (DMS) PEDESTAL [3]
			operated in standalone mode.
All clear mode	Possible with custom engineering.	Possible with custom engineering and Caltrans approval.	This system can set the mainline to all red and allow driveway vehicles to proceed in either direction.
MUTCD Compliant	MUTCD has authorized studies on their device, but it is not MUTCD approved.	In the process of getting MUTCD approval.	Not currently.
Shape of Signal on DAD	DAD has a horizontal signal; it can be changed to vertical with Caltrans approval. See Figure 3.13.	DAD has a horizontal signal; it can be changed to vertical with Caltrans approval. See Figure 3.14.	The Pedestal DAD is set up as shown below, but it can be changed to a vertical set up if requested. See Figure 3.15.
Arrow Types & Options On DAD unit	8" red arrows standard. Possible to change to 12" yellow arrows if requested.	Red arrows are standard. Yellow arrows can be used with Caltrans approval.	Yellow arrows with red light. Also possible to setup with red and yellow plus green arrows.
Optional Live Webcam	Yes, if using the galaxy remote monitor service (may also be extra data charges).	No, but device can provide power for a device.	Included standard. Also doubles as video detection for traffic.

	JTI Traffic Sentinel Driveway Assistance Device (DAD) [2]	Horizon Signal Driveway Assistance Device (DAD) [1]	Superior Traffic Systems (STS) Driveway Management Signal (DMS) PEDESTAL [3]
Power Source	PTS has battery bank with solar charging. DAD has battery bank with solar charging option.	PTS has battery bank with solar charging and optional generator enclosure for a Honda generator. DAD has a battery bank with solar charging option.	Both the PTS Driveway Device have battery bank with solar charging.
Driveway Assistance Device Versions and Power Options	DAD has 4 styles including: wheeled base (cart), towable, barrier mount, and truck mount. All styles use 2 batteries (a 4-battery source is optional). With 4 batteries, the system will work for 10 days. Under ideal CA sun conditions, it should work 30 days with the (120 watt) solar option.	Style 1: Cart with 2 batteries, works 10-14 days with the solar option added. System weights ~400lbs. Style 2: Larger trailer unit with more batteries and a larger solar panel (comes standard). This system should work indefinitely.	The Pedestal DAD comes with a standard square base and offers an optional cart for easy moving. The system uses 4 6V batteries with solar array. Using the solar assist, the equipment should run approximately 60 days with fog. A trailer-based unit is expected to be available around the start of 2019.
Safety Backup	For JTI there is no safety backup for the DAD or mainline signal. It is possible to engineer a custom intrusion alarm solution for either. A red-light extension is available on the mainline signals for slow vehicles.	Horizon can add audible alarm for PTS. The audible alarm can also be added to the DAD trailer. The audible alarm works by using a traffic sensor (like a Doppler) aimed to pick up only traffic that is close to the trailer. A short time after the	STS has clearance extender for Pedestrian traffic (option). Can also use clearance extender for slow moving traffic (option). No warning for vehicle ignoring red signal.

	JTI Traffic Sentinel Driveway Assistance Device (DAD) [2]	Horizon Signal Driveway Assistance Device (DAD) [1]	Superior Traffic Systems (STS) Driveway Management Signal (DMS) PEDESTAL [3]
		red light comes on the traffic sensor will turn on. If the traffic sensor detects any vehicles approaching closely to the trailer, it will sound an audible horn. Horizon also has available red time extension for slower cars.	
How is system transported	PTS has a trailer. Multiple DADs (cart option) can be transported on a trailer. The DAD trailers can be tandem towed.	PTS has a trailer. Multiple DADs can be transported on a trailer if using Style 1 (cart). Style 2 is set up on a trailer that is not capable of tandem towing.	PTS has a trailer. Multiple DADs can be transported on a trailer. And each DAD can be set up as a cart for easy transportability. For the new towable trailer design, which is not available now, units are transported using tandem tow.
Crash Tested	Not crash tested because MASH is replacing NCHRP350, but the MASH standard is not yet ready.	Style 1 version NCHRP350 crash tested.	Pedestal has not been crash-tested. Crash-testing not needed for trailered unit because it is a Category 4 device.
Can system operate with two AFAD's on each end of mainline	This set up is possible but would require some engineering.	Does not sell AFAD.	AFAD not currently available commercially.

	JTI Traffic Sentinel Driveway Assistance Device (DAD) [2]	Horizon Signal Driveway Assistance Device (DAD) [1]	Superior Traffic Systems (STS) Driveway Management Signal (DMS) PEDESTAL [3]
and DADs for driveway management.			
Optional Wireless Message Board Interface	<p>The PTS has wireless interconnect between the signal and a message board, which allows the message board to display the signal status of the Horizon portable traffic signal, i.e., Red Signal Ahead, Proceed with Caution Work Ahead. The Message Board Interface System is compatible with most message board systems.</p> <p>DAD does not have message board interface.</p>	<p>The PTS has wireless interconnect between the signal and a message board, which allows the message board to display the signal status of the Horizon portable traffic signal, i.e., Red Signal Ahead, Proceed with Caution Work Ahead. The Message Board Interface System is compatible with most message board systems.</p> <p>DAD does not have message board interface.</p>	<p>The PTS and the Pedestal DAD are both set up to work with a message board.</p> <p>A small message board can be mounted on either the Pedestal DAD or PTS that could display signal wait time (i.e., wait two minutes). Message board can be set up to display signal wait time continuously or can display signal wait time when vehicle is detected.</p> <p>STS uses message boards provided by All-Traffic Solutions.</p> <p>Both PTS and DAD can also be wirelessly interfaced with traditional trailer mounted CMS that can display messages (Red Signal ahead, proceed with caution, etc.)</p>

	JTI Traffic Sentinel Driveway Assistance Device (DAD) [2]	Horizon Signal Driveway Assistance Device (DAD) [1]	Superior Traffic Systems (STS) Driveway Management Signal (DMS) PEDESTAL [3]
Optional Remote Monitoring Capability	The remote monitoring system allows an authorized user to monitor Portable Traffic Signals complete with location, run time, battery status, and system logs.	The remote monitoring system allows an authorized user to monitor Portable Traffic Signals complete with location, run time, battery status, and system logs.	The remote monitoring system allows an authorized user to monitor Portable Traffic Signals complete with location, run time, battery status, and system logs. Included as part of rental agreement
Acquisition options	Purchase or rent.	Purchase. Also possible to rent standard DAD.	Typically, only rent equipment (all-inclusive price).
NOTE: This information was compiled with the help of Caltrans and from data provided by the manufacturers [5],[6],[7].			

Appendix B References

- [1] Horizon Signal Technologies, "Driveway Assistance Device," Accessed 2018.
<http://horizonsignal.com/driveway-assistance-device/>.
- [2] John Thomas Inc., "Sentinel DAD," *JTI Traffic*, Accessed 2018.
<http://www.jtitraffic.com/our-products/portable-traffic-signals/sentinel-dad/>.
- [3] Superior Traffic Services, "Our Devices," *Superior Traffic Services*, Accessed 2018.
<https://superiortrafficservices.com/our-devices/>.

Appendix C:

Low Volume Access Point Test Plan

This appendix contains the most up to date version of the test plan with minor editing incorporated. Notations are included where some items had to be changed when developing the test protocol.

I. Background

The main goal of the “Managing Low Volume Access Points in Work Zones” research study is to identify traffic control technologies that can be used with Caltrans Standard Plan T13 for the purpose of controlling vehicles entering work zones from side roads and driveways. At this stage of the research study, a potential type of commercial equipment has been identified and a testing methodology is needed to assess efficacy of the equipment. This document outlines the testing to be completed and identifies what resources will be required to accomplish the testing.

II. Objective

The objective of this testing is to ascertain the efficacy of commercial traffic control equipment applied to low volume side roads and driveways in a simulated work zone.

III. Scope

The testing described in this document is designed for a closed facility and is not intended to be conducted in a live work zone with the general public. The equipment selected for testing is a commercial STS Driveway Management Signal (DMS) [1], which is a device similar to the other commercial Driveway Assistance Devices (DAD) [2], [3]. The DMS will be used to provide traffic control to a low volume access point in a simulated work zone environment. Metrics to consider and the types of data collected will be outlined in sections to follow along with the overall strategy of the test, general procedures, personnel needed, methods used, and the expected deliverable.

IV. Geometric layout of test and general procedure

To accomplish the test objective, a location with a minor intersection will be required. Testing will be done in a closed area, and the research team will provide the vehicle used to drive through the test. Drivers will be informed that they will be driving in a simulated work zone and that they need to drive to the intersection and then make a turn (left or right depending on the test run) and stop at the end of the road.

The general geometric layout is given in Figure C.1. This layout is designed to approximate a typical scenario as shown in Caltrans RSP T13[4]. Referring to Figure C.1, Camera 2 captures vehicle stopping position, Camera 3 monitors traffic, and Camera 1 serves as a backup to capture information about the approach if it is later desired⁵.

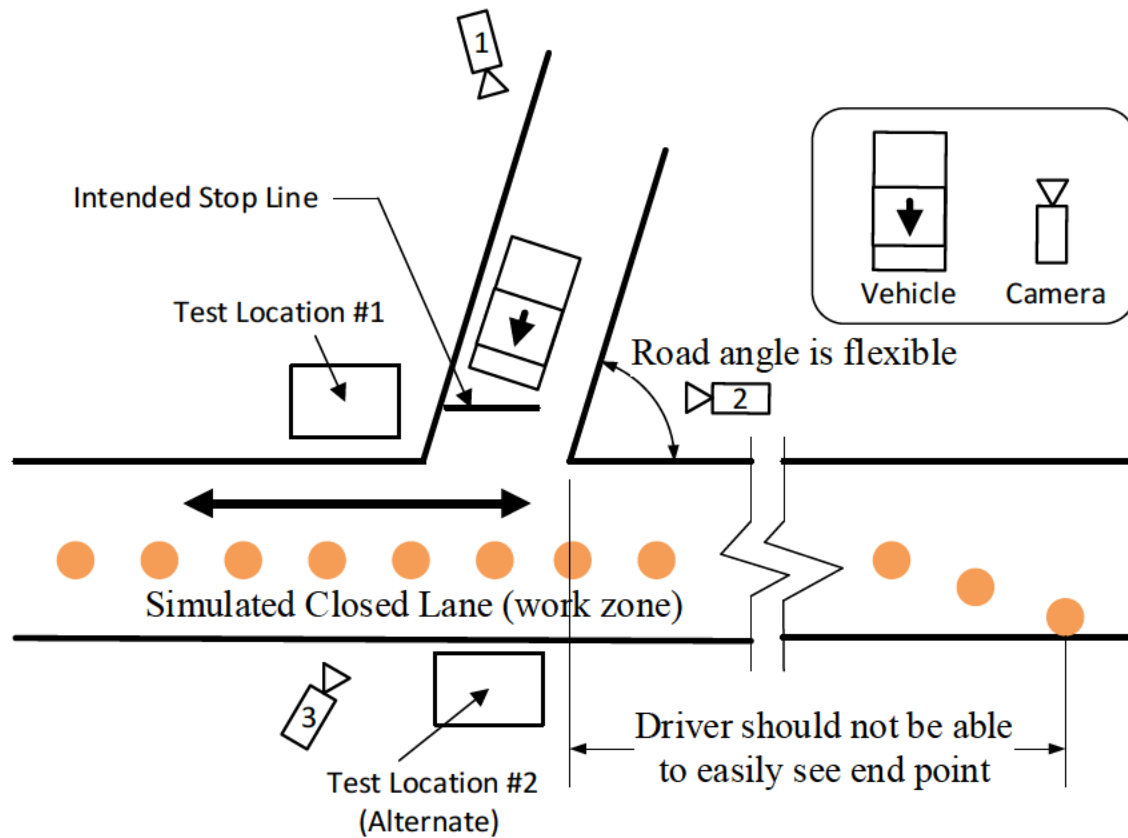


Figure C.1 Geometric Layout

The most difficult side road scenario for a driver to navigate in a work zone is when the driver cannot see the end points of the main work zone. If a driver cannot see the end points, they have no way of knowing which direction traffic is coming from or if work is even active at the site. To simulate this scenario, the driver should not be able to easily see the end of the work zone as noted in Figure C.1. In order to limit the view of the work zone ends, there are several options. The preferred option (to ensure the driver cannot see the end point) is a long work zone. If a long work zone is not feasible, other options can be considered. The first alternative option is to substitute length with a blind curve,

⁵ Camera 3 was not used since it would capture a clear view of drivers and this could not be allowed as part of the protocol.

thus obstructing view of the end point. The last alternative option is to consider building an artificial obstruction near the intersection that blocks line of sight.

Before testing begins, drivers will be instructed to follow all traffic laws and controls (i.e., yield signs, stop signs, flagger instructions, etc.) just as they would if they were driving in a real work zone environment. A researcher will not accompany the driver so as to not influence their decision.

The researchers will monitor the test progression, maintain the cameras as needed, collect data, and operate as coordinator for the other people involved. For most tests, the traffic control device operator will be positioned in a manner consistent with typical field use and follow standard operating procedures for the equipment.

V. Test configurations

The equipment under test are generally autonomous unless operated in a manual mode. One option to manually control the DMS is to manually control the mainline signals which then control the DMS. For the DMS system, it is also possible to manually control the device standalone via a remote control such as a tablet. In any case, operators used (if any) should be positioned in a manner consistent with typical field use as mentioned. If an operator is not required, a supervisor should still be present to monitor the equipment during the test. For the DMS system, two different placements named Placement #1 and Placement #2 (alternate) need to be tested as shown in Figure C.1. Placement #2 has the DMS across the street from the intersection as was done for the Driveway Assistance Device (DAD) tested in the field study of [5]. Placement #1 has the DMS near the corner of the intersection on the right side as was done in the simulated survey phase of [5]. The use of standard early warning signs such as the standard “prepare to stop” sign should also be tested. The test configurations are summarized in Table C.1.

Testing of the DMS will only be conducted using the standalone mode with a human manually controlling it. Testing with a PTS signal controlling the DMS will not be conducted. This can be modified at a later date if there is sufficient interest, time, and if the budget allows.

Table C.1 Control Method Configurations

Control Method Configurations
Driveway Management Signal (DMS) Placement #1
Driveway Management Signal (DMS) (alternate)
Driveway Management Signal (DMS) with an early warning sign

VI. Metrics

This test is designed to be completed in a controlled and closed facility; as such only some of the measured metrics commonly employed by other works are relevant. The commonly employed metrics that will be used in this test include compliance [5]-[9] and relative stopped position [8], [9]. A measurement of setup time for each test device will also be recorded for the purposes of estimating costs. Post-experience mini-interviews can also be conducted with drivers similar to the type of interviews done in the controlled study of [5] and the field study interviews of [6] and [9]. Interviews with the operators of the equipment will also be conducted. Additionally, signs of driver confusion will also be noted.

Outside of the values measured during the experiment, there are also other factors that need to be recorded and noted for each control strategy tested. These include acquisition cost of the control equipment used in the test, the number of personnel required to implement the control scenario, and the supporting equipment needed. For purposes of this work, supporting equipment is defined as anything that is not the control equipment itself but that which is necessary for the control scenario. Supporting equipment may include, but is not limited to, items such as trailers for the test equipment or extra vehicles needed to tow the test equipment. This data will be used to generate the costs of each control option. The raw data needed is summarized in Table C.2.

Table C.2 Raw Data Needed

Measured at run time	Other needed data
Compliance	Cost of control equipment
Relative Stopped Position	Number of personnel required
Setup Time	Supporting equipment
	Post experience interview for drivers and operators

VII. Personnel

At a minimum, each experiment needs a person to drive the test vehicle, one researcher/observer, and an operator or supervisor for the main control device. The person driving the test vehicle should not be familiar with the test, and it is preferable that they have limited experience with the control methods. The operator of the control device should understand how to operate the device consistent with the methods that would be used by a flagger in the field. The minimum personnel requirement is summarized in Table C.3. A second researcher may also be present to help with data collection and other tasks as they arise.

Table C.3 Minimum Required Personnel

Minimum Required Personnel
Operator for traffic control device
Test vehicle driver
Researcher

VIII. Measurement Methods

Initial layout of geometry may be done by measuring tape or laser range finder during the setup phase. As commonly seen in other works such as [7]-[9], video will be utilized for measurements. These videos need to have a form of time stamp in order to facilitate calculations done after the testing. Photos may also be used for some aspects of the documentation.

IX. Optional additions

If time, number of test drivers, and safety permits, some tests can be run with the driver listening to the car radio or other typical music player while driving. This test adds an additional variable to the data and may more realistically simulate a typical driver's environment.

X. Deliverables

The raw information generated from this test (digital video footage, digital photos, and researcher surveys) will be post processed to extract relevant data. The extracted data will serve as a deliverable, access to the raw information is limited in order to protect drivers' identities. Relevant data to extract includes driver compliance, relative stop position, observed setup time, and the costs associated with each control method.⁶ From this information comparisons between the tested options can be created and recommendations made. The final deliverable of the testing results will be contained in the final report of the overall research study.

The following section will outline the equipment needed as well as locations attributes and general geometric layout considerations.

XI. Equipment used for traffic control

Two main pieces of equipment are required for testing, the DMS signal, and a flagger remote to operate it as summarized in Table C.4. The DMS chosen will be

⁶ When developing the test protocol, measures to better protect drivers' identities were needed. As such, video, digital photos, and survey responses that quote the drivers could not be a deliverable. This section of test plan was changed to reflect the above limitations.

tested in a standalone mode as discussed above but also has the ability to function in coordination with a PTS signal. A PTS signal is included in Table C.4 as optional and is only needed if the testing is modified to include testing of the DMS in its autonomous mode.

Table C.4 Control Equipment

Control Equipment
Driveway Management Signal (DMS)
Flagger Remote for DMS (or PTS)
Optional: PTS system designed to operate with the DMS

XII. Supporting equipment

In order to accomplish the testing, various types of supporting equipment will be required as summarized in Table C.5. The video cameras used can be any standard camera or even a cell phone as long as it has the ability to add a time stamp to the video which will be needed for post-calculations. Each person in the field will need a standard safety vest, and the researchers will each need a digital device to take notes.

Table C.5 Supporting Equipment

Equipment	Purpose	Quantity
Video cameras with suitable stands	Record vehicle behavior at control point	3
Traffic cones	Simulate work zone	Configuration dependent
Road work signs as specified in T13	Simulate work zone	As specified in T13
Safety vest	Ensure people are visible	One per person
Vehicle	For test vehicle	1
Tape and laser measure	To setup initial geometry	1 each
Mobile digital device	To record notes	1 per researcher
Still Camera	To document setup and other aspects	1

XIII. Weather

This testing is intended to be done in daylight hours during dry weather with dry roads.

XIV. Minimum Runs per Device

A minimum of 5 runs per configuration is desired to aid in extracting results.

Appendix C References

- [1] "Our Devices," *Superior Traffic Services*. [Online]. Available: <https://superiortrafficservices.com/our-devices/>. [Accessed: 10-Oct-2018].
- [2] "Sentinel DAD," *JTI Traffic*. [Online]. Available: <http://www.jtitraffic.com/our-products/portable-traffic-signals/sentinel-dad/>. [Accessed: 10-Oct-2018].
- [3] "Driveway Assistance Device | Horizon Signal Technologies, Inc.," *Horizon Signal*. [Online]. Available: <http://horizonsignal.com/driveway-assistance-device/>. [Accessed: 10-Oct-2018].
- [4] California Department of Transportation, "Revised Standard Plan RSP T13." [Online]. Available: http://www.dot.ca.gov/hq/esc/oe/research_study_plans/highway_plans/stdplans_US-customary-units_15/viewable_pdf/rspt13.pdf. [Accessed: 10-Oct-2018].
- [5] M. D. Finley, P. Songchitruksa, and S. R. Sunkari, "Evaluation of innovative devices to control traffic entering from low-volume access points within a lane closure," Texas A & M Transportation Institute, 2014.
- [6] M. D. Finley, B. R. Ullman, N. D. Trout, and E. S. Park, "Studies to determine the effectiveness of automated flagger assistance devices and school crossing devices," Texas Transportation Institute, 2011.
- [7] S. D. Schrock, S. S. Patil, E. J. Fitzsimmons, and V. R. Sarikonda, "Evaluation of Temporary Traffic Signals in Conjunction with Pilot Car Operations at Two-Way Long Temporary Work Zones."
- [8] A. K. Debnath, R. Blackman, N. Haworth, and Y. Adinegoro, "Influence of Remotely Operated Stop-Slow Controls on Driver Behavior in Work Zones," *Transp. Res. Rec. J. Transp. Res. Board*, no. 2615, pp. 19–25, 2017.
- [9] H. Brown, C. Sun, S. Zhang, and Z. Qing, "Evaluation of Automated Flagger Assistance Devices," Missouri Department of Transportation, 2017.

Appendix D:

Low Volume Access Point Preliminary Concepts Proposal

I. Background

Problem

A common type of lane closure on a conventional highway involves closing one vehicle lane while the remaining lane is utilized to support bidirectional traffic flows with a temporal separation. An example of this type of lane closure is described in Caltrans T13 [1]. In some cases, there may be a low volume access point such as a driveway positioned within the work zone (WZ). Caltrans standard specifications Section 7-1.03 (Public Convenience) requires work to “maintain convenient access to driveways,” and as such it may not be possible to close the driveway [2]. Vehicles entering the work zone from low volume access points, such as driveways, need guidance on when they can enter and what direction the traffic is currently flowing. Research previously conducted has shown that there are commercial devices that can facilitate information to drivers on low volume access points by displaying an arrow in the current direction of traffic flow. A limitation of the available commercial devices is that they typically do not provide a way to physically block vehicles, and often no warning is given to workers if a vehicle ignores a red signal. If a vehicle ignores the signal and enters a work zone at the wrong time or drives in the wrong direction, it may lead to traffic collisions and traffic flow disruptions. Caltrans has decided to test the STS Driveway Management Signal (DMS) but modifications to it may be possible to improve efficacy.

Need

Increasing safety and reducing traffic disruptions in work zones is always a high priority goal at Caltrans. One method of achieving this goal is through the use of advanced technologies and novel methodologies. For this specific research, reducing the incidence of errant drivers entering a work zone from low volume access points can lead to significant benefits. Benefits that may be realized include increased safety, increased driver compliance, reduced driver confusion, reduced costs, and more.

Purpose

The primary focus of this work is to modify the STS Driveway Management Signal (or similar device) to add intrusion detection and a gate arm. Initial testing will be performed on the proof of concept modifications to ascertain

their possible effectiveness. The tests will be designed such that it is possible to compare the results of the modified equipment to equipment without modification.

Expected Benefit

It is expected that the results of this work will provide additional equipment options to consider when designing a work zone within which a low volume access point is contained. The modified equipment developed in this work should help facilitate controlled entry of vehicles entering work zones from low volume access points.

II. Caltrans Use and Proposed Concept

This research will be an extension of the work conducted for the “Managing Low Volume Access Points in Work Zones” research study in which commercial traffic control options were considered. The modifications planned in this proposal include adding an intrusion detection system and a gate arm to the commercial STS Driveway Management Signal (or similar device). The gate arm system will be designed such that the arm lowers after the red signal is given. Sensors will be employed to reduce the likelihood of the arm contacting a vehicle or a pedestrian when closing. The intrusion detection system will be based on radar and machine vision techniques. A preliminary concept of the design and intended roadway placement is shown in Figure D.1. As shown in Figure D.1, two cameras may be used to allow the machine to be deployed in alternate positions. If an intrusion is detected the system will send a message wirelessly to a relay station near the flagger which will then convert the message to a form that can be understood by the flaggers mobile device at short range. A preliminary example of how the wireless system may operate is shown in Figure D.2.

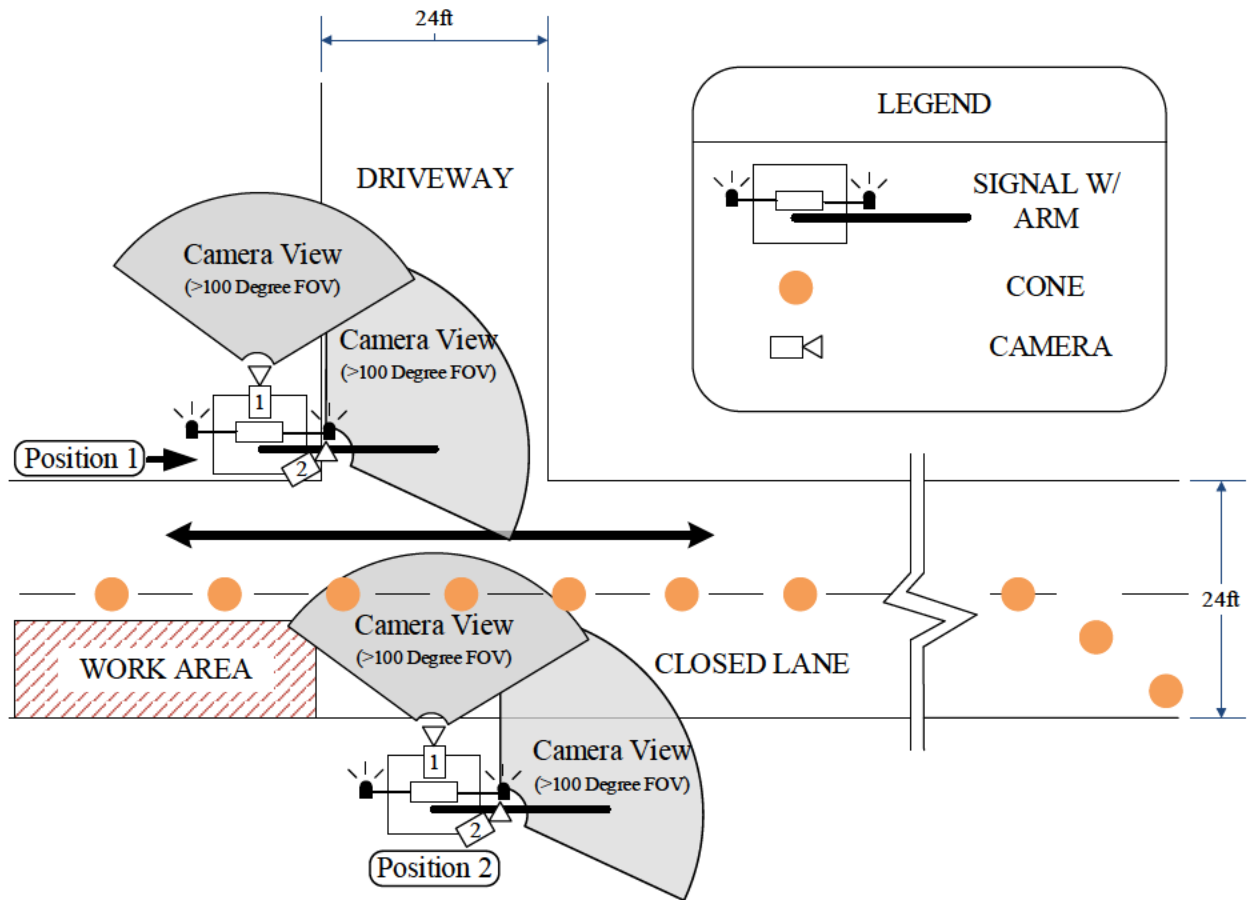


Figure D.1 Preliminary Equipment Concept and Roadway Placement

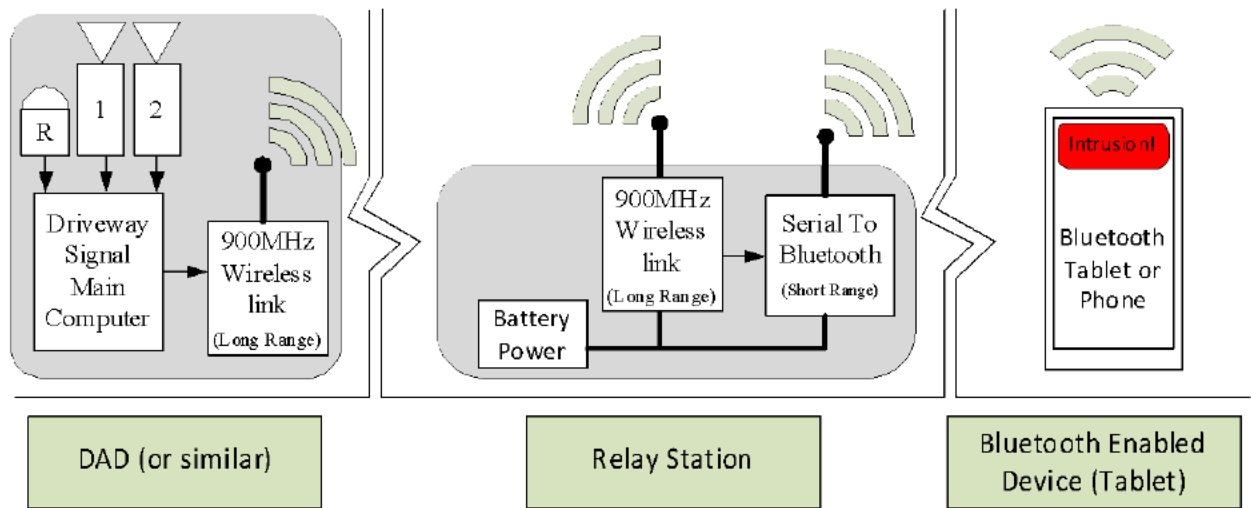


Figure D.2 Preliminary Data Transmission System

III. Tasks and Deliverables

This proposal has several key tasks which will be outlined here.

1. *Forming a Research study Panel and General Research study Management*

- In the early stages of this research study after the kickoff meeting, a Research study Panel is formed consisting of representatives from all the stakeholders to guide the conduct of this research. There will be periodic meetings with the panel throughout this proposed research.
- The deliverables for this task will be a roster identifying the members of the panel and cover general research study management, including production of quarterly reports for the duration of research.

2. *Detail the Concepts and Planned Research*

- Develop more detail for the concepts presented above and meet with research study panel. Research panel input will be incorporated into the concepts. Depending on the changes, the proposed hardware budget may change.
- The concepts will be detailed in a progress report and the final report.

3. *Development of the Test Plan & Protocol*

- A test plan and separate test protocol will be developed and presented to the panel for the evaluation. Panel's input will be incorporated into a final test plan and protocol for performance evaluation.
- Protocol that incorporates panel input will be reviewed by IRB (if required) and may require more changes.
- The test protocol will be designed considering the safety and operational improvements for Caltrans in the management of low volume access points.
- Recruitment of test drivers can start as soon as the protocol is approved by IRB.
- The test protocol will be documented in a progress report as well as in the final report.

4. *Development of Proof of Concept Hardware*

- Hardware will be developed that can be temporarily attached to a commercial STS Driveway Management Signal (or similar). The hardware will be proof of concept quality used to collect test results. These modifications will include a gate arm and a method to detect vehicles which are not responsive to the red signal.
- Potential methods to detect vehicles include radar traffic sensors, vision-based systems, and ultrasonic.
- Hardware development will be documented in a progress report as well as the final report.

6. Acquisition of Commercial Equipment

- A commercial product will be rented that can be temporarily modified to accommodate the modifications to test.
- The commercial equipment will be the STS Driveway Management Signal (or similar).
- This task has no deliverable.

6. Testing of the Modifications

- A series of tests consistent with the test plan and protocol of Task 3 will be performed and test data will be collected for further analysis. The tests will be performed near ATIRC or at another location if a change is needed to facilitate testing.
- Access to raw test data involving human test drivers will have to be restricted and follow what was approved in the IRB process.
- Test data will be presented to the panel (in accordance with above limitations) and additional tests will be performed if desired by the panel and within the budget of this research study.
- The deliverable for this task will be documentation of the test results. These results will be included in a progress report and the final report.

7. Analysis of the Results

- Test results will be analyzed in terms of performance of the equipment tested. Factors such as safety and operational improvements will be considered.

- A simple cost analysis will be performed based on estimated hardware and operational costs. The cost analysis may include comparisons to a traditional flagger.
- The deliverable for this task will be documentation of the analyses of test results and deployment costs. This will be documented in a progress reports and the final report.

8. Research Documentation and Reporting

- The deliverables for this task will consist of a final report, which covers Tasks 1 to 8.

IV. Work Time Schedule

The time schedule for the proposed research will cover 18 months. Since this research involves recruiting test drivers, timing of the project should consider when the most people would be available. The exact dates will be dependent on the exact start time of the work. The duration of each task (in months) is shown in Table D.1 and a Gantt chart in Table D.2.

Table D.1 Tasks for Concept Proposal

Task #	Task Name	Duration [Months]
1	Forming a Research study Panel and General Research study Management	18
2	Detail the Concepts and Planned Research	3
3	Development of the Test Plan & Protocol	3
4	Development of Proof of Concept Hardware	5
5	Acquisition of Commercial Equipment	2
6	Testing of the Modifications	7
7	Analysis of the Results	6
8	Research Documentation and Reporting: Composing 60% Draft Final Report	1
8	Research Documentation and Reporting: Incorporate Customer Comments/Changes to form 95% Draft Final Report	1
8	Research Documentation and Reporting: Research study Manager Review of Final Report	1
8	Research Documentation and Reporting: Finalized Final Report	1

Table D.2 Timeline of Research study

Project Quarter		1			2			3			4			5			6		
Project Month		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Calendar Year		Year 1												Year 2					
Tasks	Months	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
1	Project Management																		
2	Detail Concepts																		
3	Test Plan & Protocol																		
4	Hardware Development																		
5	Acquisition of Equipment																		
6	Testing																		
7	Analysis of Results																		
8	Draft Final Report (60%)																		
8	Incorporating Changes to the Draft Final Report (95%)																		
8	Task Manager Review of the Modified Final Report																		
8	Finalized Final Report																		

V. Budget

It is assumed that an STS Driveway Management Signal (or similar device) can be rented for testing. The rental cost is taken as \$750 per month plus \$1000 for delivery. A mobile tablet is also needed for the flagger/operator, the tablet must allow installation of experimental/custom apps. If a suitable tablet is not available for use, the budget includes up to \$800 to purchase one and the needed accessories.

The prototype intrusion detection system is comprised of two parts including: the components attached to the commercial equipment (part 1), and a receiver station positioned near the flagger (part 2). A preliminary bill of materials for part 1 is shown in Table D.3, while part 2 is shown in Table D.4. The preliminary bill of materials needed to add a gate arm system is shown in Table D.5. The estimated prices in Table D.3, Table D.4, and Table D.5 total \$2,916 (assuming only one receiver is built) and don't include costs such as shipping and taxes. The hardware shown in Table D.3, Table D.4, and Table D.5 is preliminary and design changes not yet foreseeable may require deviations from this list. A line item called "Misc. Parts/Replacements" is included to add approximately 20% to the parts budget for replacements or additions as needed.

The overall hardware budget (rental, the tablet, and custom hardware) is shown in Table D.6. Note that Table D.6 does not include staff costs, hardware shipping costs, and other expenses. These extra expenses will have to be

calculated later before finalization of the proposal. Due to changes in equipment costs, the cost estimates for the hardware may need to be updated before finalizing the budget in the future.

Table D.3 Estimated Prototype Intrusion Detection Hardware Costs

Component	Notes	Each	Num	Total
Radar	Approximately 15-meter range	\$723.00	1	\$723.00
Computer	NanoPi 4GB, 16GB eMMC, Heatsink (or similar)	\$125.00	1	\$125.00
Wireless Modem	XBEE SX or Similar	\$200.00	1	\$200.00
Modem Antenna	SMA 900MHz	\$20.00	1	\$20.00
Antenna Adaptor	RPSMA -> SMA	\$5.00	1	\$5.00
Wiring & Connectors	Various	\$100.00	1	\$100.00
Enclosure	Aluminum NEMA	\$63.00	1	\$63.00
Misc. Parts/Replacements	As Needed (~20%)	\$350.00	1	\$350.00
Bracket	Gusset Enclosure Support	\$20.00	1	\$20.00
Image Coprocessor	Movidius USB (or similar)	\$75.00	1	\$75.00
Camera	USB w/ Low Light Vision	\$53.00	2	\$106.00
Camera Dome	Approx. 8" Diameter Plastic	\$30.00	2	\$60.00
Est Total Direct Cost				\$1,847.00

Table D.4 Estimated Prototype Intrusion Detection Receiver Costs

Component	Notes	Each	Num	Total
Wireless Modem	XBEE SX or Similar	\$200.00	1	\$200.00
Wireless Modem Kit	Antenna, PSU, Cable	\$55.00	1	\$55.00
Data Bridge	RS232 to Wi-Fi or Bluetooth	\$60.00	1	\$60.00
Power Converter	Buck/Boost	\$20.00	1	\$20.00
Receiver Battery	12V 18aH SLA	\$50.00	1	\$50.00
Relay Closure	Battery Box	\$20.00	1	\$20.00
Switch and Fuse	Misc. switches and fuses	\$20.00	1	\$20.00
Misc. Parts/Replacements	As Needed (~20%)	\$85.00	1	\$85.00
Est Total Direct Cost				\$510.00

Table D.5 Estimated Prototype Gate Arm Hardware Costs

Component	Notes	Each (Est)	Num	Total
Motor Driver	Pololu VNH5019	\$25.00	1	\$25.00
Gate Arm	Plastic or Wood, 8+ Feet	\$100.00	1	\$100.00
12V Motor & Gearbox	Worm Gear Motor 8NM 33RPM	\$75.00	1	\$75.00
Bearing	10mm Sealed Ball	\$10.00	1	\$10.00
Counterweight	15lbs Cast Iron Plate	\$21.00	1	\$21.00
Enclosure	Metal	\$37.00	1	\$37.00
Misc. Bolts	Misc. Sizes (Bolts/Nuts/Washers)	\$10.00	1	\$10.00
Limit Switches	Magnetic	\$5.00	2	\$10.00
Misc. Wiring	Various	\$20.00	1	\$20.00
Ultrasonic	HRLV-EZ1 (5m)	\$33.00	1	\$33.00
Spacer	~10mm ID	\$5.00	1	\$5.00
Misc. Parts/Replacements	As Needed (~20%)	\$93.00	1	\$93.00
Base Plate	1/2" Aluminum	\$20.00	1	\$20.00
Attachment	1/2" Aluminum	\$50.00	1	\$50.00
Bracket	1/2" Aluminum	\$50.00	1	\$50.00
Est Total Direct Cost				\$559.00

Table D.6 Hardware Budget

<u>Item</u>	<u>Notes</u>	<u>Cost</u>
7 Month Rental of Commercial Equipment	\$750/month + \$1000 delivery	\$6250
Purchase of Tablet & Accessories	Must allow custom apps to be installed	\$800
Custom hardware	As shown in Table 10-8 through 10-10	\$2916
Total	-	\$9966

Appendix D References

- [1] California Department of Transportation, "Revised Standard Plan RSP T13," pp. 1, 2018.
- [2] California Department of Transportation, "Standard Specifications," 2015. [Online]. Available: http://www.dot.ca.gov/hq/esc/oe/construction_contract_standards/std_specs/2015_StdSpecs/2015_StdSpecs.pdf

Appendix E:

Potential Applicability to T11 and T12

Applicability of Equipment to Different Work Zone Scenarios

When developing new concepts, possible applications for different work zone scenarios were considered. The different work zone scenarios considered include those illustrated in T11 [1], T13 [2], and T12 [3]. The purpose of equipment like a Driveway Assistance Device (DAD) [5], [6], [7] is to indicate to drivers when it is okay to proceed and in what direction traffic is flowing. T11 [1] and T12 [3] have traffic directions spatially separated; therefore, it is believed that a driveway device or signal will not provide significant utility. Some type of driveway device or signal is well suited to scenarios like the one illustrated in T13 [2]. A brief analysis of these scenarios will now be given.

In the T11 [1] scenario, some traffic lanes are closed and traffic is merged onto the remaining lanes. A modified version of T11 plan [1] containing the main elements of the plan with an added driveway is shown in Figure E.1. In this type of scenario, traffic directions are spatially separated. A DAD placed as shown in Figure E.1 would provide limited utility because mainline traffic is flowing in one direction.

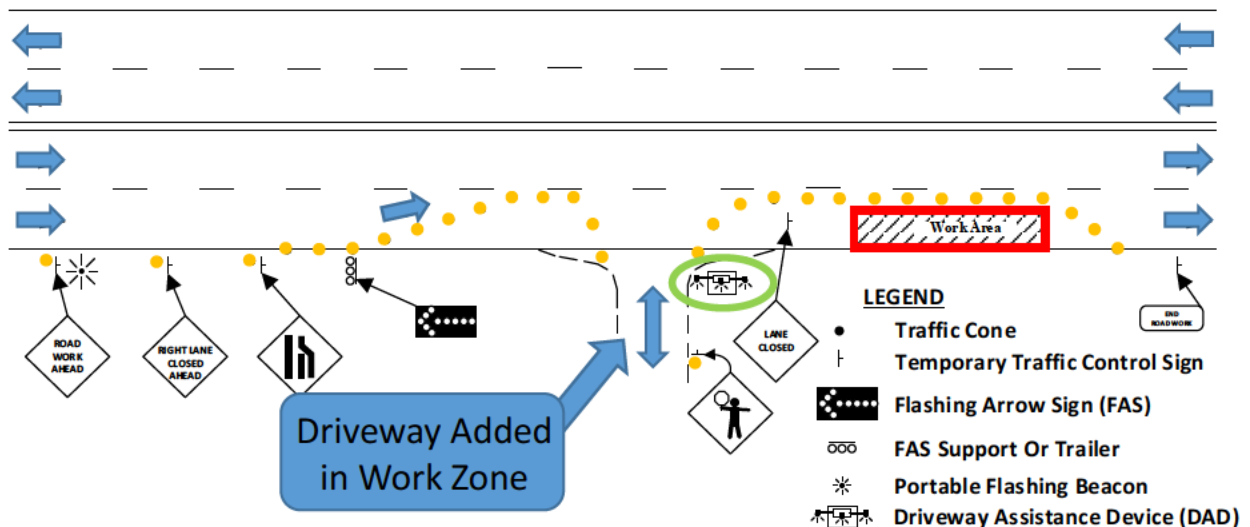


Figure E.1 Modified T11 Scenario

In the T12 [3] scenario, a whole side of the road is closed and a lane from the other side of the road is reconfigured to detour vehicles in a contraflow manner. A modified version of the T12 plan [3] containing the main elements of the plan with an added driveway is shown in Figure E.2. As in the T11 [1] scenario, opposing directions of traffic are spatially separated even though there is a

contraflow situation. In this scenario, a DAD placed as shown in Figure E.2 would provide only limited utility because drivers do not need an indication about which direction they should proceed.

If the goal is to meter traffic, or control traffic entering from the driveway, for both T11 [1] and T12 [3] scenarios multiple Traffic Control Systems (TCS) can be used. In these cases, if the direction of traffic flow is known and an Automated Flagger Assistance Device (AFAD), a Portable Traffic Signal (PTS), or a human flagger could be used.

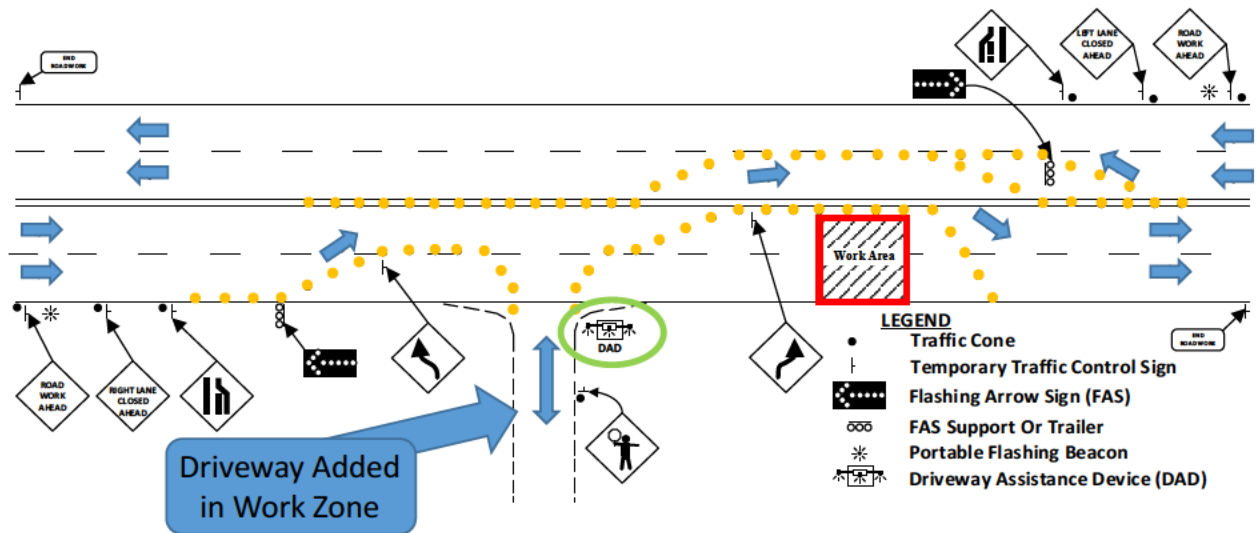


Figure E.2 Modified T12 Scenario

The T13 [2] scenario is different than T11 [1] or T12 [3] in that one lane of traffic is closed and the remaining lane must serve traffic flowing in both directions with temporal rather than spatial separation. A version of T13 [2] containing the main elements of the plan and a DAD is shown in Figure E.3. Since the traffic is not spatially separated, controllers must be used at every access point to limit the possibility of a collision. In this type of scenario, a DAD (or similar device) can provide utility for driveways and low volume access points. For a traditional DAD to work as designed (such as those from Horizon [5] or JTI [6]), an appropriate PTS must be placed at the mainline access points with or without a human flagger present. The DAD synchronizes with the mainline signals and tells drivers on the driveway which direction the traffic is currently flowing. The version of a DAD from STS [7] has the ability to operate in a standalone manner and can be controlled by the human flaggers without requiring the use of a PTS system on the mainline.

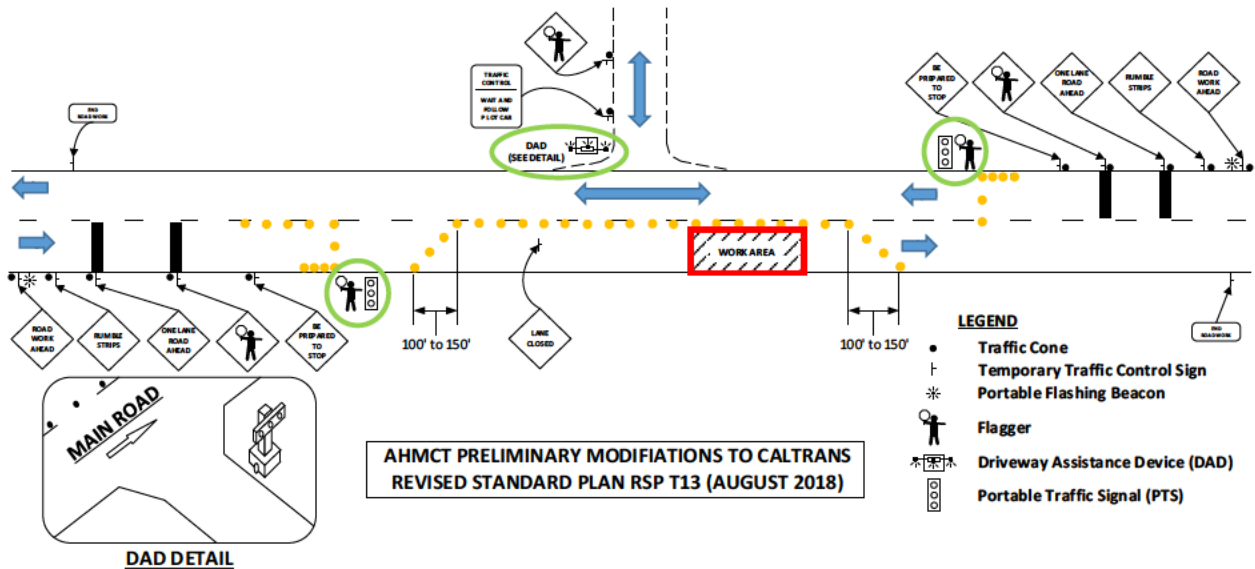


Figure E.3 Modified T13 Scenario

Appendix E References

- [1] California Department of Transportation, "Revised Standard Plan RSP T11." http://www.dot.ca.gov/hq/esc/oe/project_plans/highway_plans/stdplans_US-customary-units_15/viewable_pdf/rspt11.pdf (accessed Oct. 10, 2018).
- [2] California Department of Transportation, "Revised Standard Plan RSP T13." http://www.dot.ca.gov/hq/esc/oe/project_plans/highway_plans/stdplans_US-customary-units_15/viewable_pdf/rspt13.pdf (accessed Oct. 10, 2018).
- [3] California Department of Transportation, "Revised Standard Plan RSP T12." http://www.dot.ca.gov/hq/esc/oe/project_plans/highway_plans/stdplans_US-customary-units_15/viewable_pdf/rspt12.pdf (accessed Oct. 10, 2018).
- [5] Horizon Signal Technologies, "Driveway Assistance Device," Accessed 2018. <http://horizonsignal.com/driveway-assistance-device/>.
- [6] John Thomas Inc., "Sentinel DAD," *JTI Traffic*, Accessed 2018. <http://www.jtitraffic.com/our-products/portable-traffic-signals/sentinel-dad/>.
- [7] Superior Traffic Services, "Our Devices," *Superior Traffic Services*, Accessed 2018. <https://superiortrafficservices.com/our-devices/>.

Appendix F: Sign Wording Discussion

Several different wordings were considered for the signage to be used with the DAD. There were two main signs thought necessary: a sign to convey what the driver should do with a red signal, and a sign to convey what a driver should do with a flashing yellow (or red) arrow.

Several options were considered for the sign explaining the red signal including:

- “STOP HERE ON RED”
- “WAIT HERE ON RED”

For the flashing arrow, several types of signs have been tried by others [1], and the Caltrans panel considered various options. The first three options shown below are nearly the same as what New Jersey previously used [1]. Several options were considered including:

- “YIELD IN THE DIRECTION OF FLASHING YELLOW ARROW”
- “YIELD IN DIRECTION OF FLASHING RED ARROW”
- “YIELD IN DIRECTION OF FLASHING YELLOW ARROW”
- “YIELD ON YELLOW ARROW”
- “TURN WHEN CLEAR ON FLASHING YELLOW ARROW ONLY”

Ultimately, two signs were placed on the DAD and one in front of the DAD. The signs on the DAD included “YIELD IN DIRECTION OF FLASHING YELLOW ARROW” as well as a sign showing two red arrows with the wording “NO TURN ON RED.” The standard “STOP HERE ON RED” sign was placed before the DAD.

Appendix F References

- [1] Y. Z. Farid, D. A. Noyce, M. V. Chitturi, Y. Song, W. F. Bremer, and A. R. Bill, “Practices in One-Lane Traffic Control on a Two-Lane Rural Highway,” Transportation Research Board, Washington, D.C., NCHRP, 2018.

Appendix G:

Low Volume Access Point Test Protocol

This appendix contains the last version of the IRB approved test protocol. If future testing is completed, this protocol may have to be reapproved.

I. Objectives

Certain types of lane closures conducted by Caltrans and others require bi-directional traffic to share one lane of travel. This is typically done by setting up a reversing traffic control scenario. In some of these scenarios there may be low volume access roads that intersect the main line of traffic. Vehicles entering the main line from a low volume access point need to be directed in some manner. If a vehicle enters the main line going the wrong direction major traffic flow issues occur and a situation is created where there is a potential for a head on collision. The general objective of this research is to evaluate options for reducing traffic moving in the wrong direction within reversing traffic control work zones.

The purpose of the portion of the research involving humans driving in a simulated work zone is to ascertain the efficacy of using a commercial off the shelf STS Driveway Management Signal (DMS) to direct traffic entering from low volume side roads. The device will be operated as a standalone machine controlled by a human flagger at a remote location.

II. Background

Upon review of the options for commercial equipment available to address the issue of low volume access points, very little was found. The known designs are typically a type of traffic control device with some arrangement of arrows or lights to direct traffic. Some examples of commercial equipment include Driveway Assistance Devices (DAD) available from several manufacturers as well as the STS Driveway Management Signal. These devices are relatively new and previous studies completed to ascertain their efficacy has focused on using them in an autonomous mode where they are controlled by stop lights placed on the main line of the work zone. In certain scenarios stop lights are not used and it would be beneficial to have a traffic control device that can be operated manually by a human flagger. No known research has been

conducted to ascertain the efficacy of these devices in a manual mode. There are also several arrangements of lights used with no known published data for the arrangement of lights proposed in this test.

III. Inclusion and Exclusion Criteria

Screening of individuals will be conducted once they express interest in the study. This can be done via phone call or in person. Individuals will be asked the following questions:

- Are you over the age of 18?
- Are you legally licensed to drive a motor vehicle in the state of California?
- Can you show a copy of your driver's license on the day of the testing?
- Are you currently pregnant? (only asked if female)
- Can you operate a standard motor vehicle safely without needing modifications to accommodate special needs?

No individuals will be included from the following populations:

- Adults unable to consent
- Individuals who are not yet adults (infants, children, teenagers under 18 years old)
- Pregnant women
- Prisoners

IV. Study Timelines

Each individual will be asked to drive a vehicle through a simulated work zone. Subjects volunteer for one session at a time. It is estimated that individuals taking part in the study will need to contribute less than one hour of their time per session.

Study subjects will be enrolled at several times as needed, the anticipated date to complete enrolling study subjects is December 2020.

The estimated date to end data collection for this research is December 2020 with the analysis being completed by December 2020.

V. Procedures Involved

Setup: A simulated work zone will be setup with a "T" type of intersection as shown in Figure 1. The Driveway Management Signal (DMS) will be tested in

two locations noted as “Test Location #1” and “Test Location #2.” The intersection will be designed such that vehicles approaching the intended stop line do not have a clear view of the work zone or its end points. Cameras will be positioned as shown to capture the data needed for post processing. Camera 1 will capture the rear of the vehicles and the state of the driveway management device as such it is not anticipated that drivers will be identifiably visible in this view. Camera 2 will be adjusted to capture the lower portion of the car to measure the stopped position and it is not anticipated that this will capture an identifiable view of the driver. A changeable message sign collocated with the DMS will display “XX min delay” where XX is an appropriate length of time in minutes. The changeable message sign may optionally be vehicle actuated.

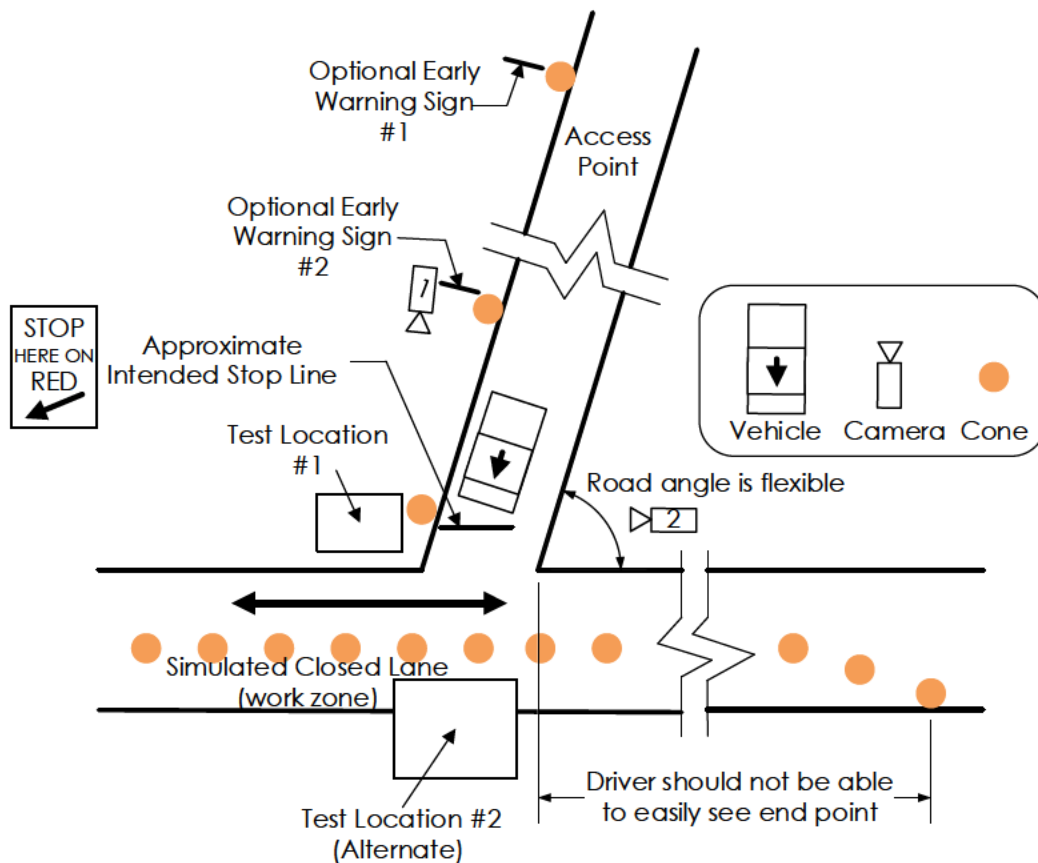


Figure 1: Simulated Work Zone Layout Showing Approximate Locations of Elements

Work Zone Length: Length of the work zone should be sufficient so that drivers cannot see the end points of the work zone from the intersection, if this is not possible some obstructions or blinders can be setup.

Low Volume Access Point Length: The length of the low volume access point is not critical as it can vary greatly in reality (from a short driveway to a low volume road) but for testing it must be long enough to support two optional early warning signs as in the test plan (Sign #1 and Sign #2). From the CAMUTCD (section 2C.05) a roadway with a speed limit of 25mph (not in heavy traffic) should have a warning sign placed 100ft before the signal (Sign #2). The CAMUTCD specification may not be directly applicable in the application of a driveway but will be used to keep the test general and as such a total low volume roadway length of at least 200 feet is recommended. Another standard early warning sign denoted Sign #1 can also be optionally included. It is beneficial if the low volume access point has a staging area where driver can start without being able to see the intersection. If no blind staging area is available, the vehicle can be positioned such that it does not start with a direct view of the intersection.

Safety: The safety of all people involved with the testing is of upmost importance, as such protocols will be in place to limit any risk to life or property.

Licensing: All test drivers must be legally licensed to drive a vehicle.

Speed Limits: drivers will be told to drive on the approach to the signal at a low speed such as would be typical for a low volume access point like a driveway (15 mph max)

Operator Positioning: Operators shall stand outside of the open lanes in the designated roadway while vehicles are in motion. The operator of the signal shall be positioned such that they can see the signal while operating similar to how an AFAD is operated in the field.

Supervisor/Researcher Positioning: Supervisors or Researchers on the ground during testing shall stay outside of the designated roadway. While outside of the roadway these individuals may choose to position themselves however is deemed best on the ground to achieve their responsibilities.

Facility: The testing location will be a low volume road. Humans acting as flaggers will temporarily stop non test traffic from entering the simulated work zone while test vehicles are running.

Cameras: Cameras will be positioned generally as shown in the test plan, these cameras should be able to operate autonomously while vehicles are in motion. Positioning or checking of data can be performed while vehicles are not actively being driven in the test.

Hydration: Testing will occur partially under summer conditions that may bring heat. As such water should be provided to all people at the test site to ensure adequate hydration.

General Procedure: Drivers will assemble in the staging area, for most tests only one vehicle will be running through the work zone at a time. For some tests 2 or 3 cars may be allowed to enter and will have to queue at the traffic control device. Variable wait times will be tried. In the staging area each driver will be instructed with the following statement:

Remember to follow all traffic laws and limit speed to 15mph at all times. You are currently in the staging area, when instructed drive ahead following the road in front of you to the intersection. At the intersection your intended destination is to the left. Once you make your turn follow the road to the marked stop area. When you reach the stop area come to a complete stop and follow the directions to drive the vehicle back to the staging area. Treat this as you would an active work zone. Any questions?

NOTE: Some drivers will be told their destination is to the right rather than left.

Once the driver has completed the turn, he or she will return to the staging area and exits the vehicle. Each driver after completion of one run will be asked to fill out an anonymous survey (attached). The car position will be reset, and there will be a short break to allow for adjustment of equipment (i.e. checking cameras and other instruments). Once ready the next driver will start the cycle.

VI. Data and/or Specimen Banking

The video data will be kept until the end of the research contract. This research does not involve collecting any bi-data.

VII. Provisions to Monitor the Data to Ensure the Safety of Subjects

This research will only involve minimal risk to subjects similar to driving at low speeds in normal life outside of the research. The subjects (drivers) information will not be collected in the survey that is being used in research.

VIII. Withdrawal of Subjects

Subjects will be withdrawn from this study without their consent if they seem unwilling or unable to operate a motor vehicle safely at any time on the day of the testing. Subjects may also be withdrawn

if they are unable or unwilling to follow the directions given. For this study, there is no partial withdraw option.

Once withdrawn, subjects will be thanked for coming to the test site and escorted back to their mode of transportation.

IX. Risks to Subjects

Risks to subjects are minimal and will not exceed those associated with driving a vehicle at slow speeds in everyday life.

It is possible testing will be performed on warm days, as such a shade structure will be provided. Water will also be provided.

The risks are just the driving risks but to mitigate such risks the testing is done on remote roadway sections on an outskirt area of the campus and traffic control is used to mitigate any risks. Furthermore during tests are only involve driving short distances with a stop signal and therefore involves very low speeds.

X. Potential Benefits to Subjects

There are no direct benefits.

XI. Provisions to Protect the Privacy Interests of Subjects

All subjects will be reminded that this is voluntary, and they can leave at any time. If a subject feels uncomfortable driving a vehicle in the simulated work zone, they can leave at any time. All questions asked during the field test are designed to ascertain information about driving and not personal life matters.

Video recorded data has been designed to be anonymous by ensuring that no clear views of the drivers are recorded.

Personally identifiable information will not be collected about the subjects other than that on the consent forms.

XII. Economic Burden to Subjects

Subjects will not be responsible for any costs of the research except for minimal expenses in transporting themselves to the test site.

XIII. Review Requirements

Are there any contractual obligations or other considerations that require IRB review of this research or review at intervals other than those required by the Common Rule or FDA? If yes, check box:

☐ No

Appendix H:

Expanded Driver Questions

This appendix contains an expanded set of questions suggested to be used in future testing. These questions were IRB approved concurrently with the test protocol in Appendix F. The new questions that drivers were not asked during this research are inserted into position 1, 2, 3, and 9. Note that these insertions change the numbering versus the numbering referenced in the main report.

1. What is your age range? (circle one)
[18-29] [30-39] [40-49] [50-59] [60+]
2. How often do you typically drive a car? (circle the best match)
[Rarely] [At least once a month] [At least once a week]
3. How long have you had a driver's license in the USA? (circle the best match)
[less than 1 year] [1-5 years] [More than 5 years]
4. Was the device and/or signs confusing? (yes/no/explain)
5. Was the signal clearly visible? (yes/no/explain)
6. Was the Stop Here sign conclusive? (yes/no/explain)
7. Have you seen a signal similar to this in use before? (yes/no/explain)
8. Was the "stop here on red" sign helpful? (yes/no/explain)
9. If the sign had said "wait here on red" instead of "stop here on red," would it have changed your response in any way? (yes/no/explain)
10. Was the "no turn on arrow" sign helpful? (yes/no/explain)
11. Would you reword any of the signs (explain)? (yes/no/explain)
12. What do you think a blinking yellow arrow means? (yes/no/explain)
13. The intent of the signal is to tell you which direction you are allowed to turn. The idea is that you can turn only in the direction that the yellow arrow is blinking or solid. You must stop and wait for any direction that shows a red arrow. Was this clear to you when you saw the signal? (yes/no/explain)

14. How do you feel about this signal vs having a human flagger provide directions? (yes/no/explain)
15. Is there anything you would change? (yes/no/explain)
16. How would you improve the device and/or signs? (yes/no/explain)
17. General comments

Appendix I: Statistical Significance of Testing Variable

A standard statistical test is used to see if there is any evidence that the early warning sign affects drivers' compliance. The data is presented in a standard 2 x 2 contingency table in Table I.1, which, on the surface, seems to show that the results are approximately the same.

Table I.1 Compliance Contingency

	With Early Warning Sign	Without Early Warning Sign	
Compliant (Waited for Signal)	5	4	R1 = 9
Non-Compliant (Ran Red Light)	1	1	R2 = 3
	C1 = 6	C2 = 5	N = 11

The standard statistical test used is the Fishers Exact Test [1]. In this case, the null hypothesis (H_0) is that the compliance does not depend on having or not having the early warning signs. The alternative (H_a) is that some dependence exists. Fishers test (simplified for a 2 x 2 table) is given in Equation 1. In Equation 1, the terms a through d are the values in the table excluding the totals rows and columns.

$$p = \frac{R1!R2!C1!C2!}{a!b!c!d!N!} \quad \text{Equation 1}$$

The cutoff p -value calculated is approximately 0.54 which is already by itself above 0.05, as such there is no need to calculate the sum of the p -values under the cutoff value. Based on this, there is no statistical evidence to support that compliance depended on the presence of the early warning sign. We cannot reject the null hypothesis; however, this is not the same as saying we accept the null hypothesis.

Appendix I References

- [1] Wolfram MathWorld, "Fisher's Exact Test -- from Wolfram MathWorld."
<https://mathworld.wolfram.com/FishersExactTest.html> (accessed May 08, 2020).

Appendix J: Paraphrased Driver Comments

This appendix contains the paraphrased and/or summarized survey response data as shown in Table J.1. The main difference between the two results is that test 1 included an early warning sign while test 2 did not. There were also some minor changes to the drivers' directions given before the test.

Table J.1 Paraphrased/Summarized Test Driver Comments

Question	Paraphrased Responses
Q1 (test 1) Was the device and/or signs confusing?	<ul style="list-style-type: none"> • Not confusing, but I didn't expect the long wait • It was not confusing, but the long wait time made me keep looking back to the flagger behind the vehicle • Not confusing • Not confusing • I did not wait because I did not think it was part of the test • Not confusing, the red direction arrows were easy to understand
Q1 (test 2) Was the device and/or signs confusing?	<ul style="list-style-type: none"> • Not confusing except for the wait time • Confused where to stop because of the distance between the sign and the light • Not confusing • Not confusing, but decided to go after waiting since the light did not change • Not confusing, but the wait time was too long
Q2 (test 1) Was the signal clearly visible?	<ul style="list-style-type: none"> • Visible with some glare on the signs mounted to the signal • No issues • Visible • Yes • Visible, but the two signs before the signal felt like too much • Visible and at a good height
Q2 (test 2) Was the signal clearly visible?	<ul style="list-style-type: none"> • Visible • The no turn on red sign was not very clear • Visible with a clear view • Clear and visible, but wish the signal was back more • Visible
Q3 (test 1) Was the Stop Here	<ul style="list-style-type: none"> • Stop here sign could be overlooked, I noticed the lights first • Yes, the cone next to it was helpful • Yes, but was not totally clear where to stop

Question	Paraphrased Responses
sign conclusive?	<ul style="list-style-type: none"> • No, I could also see a worker with a slow sign • No because there were two other signs that gave the same information • Yes and I could tell I should not turn left or right but wait
Q3 (test 2) Was the Stop Here sign conclusive?	<ul style="list-style-type: none"> • Yes • No because too far from the light and the wait time was long so I was unsure if the signal was sensing the car or not. • Yes it was clear • Yes it was useful • Yes it was good, but I had to move up a bit for the signal to see the car
Q4 (test 1) Have you seen a signal similar to this in use before?	<ul style="list-style-type: none"> • Never seen before • Never seen before, but easy to understand • Never seen before • Never seen before • Don't remember seeing that before • Never seen before
Q4 (test 2) Have you seen a signal similar to this in use before?	<ul style="list-style-type: none"> • Yes • Yes • Never seen before, but easy to understand • Never seen before • Never seen before
Q5 (test 1) Was the "stop here on red" sign helpful?	<ul style="list-style-type: none"> • Helpful but could be overlooked • Very helpful • Helpful in instructing what to do • Helpful but confusing seeing a worker with a slow sign • Not needed I could tell from the red lights what to do • Helpful, without it may have stopped further forward
Q5 (test 2) Was the "stop here on red" sign helpful?	<ul style="list-style-type: none"> • Helpful • Helpful • Helpful telling where to stop • Sign was good, but a stop line may be nice • Helpful
Q6 (test 1) Was the "no turn on	<ul style="list-style-type: none"> • Helpful making it clear this should not be treated like a stop sign • Helpful otherwise I may have treated it like a stop sign • Helpful to clarify intent

Question	Paraphrased Responses
arrow" sign helpful?	<ul style="list-style-type: none"> • Helpful • Not needed, I could tell from the red arrow not to turn • Not needed, the red arrows were enough
Q6 (test 2) Was the "no turn on arrow" sign helpful?	<ul style="list-style-type: none"> • Helpful • Helpful • Helpful, made it clear to wait • Helpful, but I moved forward a little since I was not sure if I should keep waiting • Helpful
Q7 (test 1) Would you reword any of the signs (explain)?	<ul style="list-style-type: none"> • No rewording needed, maybe make the stop here more prominent • No rewording, but maybe add something about wait time • Signs were ok as is • Make sure no worker with slow sign visible • No rewording, but too many signs • The signs are easy to understand as is
Q7 (test 2) Would you reword any of the signs (explain)?	<ul style="list-style-type: none"> • No rewording • The yield in direction of blinking yellow arrow took a while to understand • Easy to understand as they are • Understandable as is with the red lights • The signs were all short and clear
Q8 (test 1) What do you think a blinking yellow arrow means?	<ul style="list-style-type: none"> • It means yield (the sign explaining it was helpful) • Go with caution • Yield or go with caution • Go slowly in direction indicated • Yield, only proceed when clear • Go slowly with caution
Q8 (test 2) What do you think a blinking yellow arrow means?	<ul style="list-style-type: none"> • Go with caution • Yield • Yield • Go with caution or treat it like a stop sign when blinking yellow • Go with caution
Q9 (test 1) The intent of the signal is to tell you which	<ul style="list-style-type: none"> • The signs made it clear • That is what I thought • It was clear since there were arrows both ways • It was clear • Not clear, I thought I had to turn left to get to the test • It was clear

Question	Paraphrased Responses
<p>direction you are allowed to turn. The idea is that you can turn only in the direction that the yellow arrow is blinking or solid. You must stop and wait for any direction that shows a red arrow. Was this clear to you when you saw the signal?</p>	
<p>Q9 (test 2)</p>	<ul style="list-style-type: none"> • It was not clear because I did not see the lights change so I went after waiting a while • I got it but took some time to figure out • The intent was clear • Understood, but how does it know which way I want to go? • It was clear
<p>Q10 (test 1) How do you feel about this signal vs having a human flagger</p>	<ul style="list-style-type: none"> • Prefer human flagger and believe people would follow a humans instructions better • Feel better with a human • Indifferent but the signal may be more clear than a human • Signal was ok, but was unsure if it sensed me • Signal is safer than a human • Prefer the signal, it won't make errors like humans

Question	Paraphrased Responses
provide directions?	
Q10 (test 2) How do you feel about this signal vs having a human flagger provide directions?	<ul style="list-style-type: none"> • Signal may have higher efficiency than a human • Prefer humans since they are familiar but the signal is good too • Signal as easy to understand and just as good as a human • Human flagger a little better but humans may not be practical • Not as friendly as a human, but I can see people getting tired.
Q11 (test 1) Is there anything you would change?	<ul style="list-style-type: none"> • Make the stop here sign more visible • Consider adding something to encourage waiting • Add another cone where we are supposed to stop • Don't have a worker visible with a slow sign • Less signs telling you to stop • Nothing or N/A
Q11 (test 2) Is there anything you would change?	<ul style="list-style-type: none"> • A little confusing exactly where I was meant to stop relative to the stop here sign, maybe add a stop line. • Nothing • Nothing • Maybe add a stop line since I was not sure if the signal could sense me • Maybe something to let you know you are detected
Q12 (test 1) How would you improve the device and/or signs?	<ul style="list-style-type: none"> • Generally worked well, maybe add something about wait time • Nothing more to add • Nothing more to add • Nothing to improve • Can't think of anything • I think the signal would be good for people who are not fluent in English
Q12 (test 2) How would you improve the device and/or signs?	<ul style="list-style-type: none"> • Consider adding a stop line • Shorten the sign explaining to yield • Nothing needed to improve • Nothing needed to change • Maybe make it bigger and more in direct sight

Question	Paraphrased Responses
Q13 (test 1) General comments	<ul style="list-style-type: none"> • Trying different car styles and more cars • Blank • Blank • Blank • Did not pay much attention to the signal since I thought I was supposed to turn left. • Nothing or N/A
Q13 (test 2) General comments	<ul style="list-style-type: none"> • Nothing or N/A • Needs some time to understand, but may be more efficient • No changes needed • The road was a little tight • Blank

Appendix K: Flagger Fatalities

Table K.1 includes the tabulation of the flagger fatalities as contained in the OSHA database for January 2017 through 2019. These are for all flaggers fatalities including private contractors.

Table K.1 OSHA Reported Flagger Fatalities from Jan 2017 through 2019

Event Date	Report ID	State	OSHA Link
11/11/2019	316400		https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=122249.015
8/29/2019	627100	Arkansas	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=119455.015
8/23/2019	155010	Vermont	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=122206.015
7/26/2019	551800	Indiana	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=121932.015
6/18/2019	1054116	Oregon	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=117392.015
1/9/2019	830500	Colorado	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=112495.015
9/14/2018	524200	Illinois	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=109211.015
8/14/2018	1054115	Oregon	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=110679.015
6/13/2017	751910	Iowa	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=96402.015
1/15/2017	336000	Pennsylvania	https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=92211.015
1/9/2017	352450		https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=94601.015