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16. Abstract

Video imaging vehicle detection systems (VIVDSs) are becoming an increasingly common means of detecting traffic at intersections and interchanges in Texas. This interest stems from the recognition that video detection is often cheaper to install and maintain than inductive loop detectors at multi-lane intersections. It is also recognized that video detection is more readily adaptable to changing conditions at the intersection (e.g., lane reassignment, temporary lane closure for work zone activities). The benefits of VIVDSs have become more substantial as the technology matures, its initial cost drops, and experience with it grows.

This research was conducted to gather information about VIVDS planning, design, and operations and to develop guidelines that describe the "best" practices for Texas conditions. This report documents the findings from the information gathering and guideline development activities. The guidelines are intended to inform engineers about critical issues associated with each stage, to guide them in making appropriate decisions during each stage, and to enable them to thoughtfully direct others during VIVDS installation and maintenance activities.

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# VIDEO DETECTION FOR INTERSECTION AND INTERCHANGE CONTROL

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# NOTICE

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# CHAPTER 1. INTRODUCTION

## OVERVIEW

Video imaging vehicle detection systems (VIVDSs) are becoming an increasingly common means of detecting traffic at intersections and interchanges in Texas. This interest stems from the recognition that video detection is often cheaper to install and maintain than inductive loop detectors at multi-lane intersections. It is also recognized that video detection is more readily adaptable to changing conditions at the intersection (e.g., lane reassignment, temporary lane closure for work zone activities). The benefits of VIVDSs have become more substantial as the technology matures, its initial cost drops, and experience with it grows.

It is estimated that about 10 percent of the intersections in Texas currently use VIVDSs. The collective experience with the operation of these intersections has generally been positive; however, this experience is limited to a short amount of time (relative to the life of such systems). Moreover, experience with the design and installation of a VIVDS for intersection control has been limited. This limitation is due to the fact that most intersection control applications have been "turnkey" arrangements with the product vendors. Further increases in VIVDS application will require greater participation by TxDOT engineers in the planning, design, operation, and installation stages.

This research was conducted to gather information about VIVDS planning, design, and operations and to develop guidelines that describe the "best" practices for Texas conditions. This report documents the findings from the information gathering and guideline development activities. The guidelines are intended to inform engineers about critical issues associated with each stage, to guide them in making appropriate decisions during each stage, and to enable them to thoughtfully direct others during VIVDS installation and maintenance activities.

## RESEARCH OBJECTIVE

The objective of this project was to develop guidelines for planning, designing, installing, and maintaining a VIVDS at a new or existing intersection or interchange. This objective was achieved by conducting the following activities:

- evaluated several VIVDS products with a focus on detection accuracy, system performance, and ease of setup;
- developed guidelines describing when and how to use VIVDS; and
- developed guidelines for detection design and detection layout.

## RESEARCH SCOPE

The guidelines developed for this project address the use of a VIVDS to provide vehicle presence detection at a signalized intersection or interchange in Texas. The facility can be new or existing. It can be in an urban or rural environment and on a collector or arterial roadway. To the extent practical, the guidelines are applicable to all VIVDS products. They are applicable to detection designs that use one camera (for each intersection approach monitored) to provide detection at the stop line and, if needed, detection in advance of the stop line.

The guidelines are developed for intersections and interchanges that use one signal controller. The research does not explicitly address the use of a VIVDS to facilitate coordinated signal operation beyond that needed to affect stop-line detection in support of such operation. The research does not address the use of a VIVDS for measuring vehicle count, speed, headway, occupancy, or other traffic characteristics beyond that needed for basic intersection (or interchange) control using presence-mode detection.

The terms "detection design," "detection layout," "detection zone," and "detection accuracy" are used frequently in this report. *Detection design* refers to the selection of camera location and the calibration of its field of view. *Detection layout* refers to the location of detection zones, the number of detection zones, and the settings or detection features used with each zone. A *detection zone* is defined to be one or more VIVDS detectors that are configured (or linked) to act as one detector and that are separated from upstream and downstream detection zones by at least the effective length of a vehicle. *Detection accuracy* relates to the number of times that a VIVDS reports either a detection when a vehicle is in the detection zone or no detection when a vehicle is not in the detection zone. Violation of either condition represents a discrepancy between the phase-call information provided by the VIVDS and the true call information, as would be provided by a perfect detector.

## RESEARCH APPROACH

A series of work tasks were conducted for this project. The activities associated with these tasks include:

- experiences with the installation and maintenance of VIVDSs were obtained from TxDOT engineers through a series of interviews,
- developing guidelines for VIVDS design and operation,
- conducting field studies at eight intersections and two interchanges in Texas,
- data from the field studies were used to evaluate and refine the guidelines, and
- documenting guidelines in an *Intersection Video Detection Manual* and a *Field Handbook*.

The manual was developed to help engineers determine when a VIVDS is appropriate, what functionality is needed, and how the detection components should be designed and operated. Information useful to signal technicians regarding VIVDS operations is presented in the handbook.

# CHAPTER 2. REVIEW OF VIVDS APPLICATIONS AND ISSUES

## OVERVIEW

This chapter presents the findings from a review of the literature on VIVDS applications. Also presented are the issues associated with VIVDS design and operation. Initially, several VIVDS products that are used in Texas are inventoried and their more-relevant features identified. Then, the common VIVDS applications are described and the conditions are identified for which VIVDS applications have been found to be cost-effective. Finally, there is a discussion of the technology and processing limitations associated with a VIVDS and how these challenges have been overcome through adherence to specific design and operation practices.

## APPLICATION CONSIDERATIONS

### Hardware and Features

The typical VIVDS uses one video camera to monitor each intersection approach and a central image processor unit that analyzes the video signal from multiple cameras. The central processor determines the status of each detection zone and communicates this information to the controller through the appropriate detector input terminals or bus. This type of system is shown in Figure 2-1. Several manufacturers also market single-camera processors that require less space in the cabinet (relative to the multiple-camera processor) and can be incrementally added to the controller cabinet on an "as needed" basis.

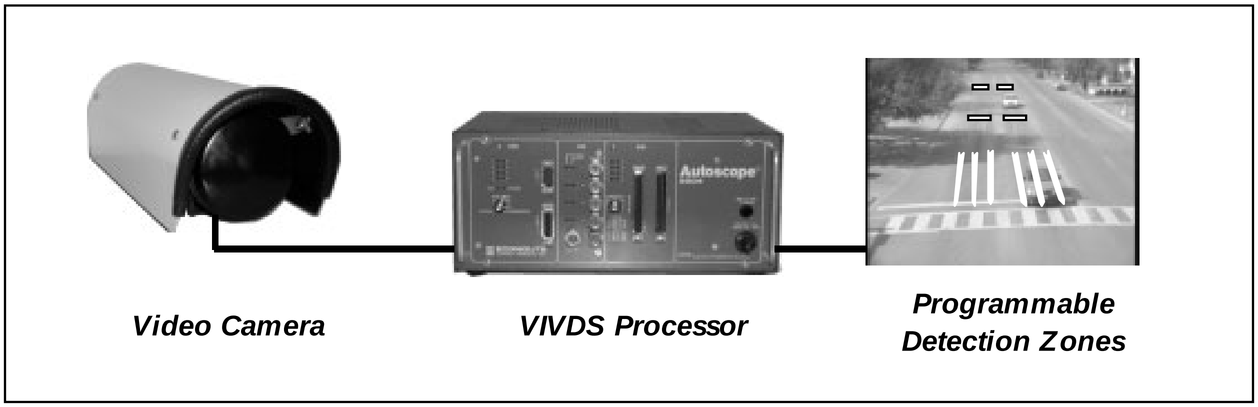


**Figure 2-1. Typical VIVDS Components.**

VIVDSs are available from several manufacturers including Image Sensing Systems, Iteris, Peek Traffic Systems, Traficon, Nestor Traffic Systems, and Transfomation Systems. The first three of these manufacturers collectively account for most of the sales for intersection applications in

Texas. The Traficon system is receiving increased attention due to its ease of installation and low initial cost. The characteristics of several VIVDS products are listed in Table 2-1.

**Table 2-1. Overview of Selected VIVDS Products.**

| Characteristic | Product Name | | | |
|---|---|---|---|---|
| | **Autoscope®** | **Vantage®** | **VideoTrak®** | **Traficon®** |
| Manufacturer | Image Sensing Systems, Inc. | Iteris, Inc. | Peek Traffic Systems, Inc. | Traficon NV |
| Signal control equipment partner | Econolite Control Products, Inc. | Eagle Traffic Control Systems | Peek Traffic Systems, Inc. | Traffic Control Technologies |
| Multiple-camera model (max. number of camera inputs) | 2004STD (6) | Vantage Plus (6) | VT910 (8) | not available |
| Single-camera model | Solo MVP | Vantage Edge | not available | VIP 3.1 & 3.2 |
| Maximum number of detection zones per camera | 32 | 24 | 32 | 24 |
| Maximum number of detection zones per processor [1] | 2004STD: 128<br>Solo MVP: 256 | Vantage Plus: 144<br>Vantage Edge: 24 | 128 | VIP 3.1: 24<br>VIP 3.2: 48 |
| Maximum number of detector outputs per processor [1] | 32 | Vantage Plus: 32<br>Vantage Edge: 24 | 64 | 24 |
| Requires a field setup computer | Yes | No | Yes | No |
| Field communications link [1] (camera-to-processor communications options) | 2004STD: coax<br>Solo MVPl: twisted pair | coax or wireless | coax | coax |
| Video image motion stabilization | Yes | Yes | Yes | Yes |
| Warranty period (parts & labor) | 2 years | 2 years | 2 years | 2 years |

Notes:
1 - Characteristics are listed by VIVDS model when differences among models exist.

As the information in Table 2-1 shows, each manufacturer offers a multiple-camera model that can accept several camera inputs and a single-camera model. The multiple-camera model is designed for typical three-leg or four-leg intersections. In contrast, the single-camera model may be better suited to complex intersections or situations where only one approach would benefit from video detection.

Differences between manufacturers exist primarily in their product's setup procedures and their field communications links. The Iteris and Traficon products do not require a field setup computer. Also, two manufacturers offer a wireless communication capability; however, power for the remote camera is typically provided through a cable connection.

Table 2-2 summarizes some of the features supported by the VIVDS products listed in Table 2-1. The number of products that support each feature is listed in the last column. The information in this table is indicative of the challenges faced by VIVDS manufacturers to provide accurate presence detection. These challenges include camera motion, shadows, reflections, detection distance, and contrast loss. The number of products supporting each feature is an indication of the extent of the associated impact.

**Table 2-2. Functional Capabilities of Several VIVDS Products.**

| Feature | Function/Issues Addressed | Number of Products Supporting Feature |
|---|---|---|
| Image Stabilization Algorithm | Algorithm that monitors the video image to quantify the extent of camera motion (due to wind or vibration) and minimizes the adverse effect of this motion on detection accuracy. | 4 |
| Sun Location Algorithm | Algorithm that computes seasonal changes in the position of the sun in order to reduce the frequency of unnecessary calls due to shadows. | 1 |
| Night Reflection Algorithm | Algorithm that monitors the video image to identify and mitigate the adverse effect of headlight reflections from the pavement. | 1 |
| Advance Detector Algorithm | Algorithm providing heightened sensitivity to detectors that are located in the top one-third of the monitor and that are monitoring vehicle presence at a point upstream of the stop line. | 1 |
| Contrast Loss Detector | Detector used to monitor the loss in image contrast (e.g., due to fog or heavy rain). This detector places a continuous call if image contrast is below acceptable levels. | 3 |
| Advance Detector | Detector located upstream of the stop line that measures vehicle speed and holds the call until the vehicle has time to travel through the approach dilemma (or indecision) zone. | 1 |
| Directional Detector | Detector that monitors vehicle presence and travel direction. This detector places a call only if the vehicle is traveling in a specified direction. | 4 |
| Boolean Detector Modifier | Feature that allows detection zones to be linked together using Boolean logic functions (e.g., AND, OR) to produce a single detection output. | 3 |
| Time-of-Day Detector Modifier | Feature that automatically changes the detection layout and design at specified times during a 24-hour period. | 1 |

## Common Applications

### *Stop-Line Detection*

For signalized intersection applications, a VIVDS is most often used to provide presence-mode detection in the vicinity of the stop line. The VIVDS cameras can be mounted on the mast arm or on the mast-arm pole. A VIVDS can provide reliable presence detection when the detection zone is relatively long (say, 40 ft or more). However, its limited ability to measure gaps between vehicles compromises the usefulness of several controller features that rely on such information (e.g., volume-density control, adaptive protected-permissive left-turn phasing) (*1, 2*).

### *Stop-Line Plus Advance Detection*

A VIVDS is sometimes used to provide advance detection on high-speed intersection approaches. However, some engineers are cautious about this use because of difficulties associated with the accurate detection of vehicles that are distant from the camera (*3*). Of those agencies that use a VIVDS for advance detection, the most conservative position is that it should not be used to monitor vehicle presence at distances more than 300 ft from the stop line. This position likely stems from guidance provided by the VIVDS manufacturers in their product manuals. For example, one manual provides the following guidance:

> "If your setup was optimal, you should be able to extend out ten feet for every one foot of camera elevation to a maximum distance of around three hundred feet" (*4, p. 108*).

The guidance cited above is similar to that provided in the manuals of other VIVDS products. It is referred to herein as the "10 ft to 1 ft" rule.

### *Cost-Effective Applications*

A VIVDS is primarily used in situations where its high initial cost is offset by that associated with installing and maintaining inductive loop detectors (*5*). VIVDSs have been generally recognized as cost-effective, relative to alternative detection systems, in the following situations:

- as a temporary detection system during intersection reconstruction (especially when lane assignments change during the course of the reconstruction project),
- as a temporary detection system at large intersections scheduled for overlay,
- as a permanent detection system when inductive loop life is short due to poor pavement, and
- as a permanent detection system when it is anticipated that lane location or assignment may change in less than three years.

The first situation noted above was investigated by Courage et al. (*5*). They found that the benefit-to-cost ratio of this VIVDS application was quite high (i.e., 10:1) because it allowed actuated operation to be maintained during lengthy reconstruction projects. The second situation is consistent with the Waco District's experience with Valley Mills Drive in Waco, Texas (*6*). The third situation reflects the experiences of TxDOT's Corpus Christi District (*6*). In this district, the combination of heavy truck traffic and poor soil conditions results in a relatively short life for inductive loops.

The City of Santa Clarita, California, has developed guidelines to determine when a VIVDS is appropriate for a particular intersection (*7*). At a typical intersection approach, the presence of any of the following conditions is considered to be sufficient to justify the use of a VIVDS:

- when the loop detection zones equal or exceed 100 ft,
- when the loop installation is physically impractical due to poor pavement, and
- when the pavement in which the loop is placed will be reconstructed in less than three years or during overlay projects at large intersections where the cost of replacing all loops exceeds the cost of installing the VIVDS.

*Special Applications*

The flexibility of a VIVDS has been found useful at unusual intersection approaches where inductive loops (and associated lead-ins) cannot be installed or are prohibitively expensive to install (*7*). Situations where these conditions may exist include:

- approaches that cross railroad tracks,
- approaches where one or more detection zones are located on a bridge deck, and
- approaches where special permits are required for installation of one or more inductive loops or the associated lead-in cables.

The first situation recognizes the difficulty associated with obtaining permission from the railroad companies to install conduits under their railroad tracks. This need arises when the railroad tracks are located in the detection zone of one or more intersection approach legs. The second situation recognizes the reluctance of most agencies to cut loops into a bridge deck due to possible compromises in the bridge deck's structural integrity. The third situation is a more general variant of the previous two situations and recognizes that underground utilities, machinery, and culverts sometimes pose special problems with the installation of loops or loop lead-ins.

In addition to vehicle control, the VIVDS can be used to provide a surveillance function at high-volume locations (*5*). Specifically, it can be used to remotely monitor intersection operations from a central control facility or a traffic management center.

## Life-Cycle Costs

Recent estimates of the life-cycle costs of a VIVDS have been reported by Chatziioanou (*8*) and by Middleton et al. (*6*). These estimates are based on the initial cost of purchasing and installing the system as well as its maintenance costs. Middleton et al. (*6*) found that a VIVDS is cost-effective whenever one video camera can replace three or more loops (e.g., a four-leg intersection with 12 lanes and a stop-line detector in each lane). They reported annualized life-cycle costs for a VIVDS of $3370 per intersection, compared with $3278 for inductive loops. Motorist delay costs due to installation or maintenance were not included nor was the cost of electricity to power the VIVDS.

Chatziioanou (*8*) provided a figure illustrating the relationship between present-worth life-cycle costs of a VIVDS and an inductive loop system based on the number of lanes served at an intersection. His analysis included all of the costs considered by Middleton plus motorist delay, power consumption, and liability due to system failure. His analysis included both a "low" and a "high" loop installation cost to add more range to the findings. The resulting relationship is reproduced in Figure 2-2.

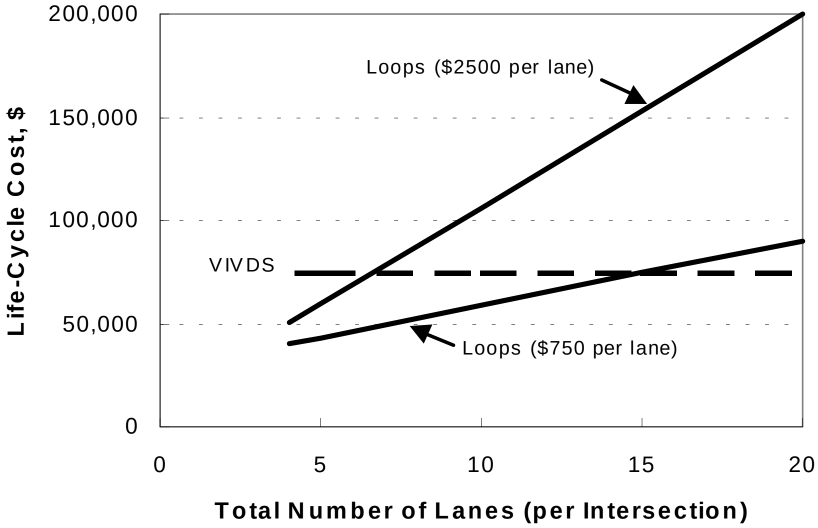


Figure 2-2. Life-Cycle Costs for Two Alternative Detection Systems.

The trends in Figure 2-2 show that when loop installation costs are about $750 per lane, an intersection would need to have 15 approach lanes or more before a VIVDS would be less expensive than loops. However, if loop installation costs are $2500 per lane, then a VIVDS would be less expensive at any intersection with six or more lanes.

## DESIGN ISSUES

VIVDS design elements consist primarily of the camera mounting location and its field-of-view calibration. In this regard, design considerations include the camera's height, offset (measured perpendicular to the direction of travel), distance from the stop line, pitch angle (relative to a horizontal plane), and lens focal length. The first three considerations refer to "camera location" and the last two considerations refer to the "field-of-view calibration." The variables associated with several of these considerations are illustrated in Figure 2-3. Lens focal length refers to the degree to which the field of view is magnified (or "zoomed"). Intersection lighting is also an important design consideration as it relates to VIVDS performance. Issues associated with these VIVDS design elements are described in this section.

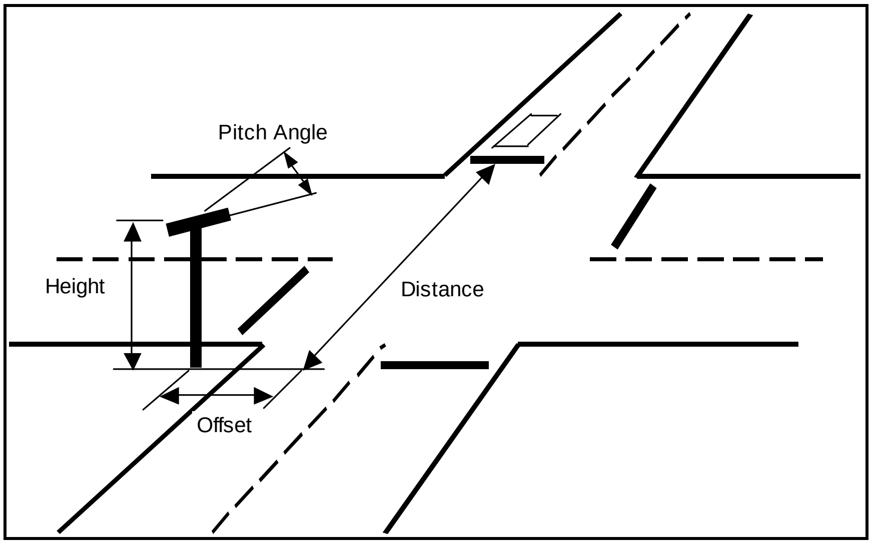


**Figure 2-3. Variables Defining a Camera's Location and Field of View.**

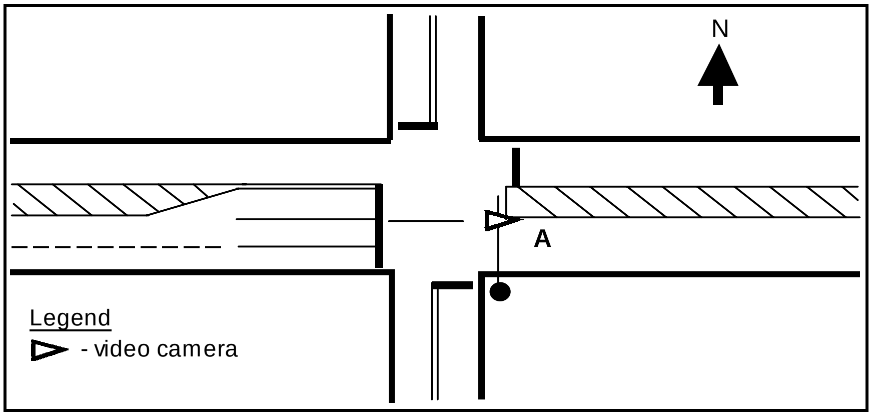
## Camera Location

Camera location is an important factor influencing detection accuracy (*8*). Guidance provided by several VIVDS product manuals consistently describes an optimal location as one that provides a stable, unobstructed view of each traffic lane on the intersection approach (*4, 9*). Moreover, the view must include the stop line and extend back along the approach for a distance equal to that needed for the desired detection layout. An example of an optimal camera location is identified by the letter "A" in Figure 2-4a. Its associated field of view is shown in Figure 2-4b. The factors that are reported to make this camera location optimal are described in this section.

### *Camera Height and Offset*

The VIVDS product manuals indicate that detection accuracy will improve as camera height increases, within the range of 20 to 40 ft (*4, 9, 10*). Increased height improves the camera's view of each approach traffic lane by minimizing the adverse effects of occlusion. Occlusion refers to a situation where one vehicle blocks or obscures the camera's view of a second vehicle.

Three types of occlusion are present with most camera locations: adjacent-lane, same-lane, and cross-lane. Adjacent-lane (or horizontal) occlusion occurs when the blocked and blocking vehicles are in adjacent lanes. Figure 2-5 illustrates this type of occlusion. In this figure, the truck in the through lane blocks the camera's view of the left-turn lane. The truck is likely to inadvertently trigger a call for the left-turn phase (regardless of whether the phase is needed). Moreover, if the left-turn phase leads the through phase, the left-turn phase is likely to extend to its maximum duration.



**a. Illustrative Optimal Camera Location.**

**b. Illustrative Optimal Field of View.**

**Figure 2-4. Illustrative Optimal Camera Location and Field of View.**

Figure 2-6 illustrates the potential for adjacent-lane occlusion when the camera is mounted on the left side of the approach. Although occlusion by a vehicle is not explicitly shown in this figure, its potential is quite real given the flat angle of the camera and the location of the detection zones (the upstream corner of each zone is denoted by a numeral).

Figure 2-5. Adjacent-Lane Occlusion with Right-Side Camera.

Figure 2-6. Adjacent-Lane Occlusion with Left-Side Camera.

Adjacent-lane occlusion from a left-side camera can be caused by vehicles approaching or departing the intersection. A vehicle waiting in the left-turn bay will occlude the camera's view of the adjacent through lane. A tall vehicle departing the intersection in the inside through lane will occlude the left-turn bay. Either type of occlusion can lead to unneeded calls for the left-turn or through phase. In Figure 2-6, a truck departing from the intersection in the outside lane casts a shadow (from the luminaire) and triggers an unnecessary call for the left-turn phase (as denoted by the four highlighted corners for each of two detection zones in the left-turn bay).

Adjacent-lane occlusion can be eliminated when the camera is mounted directly in front of the traffic movements it monitors, as shown in Figure 2-4a. If this central location cannot be achieved and the camera is mounted on the left or right side of the approach, then the occlusion can be minimized by increasing camera height. One product manual recommends increasing the camera height by 3.3 ft (above that used for a central location), if the camera is located on the left or right side (*10*).

Same-lane (or vertical) occlusion occurs when the blocked and blocking vehicles are in the same lane. Figure 2-7 illustrates this type of occlusion. The tall truck at the stop line blocks the camera's view of the lane just behind the truck's trailer. Same-lane occlusion prevents the separate detection of successive vehicles as they cross the stop line. This type of occlusion is not problematic when presence-mode operation is combined with a stop-line detection zone. Same-lane occlusion is largely a problem when count measurements are needed by the controller (such as for volume-density operation). The extent of this problem increases as the distance between the location of measurement and the stop line increases.

**Figure 2-7. Same-Lane Occlusion.**

One manual indicates that a camera height of 20 ft or more is sufficient to minimize the effect of same-lane occlusion for presence-mode operation on a two-lane approach (*10*). The guidance in this manual recommends an increase in height of 3.3 ft for each additional approach lane that is monitored. When detection zone is located upstream of the stop line, several manuals recommend 1 ft of camera height for every 10 ft between the camera and the upstream edge of the most distant detection zone (*4, 9, 10*).

Cross-lane occlusion occurs when a vehicle crosses between the camera and the intersection approach being monitored. This crossing vehicle momentarily obstructs the camera view of the subject approach and prohibits the VIVDS from sensing vehicle presence. There is also the possibility that the crossing vehicle will trigger an unnecessary call to the subject approach. However, most VIVDS products have detectors that can be set to operate in a "directional" mode such that crossing vehicles are ignored.

### *Camera Mount*

Desirable camera heights and offsets are often limited by the availability of structures that can provide a stable camera mount. Considerations of height, offset, and stability often require a compromise location that is subjectively determined to provide the best performance. Camera mounting locations vary widely with each intersection. Typical locations include luminaire arms, signal head mast arms, and signal poles. Figure 2-8 shows a camera mounted on a mast arm. Figure 2-9 shows a camera mounted on a luminaire arm. Of the two mountings, the former provides the optimal camera offset; however, it is likely to be associated with more wind-induced motion.

As noted in Table 2-1, most VIVDS manufacturers incorporate image stabilization algorithms in their products. Unfortunately, these manufacturers do not quantitatively describe the amount of movement that can be mitigated by their respective algorithms. Casual observation of VIVDS installations suggests that satisfactory performance is realized with a mast arm mount; however, there is no published information available to support this observation.

## Field-of-View Calibration

Calibration of the camera field of view is based on a one-time adjustment to the camera pitch angle and the lens focal length. Guidance provided in several VIVDS product manuals consistently describes an optimal field of view as one that has the stop line parallel to the bottom edge of the view and in the bottom one-half of this view (*4, 9*). The optimal view also includes all approach traffic lanes. The focal length would be adjusted such that the approach width, as measured at the stop line, equates to 90 to 100 percent of the horizontal width of the view. Finally, the view must exclude the horizon. An optimal field of view is shown in Figure 2-4b. The factors that are reported to make this field of view optimal are described in this section.

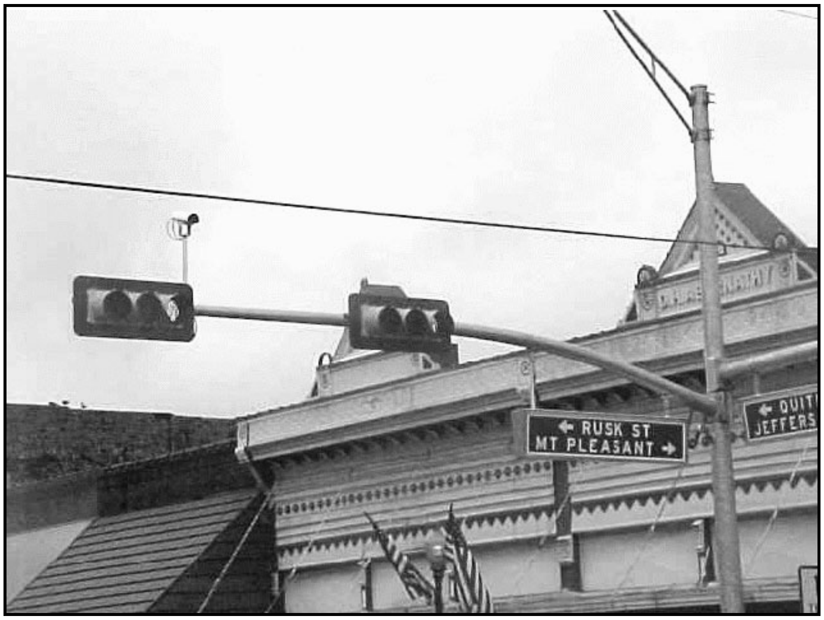


Figure 2-8. Mast Arm Camera Mount.

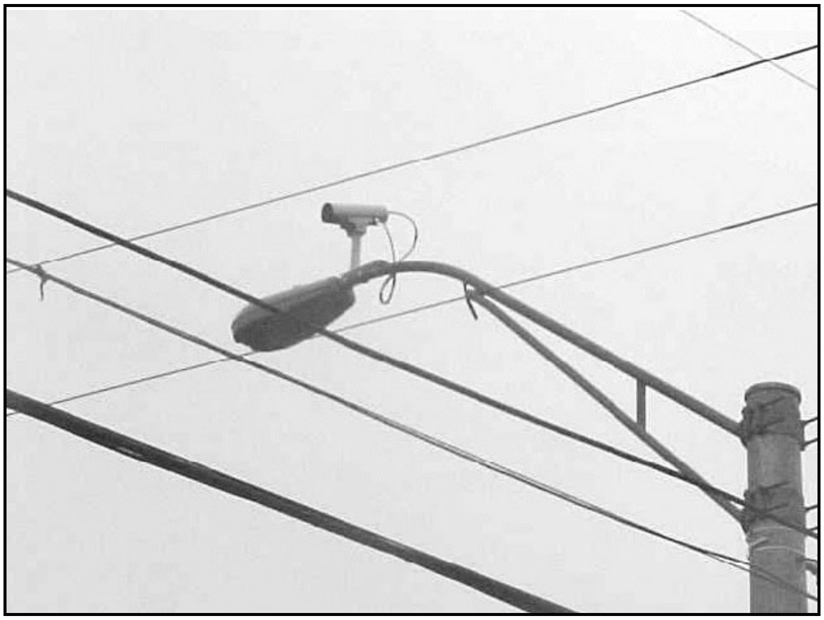


Figure 2-9. Luminaire Arm Camera Mount.

*Pitch Angle*

The VIVDS product manuals indicate that detection accuracy is significantly degraded by glare from the sun and, sometimes, from strong reflections from smooth surfaces (*4, 9*). Both reflection and sun glare are illustrated in Figure 2-10. Sun glare represents direct sunlight entering the camera (typically during dawn or dusk hours). Reflections emanate as "stars" of bright light coming from vehicle corners or edges.

**Figure 2-10. Reflection and Glare from the Sun.** (*2*)

Glare causes the video image to lose contrast and severely limits the VIVDS processor's ability to identify the outline of a vehicle. Larger pitch angles, as defined in Figure 2-3, can reduce the impact of sun glare. Sun glare typically causes problems for the eastbound and westbound approaches.

Reflections have both positive and negative effects on detection accuracy. On the positive side, a reflection represents a very significant change in contrast that ensures detection of a vehicle. The negative element of a reflection is that it can sometimes over-represent the actual size or location of the vehicle (especially at night). Middleton et al. (*6*) note that a lens equipped with an automatic iris will minimize the adverse effects of reflection.

To avoid the deleterious effects of sun glare, the VIVDS product manuals recommend that the camera be angled downward sufficiently far as to exclude the horizon from the field of view. Guidance with regard to the "10 ft to 1 ft" rule, implies a minimum pitch angle of about 6.0 degrees. VIVDS processors have the ability to detect excessive glare or reflection and automatically invoke a maximum recall on the troubled approach. However, as noted by Baculinao (*2*), this action can lead to excessive delay if the troubled eastbound or westbound approach has a low traffic volume, relative to the northbound or southbound movements. Middleton et al. (*6*) note that an infrared filter on the camera lens can reduce the adverse effects of glare.

### *Focal Length*

Detection accuracy is dependent on the size of the detected vehicle, as measured in the field of view. Accuracy improves as the vehicle's video image size increases. Image size, in turn, can be increased by increasing the lens focal length. Figure 2-11 illustrates the effect of focal length on vehicle image size. Figure 2-11a illustrates the field of view with an 8 mm focal length. Figure 2-11b illustrates the field of view with a 16 mm focal length. The larger image size of the vehicles in Figure 2-11b provides more pixels of information for the VIVDS processor to analyze.

**a. Focal Length of 8 mm.** **b. Focal Length of 16 mm.**

**Figure 2-11. Effect of Focal Length on Vehicle Image Size.**

### *Other Considerations*

In addition to pitch angle and focal length, the VIVDS manuals describe several additional factors that should be considered when establishing the field of view. These factors include light sources and power lines. If the pitch angle or focal length cannot be adjusted to avoid the presence of these factors in the field of view, then alternative camera locations should be considered. If such locations cannot be found, then careful detection zone layout can minimize the effect of light sources or power lines on detection accuracy.

**Lights in the Field of View.** The camera field of view should be established to avoid inclusion of objects that are brightly lit in the evening hours, especially those that flash or vary in intensity. These sources can include luminaires, signal heads, billboard lights, and commercial signs.

The light from these sources can cause the camera to reduce its sensitivity (by closing its iris), which results in reduced detection accuracy. If these sources are located near a detection zone, they can trigger unnecessary calls. Figure 2-6 illustrates a case where the signal indications are sufficiently close to the detection zones as to cause an occasional unnecessary call.

**Power Lines and Cables.** The presence of overhead power lines or span-wire-mounted signal heads can pose problems during windy conditions. During daytime hours, the swaying lines or heads can trigger unnecessary calls if they move into and out of a detection zone. During the nighttime hours, a swaying signal head is likely to reduce the effectiveness of the camera lens' automatic iris (or electronic shutter) feature and, thereby, reduce detection accuracy.

The effect of various light sources on the video image is shown in Figure 2-12. Fixed lighting for adjacent parking lots are shown in the upper corners of the photographs. The two smaller points of light above the vehicles are span-wire-mounted signal heads. Figures 2-12a and 2-12b were taken about 0.5 s apart on an evening with moderate winds. A comparison of the two figures illustrates significant variation in light level in a short span of time. Figure 2-12b is also slightly darker overall indicating that the automatic iris (or electronic shutter) has started to close in response to the excessive glare.

**a. Heads at Minimum Light Position.** **b. Heads at Maximum Light Position.**

**Figure 2-12. Swaying Span-Wire-Mounted Signal Heads.**

## Intersection Lighting

Most VIVDSs have separate image-processing algorithms for daytime and nighttime conditions. The daytime algorithm searches for vehicle edges and shadows. During nighttime hours, the VIVDS searches for the vehicle headlights and the associated light reflected from the pavement.

Research has found that the nighttime algorithm is less accurate than the daytime algorithm and also has a tendency to place calls before the vehicle actually arrives to the detection zone (*3, 6*). Specifically, many VIVDS products tend to have difficulty distinguishing between a vehicle and the segment of roadway it lights with its headlights. This problem is illustrated in Figure 2-13.

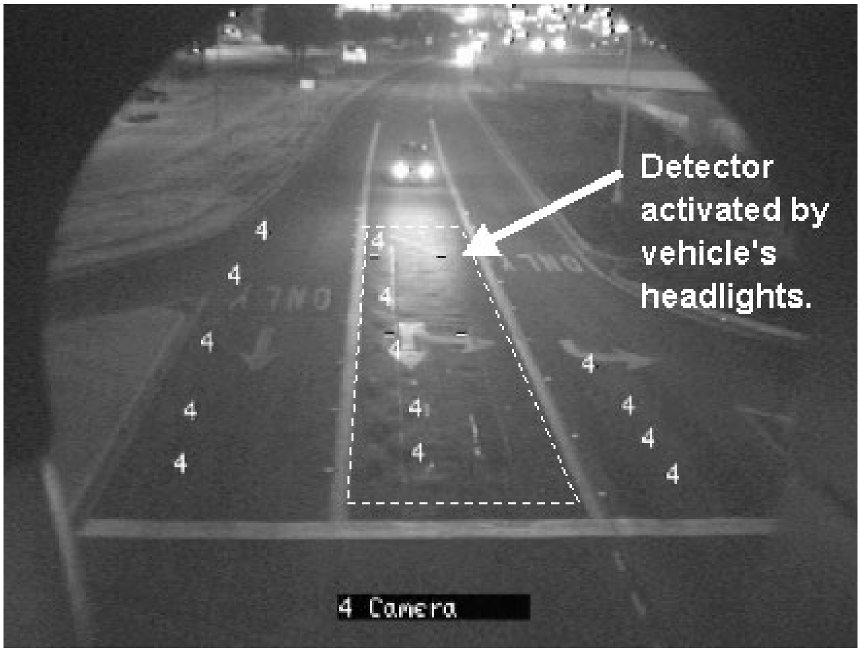


**Figure 2-13. Detection of Headlight Reflection.**

Figure 2-13 shows a vehicle approaching the stop-line detection zone at a frontage road intersection. The light from the vehicle's headlights illuminates the pavement in the detection zone and triggers a call for service (this call is indicated in the figure by the four highlighted corners of the upstream detector). The consequences of this "early" detection are minimal if it occurs during the red indication. If it occurs during the green indication, the phase would be unnecessarily extended and further delay the conflicting traffic movements. Grenard et al. (*3*) found that intersection lighting can minimize the extent of this problem.

## OPERATION ISSUES

Once installed, the performance of the VIVDS is highly dependent on the manner in which its detection zones are defined and operated. In this regard, layout and operations decisions include zone location, detection mode, detector settings, controller settings, and verification of daytime and nighttime performance. Issues related to the first four decision areas are discussed in the section titled "Detection Zone Layout." Issues related to the last decision area are discussed in a subsequent section titled "On-Site Performance Checks."

### Detection Zone Layout

Detection zone layout is an important factor influencing the performance of the intersection. Guidance provided by several VIVDS product manuals indicates that there are several factors to consider including: zone location relative to the stop line, the number of VIVDS detectors used to constitute the zone, whether the detectors are linked using Boolean logic functions, whether the zone monitors travel in a specified direction, and whether the zone's call is delayed or extended (*4, 9, 10*). An example of an optimal detection zone layout is illustrated in Figure 2-14. The factors that are reported to make this layout optimal are described in this section.

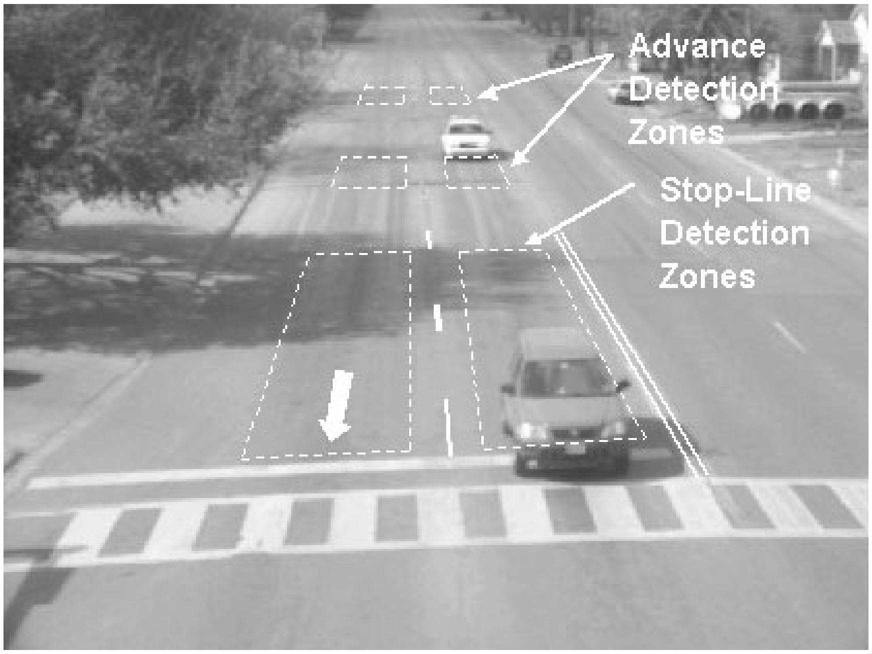


**Figure 2-14. Illustrative Optimal Detection Zone Layout.**

*Detection Zone Location*

Like inductive loops, VIVDS detectors can be placed within a lane or across several lanes. They can be placed at the stop line or several hundred feet in advance of it. The VIVDS product manuals offer some guidance for locating a VIVDS detection zone and the detectors that comprise it. These guidelines are summarized and described in Table 2-3.

It is inferred by the discussion in the VIVDS manuals that queue service at the start of the phase is provided by presence-mode stop-line detection. The implication is that volume-density operation is not accommodated by a VIVDS. Baculinao (*2*) noted this limitation when trying to use a VIVDS to support volume-density operation. The advance detection zone had difficulty counting the true number of vehicles arriving during the red indication. To overcome this limitation, he added a stop-line detection zone and used a controller feature to disconnect this zone after queue clearance. Thereafter, the phase was extended by the advance detection zone.

**Table 2-3. Detection Zone Location Guidance Provided by VIVDS Manufacturers.**

| Application | Guideline | Rationale |
|---|---|---|
| Stop-Line Detection | Stop-line detection zone typically consists of several detectors extending back from the stop line. | For reliable queue service, stop-line detection typically requires monitoring a length of pavement 40 ft or more in advance of the stop line. |
| | Put one detection zone downstream of the stop line if drivers tend to stop beyond this line (*4*). | Avoid having one long detector straddle a pavement marking. |
| | Use specific techniques to heighten detector sensitivity (e.g., overlap individual detectors slightly) (*4*). | Vehicle coloration and reflected light may combine to make some vehicles hard to detect. |
| Advance Detection | Advance detection typically consists of two detectors strategically located on the approach. | Advance detection uses passage time to extend the green for vehicles in the dilemma zone. |
| | Advance detectors can reliably monitor vehicles at a distance (from the camera) of up to 10 ft for every 1 ft of camera height (*4, 9)*. | Detection accuracy degrades as the location being monitored by the VIVDS becomes more distant from the camera. |
| Individual Detector | Avoid having pavement markings cross or straddle the boundaries of the detection zone (*4, 9, 10*). | Camera movement combined with high-contrast images may confuse the processor and trigger an unneeded call. |
| | The detector length should approximately equal that of the average passenger car (*4, 9, 10*). | Maximize sensitivity by correlating the number of image pixels monitored with the size of the typical vehicle being detected. |

### *Detection Mode*

One reported benefit of a VIVDS is the large number of detection zones that can be used and the limitless ways in which they can be combined and configured to control the intersection. Both pulse-mode and presence-mode detectors can be used, where the latter can have any desired length. In addition, VIVDS detectors can be set to detect only those vehicles traveling in one direction (i.e., directional detectors). They can also be linked to each other using Boolean functions (i.e., AND, OR). The use of these features is shown in Figure 2-15. The detector labeled "delay" in this figure is described in the next section.

Figure 2-15 is an idealized illustration of alternative detection modes. The approach shown has presence-mode stop-line detection in each of the through and left-turn lanes. The zones in the two through lanes are linked using an OR logic function. Detection of a vehicle in either lane will trigger a call to the through phase. This operation is identical to that achieved when both detectors are assigned to the same channel. However, the linkage allows for the specification of a common delay or extension time for both detectors (*4, 9*).

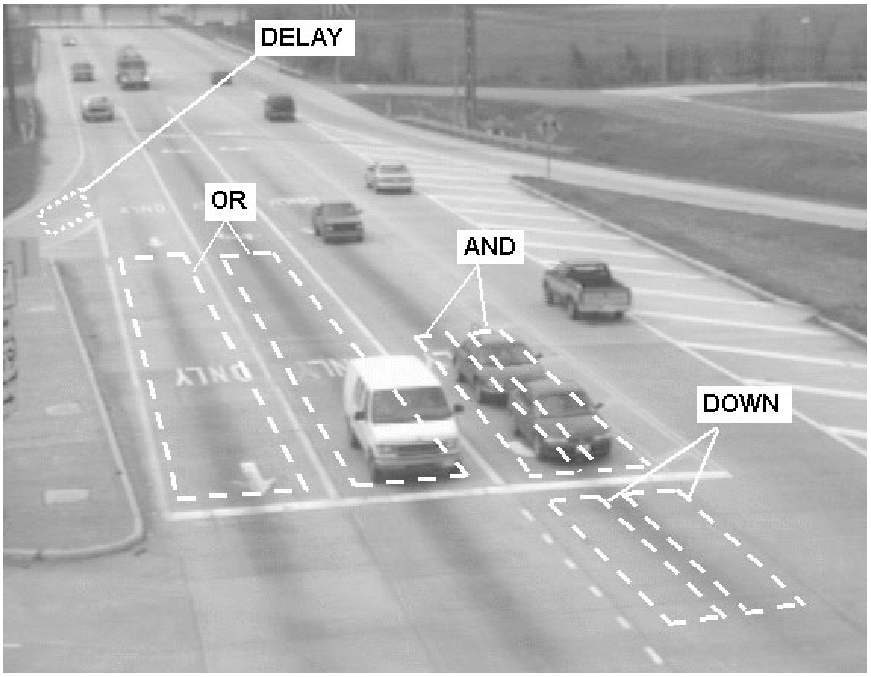


**Figure 2-15. Alternative Detection Modes.**

The left-turn bay in Figure 2-15 uses two parallel detection zones for improved selectivity and sensitivity. Specifically, the right-side camera offset raises the possibility of an unneeded call from a tall vehicle in the adjacent through lane. The AND linkage for the two left-turn detection zones minimizes this problem. Also, for some VIVDS products, the use of two detectors in the same lane improves detection sensitivity.

Lastly, the intersection approach shown in Figure 2-15 is skewed from 90 degrees, which results in a large distance between the stop line and the cross street. This setback distance is especially significant for the left-turn movements. In anticipation that left-turn drivers may creep past the stop line while waiting for a green indication, additional detectors are located beyond the stop line. However, they are directional detectors (as denoted by the word DOWN), such that they prevent crossing vehicles from triggering an unneeded call.

*Detector and Controller Settings*

Video detectors have delay and extend settings that can be used to screen calls or add time to their duration, as may be needed by the detection design. The controller passage time setting is also available to provide the overall operation intended by the detection design.

The delay and extend settings are identical in performance and purpose to those available with inductive loop amplifiers. The use of the delay setting is shown in Figure 2-15. The detector in the right-turn lane is used as a queue detector to trigger a call to the through movement in the event that the right-turning drivers cannot find adequate gaps in traffic. The delay is set to about 2 s, such that a turning vehicle does not trigger a call unless it is stopped in queue.

The review of VIVDS product manuals revealed a general lack of guidance describing when the various detector settings should be used. Moreover, these manuals do not describe techniques for the effective use of the detector or passage time settings in conjunction with a VIVDS installation. From this absence of guidance, it is inferred that the VIVDS manufacturers believe that the traditional techniques for designing the layout for inductive loop detectors are applicable to VIVDS detection zone layout.

Baculinao (*2*) described a series of operational problems that surfaced when the City of Santa Clarita, California, converted from inductive loops to video detection at several intersections. Through a process of trial-and-error, they discovered that their procedures for defining detector layout and operation resulted in unacceptable performance when directly applied to a VIVDS installation.

One problem Baculinao (*2*) found was related to the effective increase in vehicle length that resulted from video detection. This problem is illustrated in Figure 2-16 for a bus. In this figure, the bus's detected length is almost twice its actual length because of the effect of same-lane occlusion. Baculinao (*2*) found that the passage time setting had to be reduced from 3.5 to 2.0 s to yield operation equivalent to that obtained when using inductive loops.

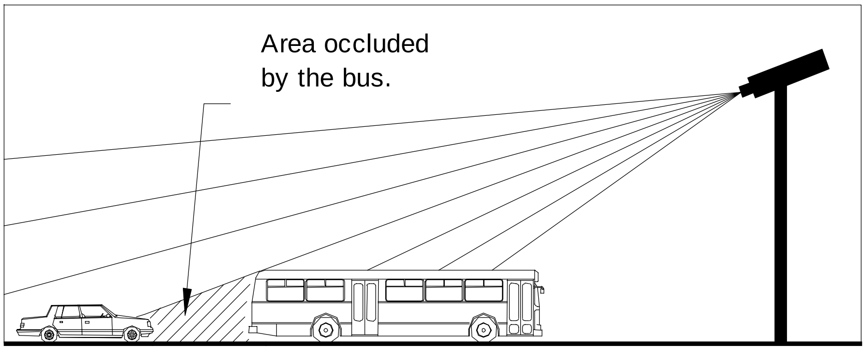


**Figure 2-16. Effect of Same-Lane Occlusion on Detected Vehicle Length.** (*2*)

## On-Site Performance Checks

The performance of VIVDS products is adversely affected by both environmental and temporal conditions. Environmental conditions include fog, rain, wind, and snow. These conditions have a direct effect on the contrast and brightness information captured by the camera. Indirectly, they cause condensation and dirt buildup on the camera lens that further degrade VIVDS performance. Temporal conditions include changes in light level and reflected light that occur during a 24-hour period and during the course of a year (i.e., seasonal changes in sun position).

In recognition of the wide range of factors that can influence VIVDS performance, at least one VIVDS manual encourages an initial check of the detector layout and operation during the "morning, evening, and at night" (*4, p. 109*) to verify the operation is as intended. Recommendations for periodic checks at specified time intervals (e.g., every six months) are not offered by the manufacturers. One VIVDS product has the ability to adapt to seasonal changes in sun location (and the resulting shadows); however, the manner by which this feature functions is not described in the product manual (*9*). Moreover, the effectiveness of this feature has not been documented in the research literature.

# CHAPTER 3. SURVEY OF TxDOT PRACTICE

## OVERVIEW

This chapter summarizes the findings from a survey of the video detection experiences of several TxDOT engineers and technicians. These individuals collectively represent five TxDOT districts as well as the Traffic Division in Austin. The survey consisted of a structured interview using a prepared set of questions. The questions ranged from basic questions of VIVDS equipment inventory to problems encountered with VIVDSs and techniques used to overcome these problems.

The TxDOT districts visited and individuals contacted are listed in Table 3-1. As the data in the table indicate, the information obtained reflects the collective experience of 18 individuals supervising 632 signalized intersections of which 209 intersections are equipped with a VIVDS. The information shared by these individuals is summarized in this chapter.

**Table 3-1. Survey Contacts.**

| Survey Participants | | TxDOT District | Total Signalized Intersections | Intersections with Video Detection | Oldest VIVDS in Service, years |
|---|---|---|---|---|---|
| Mr. Gary Barnett | Mr. Carlos Ibarra | Atlanta | 117 | 39 (33%) | 6.0 |
| Mr. Kirk Barnes | | Bryan | 85 | 1 (1%) | 1.5 |
| Mr. Wayne L. Carpenter<br>Mr. Ismael C. Soto<br>Mr. Robert J. Traynor | Mr. Jorge A. Salinas<br>Mr. Bill Randall<br>Mr. Dexter C. Turner | Corpus Christi | 170 | 130 (76%) | 3.5 |
| Mr. Herbert Bickley<br>Mr. Stephen Walker | Mr. Richard Ivy | Lufkin | 100 | 29 (29%) | 7.0 |
| Mr. Calvin Brantley<br>Ms. Juanita Daniels<br>Mr. Glenn Kitson | Mr. Larry W. Combs<br>Mr. Peter Eng<br>Mr. Rusty Russell | Tyler | 160 | 10 (6%) | 2.5 |
| Mr. David Danz<br>Mr. Brian Van De Walle | Mr. David Mitchell | Traffic Division | -- | -- | -- |
| | | **Total:** | 632 | 209 (33%) | 20.5 |

## APPLICATION CONSIDERATIONS

### Inventory

Information obtained during the interviews suggests that TxDOT is installing a VIVDS at about one-half of all newly constructed intersections. The interviewees speculated that TxDOT has a VIVDS at about 650 signalized intersections, representing about 10 percent of the signalized intersections on the state highway system. The first TxDOT installations occurred about 1990 with the annual number of installations increasing each year since then.

Three VIVDS products were found to be in use at the time of the interviews. The most commonly found product is the Vantage system which is manufactured by Iteris, Inc. It accounts for about 90 percent of all VIVDSs being used by TxDOT. The Autoscope, manufactured by Image Sensing Systems, Inc., is used at about 8 percent of intersections. The remaining 2 percent of intersections were found to have the VideoTrak system, which is manufactured by Peek Traffic Systems, Inc.

### Advantages

Discussions with the TxDOT staff indicated that a VIVDS has several advantages relative to an inductive loop system. The primary advantage relates to the "time-between-failure." VIVDSs have been found to be very reliable in this regard with failures being a rare experience. It should be noted that "failure" is defined to be any disruption that prevents vehicles from being detected consistently and reliably for an extended period of time.

The sources of failure for inductive loops are significant and are generally a consequence of breakage in the loop wire or its lead-in. Loop wire breakage can be due to deterioration and deformation of asphaltic pavements that results from a combination of frequent high temperatures and heavy truck loads. Breakage can also occur as a result of pavement milling and resurfacing operations. The percent of loops failing each year ranges from 4 to 40 percent, depending on the district's overall soil properties and volume of heavy trucks. These percentages are consistent with the findings reported previously by Middleton et al. (*6*). They translate into an average loop life ranging from 2.5 to 25 years.

Another reported advantage of a VIVDS is that it allows the engineer to easily relocate detection zones when lanes are temporarily closed due to construction activities. Also, the locations of advance detection zones can also be easily adjusted if the approach speed changes significantly.

### Life-Cycle Costs

Several factors are considered in the selection of a detection system (e.g., VIVDS, loops, etc.). These factors include: equipment cost, installation cost, road-user costs during installation, and maintenance cost. The first two factors are essentially direct costs whereas the latter two are indirect costs associated with a system.

Historically, inductive loops have been found to be more cost-effective; however, in the last few years, the cost of a VIVDS has decreased making it cost-competitive in many situations. In general, each district has (at some point in time) performed an analysis of the direct costs of a VIVDS and an inductive loop system for a typical intersection. If this analysis confirms that the two systems are cost-competitive, the district tends to use a VIVDS thereafter for all new installations.

### *Detection System Cost*

The cost of installing and maintaining a VIVDS and an inductive loop system at a new intersection was discussed. The direct cost components of a VIVDS include the initial cost of the equipment, the cost to purchase and install the coaxial cable, the labor cost associated with the installation of the VIVDS cameras, and the cost of setting up the detection zones. These costs were estimated to total about $23,000 for a typical, four-camera VIVDS; a breakdown of cost components is shown in Table 3-2. The total 10-year cost represents a present-worth analysis based on a 3.0-percent annual interest rate.

**Table 3-2. Representative Detection System Cost Comparison.**

| Detection System | Component | Direct Cost, $ | Maintenance Costs, $/yr | Total 10-Year Cost, $ |
|---|---|---|---|---|
| VIVDS | Hardware (processor + four cameras) | 16,000 | | |
| | Install coaxial wire lead-ins for four cameras | 3000 | | |
| | Install cameras and set up detection zones | 4000 | | |
| | Total: | 23,000 | 600 | 28,000 |
| Inductive Loops[1, 2] | Loops installed only at stop line | 22,000 | 800 | 29,000 |
| | Loops installed in advance and at stop line | 37,000 | 1600 | 51,000 |

Notes:
1 - Loop costs are based on a high-speed, four-lane major road intersecting with a low-speed, two-lane minor road.
2 - Maintenance costs for loops are based on an average loop life of 10 years.

Also shown in Table 3-2 is an estimate of the cost of an inductive loop detection system for a typical intersection. This cost estimate is based on the following assumptions: a 40-ft inductive loop located at the stop line costs $900; a 6.0-ft loop located in advance of the stop line costs $550; three 6.0-ft loops are installed in each lane of both major-road approaches; left-turn bays are present for all approaches; conduit installation for advance loop detection is $4000 per approach; traffic control for a through lane closure costs $1000; and the agency waits for two loops to fail before making a repair. The costs shown do not include road-user costs during installation or repair. Other assumptions are listed in the table footnotes.

The costs listed in Table 3-2 are intended to illustrate the points raised during the interviews and the general trends in relative cost that have been reported. These costs indicate that a VIVDS has an initial cost that is slightly higher than that of inductive loops for a stop-line-only application. The cost of the additional loops for an advance detection application reverses this trend. Regardless, the VIVDS has a much lower total cost (over a 10-year period) when the cost of loop replacement is considered.

The selection of a detection system at an existing intersection is complicated by the fact that the existing inductive loop system is often in place and providing some service. Under these circumstances, the wholesale replacement of the loops with a VIVDS is sometimes difficult to justify. It was noted that one district has overcome this complication by using a single-camera VIVDS product (e.g., Autoscope Solo®, Vantage Edge®). This district's policy is to install a single-camera VIVDS when one or more loops fail on a given intersection approach. Following this policy, when single-camera VIVDSs are in service on two approaches and the loops fail on a third approach, the entire detection system is then upgraded to a four-camera VIVDS.

### *Design Life*

It is believed that the VIVDS equipment is designed for a 10-year life. The majority of VIVDSs at TxDOT intersections have been in service less than six years. As a result, TxDOT has not fully experienced the life cycle of its VIVDS equipment. To date, there appears to be no evidence to suggest that VIVDS hardware will not last at least seven to ten years.

## DESIGN ISSUES

### Camera Location

This section addresses the issues involved when installing the VIVDS cameras at a given intersection. Camera location is defined by several variables that include: distance between the camera and detection zone, offset of the camera relative to the through traffic lanes, and the height of the camera. These variables are illustrated in Figure 2-3.

### *Camera Offset*

The interviewees indicated that the preferred camera offset location was dependent on whether the approach being monitored has a left-turn bay. If it has a left-turn bay, the preferred camera location is over the lane line separating the left-turn bay and the adjacent (oncoming) through lane. This location is shown as point "A" in Figure 3-1, as applied to the eastbound approach. If the approach does not have a left-turn bay, the preferred location is centered on the approach lanes, as shown by location "B" for the westbound approach. Other camera locations are being used, as denoted by locations "C" and "D." These locations were generally used when locations "A" or "B" were not available or when they did not provide the desired camera height.

### *Camera Height*

The preferred camera height is based on the desired distance at which the furthest upstream detection zone is located. In general, greater height is needed for more distant detection. For example, Middleton et al. (*11*) indicate that a 55-mph approach speed typically requires three advance detectors, with the furthest detector being 415 ft from the stop line (and about 500 ft from the camera). VIVDS manufacturers recommend a camera height that is 1/10th the distance of the most-distant detection zone (*4, 9, 10*). In Chapter 2, this guidance is referred to as the "10 ft to 1 ft" rule. This rule translates into the need for a camera height of 50 ft to provide advance detection on a 55-mph approach.

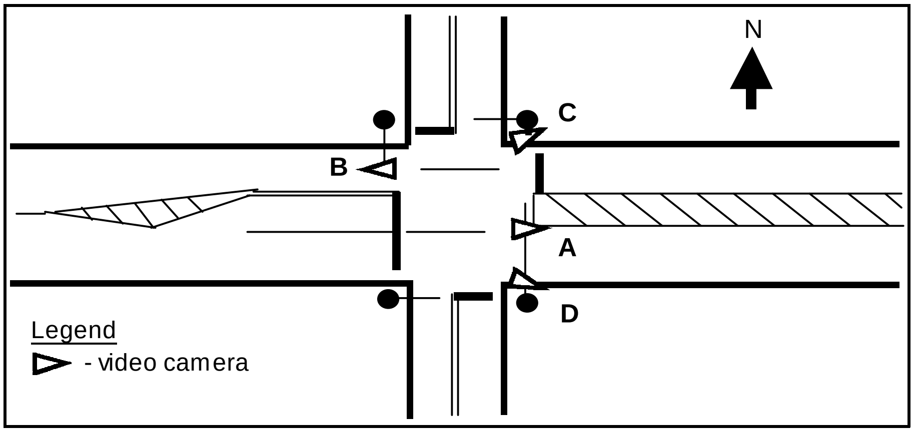


**Figure 3-1. Alternative Camera Locations.**

It was stated during the interviews that the “10 ft to 1 ft” rule was more appropriate for vehicle count and speed measurement, but that a height equal to 1/17th of the detection distance is acceptable for vehicle presence detection. This ratio translates into a 29-ft (= 500/17) mounting height for a 55-mph approach.

At least one TxDOT district uses a two-camera system to provide advance detection on a high-speed intersection approach. One camera is centrally mounted on the mast arm. It has a wide-angle lens and is used to monitor vehicles near the stop line. The second camera is mounted high (say, 32 ft or more) on the mast-arm pole or a nearby luminaire pole. Its lens is adjusted to “zoom in” on the location of the distant upstream detection zones.

*Combined Offset and Height Considerations*

The preferred camera offset and height (as defined in the previous two paragraphs) are often achieved for low-speed approaches by locating the camera on a 5-ft riser attached to the signal head mast arm. This type of mounting is shown in Figure 2-8.

Unfortunately, the preferred camera offset and height cannot be achieved for high-speed approaches or at intersections with signals supported by span-wire. As a result, two compromise camera locations are being used. Both locations have the camera mounted on the signal pole at the necessary height (or on a luminaire arm extending from the pole). This type of mounting is shown in Figure 2-9.

The particular pole on which the camera is mounted is dependent on the phase sequence used to control the subject approach. For approaches without a left-turn phase, the camera is mounted on the pole (or luminaire arm) located on the right-side, far corner of the intersection (i.e., point D in Figure 3-1 for the eastbound approach).

For approaches with a left-turn phase and bay, location "D" is problematic because the projected outline of a tall through vehicle can extend into the left-turn bay and unnecessarily call the left-turn phase. To avoid this problem, the camera is mounted on the left-side, far corner of the intersection (i.e., point C in Figure 3-1 for the eastbound approach). This location minimizes false calls for service to the left-turn phase; any false calls for the through phase by a tall left-turn vehicle would have limited impact because through vehicles are present during most cycles. It was also noted that a 10-s delay setting was used for the left-turn detectors to prevent unnecessary calls by departing vehicles.

*Features Facilitating Installation*

The experience of the districts interviewed is almost exclusively based on the use of coaxial cable for video communications and the use of a four-camera VIVDS processor (the interchanges require a six-camera processor). Limited experience was reported with the single-camera and wireless technologies that have been made available during the past year.

It was reported that a lens adjustment module is an essential VIVDS-related installation device. This device connects to the back of the camera and is used during the camera installation to adjust the camera's zoom and focus settings. This device is typically provided by the contractor during the initial VIVDS installation; however, some districts have found it necessary to have one available to their staff to facilitate subsequent camera adjustments or replacements. It was also noted that this device is not standardized among VIVDS manufacturers and that a separate device is needed for each type of VIVDS product used in the district.

Several districts report that a large, ground-mounted controller cabinet is needed to house the typical multiple-camera VIVDS processor. This need for space is particularly important when the VIVDS processor is accompanied by a monitor in the cabinet (a desirable arrangement that is available with some VIVDS products). It was reported by several districts that the smaller, pole-mounted cabinet does not provide adequate space for the VIVDS equipment. Although, at least one district has installed a VIVDS in a pole-mounted cabinet. It was also noted that cabinet size will be less of an issue when rack-mounted VIVDS products are more readily available.

### Field-of-View Calibration

The camera field of view is established by adjusting the camera pitch angle and the lens focal length. Specifically, pitch angle is increased until the top of the field of view excludes the horizon and just extends beyond the furthest point on the approach pavement that will be monitored by a VIVDS detection zone.

The lens focal length is adjusted using the zoom feature such that the stop line is in the bottom half of the screen and a vehicle at the stop line is about the size of the installer's thumb (on a 9-inch monitor). A preferred field of view is shown in Figure 2-4.

## Special Interchange Issues

### *Communications*

VIVDS cameras are typically connected to the VIVDS processor with coaxial cables. The type of cable used depends on the distance between the camera and the VIVDS processor. Standard RG-59 coaxial cable has been used routinely at distances up to 500 ft. Some degradation in signal quality has been observed when the cameras are more than 1000 ft from the cabinet. Distances of this magnitude are common at diamond interchanges controlled by a single controller. The addition of splices in the cable adds to the image degradation.

The use of a common conduit for both the coaxial cable and the power cable can cause image degradation, especially for longer cable lengths. Video communications problems were reported at one diamond interchange installation. The video signal quality was restored by using separate conduits for the coaxial cable and the power cable.

Wireless communication between the VIVDS cameras and processor is an alternative to the use of coaxial cable. At least one VIVDS manufacturer offers a wireless camera. In this instance, the video information is transmitted to a receiver in the controller cabinet. Power for the camera is provided by a cable or solar panel. A successful application of wireless communication was reported for transmission distances of 300 to 400 ft.

### *Shadows*

Shadows extending across an intersection approach can present challenging problems for image-processing software (*6*). These shadows can extend into a detection zone and trigger false calls or compromise the VIVDS processor's ability to detect vehicles. Shadows diminish the brightness and contrast information available to the image processor and, thus, make it difficult for the processor to discern the outline of the actual vehicle. Shadows can extend from trees, signs, buildings, or bridge structures adjacent to the roadway. They can also extend from tall vehicles into an adjacent lane.

Figure 3-2 illustrates the shadow problem inherent to a diamond interchange where the major road passes over the cross road. The shadow of the overhead bridge structure may cause problems for some VIVDS products during bright sunlight conditions. The vehicles in the shadow of the bridge are likely to be more challenging for the VIVDS to detect than vehicles not in this shadow.

**Figure 3-2. Shadows from Tall Vehicles and Bridge Structures.**

## OPERATION ISSUES

The operation of the VIVDS is defined by the layout and operation of the detection zones. Satisfactory layout requires consideration of the following issues: (1) precision of the detection zone layout, (2) detection mode, and (3) detector and controller settings. Satisfactory operation requires verification of the initial layout and occasional on-site performance checks. The layout and operation for a new VIVDS installation is typically established by the VIVDS vendor, under the direction of the TxDOT engineer. Many TxDOT districts are becoming more involved in the setup and maintenance of the VIVDS following its initial installation. Other districts have on-site service agreements that require the vendor to provide VIVDS maintenance services.

### Detection Zone Layout

#### *Detection Zone Location*

A key to safe and effective intersection operation is the proper location of the detection zones. Zone location is defined as the distance between the upstream edge of the zone and the stop line. Zone layout requires the engineer to draw each detector in the zone on the two-dimensional image plane of the VIVDS monitor such that its projection into the plane of the pavement is exactly where the inductive loop would have been installed for the same purpose. Stop-line detection zone location is dictated by the need to fully serve the queue. Advance detection zone location is dictated by the need to provide dilemma zone protection (*11*).

Some districts require that the VIVDS vendor measure and mark relevant detection zone distances along the approach with traffic cones to facilitate the precise location of the zones. However, most districts do not make this requirement and allow the vendor to estimate distances using the standardized spacing of the pavement lane markings.

### *Detection Mode*

Each VIVDS detection zone has a "directional" mode that allows it to submit calls only for traffic moving in one specified direction. This mode was not found to be widely used by the TxDOT staff because of several reasons. One reason offered is that this mode appears to reduce the sensitivity of the detection zone, relative to a zone operating in a non-directional mode. It was also noted that this mode required a lengthy tuning period each time the approach detection configuration was changed. Finally, it was noted that the detector delay setting (described in the next section) could often be used to accomplish the same functionality as the directional mode. There was no mention of the use of the detector's Boolean logic functions.

### *Detector and Controller Settings*

VIVDS detection zones typically support several of the advanced features available from inductive loop amplifiers. In particular, VIVDS detection zones have a delay setting and an extend setting. However, none of the interviewees reported using the extend setting of the VIVDS detectors.

The delay setting is sometimes used to reduce the frequency of unneeded calls. Specifically, a few seconds of delay is often set on the detectors in the stop-line detection zone of each minor-road approach. This setting offers two benefits. First, it eliminates false calls to the minor-road phases by major-road vehicle headlights (such as when a major-road vehicle makes a right turn and its headlights sweep across the minor-road stop-line detection zone). Second, it eliminates false calls to the minor-road phases by tall major-road vehicles (i.e., when tall vehicles cross the view of the minor-road camera and momentarily project their image onto the minor-road stop-line detection zones).

With regard to controller passage time, it was noted that the values used for this setting are the same, regardless of whether a VIVDS or an inductive loop system is used for detection. However, at least one interviewee did acknowledge that different settings might be needed by the two systems given their unique method of detection. Specifically, it was pointed out that an inductive loop and a VIVDS detection zone that monitor the same pavement surface area do not detect a vehicle's presence (i.e., hold a call) for the same length of time. The same vehicle that crosses an inductive loop in a fraction of a second could be detected by a VIVDS detection zone for two or three seconds. As a result, the passage time setting should be shorter when used with a VIVDS (although, there is no agreement on the amount of the reduction).

It was observed by one interviewee that there is a need for training of TxDOT personnel in the area of VIVDS detection zone layout. This need will increase as TxDOT increases the number of intersections at which they perform the setup. One specific area of concern was the apparent use of numerous detection zones along a given approach. This lengthy area of detection was found to produce long extensions of the green indication and appeared to be very inefficient.

## On-Site Performance Checks

### *Return Visit to Verify Operation*

Most of the interviewees agreed that the intersection should be revisited one or more times in the days subsequent to the initial VIVDS turn-on date. The purpose of this visit is to verify that the detection system is providing acceptable operation and, if needed, to refine the detection layout. One interviewee suggested that the repeat visit should include both daytime and nighttime observations due to significant differences in light level during these two time periods.

When asked about the number of return visits actually conducted, it was learned that workloads sometimes interfered with the scheduling of these routine maintenance checks. In fact, the number of intersections actually revisited was estimated to be about 10 to 20 percent. When such visits are conducted, it was noted that the "simpler" VIVDSs were not often found to require additional adjustments. In contrast, the multi-function VIVDSs would often require some adjustment of the detection zones and possibly a third visit to converge on an optimal operation.

### *Maintenance*

Several maintenance issues were reported during the interviews; however, none were presented as frequent, costly, or unresolvable. Most of the maintenance issues related to the cameras and their ability to sustain the field of view established on the day they were initially installed.

**Camera Replacement.** Three districts noted that each VIVDS product has a unique set of camera cable connectors on the back of the camera housing. This unique arrangement requires districts that use multiple VIVDS products to maintain an inventory of several different types of cameras to ensure quick repairs.

**Camera Realignment.** One district reported the occasional need to realign the cameras after a storm. Another district reported that the seasonal changes in the sun's position can cause a glare to occur in the camera during some months of the year. Given the unpredictability of these events, the need for a follow-up adjustment is not often known until poor service is reported by a motorist.

**Camera Lens Cleaning.** It was reported that districts in coastal areas need to clean some camera lenses relatively often due to the high humidity of the coastal air. The Corpus Christi District found that the frequency of this activity varies, depending on the proximity of the intersection to sources of airborne dust. For example, an intersection near a bauxite plant needs to have its camera lenses cleaned every six weeks, while an intersection near a residential subdivision needs to have its camera lenses cleaned every six months.

**Detection Zone Layout Verification.** Routine service checks of VIVDS operation have been found to take more time than was previously spent at intersections with inductive loop detectors. This added time stems partly from the VIVDS's inability to provide an electronic report that records the detection zone layout. Without this report, the service technician must rely on his or her judgment and recollection as to whether the detection zones or their settings are unchanged. If the location of a detector is determined to be changed (say, due to movement of the mast arm supporting the camera), the report could be used to quickly restore the original location.

**Failure Rate.** The failure rate of the VIVDS products was investigated during the interviews. Only three VIVDS failures were reported, out of the 209 VIVDSs for which the group had experience. One of the three VIVDSs failed after seven years of service and the other two VIVDSs failed after five years of service. Two districts also indicated that they have had individual modules within the VIVDS processor fail due to apparent lightening strikes. However, the rate of these failures was no greater than that of other controller hardware under similar conditions.

**Field Setup Computer.** Several VIVDS products can be set up or adjusted in the field with only a video monitor and a computer pointing device (i.e., a "mouse"). Because this equipment has a relatively low cost, it is routinely purchased for each intersection installation and left permanently inside the controller cabinet. Other VIVDS products require the use of a field setup computer (typically a laptop computer) for setup or adjustment. This computer is generally too expensive to be purchased for each intersection; thus, the technician must carry it to the site for each maintenance visit. The TxDOT staff consistently indicated a preference to use VIVDS products that do not require a field setup computer. The reasons for this preference related to the added difficulty of using this computer and the difficulty of arranging to have it in the service truck prior to the site visit.

**Software Version.** VIVDS software has undergone an intense development cycle that has resulted in relatively frequent releases of new software versions. This pattern of frequent software upgrade has made it difficult for TxDOT staff to keep their VIVDS inventory current with the newest software release. As a result, the collective VIVDS inventory in many TxDOT districts has had a mixture of old and new software versions. This mix has occasionally caused some maintenance problems as it required the engineer or technician to constantly be aware of the specific software version on each VIVDS unit. Fortunately, the VIVDS technology is maturing and software upgrades are becoming less frequent.

# CHAPTER 4. DEVELOPMENT OF DESIGN AND OPERATIONS GUIDELINES

## OVERVIEW

This chapter describes the development of guidelines for the design and operation of a VIVDS at a signalized intersection or interchange. The basis for the guidelines is the information obtained from the review of the literature and the survey of TxDOT practice, as described in Chapters 2 and 3, respectively. The effectiveness of the guidelines was evaluated using field data collected at several intersections and interchanges in Texas. Guideline development is described in the first section of this chapter. Guideline evaluation is described in the second section.

## GUIDELINE DEVELOPMENT

Guidelines addressing three VIVDS issues are developed in this section. The first guideline describes the conditions where a VIVDS is more cost-effective than an inductive loop system. The second guideline describes minimum camera height controls. These controls are intended to minimize occlusion and maintain reasonably reliable advance detection. The third guideline describes recommended VIVDS detection zone layouts for stop-line detection and for advance detection.

### Life-Cycle Cost Analysis

The life-cycle costs of a four-camera VIVDS and an inductive loop system were examined to determine the conditions where a VIVDS was cost-effective. A life-cycle cost approach was used due to the significant differences in maintenance cost associated with each system. The costs to install and maintain each system at a newly constructed intersection were computed for this analysis. These costs were annualized using an equipment life of 10 years and a 3.0-percent annual interest rate. The intersection evaluated has a high-speed major road and a low-speed minor road. Left-turn bays are provided on all approaches. The initial cost of installing a four-camera VIVDS was estimated to be $23,000. Annual VIVDS maintenance was estimated at $600.

The cost of an inductive loop detection system is based on the following assumptions: a 40-ft inductive loop located at the stop line costs $900; a 6.0-ft loop located in advance of the stop line costs $550; three 6.0-ft loops are installed in each lane of both major-road approaches; left-turn bays are present for all approaches; and conduit installation for advance loop detection is $4000 per approach. Traffic control for a through lane closure costs $1000; however, the agency is assumed to wait until two loops are disabled before making repairs. This policy reduces traffic control costs to $500 for each loop repair.

Figure 4-1 shows the results of the life-cycle cost analysis. The trends in this figure indicate that the annualized cost of the four-camera VIVDS is $3300. This value is consistent with the VIVDS cost reported by Middleton et al. (*6*).

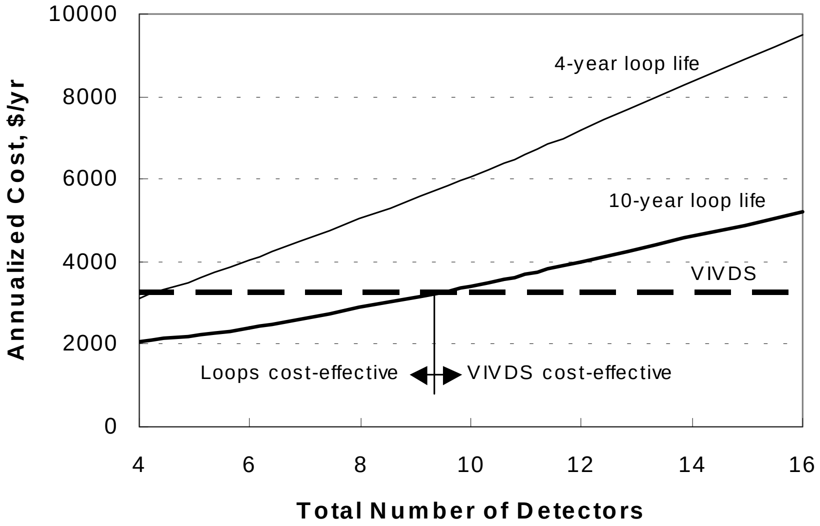


**Figure 4-1. Comparison of VIVDS and Inductive Loop Detection Costs.**

The analysis of inductive loop costs revealed a strong dependence on the number of inductive loops needed at an intersection and the life of these loops. In areas where the average loop life is 10 years, the annualized cost of an inductive loop system ranges from $2000 to $5200, depending on the total number of loops installed at the intersection. At intersections with nine loops, the annual cost of a four-camera VIVDS is about equal to that for an inductive loop system. This finding is consistent with that of Chatziioanou (*8*). A VIVDS is more cost-effective than a loop system at intersections that need more than nine detection zones. In areas where the average loop life is only four years, a VIVDS is found to be cost-effective when only five detection zones are needed.

The trends in Figure 4-1 suggest that the break-even number of lanes varies with average loop life. The results of an analysis of this relationship are shown in Figure 4-2. The trend line in this figure identifies the minimum number of detection zones needed to justify the cost of a four-camera VIVDS. The figure is applicable to intersections with stop-line detection. The analysis was repeated for intersections with advance detection; however, the findings indicated that it was always cost-effective to use a VIVDS when advance detection is desired.

To illustrate the use of this figure, consider an intersection of a four-lane highway with a two-lane minor road. The major road has a left-turn bay on each approach. A total of eight stop-line detectors would be needed if VIVDS is not used. The area in which the intersection is located has an average loop life of six years. This combination of eight detectors and six years intersects above the trend line indicating that a four-camera VIVDS is cost-effective at this intersection. However, if average loop life is 10 years in this area, then an inductive loop system would be more cost-effective at this intersection.

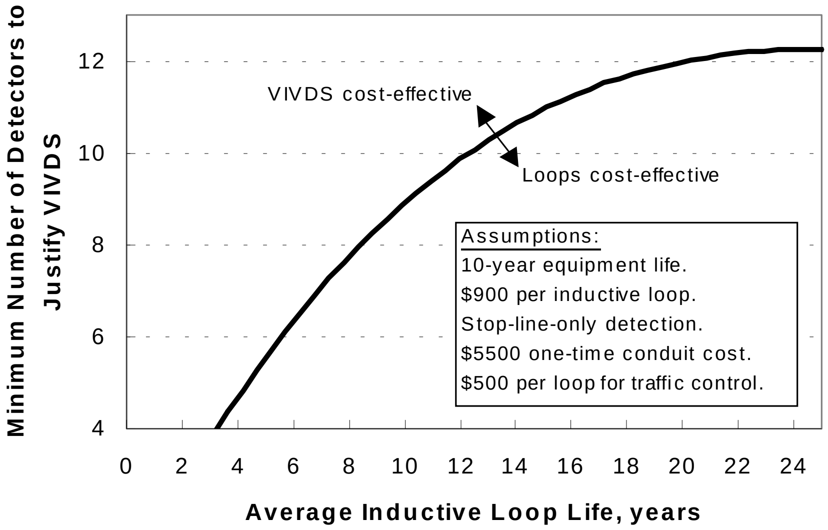


**Figure 4-2. Minimum Number of Detectors to Justify VIVDS Cost.**

## Camera Location

This section describes guidelines for determining the minimum camera height for a specified camera offset and distance to the stop line. Factors considered in the development of this guidance include adjacent-lane occlusion, the camera height-to-detection-distance ratio, and approach speed.

### *Minimum Height to Reduce Occlusion*

Adjacent-lane occlusion results when a tall vehicle in one lane blocks the camera's view of a more distant, adjacent lane. This type of occlusion occurs when the camera is too low, offset too far from the traffic lanes, or both. The geometry between camera height and offset for a "critical" combination of vehicle height and width is shown in Figure 4-3.

Figure 4-3 is intended to represent an intersection approach with two through lanes and a left-turn bay. The camera is mounted on the right-side of the approach. The line extending downward from the camera represents the line of sight that just clears the through vehicle's roof yet ends at a point no less than 3.0 ft into the left-turn bay (based on a 6.0-ft vehicle width). The camera shown is at the minimum height for the associated offset ($y_o$). An increase in offset would require an increase in camera height to provide the same, "critical" view. A lower camera height would result in the through vehicle's image being projected into the left-turn lane sufficiently far as to compromise the VIVDS processor's ability to detect left-turn vehicles.

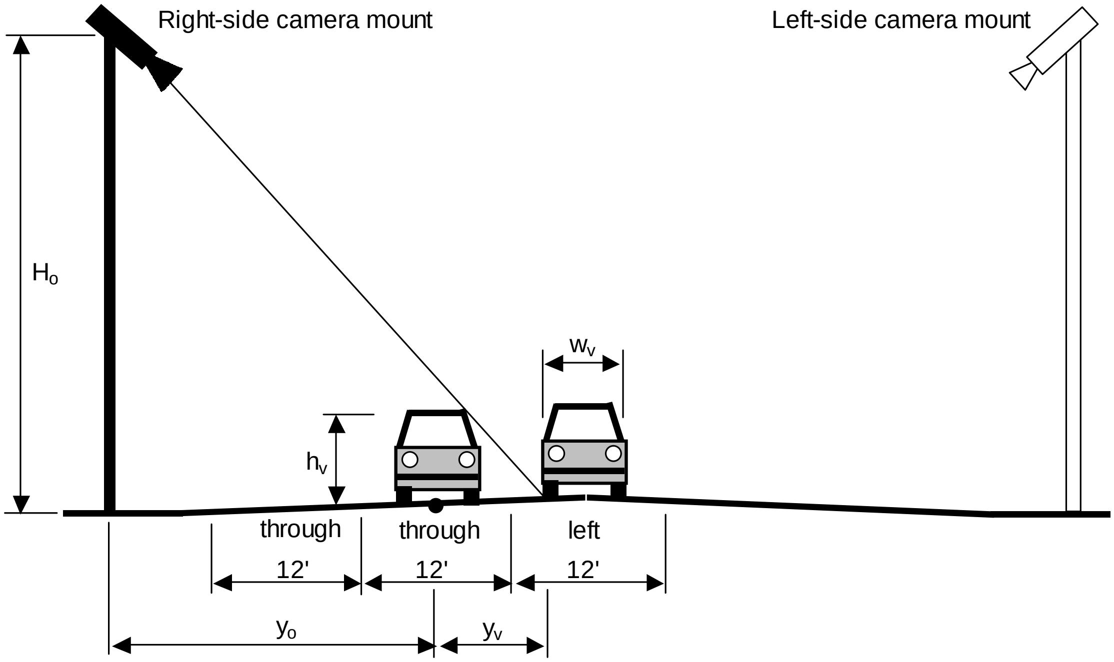


**Figure 4-3. Geometric Relationship Between Camera Height and Offset.**

The minimum camera height $H_o$ for a specified offset $y_o$ (relative to the center of the approach lanes) is computed using the following equation:

$$H_o = \frac{|y_o - y_v|}{w_L - w_v} h_v \tag{1}$$

where:

$H_o$ = minimum camera height to reduce adjacent-lane occlusion, ft;
$y_o$ = lateral offset of camera, relative to the center of the approach traffic lanes, ft;
$y_v$ = distance from the center of the approach traffic lanes to the near side of the vehicle in the most distant approach traffic lane, ft;
$h_v$ = height of the design passenger car (use 4.5 ft), ft;
$w_v$ = width of the design passenger car (use 6.0 ft), ft; and
$w_L$ = width of the traffic lane (use 12 ft), ft.

The vehicle dimensions cited in the variable list are representative of the average intermediate passenger car, as described by Ramsey and Sleeper (*12*).

Equation 1 was used to compute the minimum heights listed in Table 4-1 for right-side camera offsets. It was modified slightly to facilitate the computation of minimum heights for left-side camera offsets. A camera that is mounted at or above the minimum height should only experience occlusion when a passenger van, sport-utility vehicle, bus, or commercial truck is in the lane adjacent to the most distant lane. Interpolation between cell values is appropriate for offsets intermediate to the values listed.

**Table 4-1. Minimum Camera Height to Reduce Adjacent-Lane Occlusion.**

| Camera Location | Lateral Offset[1], ft | No Left-Turn Lanes | | | One Left-Turn Lane | | | Two Left-Turn Lanes | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Through+Right Lanes[2] | | | Through+Right Lanes[2] | | | Through+Right Lanes[2] | | |
| | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| | | Minimum Camera Height ($H_o$)[3, 4], ft | | | | | | | | |
| Left Side of Approach | -75 | 54 | 50 | 45 | 59 | 54 | 50 | 63 | 59 | 54 |
| | -65 | 47 | 42 | 38 | 51 | 47 | 42 | 56 | 51 | 47 |
| | -55 | 39 | 35 | 30 | 44 | 39 | 35 | 48 | 44 | 39 |
| | -45 | 32 | 27 | 23 | 36 | 32 | 27 | 41 | 36 | 32 |
| | -35 | 24 | 20 | 20 | 29 | 24 | 20 | 33 | 29 | 24 |
| | -25 | 20 | 20 | 20 | 21 | 20 | 20 | 26 | 21 | 20 |
| | -15 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| | -5 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Center | 0 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Right Side of Approach | 5 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| | 15 | 20 | 20 | 20 | 20 | 20 | 23 | 20 | 20 | 20 |
| | 25 | 20 | 20 | 20 | 21 | 26 | 30 | 20 | 21 | 26 |
| | 35 | 20 | 20 | 20 | 29 | 33 | 38 | 24 | 29 | 33 |
| | 45 | 20 | 20 | 20 | 36 | 41 | 45 | 32 | 36 | 41 |
| | 55 | 20 | 20 | 20 | 44 | 48 | 53 | 39 | 44 | 48 |
| Left Side ($y_v$), ft | | -3 | -9 | -15 | 3 | -3 | -9 | 9 | 3 | -3 |
| Right Side ($y_v$), ft | | | | | -3 | -9 | -15 | 3 | -3 | -9 |

Notes:

1 - Lateral offset of camera measured from the center of the approach traffic lanes (including turn lanes). Cameras to the left of center have a negative offset.

2 - Total number of through and right-turn lanes on the approach.

3 - Based on a vehicle height $h_v$ of 4.5 ft and a vehicle width $w_v$ of 6.0 ft.

4 - Underlined values in each column correspond to typical lateral offsets when the camera is mounted within 10 ft of the edge of traveled way.

The values listed in Table 4-1 are shown to always exceed 20 ft. In fact, Equation 1 will yield heights less than this value; however, 20 ft represents a practical minimum height in recognition of the dirt, spray, and mist that can collect on the camera lens at lower heights.

The trends in Table 4-1 confirm that a camera mounted in the center of the approach is associated with the lowest minimum height. This minimum increases with offset and is particularly large for cameras located on the left side of the approach.

The underlined values in Table 4-1 correspond to typical lateral offsets for the associated number of lanes *when* the camera is mounted within 10 ft of the edge of traveled way. For example, a camera mounted on the right side of a single-lane approach (with one left-turn bay) is likely to have an offset of about 15 ft, which corresponds to a minimum camera height of 20 ft. A camera mounted on the left side of this same approach is likely to have an offset of about 25 ft and require a minimum height of 21 ft.

### *Minimum Height for Advance Detection*

Several VIVDS manufacturers recommend a "10 ft to 1 ft" rule to determine minimum camera height for advance detection. This rule relates camera height to the "detection distance" (i.e, the distance between the camera and the section of pavement being monitored by the VIVDS). Effectively, it defines the maximum detection distance for a given camera height. The justification for this rule is not offered in the VIVDS product manuals; however, it implies that detection accuracy will degrade if the camera is below the minimum height for a specified distance.

The most distant detection zone used for advance detection is typically based on the boundaries of the dilemma zone. This zone represents a section of the approach pavement within which the population of drivers are collectively indecisive when presented a yellow indication. Research by Zegeer and Deen (*13*) suggests that this zone begins at 5.0-s travel time from the stop line and ends at 2.0 to 2.5 s from the stop line. At a speed of 45 mph, this travel time equates to 330 ft. Allowing for 70 ft from the camera to the stop line, the distance between the camera and the most distant detection zone is 400 ft. When combined with the "10 ft to 1 ft" rule, this distance requires a minimum camera height of 40 ft. Higher speeds require an increase in this minimum height.

The interview with TxDOT staff indicated that a distance-to-height ratio $R$ of 17 (i.e., 17 ft to 1 ft) yields acceptable detection accuracy. For a given distance, this ratio allows for lower camera heights than does the "10 ft to 1 ft" rule (which corresponds to a ratio $R$ of 10).

The minimum camera height for a defined detection distance is computed as:

$$H_a = \frac{x_1 + x_c}{R} \qquad \textbf{(2)}$$

with,

$$x_1 = 1.47\ t_{bz}\ V_{95} \tag{3}$$

where:

$H_a$ = minimum camera height for advance detection, ft;
$x_1$ = distance between the stop line and the upstream edge of the most distant zone, ft;
$x_c$ = distance between the camera and the stop line, as measured parallel to the direction of travel, ft;
$R$ = distance-to-height ratio (use 17);
$t_{bz}$ = travel time from the start of the approach dilemma zone to the stop line (use 5.0 s), s; and
$V_{95}$ = 95th percentile speed (= 1.07 x $V_{85}$), mph.

The factor of "1.07" used to estimate the 95th percentile speed is based on the assumption that the distribution of speeds is normal with a standard deviation equal to 12 percent of the mean speed.

The distance between the camera and stop line $x_c$ should reflect the location of the line beyond which most drivers stop. In most instances, drivers stop behind the marked stop line, and $x_c$ is measured to this line. In other instances, the stop line is not marked or drivers routinely stop beyond the marked line. In these instances, the distance $x_c$ should be measured to the "effective" stop line (i.e., the location beyond which most drivers stop).

The minimum heights obtained from Equation 2 are listed in Table 4-2 for a range of speed limits. The value of $x_1$ associated with each speed is listed in the last row of Table 4-2. These distances are very consistent with those used in Texas, as described by Middleton et al. (*11*).

The distances shown in Table 4-2 indicate that minimum camera heights range from 24 to 36 ft, depending on the distance between the camera and stop line and on the approach speed limit. The heights shown will always provide a view of the approach between the stop line and the upstream detection zone (provided that a lens focal length of 6.0 mm or larger is used).

Tables 4-1 and 4-2 should be used together to determine the minimum camera height for approaches with stop line and advance detection. The higher value obtained from either table would represent the required minimum height. To illustrate their use, consider a four-lane highway with intersection approaches that include two through lanes and one left-turn bay. The distance between the mast-arm pole and the stop line is 100 ft, as measured in the direction of travel. The approach speed limit is 55 mph. Table 4-2 indicates that the minimum height needed for advance detection is 31 ft. This height exceeds that available from a mast-arm mount (i.e., 24 ft), so a right-side pole mount is considered for the camera. Table 4-1 indicates that a camera mounted just outside the edge of traveled way (i.e., offset 18 ft from the center of the three-lane approach) will require a minimum height of about 22 ft (by interpolation). Of the two minimum heights specified (i.e., 31 and 22 ft), the larger value of 31 ft represents the minimum for this approach. Thus, the camera should be mounted at a height of 31 ft or more on the right-side mast-arm pole.

**Table 4-2. Minimum Camera Height for Advance Detection.**

| **Distance Between Camera and Stop Line**[1]**, ft** | **Approach Speed Limit**[2]**, mph** | | | |
|---|---|---|---|---|
| | **45** | **50** | **55** | **60** |
| | **Minimum Camera Height ($H_a$)**[3, 4]**, ft** | | | |
| 50 | 24 | 26 | ▨ | ▨ |
| 60 | 24 | 27 | ▨ | ▨ |
| 70 | 25 | 27 | ▨ | ▨ |
| 80 | 25 | 28 | 30 | 32 |
| 90 | 26 | 28 | 31 | 33 |
| 100 | 27 | 29 | 31 | 34 |
| 110 | 27 | 30 | 32 | 34 |
| 120 | 28 | 30 | 32 | 35 |
| 130 | 28 | 31 | 33 | 35 |
| 140 | 29 | 31 | 34 | 36 |
| 150 | 30 | 32 | 34 | 36 |
| Distance to Furthest Zone ($x_1$)[5], ft | 353 | 392 | 431 | 470 |

Notes:

1 - Distance between the camera and the stop line, as measured parallel to the direction of travel.

2 - Approach speed limit is assumed to equal the 85th percentile speed $V_{85}$.

3 - Based on a distance-to-height ratio $R$ of 17:1.

4 - Shaded cells indicate conditions where the stop line is not in view after the lens is zoomed to ensure that the height of a vehicle at the most distant detector is at least 3.0 percent of the vertical image height.

5 - Distances based on 5.0-s travel time at the 95th percentile speed (= 1.07 x $V_{85}$).

## Detection Zone Layout

### *Stop-Line Detection*

This section describes guidelines for determining an efficient detection zone layout for stop-line detection. Stop-line detection is typically used on low-speed intersection approaches and in left-turn bays. Guidelines for determining the layout for advance detection zones are provided in the next section.

**Procedure.** The following equation is used to define the relationship between stop-line detection length and controller passage time:

$$l_{sl} = v_q\,(MAH - PT) - l_v^* \tag{4}$$

with,

$$l_v^* = (l_v - l_{ro}) + x_c \frac{h_v}{h_c} \tag{5}$$

where:

$l_{sl}$ = length of the stop-line detection zone, ft;
$v_q$ = maximum queue discharge speed, as measured at the stop line (use 40 f/s), ft/s;
$MAH$ = maximum allowable headway (use 3.0 s), s;
$PT$ = controller passage time, s;
$l_v^*$ = effective length of vehicle, ft;
$l_v$ = length of design vehicle (use 16.7 ft), ft;
$l_{ro}$ = distance from back axle to back bumper (use 4.3 ft), ft;
$x_c$ = distance between the camera and the stop line, as measured parallel to the direction of travel, ft;
$h_v$ = height of the design passenger car (use 4.5 ft), ft; and
$h_c$ = height of camera, ft.

A value of 3.0 s is used for the maximum allowable headway based on guidance provided by Kell and Fullerton (*14*). The vehicle dimensions cited in the variable list are representative of the average intermediate passenger car, as described by Ramsey and Sleeper (*12*).

The effective length of vehicle $l_v^*$ is used in Equation 4 in recognition of the backward projection of the vehicle image in the plane of the pavement, as created by a two-dimensional camera image. A vehicle's effective length is always longer than its actual length $l_v$ when the camera is in front of the vehicle. The geometry used to define the effective vehicle length is shown in Figure 4-4.

**Simulation Analysis.** Viable combinations of detector length and passage time were evaluated by Lin (*15*) using simulation. His objective was to find the combination of length and passage time that yielded the least delay. He concluded that detector lengths of 80 ft with a 0.0-s passage time were able to consistently yield lower delays than shorter detectors and longer passage times.

Lin (*15*) also noted that 80-ft inductive loop detectors were relatively expensive and, because of this cost, that shorter loops were often preferred by engineers. One advantage of a VIVDS detection zone is that its length has no impact on the cost to maintain or operate the system. Hence, Lin's (*15*) recommendation to use long loops is easily accomplished with a VIVDS.

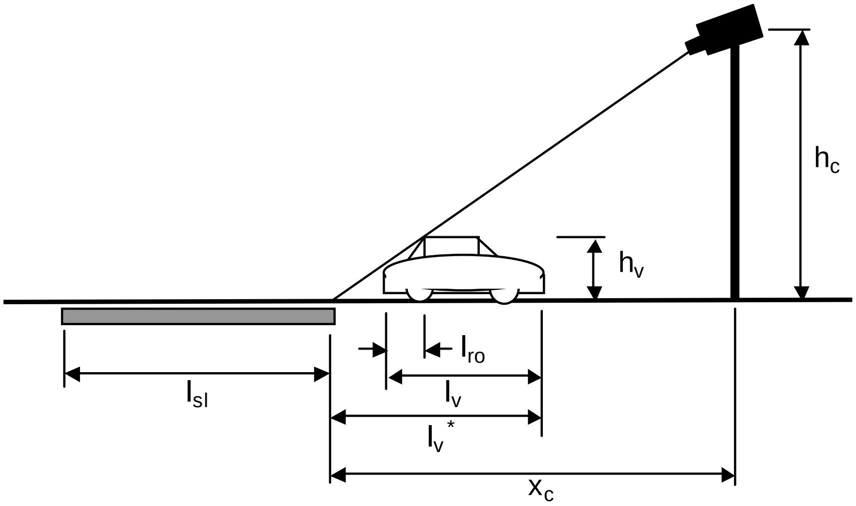


**Figure 4-4. Geometric Relationship Between Camera Height and Vehicle Length.**

Computer simulations of a two-lane intersection approach were conducted for this research to verify the applicability of Lin's findings to VIVDS detection. A series of simulations were conducted for approach volumes ranging from 200 to 1800 veh/h. The CORSIM simulation model was used for the simulation experiments. Passage times of 0.0 s and 1.1 s were evaluated. CORSIM vehicle lengths were either 14 or 16 ft. The distribution of vehicle types yielded an average vehicle length of 15.6 ft. Equation 5 was used with a stop-line distance $x_c$ of 50 ft and a camera height of 30 ft to define an effective vehicle length $l_v^*$ of 18.8 ft (= 15.6 − 4.3 + 50 × 4.5 / 30). Equation 4 was used with a maximum allowable headway *MAH* of 3.0 s and a passage time *PT* of 0.0 s to compute a stop-line detection zone length of 101.2 ft (= 40 × (3.0 − 0.0) − 18.8).

The effect of camera height on vehicle length was accommodated in the simulation by computing an equivalent CORSIM detector length $l_{sl,sim}$ using the following equation:

$$l_{sl,sim} = l_{sl} + l_v^* - l_v \qquad \textbf{(6)}$$

This equation produces a simulated detector length equivalent to that provided by a VIVDS zone of length $l_{sl}$. The application of this equation yielded a CORSIM stop-line detection zone length of 104.4 ft (= 101.2 + 18.8 - 15.6). Unfortunately, CORSIM limits detection zone length to a maximum of 100 ft. So, the *MAH* was reduced to 2.9 s to yield a simulated length $l_{sl,sim}$ of 100 ft. This *MAH* was also used to compute a detection zone length of 56 ft for the evaluation of the 1.1-s passage time. The results of the analysis are shown in Figure 4-5. Each data point shown reflects an average for one hour of simulated traffic events.

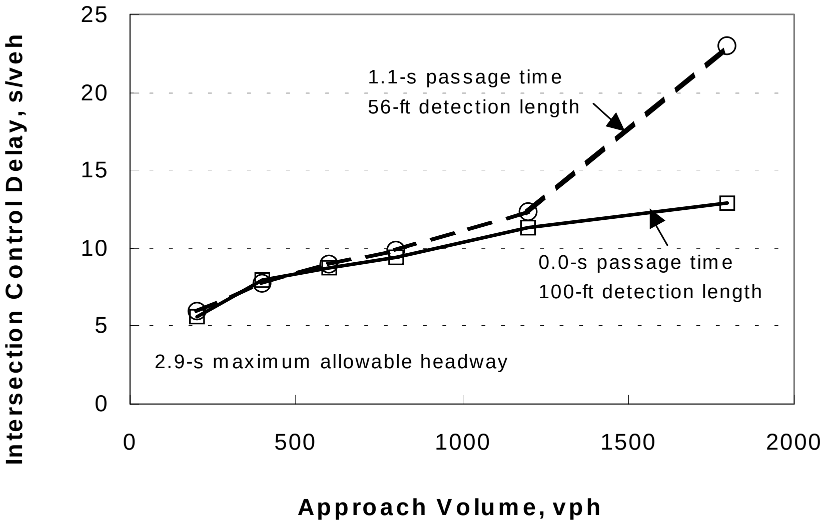


Figure 4-5. Effect of Passage Time and Detection Length on Delay.

The trends shown in Figure 4-5 confirm Lin's (*15*) findings regarding the benefit of longer detection zone lengths for stop-line detection. The benefits are particularly significant at the higher volume levels. The trends shown are based on a maximum green setting of 60 s. Similar trends were found for a maximum green setting of 40 s.

**Guidelines.** Equations 4 and 5 were used to compute the appropriate stop-line detection zone lengths for a 0.0-s passage time and a 3.0-s maximum allowable headway. These lengths are listed in Table 4-3. Use of these lengths should result in lower delay than that realized by longer passage times or shorter detection zone lengths.

During the initial VIVDS setup, the detection zone length should be measured along the roadway with a distance wheel. The most distant upstream edge should be marked with a traffic cone placed on the outside edge of the traveled way. One or more VIVDS detectors should then be drawn on the VIVDS monitor such that the entire length of the resulting detection zone is monitored by the VIVDS processor. The traffic cone can then be removed.

### *Stop-Line Plus Advance Detection*

This section describes guidelines for determining an efficient detection zone layout when advance detection is needed. This type of detection is typically used to provide a safe phase termination for the high-speed through movements on an intersection approach. Stop-line detection is also included with the advance detection to provide efficient service to the queue during the initial portion of the phase.

Table 4-3. Stop-Line Detection Zone Length for VIVDS Applications.

| Distance Between Camera and Stop Line ($x_c$)[1], ft | Camera Height ($h_c$), ft | | | | |
|---|---|---|---|---|---|
| | 24 | 28 | 32 | 36 | 40 |
| | Stop-Line Detection Zone Length ($l_{sl}$)[2], ft | | | | |
| 30 | 102 | 103 | 103 | 104 | 104 |
| 40 | 100 | 101 | 102 | 103 | 103 |
| 50 | 98 | 100 | 101 | 101 | 102 |
| 60 | 96 | 98 | 99 | 100 | 101 |
| 70 | 94 | 96 | 98 | 99 | 100 |
| 80 | 93 | 95 | 96 | 98 | 99 |
| 90 | 91 | 93 | 95 | 96 | 97 |
| 100 | 89 | 92 | 94 | 95 | 96 |
| 110 | 87 | 90 | 92 | 94 | 95 |
| 120 | 85 | 88 | 91 | 93 | 94 |
| 130 | 83 | 87 | 89 | 91 | 93 |
| 140 | 81 | 85 | 88 | 90 | 92 |
| 150 | 79 | 83 | 87 | 89 | 91 |

Notes:

1 - Distance between the camera and the stop line, as measured parallel to the direction of travel.

2 - Lengths shown are based on a 3.0-s maximum allowable headway and a 0.0-s passage time setting.

**Procedure.** The layout of the advance detection zone includes: (1) establishing the proper location for each zone, (2) determining the extension setting for each zone, and (3) determining the passage time needed by the collection of zones. Two advance detection zones are used. Occasionally, the second detection zone (in the direction of travel) may need to operate with a small extension time. The advance detection zones should be connected to a common controller detector channel. This channel should be different than that used for the stop-line detection zone. The stop-line detection zone should be connected to its own detector channel.

The procedure for determining the location for the two advance detection zones is described in the following paragraphs. This procedure is based on the guidelines provided in the *Manual of Traffic Detector Design*; however, they have been extended for application to a VIVDS (*16*).

The first step is to compute the upper and lower design speeds for which advance detection will be provided. The upper design speed is defined as the 95th percentile speed, and the lower design speed is defined as the 5th percentile speed. The detection layout developed in this section is intended to provide dilemma zone protection for drivers traveling at speeds within this range.

The distance computed for each advance detection zone is measured from the stop line to the upstream edge of the zone. An advance detection zone $l_d$ is defined to be 20 ft in length (i.e., about the length of a passenger car), based on guidance provided in several VIVDS manuals (*4, 9, 10*).

The most distant detection zone $x_1$ is located at the beginning of the dilemma zone for the upper design speed. The beginning of the dilemma zone is defined as 5.0 s travel time from the stop line based on data reported by Zegeer and Deen (*13*). The corresponding distance is computed using Equation 3. The second advance detection zone $x_2$ is located at the beginning of the dilemma zone for lower speed $v_2$ and is computed using the following equation:

$$x_2 = t_{bz} v_2 \qquad \textbf{(7)}$$

with,

$$v_2 = \frac{x_1 - l_d - l^*_{v,1}}{t_{bz} + PT} \qquad \textbf{(8)}$$

and

$$l^*_{v,1} = (l_v - l_{ro}) + (x_1 + x_c - l_d)\frac{h_v}{h_c} \qquad \textbf{(9)}$$

where:

$x_2$ = distance between the stop line and the upstream edge of the second detection zone, ft;
$v_2$ = speed associated with the second detection zone, fps;
$t_{bz}$ = travel time from the start of the approach dilemma zone to the stop line (use 5.0 s), s;
$x_1$ = distance between the stop line and the upstream edge of the most distant detection zone, ft;
$l_d$ = length of each advance detection zone (use 20 ft), ft;
$l_{v,1}{}^*$ = effective length of vehicle at the first detection zone, ft;
$PT$ = controller passage time, s;
$l_v$ = length of design vehicle (use 16.7 ft), ft;
$l_{ro}$ = distance from back axle to back bumper (use 4.3 ft), ft;
$x_c$ = distance between the camera and the stop line, as measured parallel to the direction of travel, ft;
$h_v$ = height of the design passenger car (use 4.5 ft), ft; and
$h_c$ = height of camera, ft.

The effect of approach grade on the geometric relationships in Equation 9 was examined. This examination revealed that grades in the range of -10 percent to +10 percent have a negligible effect on the effective vehicle length.

The combined passage time and spacing between the two detection zones is such that any vehicle traveling faster than $v_2$ and located between the zones is likely to be in its dilemma zone. This vehicle will extend the green until it reaches the end of its dilemma zone. The passage time is too short for vehicles traveling slower than $v_2$ to reach the second detection zone before the phase ends. However, this operation is acceptable as these vehicles have not yet reached their dilemma zone (which begins after distance $x_2$).

A vehicle traversing the second detection zone will place a second call to extend the green. The duration of this call must be such that the vehicle can reach the end of the dilemma zone. The end of the zone is defined as being between 2.0 and 2.5 s travel time from the stop line (the exact value in this range depends on the vehicle's speed). The controller passage time is generally sufficient for this purpose. Occasionally, the call from the last detection zone must be extended (beyond that provided by the passage time) to provide dilemma zone protection to all vehicles in the design speed range. In these instances, the detection zone should be set to have a small extension time. This extension time can be computed as:

$$E_2 = larger\ of\!: \left[ \begin{array}{l} \dfrac{x_2 - x_{ez} - l_d - l^*_{v,2}}{v_e} - PT \\ \\ 0.0 \end{array} \right. \tag{10}$$

with,

$$x_{ez} = 0.8\, v_e + \frac{v_e^2}{40.8} \tag{11}$$

and

$$l^*_{v,2} = (l_v - l_{ro}) + (x_2 + x_c - l_d)\frac{h_v}{h_c} \tag{12}$$

and

$$v_e = larger\ of\!: [1.47\, V_5,\ v_2] \tag{13}$$

where:

$E_2$ = extension time setting for the second detection zone, s;
$x_{ez}$ = distance between the stop line and the end of the dilemma zone, ft;
$l_{v,2}{}^*$ = effective length of vehicle at the second detection zone, ft;
$v_e$ = speed used to define the extension setting, fps; and
$V_5$ = 5th percentile speed (= 0.717 x $V_{85}$), mph.

The factor of "0.717" used to estimate the 5th percentile speed is based on the assumption that the distribution of speeds is normal with a standard deviation equal to 12 percent of the mean speed. The constants in Equation 11 are based on a best-fit to the data reported by Zegeer and Deen (*13*).

**Simulation Analysis.** Computer simulations of a two-lane intersection approach were conducted for this research to determine the most effective passage time setting for advance detection design. A series of simulations were conducted for approach volumes ranging from 200 to 800 veh/h. The CORSIM simulation model was used for the simulation experiments. Passage times of 1.1, 1.5, and 2.0 s were evaluated. Passage times less than 1.1 s could not be evaluated because of limitations with the simulation model. CORSIM vehicle lengths were either 14 or 16 ft. The distribution of vehicle types yielded an average vehicle length of 15.6 ft.

The effect of camera height on vehicle length was accommodated by computing an equivalent CORSIM detector length $l_{d,sim}$ using the following equation:

$$l_{d,sim} = l_d + l_v^* - l_v \tag{14}$$

This equation produces a simulated detector length equivalent to that provided by a VIVDS zone of length $l_d$.

Equations 3 and 7 through 14 were used to develop the detection layout. The resulting values are listed in Table 4-4. As indicated in this table, Equation 14 yielded CORSIM detector lengths of 73.1 ft for the first detector and about 50 ft for the second detector. The amount by which these lengths exceed 20 ft is an indication of the effect of vehicle height, camera height, and the video conversion of three-dimensional objects in the plane of the pavement to a two-dimensional image plane.

The length of the stop-line detection zone was obtained from Table 4-3. These lengths are based on the use of a 0.0-s controller passage time. To achieve the equivalent operation with a nonzero passage time, the stop-line detector's "inhibit" feature was invoked (i.e., via a Type III CORSIM detector). The inhibit feature disabled the stop-line detector after the queue (waiting at the start of the phase) was served. In this manner, the stop-line detector functioned as if a 0.0-s passage time was set on the controller.

The results of the simulation analysis are shown in Figures 4-6 and 4-7. The trends shown are based on a maximum green setting of 60 s. Each data point shown in these figures reflects an average for one hour of simulated traffic events. Figure 4-6 shows that intersection control delay is lowest when a 1.1-s passage time is used. This passage time is also least sensitive to approach volume. A similar trend was found for a maximum green setting of 40 s.

## Table 4-4. Detection Zone Layout for Simulation Analysis.

| Detection Zone | Variable | Passage Time ($PT$)[1], s | | |
|---|---|---|---|---|
| | | 1.1 | 1.5 | 2.0 |
| First | 85th percentile Speed ($V_{85}$), mph | 45 | 45 | 45 |
| | Distance between the stop line and upstream edge ($x_1$), ft | 353 | 353 | 353 |
| | Effective length of vehicle ($l_{v,1}$*), ft | 68.7 | 68.7 | 68.7 |
| | Simulated detector length ($l_{d,sim,1}$), ft | 73.1 | 73.1 | 73.1 |
| Second | Speed associated with the second detection zone ($v_2$), ft/s | 43.3 | 40.6 | 37.7 |
| | Distance between the stop line and upstream edge ($x_2$), ft | 216 | 203 | 189 |
| | Effective length of vehicle ($l_{v,2}$*), ft | 48.3 | 46.3 | 44.1 |
| | Simulated detector length ($l_{d,sim,2}$), ft | 52.7 | 50.7 | 48.5 |
| | Speed used to define the extension setting ($v_e$), ft/s | 47.3 | 47.3 | 47.3 |
| | Distance between stop line and end of the dilemma zone ($x_{ez}$), ft | 92.7 | 92.7 | 92.7 |
| | Extension time setting ($E_2$), s | 0.1 | 0.0 | 0.0 |

Note:

1 - Values based on an average CORSIM vehicle length $l_v$ of 15.6 ft, a camera height $h_c$ of 30 ft, and a distance between the camera and stop line $x_c$ of 50 ft.

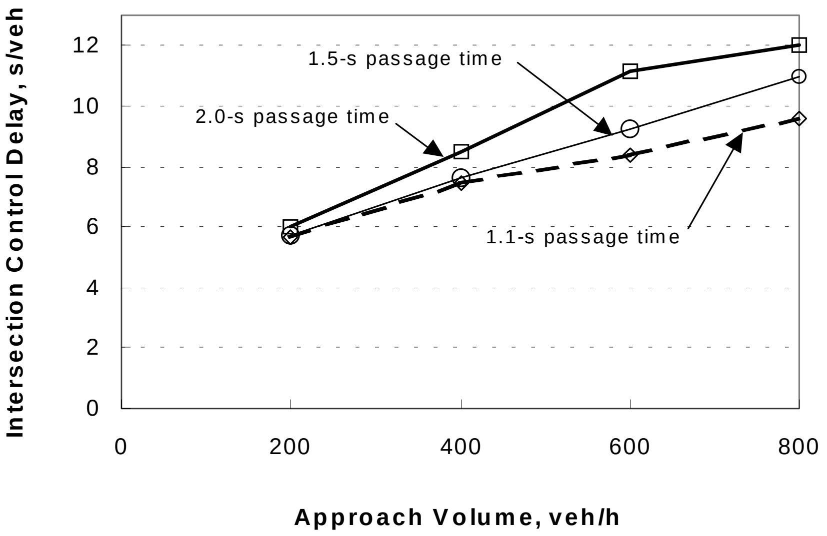


Figure 4-6. Effect of Passage Time on Delay.

Figure 4-7 shows the effect of passage time on max-out frequency. This frequency represents the percentage of phases ended by max-out. A max-out occurs when a continuous stream of calls is placed during the green indication such that the phase is extended to its maximum limit (i.e., max-out). The trends in Figure 4-7 indicate that a 1.1-s passage time is associated with the lowest frequency of max-out. Similar trends were found for a maximum green setting of 40 s.

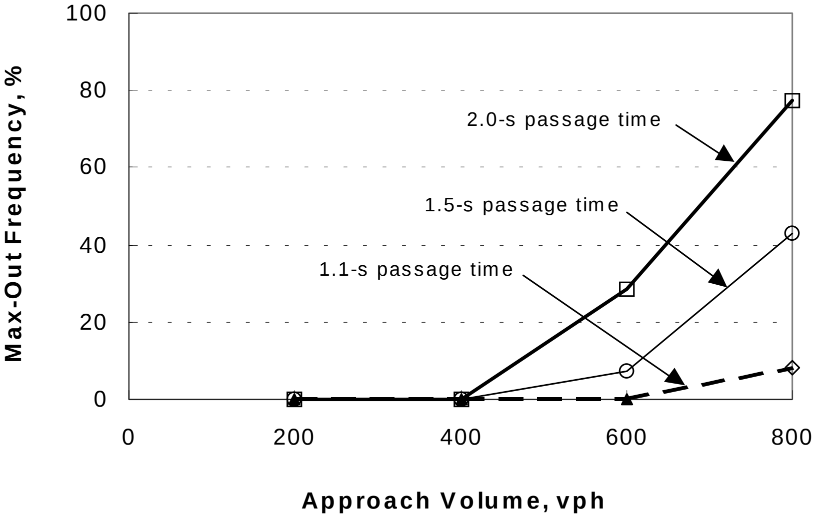


**Figure 4-7. Effect of Passage Time on Max-Out Frequency.**

Based on the results of the simulation analysis, a passage time of 1.0 s was selected for advanced detection zone layout for VIVDS applications.

**Guidelines.** Equations 3 and 7 through 13 were used to compute the appropriate advance detection zone locations and extension settings for VIVDS applications. These values are listed in Table 4-5. They are based on a passage time of 1.0 s. The use of these values should provide lower delay than that incurred with other locations or passage times.

When used with advance detection, the stop-line detection zone layout should follow the guidelines described in the previous section, "Stop-Line Detection." Specifically, the length of this zone should be obtained from Table 4-3.

One difference exists between the layout of the stop-line detection zone *with* advanced detection and the layout of the stop-line zone *without* advance detection. When used with advance detection, the controller has a 1.0-s passage time that is required by the advance detection zones. When used without advance detection, a 0.0-s passage time is required. Because the 1.0-s passage time is required when the stop-line detection zone is used with advance detection, it is necessary to make a slight modification to the stop-line detection zone's operation. Specifically, the detector channel serving the stop-line detection zone should have the "inhibit" feature (e.g., Special Detector Mode 4 in Eagle controllers) invoked. The stop-line detector channel in the controller should also have 0.0 s set on its delay and extend timers. The inhibit feature disables the stop-line detection zone after the queue, waiting at the start of the phase, has been served. It should be noted that the advance detection zones should be served by a detector channel that is separate from that of the stop-line detection zone.

**Table 4-5. Advance Detection Zone Layout for VIVDS Applications.**

| **Approach Speed Limit[1], mph** | **Distance to 1st Det. Zone ($x_1$)[2], ft** | **Distance Between Camera and Stop Line ($x_c$)[3], ft** | **Camera Height ($h_c$), ft** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **24** | **28** | **32** | **36** | **40** | **24** | **28** | **32** | **36** | **40** |
| | | | **Distance to 2nd Det. Zone ($x_2$)[2], ft** | | | | | **Extension on 2nd Det. Zone ($E_2$), s** | | | | |
| 60 | 470 | 80 | 282 | 294 | 303 | 310 | 315 | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 |
| | | 100 | 279 | 291 | 301 | 308 | 313 | 0.0 | 0.0 | 0.1 | 0.3 | 0.4 |
| | | 150 | 271 | 285 | 295 | 302 | 309 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 |
| 55 | 431 | 80 | 256 | 267 | 275 | 281 | 286 | 0.0 | 0.0 | 0.2 | 0.3 | 0.5 |
| | | 100 | 252 | 264 | 272 | 279 | 284 | 0.0 | 0.0 | 0.1 | 0.3 | 0.4 |
| | | 150 | 245 | 257 | 267 | 274 | 280 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 |
| 50 | 392 | 50 | 234 | 243 | 250 | 256 | 260 | 0.0 | 0.1 | 0.3 | 0.5 | 0.6 |
| | | 100 | 226 | 236 | 244 | 251 | 255 | 0.0 | 0.0 | 0.1 | 0.3 | 0.4 |
| | | 150 | 218 | 230 | 239 | 245 | 251 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 |
| 45 | 353 | 50 | 207 | 216 | 222 | 227 | 231 | 0.0 | 0.1 | 0.3 | 0.5 | 0.6 |
| | | 100 | 199 | 209 | 216 | 222 | 226 | 0.0 | 0.0 | 0.0 | 0.3 | 0.4 |
| | | 150 | 192 | 202 | 210 | 217 | 222 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 |

Notes:
1 - Approach speed limit is assumed to equal the 85th percentile speed $V_{85}$.
2 - Distances shown are based on a 20-ft detection zone length and a 1.0-s passage time setting.
3 - Distance between the camera and the stop line, as measured parallel to the direction of travel.

During the initial VIVDS setup, the beginning and end of each advance detection zone should be measured along the roadway with a distance wheel. The location of the beginning of the zone is listed in Table 4-5. The end of the zone is 20 ft closer to the stop line. Each edge should be marked with a traffic cone placed on the outside edge of the traveled way. One or more VIVDS detectors should then be drawn on the VIVDS monitor such that the entire length of the resulting detection zone is monitored by the VIVDS processor. The traffic cones can then be removed.

As a last step in the setup, the extension setting on the second advance detection zone should be set at the value listed in Table 4-5. This setting should be set in the VIVDS. It should be applied to all detectors that comprise the second detection zone. The delay and extend timers provided in the controller for each detector channel should be set at 0.0 s.

## GUIDELINE EVALUATION

This section describes the activities undertaken to evaluate the guidelines developed in the previous sections. These activities included the development of a field study plan, the conduct of a series of field studies, the evaluation of selected VIVDS design alternatives, and the evaluation of the detection zone layout guidelines.

Field studies were conducted at each of several signalized intersections and interchanges. The objective of the studies was to evaluate the effect of changes to the VIVDS at each intersection or interchange. The changes implemented included alternative VIVDS hardware, alternative detection designs, and alternative detection layouts. The effects of each change were evaluated using a before-after study. During each study, data were collected that described the VIVDS's detection accuracy and the intersection's traffic operation. For each intersection approach, the data collection and analysis focused on the through traffic movement and any turn movements that were controlled by the through phase.

The following sections describe the findings from the evaluation of alternatives. Initially, the field study plan is described. This description includes a review of the types of data collected and the methods used for their collection. Then, the data are summarized and trends discussed. Finally, the data are used to demonstrate the effectiveness of the guidelines developed in the previous section.

### Field Study Plan

#### *Study Site Characteristics*

Eight intersections and two interchanges were included in the before-after studies. These intersections or interchanges (referred to hereafter as "study sites") were identified through discussions with TxDOT staff. The primary criterion used to identify the study sites was that the candidate site must have an operational VIVDS. Also, it was desired that the set of 10 study sites collectively reflect a range of area types, traffic volumes, signal phase sequences, and camera mounting locations. The location of each site is listed in Table 4-6.

Table 4-7 identifies additional characteristics of each study site. These characteristics include the camera mounting location, signal head mounting type, and the average signal cycle length. As the data indicate, the sites collectively offer a range in camera and signal head mounting locations. Cycle length also varies widely among the sites.

Table 4-8 identifies the lane assignment, signal phasing, and speed limit for each intersection approach. The lane assignment data indicate that the sites collectively include approaches both with and without left-turn bays. Some of the study sites also include protected left-turn phasing while others do not. The range of speeds represented is quite broad, varying from 25 to 70 mph.

## Table 4-6. Study Site Locations.

| No. | District | City | Location | Junction Type | | Area Type |
|---|---|---|---|---|---|---|
| | | | | Intersection | Interchange | |
| 1 | Atlanta | Atlanta | U.S. 59 & S.H. 77 | ✔ | | Urban |
| 2 | | Marshall | U.S. 80 & F.M. 1997 | ✔ | | Urban |
| 3 | | Linden | U.S. 59 & F.M. 125 | ✔ | | Rural |
| 4 | | Domino | U.S. 59 & F.M. 3129 | ✔ | | Rural |
| 5 | Corpus Christi | Sinton | U.S. 181/BU. 77 & S.H. 188 | ✔ | | Urban |
| 6 | | Driscoll | U.S. 77 & F.M. 665 | ✔ | | Urban |
| 7 | Lufkin | Lufkin | U.S. 59 & Loop 287 | | ✔ | Urban |
| 8 | | Lufkin | U.S. 69S & Loop 287 | | ✔ | Urban |
| 9 | Tyler | Henderson | S.H. 79 & U.S. 259 | ✔ | | Urban |
| 10 | | Canton | S.H. 64 & S.H. 19 | ✔ | | Urban |

## Table 4-7. Study Site Characteristics - Camera Mounting and Cycle Length.

| No. | Location | Camera Mounting | Signal Head Mount | Cycle Length [1], s |
|---|---|---|---|---|
| 1 | U.S. 59 & S.H. 77 | Pole | Mast arm | 81 ±26 |
| 2 | U.S. 80 & F.M. 1997 | Pole | Mast arm | 80 ±18 |
| 3 | U.S. 59 & F.M. 125 | Pole | Span wire | 65 ±33 |
| 4 | U.S. 59 & F.M. 3129 | Pole [2] | Mast arm | 108 ±76 |
| 5 | U.S. 181/BU. 77 & S.H. 188 | Mast arm | Mast arm | 53 ±20 |
| 6 | U.S. 77 & F.M. 665 | Pole | Span wire | 74 ±26 |
| 7 | U.S. 59 & Loop 287 | Mast arm | Mast arm | 109 ±26 |
| 8 | U.S. 69S & Loop 287 | Mast arm | Mast arm | 72 ±20 |
| 9 | S.H. 79 & U.S. 259 | Pole | Span wire | 81 ±15 |
| 10 | S.H. 64 & S.H. 19 | Pole | Span wire | 82 ±17 |

Notes:

1 - Values reported are cycle length average and standard deviation (average ±std. dev.).

2 - The southbound approach at this location has the camera mounted on the mast arm.

## Table 4-8. Study Site Characteristics - Geometry, Phasing, and Speed Limit.

| No. | Location | Intersection Approach | Approach Lanes | | | Left-Turn Phasing [1] | Speed Limit, mph |
|---|---|---|---|---|---|---|---|
| | | | Left | Thru | Right | | |
| 1 | U.S. 59 & S.H. 77 | Northbound | 1 | 2 | 0 | Lead | 45 |
| | | Southbound | 1 | 2 | 0 | Lead | 50 |
| | | Eastbound | 2 | 1 | 0 | Lead | 50 |
| | | Westbound | 1 | 1 | 0 | Lead | 45 |
| 2 | U.S. 80 & F.M. 1997 | Northbound | 1 | 1 | 0 | Lag | 35 |
| | | Southbound | 1 | 1 | 0 | Lag | 25 |
| | | Eastbound | 1 | 2 | 0 | Lag | 40 |
| | | Westbound | 1 | 2 | 1 | Lag | 40 |
| 3 | U.S. 59 & F.M. 125 | Northbound | 0 | 2 | 0 | none | 50 |
| | | Southbound | 0 | 2 | 0 | none | 50 |
| | | Eastbound | 0 | 1 | 0 | none | 45 |
| | | Westbound | 0 | 1 | 0 | none | 45 |
| 4 | U.S. 59 & F.M. 3129 | Northbound | 1 | 2 | 1 | none | 70 |
| | | Southbound | 1 | 2 | 0 | Lead | 70 |
| | | Eastbound | 0 | 1 | 0 | none | not posted |
| | | Westbound | 1 | 0 | 1 | none | 55 |
| 5 | U.S. 181/BU. 77 & S.H. 188 | Northbound | 0 | 2 | 0 | none | 35 |
| | | Southbound | 0 | 2 | 0 | Lead | 40 |
| | | Eastbound | 0 | 2 | 0 | none | 35 |
| | | Westbound | 0 | 2 | 1 | Lead | 30 |
| 6 | U.S. 77 & F.M. 665 | Northbound | 1 | 2 | 0 | Lead | 40 |
| | | Southbound | 1 | 2 | 0 | Lead | 40 |
| | | Eastbound | 0 | 1 | 1 | none | 55 |
| | | Westbound | 1 | 1 | 1 | Lead | 55 |
| 7 | U.S. 59 & Loop 287 (Interchange) | Northbound | 0 | 2 | 1 | 4-Phase with fixed transition interval | 45 |
| | | Southbound | 1 | 2 | 1 | | 45 |
| | | Eastbound | 1 | 1 | 0 | | 40 |
| | | Westbound | 1 | 2 | 0 | | 40 |
| 8 | U.S. 69S & Loop 287 (Interchange) | Northbound | 1 | 2 | 0 | 4-Phase with fixed transition interval | 50 |
| | | Southbound | 1 | 2 | 0 | | 50 |
| | | Eastbound | 0 | 1 | 0 | | 40 |
| | | Westbound | 1 | 1 | 0 | | 40 |
| 9 | S.H. 79 & U.S. 259 | Northbound | 1 | 2 | 0 | dir. separation | 40 |
| | | Southbound | 1 | 3 | 0 | dir. separation | 40 |
| | | Eastbound | 0 | 1 | 0 | dir. separation | 25 |
| | | Westbound | 1 | 1 | 0 | dir. separation | 45 |
| 10 | S.H. 64 & S.H. 19 | Northbound | 1 | 2 | 1 | Lead | 45 |
| | | Southbound | 1 | 1 | 1 | Lead | 35 |
| | | Eastbound | 1 | 1 | 1 | Lead | 30 |
| | | Westbound | 1 | 1 | 1 | Lead | 30 |

Note:
1 - Left-Turn Phasing: "dir. separation" = phase serves all movements on one approach and presents red to all other approaches.

VIVDS performance is generally believed to be influenced by camera location, pitch angle, and focal length. Camera location was measured using a Cartesian coordinate system (*x, y, z*) with (0, 0, 0) located at the intersection of the center of the approach traffic lanes. As shown in Figure 4-8, the *x*-axis is oriented in the direction of travel, the *y*-axis is perpendicular to the direction of travel, and the *z*-axis is perpendicular to the plane of the pavement. Distances in the *x*, *y*, and *z* directions are referred to as "distance," "offset," and "height," respectively.

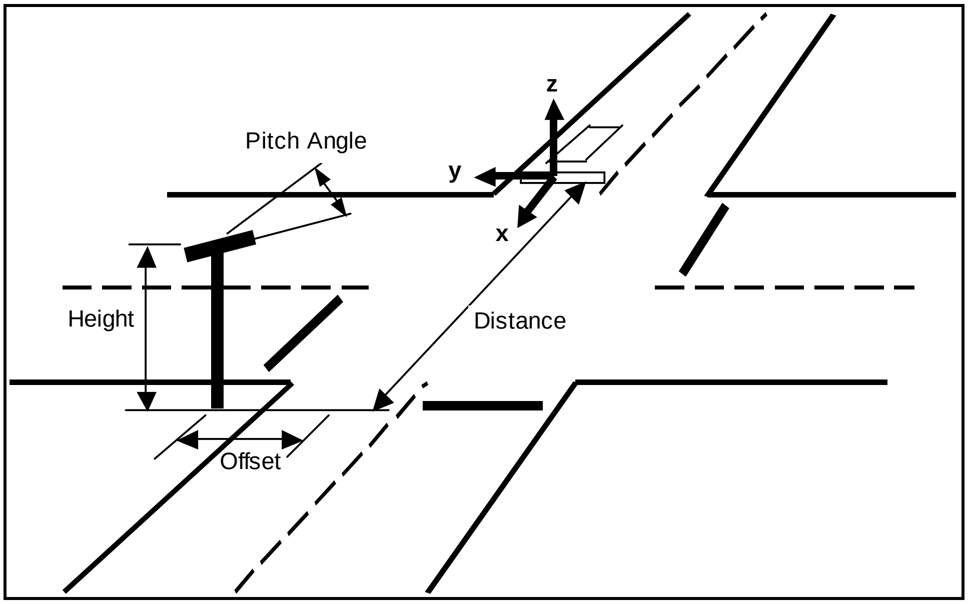


**Figure 4-8. Camera Location and Coordinate System.**

The camera location variables for each study site and approach are listed in Table 4-9. The camera pitch angle and focal length were computed by locating objects (e.g., the stop line, lane lines, etc.) in the camera field of view and by using the geometric relationships associated with camera optics.

The minimum camera height guidelines provided in the section titled "Camera Location" were used to evaluate the camera heights listed in Table 4-9. Based on this evaluation, it was found that 85 percent of the sites (34 of 40) had cameras that were above the minimum height needed to reduce occlusion. It was also found that 19 sites had approach speeds of 45 mph or more and advance detection. Of these sites, 63 percent (12 of 19) had cameras above the minimum height needed for advance detection. Overall, 70 percent of the sites (28 of 40) were in compliance with the applicable minimum height recommendations.

## Table 4-9. Study Site Characteristics - Camera Location.

| No. | Location | Intersection Approach | Camera Coordinates[1], ft |  |  | Pitch Angle[2], degrees | Focal Length[2], mm |
|---|---|---|---|---|---|---|---|
|  |  |  | Distance (x) | Offset (y) | Height (z) |  |  |
| 1 | U.S. 59 & S.H. 77 | Northbound | 125 | 30 | 36 | 7 | 11 |
|  |  | Southbound | 128 | 20 | 28 | 5 | 12 (11) |
|  |  | Eastbound | 143 | 25 | 37 | 8 | 16 (13) |
|  |  | Westbound | 149 | 46 | 36 | 9 | 17 (13) |
| 2 | U.S. 80 & F.M. 1997 | Northbound | 147 | 19 | 36 | 11 (10) | 19 (20) |
|  |  | Southbound | 126 | 15 | 37 | 11 | 19 |
|  |  | Eastbound | 96 | 22 | 36 | 12 | 12 |
|  |  | Westbound | 120 | 23 | 36 | 12 (13) | 8 (10) |
| 3 | U.S. 59 & F.M. 125 | Northbound | 124 | 27 | 28 | 10 | 14 |
|  |  | Southbound | 110 | 32 | 29 | 11 | 13 (11) |
|  |  | Eastbound | 78 | 25 | 26 | 12 (13) | 15 (14) |
|  |  | Westbound | 89 | 10 | 29 | 15 (13) | 12 (15) |
| 4 | U.S. 59 & F.M. 3129 | Northbound | 71 | -26 | 37 | 3 | 57 |
|  |  | Southbound | 79 | 0 | 25 | 10 | 13 |
|  |  | Eastbound | 81 | 14 | 28 | 13 | 13 |
|  |  | Westbound | 73 | 17 | 27 | 9 | 12 |
| 5 | U.S. 181/BU. 77 & S.H. 188 | Northbound | 99 | 2 | 25 | 10 | 11 |
|  |  | Southbound | 105 | 3 | 25 | 10 | 8 |
|  |  | Eastbound | 95 | 3 | 25 | 10 | 12 |
|  |  | Westbound | 98 | -4 | 24 | 9 | 16 |
| 6 | U.S. 77 & F.M. 665 | Northbound | 56 | -70 | 37 | 20 | 7 |
|  |  | Southbound | 56 | -70 | 34 | 8 | 6 |
|  |  | Eastbound | 100 | -1 | 33 | 11 | 14 |
|  |  | Westbound | 115 | -7 | 38 | 11 | 10 |
| 7 | U.S. 59 & Loop 287 | Northbound | 79 | 0 | 24 | 16 | 7 |
|  |  | Southbound | 65 | -6 | 27 | 14 | 7 |
|  |  | Eastbound | 62 | 2 | 25 | 15 | 7 |
|  |  | Westbound | 50 | 3 | 24 | 15 | 8 |
| 8 | U.S. 69S & Loop 287 | Northbound | 41 | 7 | 25 | 21 | 7 |
|  |  | Southbound | 50 | 6 | 26 | 14 | 8 |
|  |  | Eastbound | 56 | 6 | 26 | 19 | 6 |
|  |  | Westbound | 52 | -1 | 27 | 17 | 8 |
| 9 | S.H. 79 & U.S. 259 | Northbound | 124 | 34 | 29 | 10 | 16 |
|  |  | Southbound | 110 | 37 | 36 | 15 | 9 |
|  |  | Eastbound | 118 | 51 | 30 | 11 | 14 |
|  |  | Westbound | 105 | 6 | 32 | 11 | 13 |
| 10 | S.H. 64 & S.H. 19 | Northbound | 127 | 24 | 27 | 10 | 14 |
|  |  | Southbound | 116 | 26 | 28 | 12 | 13 |
|  |  | Eastbound | 124 | 33 | 25 | 7 | 12 |
|  |  | Westbound | 123 | 22 | 31 | 10 | 14 |

Notes:

1 - Distance = distance from the camera to the stop line, as measured parallel to the direction of travel; Offset = distance from the center of the approach to the camera, as measured perpendicular to the travel direction (negative offsets are to the driver's left).

2 - These values were unchanged between "before" and "after" studies; exceptions to this rule show the "after" value in parentheses.

Following each "before" study, a change was made to the VIVDS hardware, its detection design, its detection layout, or some combination of all three. The sites located in the Atlanta District (i.e., Sites 1, 2, 3, and 4) underwent changes in hardware, detection design, and detection layout. The detection design and layout studied at these sites was that which was implemented by the VIVDS hardware installer. The sites in the Corpus Christi, Lufkin, and Tyler Districts underwent a change only in detection layout. The layout that was implemented was based on the guidelines described in the section titled "Detection Zone Layout."

The changes implemented at each site are listed in Table 4-10. As noted in the last column of this table, problems were encountered at the intersection of S.H. 79 and U.S. 259 in Henderson that precluded the conduct of an "after" study. Specifically, the VIVDS hardware at this location would not accept a change in detection design. After trying unsuccessfully to implement the proposed changes, the "after" study was abandoned at this location.

**Table 4-10. Changes Implemented at Each Study Location.**

| No. | Location | Hardware[1] | | Detection Changes? |
|---|---|---|---|---|
| | | Before | After | |
| 1 | U.S. 59 & S.H. 77 | Vantage | Autoscope | Yes, design and layout by equipment installer. |
| 2 | U.S. 80 & F.M. 1997 | Autoscope | VideoTrak | Yes, design and layout by equipment installer. |
| 3 | U.S. 59 & F.M. 125 | Autoscope | Traficon | Yes, design and layout by equipment installer. |
| 4 | U.S. 59 & F.M. 3129 | VideoTrak | Vantage | Yes, design and layout by equipment installer. |
| 5 | U.S. 181/BU. 77 & S.H. 188 | Vantage | n.c. | Yes, layout only using recommended guidelines. |
| 6 | U.S. 77 & F.M. 665 | Vantage | n.c. | Yes, layout only using recommended guidelines. |
| 7 | U.S. 59 & Loop 287 | Vantage | n.c. | Yes, layout only using recommended guidelines. |
| 8 | U.S. 69S & Loop 287 | Vantage | n.c. | Yes, layout only using recommended guidelines. |
| 9 | S.H. 79 & U.S. 259 | Autoscope | n.c. | No, software problems precluded changes. |
| 10 | S.H. 64 & S.H. 19 | Autoscope | n.c. | Yes, layout only using recommended guidelines. |

Note:
1 - n.c. = no change.

### *Data Collection*

**Database Composition.** The field studies were designed to collect the data needed to evaluate the alternative VIVDS hardware, detection designs, and detection layouts. Collectively, the data gathered describe the geometric elements, traffic control features, traffic operations, and VIVDS performance at each intersection. VIVDS performance was assessed in terms of detection accuracy and intersection operation.

Detection accuracy relates to the number of times that a VIVDS reports either a detection when a vehicle is in the detection zone or no detection when a vehicle is not in the detection zone.

Violation of either condition represents a discrepancy between the phase-call information provided by the VIVDS and the true call information, as would be provided by a perfect detector. The measures used to quantify detection accuracy include discrepant call frequency and error rate. The former measure relates to the number of discrepant calls per signal cycle and the latter relates to the ratio of discrepant calls to true calls.

Figure 4-9 illustrates the two types of discrepancies: "unneeded calls" and "missed calls." In this figure, the true occurrence of a call is shown by the lowest trend line. A vehicle call is shown to truly arrive at time 1.0 s and depart at 2.0 s, again at 2.7 s and 3.7 s, and again at 5.7s and 7.0 s. However, the VIVDS reports the first call as arriving at 0.7 s thereby placing an "unneeded call" for 0.3 s. The VIVDS then reports the first departure at 2.3 s which also represents an unneeded call of 0.3 s duration. At 4.7 s, the VIVDS reports another unneeded call. In this instance, there was no corresponding true call.

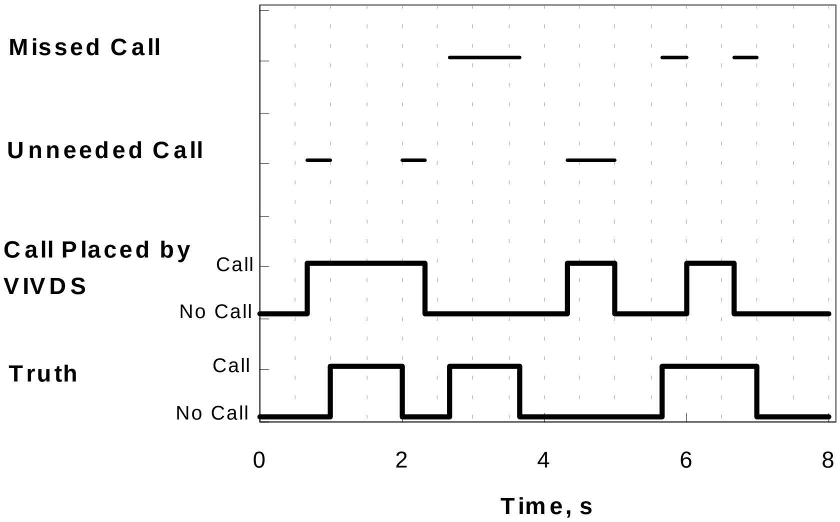


**Figure 4-9. Discrepancy Due to Missed and Unneeded Calls.**

A missed call is the opposite of an unneeded call. For example, the vehicle call arrival at 2.7 s is not detected by the VIVDS and, thus, represents a "missed call." Similarly, the true call arrival at 5.7 s is not detected by the VIVDS until 6.0 s. This delay also represents a missed call as does the VIVDS late response to the true call departure at 7.0 s.

It is recognized that small discrepancies are to be expected for all detection systems. It is also recognized that some small discrepancies may be due to drift in the time clocks of the data collection devices. To minimize the impact of these deviations, discrepancies of less than 0.3 s were not identified for this project nor recorded in the database.

Two measures of performance were used to describe the overall operation of the intersection. The first measure is "phase max-out." It is computed as the percentage of cycles that are terminated by max-out (i.e., by extending the green to its maximum limit). It is correlated with intersection performance during the green indication. Phase termination by max-out tends to increase delay to the subject movement. It is also less safe than termination by "gap-out."

The second performance measure is "control delay." This measure represents the delay incurred by the motorist as a consequence of signal control. Delay can be particularly lengthy if a vehicle waiting at the stop line is not detected. It is also lengthy if a vehicle is initially detected but its call is then dropped by the VIVDS before being served.

**Data Collection Equipment.** Four videotape recorders and an industrial computer were used to collect the raw data. The computer was housed in the controller cabinet during the course of the study. It recorded the time each signal phase and detector input was activated during the study. The video recorders were housed in a vehicle parked in the vicinity of the controller cabinet. One recorder was used to record one VIVDS camera input. All total, four cameras and associated intersection approaches were monitored at each site. A photocell sensor was monitored by the computer and used to continuously record the ambient light level during each study. A schematic of the data collection system and its relationship to the controller hardware is shown in Figure 4-10.

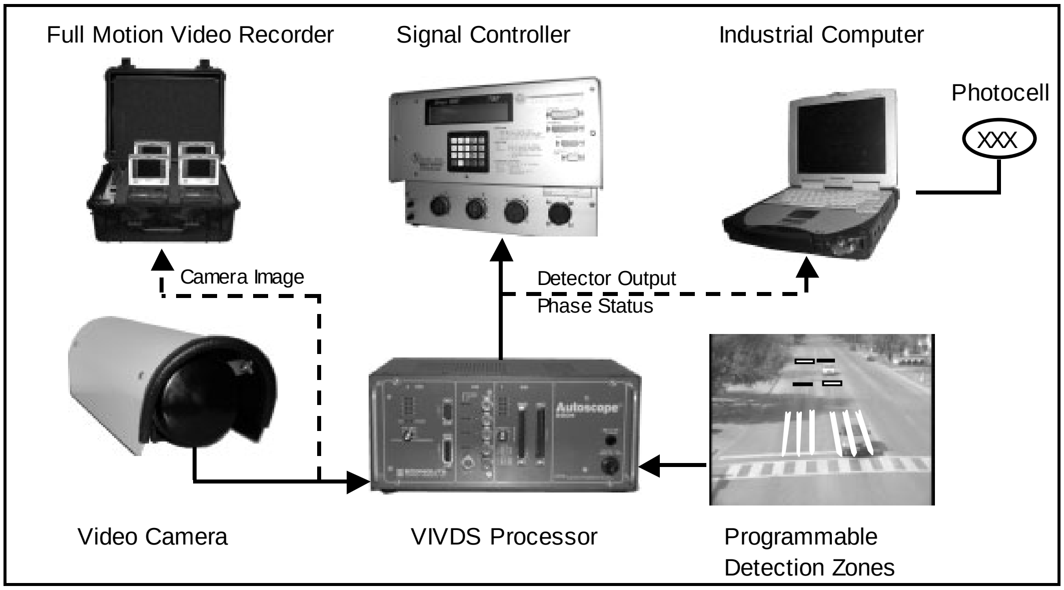


**Figure 4-10. Data Collection System and Controller Monitoring Points.**

**Data Collection Process.** All data for a given study were collected in one 24-hour period. Equipment installation took place from 9:00 to 11:00 a.m. Wire lead-ins from the computer's digital input/output card were connected to the controller back panel. One wire was connected to each of the eight detector terminals, and one wire was connected to each of the eight phase terminals. In addition, an isolation transformer was inserted in each video lead-in. One transformer output was used to restore the video feed to the VIVDS, and a second output was used to provide video for the recorder. The cabinet door was closed after the equipment was installed. Figure 4-11 illustrates the data collection equipment just prior to the start of study.

**a. Video Recorder Setup.** **b. Computer Setup.**

**Figure 4-11. Data Collection Equipment Setup.**

Data were collected during three two-hour study periods. One study period took place about midday (sun overhead), a second took place during the evening rush hour (sun on the horizon), and a third period took place during the evening (after sunset). This pattern provided the widest range of lighting levels and traffic volume conditions. It should also be noted that rain occurred during several of the "before" studies in the Atlanta District.

In addition to the video and controller data, other data were manually collected during each study. These data include measurements of the intersection geometry as well as a record of approach speed limits, signal phasing, controller settings, camera location, and detector settings (e.g., delay, extension, presence, pulse, directional, etc.). The data collected during each "before" and "after" study are listed in Column 4 of Table 4-11.

**Data Reduction Process.** All total, 480 hours of operation were recorded representing about 22,000 signal cycles. Several types of data were extracted from the videotapes and computer files. The process focused on the performance of the through traffic movement and any turn movements that were controlled by the through phase. The data reduced from the videotape and the computer files are identified in Columns 3 and 5, respectively, of Table 4-11.

**Table 4-11. Database Elements.**

| Category | Data Type | Data Collection Method | | |
|---|---|---|---|---|
| | | Reduced from Videotape | Site Survey | Reduced from Computer Files |
| Geometric Characteristics | Number and width of intersection traffic lanes | | ✔ | |
| | Photo log | | ✔ | |
| Camera Location | Camera coordinates (x, y, z) | | ✔ | |
| | Pitch angle | | computed | |
| | Focal length | | computed | |
| Traffic Control Characteristics | Speed limit | | ✔ | |
| | Phase sequence | | ✔ | |
| | Controller settings | | ✔ | |
| | Detection zone layout | | ✔ | |
| | Detection zone settings (delay, extend) | | ✔ | |
| Environment | Weather (clear, fog, rain) | ✔ | | |
| | Glare or reflection (from headlights, sun) | ✔ | | |
| | Camera motion (due to wind and vibration) | ✔ | | |
| | Image quality (static, bad signal) | ✔ | | |
| | Light level (illuminance) | | | ✔ |
| Detection Accuracy | Unneeded call frequency | ✔ | | |
| | Missed call frequency | ✔ | | |
| | True call frequency | ✔ | | |
| Operational Characteristics | Cycle length | | | ✔ |
| | Phase max-out frequency | | | ✔ |
| | Control delay | ✔ | | |

Note:
1 - "computed" = data were estimated based on physical measurements taken during the site survey.

The video data reduction process consisted of replaying the videotapes in slow motion and manually recording two types of data. During the first replay, the time that vehicles were truly in a detection zone was recorded for the purpose of quantifying detection accuracy. Ultimately, these "true" events were compared with the VIVDS output (as recorded in the computer files) to determine the frequency of discrepant calls. During the second replay, the count of vehicles traversing the stop line as well as the number of vehicles stopped by the signal were recorded for the purpose of quantifying control delay.

Due to time constraints, only a subset of the data collected were reduced. Specifically, it was decided to select only those approaches for which the video field of view included a view of one or more signal indications. These views allowed for the most precise synchronization between the computer time clock and the videotape recorder time clock. This criteria enabled accuracy data to be extracted for at least one approach at each site, with the exception of the sites in the Lufkin District. This level of sampling resulted in the extraction of accuracy data for 493 signal cycles.

In contrast to the accuracy data, the max-out frequency and delay data were gathered for almost all of the approaches studied. A sampling technique was used to extract the delay data. Specifically, delay data were extracted for one 15-minute time period during each of the midday and evening hours at each approach. Delay data were not gathered on the northbound approach at one site (i.e., U.S. 59 & F.M. 3129) due to limitations in the camera field of view. Delay data were collected for 1503 signal cycles. Max-out data were extracted from the computer files using a software program. In this manner, max-out data could be extracted for all approaches at all sites without the use of the videotapes. Max-out data were collected for 1140 signal cycles.

## Evaluation of VIVDS Design Alternatives

This section summarizes an evaluation of the VIVDS design alternatives implemented at each of the study sites. These alternatives were previously identified in Table 4-10. Initially, the content of the database is summarized using averages and totals. Then, the data are examined by comparing the performance measures with various study site characteristics (as listed in Tables 4-7, 4-8, and 4-9). Finally, the changes in VIVDS hardware are evaluated by comparing the performance measures computed for the "before" and "after" studies.

### *Database Summary*

Table 4-12 summarizes the average frequency of discrepant calls and true calls for each site and approach. The ratio of these two call frequencies is referred to as the "Error Rate" and is listed in the last two columns. The last three rows of this table summarize the frequencies and rates for select groups of sites as well as for all sites combined. As indicated in Table 4-10, Sites 1, 2, 3, and 4 were subject to changes in hardware, detection design, and detection layout. Sites 5, 6, 7, 8, 9, and 10 were slated for changes only to the detection layout. It should be noted that an "after" study was not conducted at Site 9 (in Henderson) due to VIVDS software problems.

The summary statistics in Table 4-12 indicate that one or more discrepant calls occur each cycle. The overall average error rates indicate that there are about 1.8 to 1.9 discrepant calls for each true call. The rates at the bottom of the table indicate that the hardware changes at Sites 1, 2, 3, and 4 resulted in a slight increase in error rate. In contrast, the detection layout changes at the other sites resulted in a slight reduction in error rate.

The duration of the discrepant calls was also examined to provide some understanding of its relationship to call frequency. For this analysis, the duration of all discrepant calls occurring each cycle was totaled and divided by the number of discrepant calls for the same signal cycle. The result of this division was the average discrepant call duration per discrepant call. The distribution of these averages for 493 signal cycles is shown in Figure 4-12.

## Table 4-12. Database Summary - Phase Call Frequency.

| No. | Location | Intersection Approach | Observations, cycles | | Call Frequency, calls/cycle | | | | Error Rate, dis. calls/true calls | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Discrepant Calls | | True Calls | | | |
| | | | Before | After | Before | After | Before | After | Before | After |
| 1 | U.S. 59 & S.H. 77 | Northbound | 15 | 15 | 4.7 | 2.9 | 3.2 | 2.1 | 1.5 | 1.4 |
| | | Southbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Eastbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Westbound | -- | 10 | -- | 2.1 | -- | 1.6 | -- | 1.3 |
| 2 | U.S. 80 & F.M. 1997 | Northbound | 15 | 15 | 2.3 | 6.1 | 1.4 | 1.9 | 1.6 | 3.2 |
| | | Southbound | -- | 15 | -- | 2.1 | -- | 1.1 | -- | 1.9 |
| | | Eastbound | 15 | 15 | 5.3 | 8.7 | 3.6 | 7.7 | 1.5 | 1.1 |
| | | Westbound | 10 | 15 | 7.5 | 9.1 | 4.9 | 5.2 | 1.5 | 1.8 |
| 3 | U.S. 59 & F.M. 125 | Northbound | 15 | 15 | 3.1 | 3.6 | 2.3 | 2.0 | 1.3 | 1.8 |
| | | Southbound | -- | 10 | -- | 2.5 | -- | 1.5 | -- | 1.7 |
| | | Eastbound | 15 | 15 | 2.9 | 3.3 | 2.0 | 1.5 | 1.5 | 2.2 |
| | | Westbound | -- | 10 | -- | 0.9 | -- | 0.4 | -- | 2.3 |
| 4 | U.S. 59 & F.M. 3129 | Northbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Southbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Eastbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Westbound | 15 | 5 | 3.9 | 1.6 | 1.6 | 1.0 | 2.4 | 1.6 |
| 5 | U.S. 181/BU.77 & S.H. 188 | Northbound | 15 | 15 | 4.0 | 5.6 | 1.5 | 2.2 | 2.7 | 2.5 |
| | | Southbound | 15 | 15 | 1.6 | 3.6 | 1.2 | 1.8 | 1.3 | 2.0 |
| | | Eastbound | 15 | 15 | 2.7 | 4.7 | 1.4 | 2.3 | 1.9 | 2.0 |
| | | Westbound | -- | -- | -- | -- | -- | -- | -- | -- |
| 6 | U.S. 77 & F.M. 665 | Northbound | 15 | 10 | 16.0 | 15.9 | 5.6 | 7.3 | 2.9 | 2.2 |
| | | Southbound | 10 | 10 | 14.6 | 12.6 | 6.6 | 6.5 | 2.2 | 1.9 |
| | | Eastbound | 15 | 15 | 3.4 | 4.5 | 1.3 | 2.7 | 2.6 | 1.7 |
| | | Westbound | 10 | 15 | 5.0 | 4.8 | 2.0 | 2.2 | 2.5 | 2.2 |
| 7 | U.S. 59 & Loop 287 | Northbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Southbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Eastbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Westbound | -- | -- | -- | -- | -- | -- | -- | -- |
| 8 | U.S. 69S & Loop 287 | Northbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Southbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Eastbound | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Westbound | -- | -- | -- | -- | -- | -- | -- | -- |
| 9 | S.H. 79 & U.S. 259 | Northbound | -- | | -- | | -- | | -- | -- |
| | | Southbound | 10 | | 7.6 | | 5.7 | | 1.3 | -- |
| | | Eastbound | -- | | -- | | -- | | -- | -- |
| | | Westbound | 13 | | 2.8 | | 1.0 | | 2.8 | -- |
| 10 | S.H. 64 & S.H. 19 | Northbound | 10 | 10 | 9.4 | 8.5 | 6.1 | 4.1 | 1.5 | 2.1 |
| | | Southbound | 5 | 5 | 10.6 | 2.4 | 7.4 | 1.2 | 1.4 | 2.0 |
| | | Eastbound | 5 | 5 | 10.0 | 4.6 | 4.2 | 2.2 | 2.4 | 2.1 |
| | | Westbound | -- | -- | -- | -- | -- | -- | -- | -- |
| **Sites 1, 2, 3, 4 (hardware changes):** | | | 100 | 140 | 4.1 | 4.3 | 2.6 | 2.6 | **1.6** | **1.7** |
| **Sites 5, 6, 7, 8, 9, 10 (detection changes):** | | | 138 | 115 | 6.7 | 6.5 | 3.2 | 3.2 | **2.1** | **2.0** |
| **All Sites:** | | | 238 | 255 | 5.6 | 5.3 | 2.9 | 2.9 | **1.9** | **1.8** |

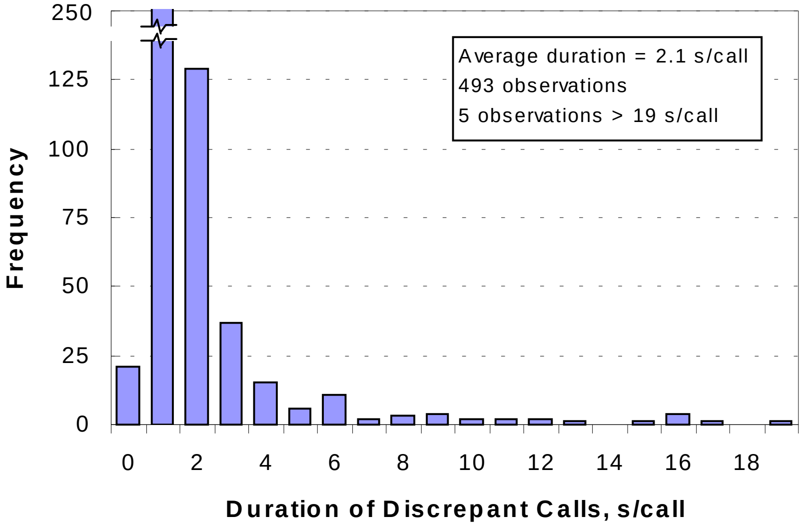


**Figure 4-12. Distribution of Discrepant Call Duration.**

Figure 4-12 indicates that about 80 percent of the discrepant calls averaged less than 2.0 s/call in any given cycle. The average duration of discrepant calls was about 2.1 s/call. For five of the 493 cycles, the average discrepant call duration exceeded 19 s/call.

The 20 percent of discrepant calls that were 2.0 s/call or longer were examined more closely as they were likely to have the greatest impact on performance. This subset of all discrepant calls is associated with an average of 4.1 discrepant calls per cycle with an average duration of about 6.0 s/call. These statistics suggest that, during about 20 percent of the signal cycles, a phase experienced about 4.1 missed or unneeded calls, and the total duration of these calls averaged 24.6 s *each* cycle.

Table 4-13 summarizes the operational performance measures at each of the study sites. Both measures listed apply to the through traffic movements on each approach. As with Table 4-12, the last three rows of Table 4-13 summarize the performance measures for selected groups of sites and for all sites. The data in these rows indicate that the changes at Sites 1, 2, 3, and 4 reduced the max-out percentage and control delay. A similar trend was found for those sites where the detection layout was changed. These findings suggest that all changes generally improved the operation of the intersections (or interchanges).

## Table 4-13. Database Summary - Max-Out Percentage and Control Delay.

| No. | Location | Intersection Approach | Phase Max-Out, % cycles | | | | Control Delay, s/veh | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Obs.[1] | Before | After | Change | Obs.[1] | Before | After | Change |
| 1 | U.S. 59 & S.H. 77 | Northbound | 15 | 0 | 7 | 7 | 2 | 42 | 38 | -4 |
| | | Southbound | 15 | 7 | 7 | 0 | 2 | 33 | 20 | -13 |
| | | Eastbound | 15 | 53 | 20 | -33 | 2 | 18 | 15 | -3 |
| | | Westbound | 15 | 13 | 0 | -13 | 2 | 42 | 32 | -10 |
| 2 | U.S. 80 & F.M. 1997 | Northbound | 15 | 0 | 0 | 0 | 2 | 25 | 21 | -4 |
| | | Southbound | 15 | 0 | 7 | 7 | 2 | 28 | 18 | -10 |
| | | Eastbound | 14 (15) | 50 | 53 | 3 | 2 | 11 | 12 | 1 |
| | | Westbound | 9 (15) | 44 | 47 | 3 | 1 | 10 | 9 | -1 |
| 3 | U.S. 59 & F.M. 125 | Northbound | 15 | 0 | 0 | 0 | 2 | 6 | 6 | 0 |
| | | Southbound | 0 (15) | -- | 0 | -- | 2 | 5 | 7 | 2 |
| | | Eastbound | 15 | 0 | 0 | 0 | 2 | 16 | 26 | 10 |
| | | Westbound | 0 (15) | -- | 0 | -- | 2 | 12 | 19 | 7 |
| 4 | U.S. 59 & F.M. 3129 | Northbound | 15 | 67 | 0 | -67 | -- | -- | -- | -- |
| | | Southbound | 0 (15) | -- | 0 | -- | 2 | 11 | 11 | 0 |
| | | Eastbound | 0 (5) | -- | 0 | -- | 2 | 0 | 0 | 0 |
| | | Westbound | 15 | 27 | 0 | -27 | 2 | 42 | 32 | -10 |
| 5 | U.S. 181/BU. 77 & S.H. 188 | Northbound | 15 | 7 | 0 | -7 | 2 | 11 | 13 | 2 |
| | | Southbound | 15 | 27 | 13 | -14 | 2 | 14 | 16 | 2 |
| | | Eastbound | 15 | 0 | 7 | 7 | 2 | 13 | 15 | 2 |
| | | Westbound | 15 | 13 | 7 | -6 | 2 | 14 | 11 | -3 |
| 6 | U.S. 77 & F.M. 665 | Northbound | 15 | 0 | 0 | 0 | 2 | 11 | 6 | -5 |
| | | Southbound | 15 | 7 | 0 | -7 | 2 | 10 | 8 | -2 |
| | | Eastbound | 15 | 7 | 0 | -7 | 2 | 35 | 36 | 1 |
| | | Westbound | 15 | 27 | 7 | -20 | 2 | 37 | 13 | -24 |
| 7 | U.S. 59 & Loop 287 | Northbound | 15 | 27 | 7 | -20 | 2 | 27 | 28 | 1 |
| | | Southbound | 15 | 60 | 33 | -27 | 2 | 35 | 30 | -5 |
| | | Eastbound | 15 | 47 | 27 | -20 | 2 | 46 | 41 | -5 |
| | | Westbound | 15 | 13 | 7 | -6 | 2 | 43 | 41 | -2 |
| 8 | U.S. 69S & Loop 287 | Northbound | 15 | 20 | 0 | -20 | 2 | 27 | 23 | -4 |
| | | Southbound | 15 | 20 | 0 | -20 | 2 | 38 | 25 | -13 |
| | | Eastbound | 15 | 13 | 13 | 0 | 2 | 33 | 29 | -4 |
| | | Westbound | 15 | 0 | 0 | 0 | 2 | 37 | 24 | -13 |
| 9 | S.H. 79 & U.S. 259 | Northbound | 15 (0) | 20 | | | 2 (0) | 24 | | |
| | | Southbound | 15 (0) | 53 | | | 2 (0) | 19 | | |
| | | Eastbound | 15 (0) | 0 | | | 2 (0) | 52 | | |
| | | Westbound | 15 (0) | 7 | | | 2 (0) | 37 | | |
| 10 | S.H. 64 & S.H. 19 | Northbound | 15 | 80 | 0 | -80 | 2 | 20 | 32 | 12 |
| | | Southbound | 15 | 80 | 7 | -73 | 2 | 28 | 31 | 3 |
| | | Eastbound | 15 | 53 | 13 | -40 | 2 | 12 | 15 | 3 |
| | | Westbound | 15 | 33 | 0 | -33 | 2 | 24 | 22 | -2 |
| **Sites 1, 2, 3, 4 (hardware changes):** | | | 173 (230) | 21 | 9 | **-12** | 25 | 23 | 20 | **-3** |
| **Sites 5, 6, 7, 8, 9, 10 (detection changes):** | | | 360 (300) | 26 | 7 | **-19** | 48 (40) | 26 | 23 | **-3** |
| **All Sites:** | | | 533 (530) | 24 | 8 | **-16** | 73 (65) | 25 | 22 | **-3** |

Note: 1 - Basis for max-out obs. is cycle ("after" obs. in parentheses if different from "before"). Basis for delay obs. is 15 minutes.

**Analysis of Factor Effects.** This section describes an analysis of the relationship between the frequency of call discrepancies and various factors that might cause their occurrence. The analysis considered a wide range of variables that would be useful to an engineer during the design of a VIVDS camera system. These variables include camera location (*x, y, z*), camera pitch angle, and camera focal length. The findings described in this section focus on those variables that show a cause-and-effect relationship. Each observation in the database represents events that occurred during one signal cycle.

The relationship between true call frequency and discrepant call frequency is shown in Figure 4-13. The trend in this figure indicates that there is typically about 1.83 discrepant calls for each true call. As noted with regard to Figure 4-12, most of these discrepancies are less than 2.0 s in duration. It was frequently observed that the discrepancies less than 2.0 s were associated with the arrival or departure of a true call. In this regard, the VIVDS tended to register a call a fraction of a second before or after its true arrival (or departure). The wholly missed or unneeded discrepancies were less frequent and often had a duration in excess of 2.0 s.

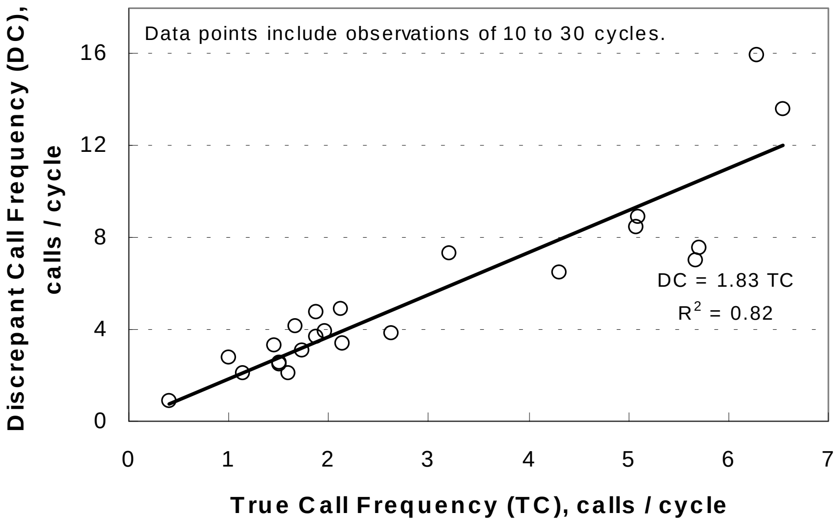


Figure 4-13. Relationship Between True Calls and Discrepant Calls.

There are only 23 data points shown in Figure 4-13. Each data point in this figure represents the average discrepancy for the 10 to 30 cycles observed for a given site and approach. This aggregation was used because plots with all 493 data points tended to be quite "busy" and often obscured the portrayal of trends in the data.

Figure 4-14 illustrates the effect of camera height and motion on error rate. The use of error rate removes the effect of true call frequency from the data and allows for a closer examination of secondary effects, such as camera height or motion, on the occurrence of discrepancies.

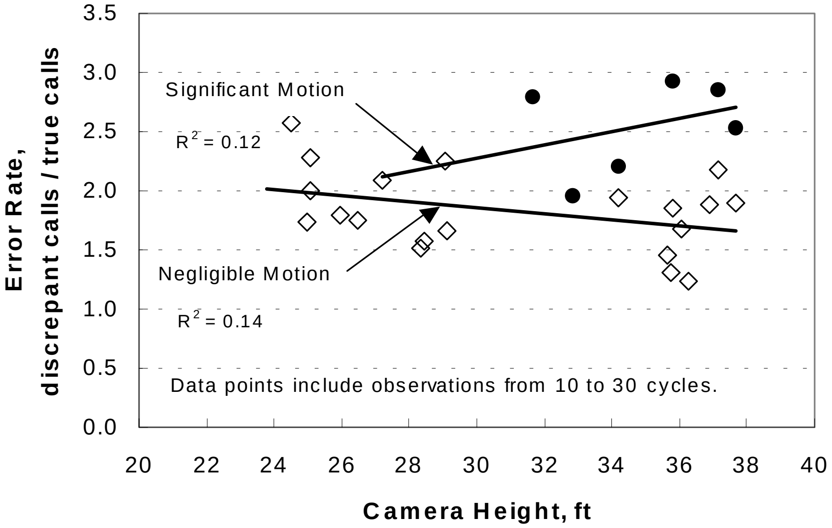


Figure 4-14. Effect of Camera Height and Motion on Error Rate.

The data in Figure 4-14 indicate that increasing camera height tends to decrease the call error rate, provided that there is no camera motion. However, several sites did experience significant camera motion (due to high winds or the passage of heavy vehicles) during some periods of the day. At these sites and during conditions of significant camera motion, the call error rate increased with increasing camera height.

The trend lines in Figure 4-14 suggest that there is a "point of diminishing returns" with respect to camera height when the camera support structure is susceptible to instability. Specifically, the data indicate that increasing camera height tends to improve accuracy, provided that there is no camera motion. The trends in Figure 4-14 indicate that camera heights of 34 ft or more may be associated with above-average errors *unless* the camera is mounted on a stable pole.

Figure 4-15 illustrates the effect of camera location on call error rate. Camera offset is categorized as "Left," "Center," and "Right" in this figure. These categories indicate the location of the camera relative to the intersection approach it monitors. All three categories are shown in Figure 4-16, as they relate to the eastbound approach at an intersection. The trends in Figure 4-15 suggest that cameras located on the left side are associated with a 20 percent higher error rate than those in the center location. However, it should be noted that the data for the left-side locations were available from only one site, and it is possible that other site factors could explain some of the observed errors.

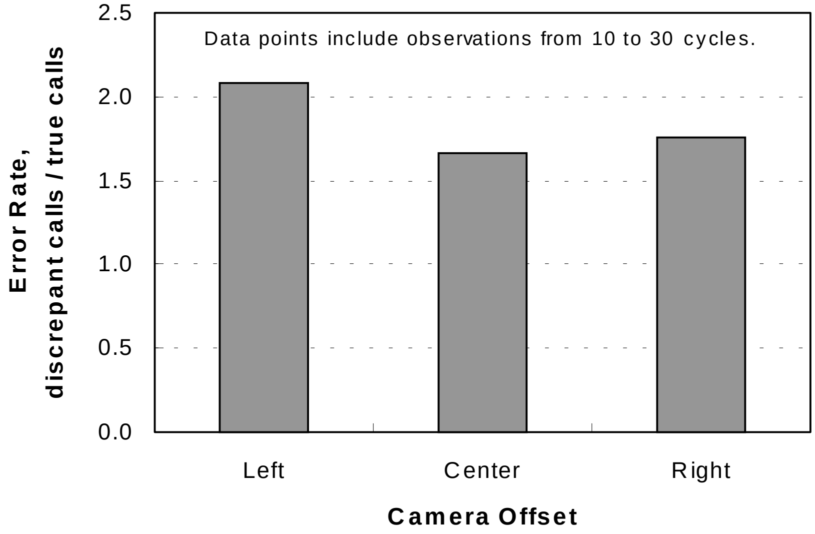


Figure 4-15. Effect of Camera Offset on Error Rate.

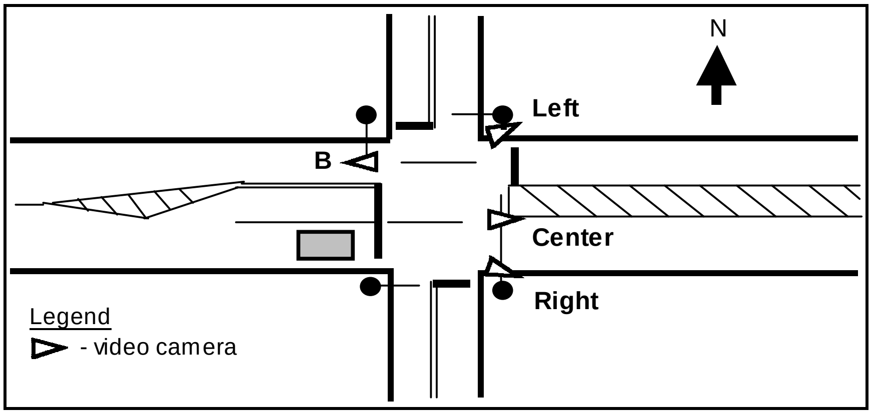


Figure 4-16. Camera Offset Categories.

The relationship between discrepant call frequency and delay was also examined. The results of this examination are shown in Figure 4-17. Only cycles with lengthy discrepant calls (i.e., those that incurred a total of 2.5 s or more per cycle) were used to develop Figure 4-17. This screening was performed because lengthy discrepancies are more likely to have an impact on delay. Each data point shown represents the average delay for 10 signal cycles (all cycles were sorted by error rate before averaging). This aggregation was performed to facilitate the graphic portrayal of the underlying trend in the data.

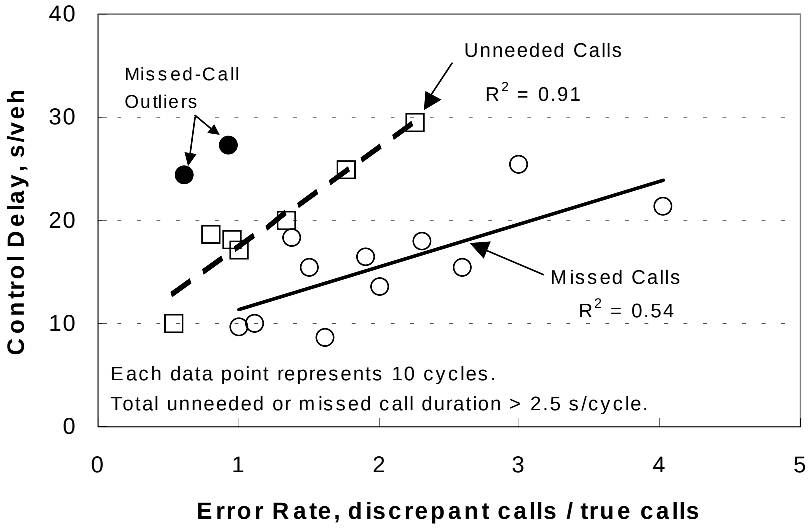


**Figure 4-17. Effect of Error Rate on Control Delay.**

The trend lines shown in Figure 4-17 confirm that unneeded calls increase control delay. This increase generally reflects the consequences of unnecessarily placing a call (say, by a left-turn vehicle) for service during the red indication. This call results in the subject phase receiving a green indication when there are no vehicles to be served. The consequence of this unneeded phase is an increase in cycle length which ultimately causes an increase in delay to all vehicles arriving in subsequent phases (including the subject phase).

The effect of a missed call on delay is less clear. Two data points shown in Figure 4-17 associate high delay with an error rate of less than 1.0. All other missed-call data points coincide with error rates of 1.0 or more and show a logical trend of increasing delay with an increasing rate of missed calls. A missed call can directly lead to added delay when it occurs during the red indication. In this situation, the missed vehicle may wait for an extended period of time until its driver grows impatient and creeps forward (triggering a call) or a second vehicle arrives (and is detected). A missed call during the green indication can also lead to increased delay if some portion of the queue, waiting at the start of green, is unserved. A closer examination of the two data points with high delay and an error rate less than 1.0 did not yield any logical explanation for their deviance from the trend line.

Other variables were also examined during this evaluation. These variables include: downstream distance to the camera location (*x*), camera pitch angle, and camera focal length. However, none of these variables was found to have an observable effect on performance.

**Desirable Camera Height Guidelines.** The trends found in the previous section were used to develop a guideline for camera location. This guideline is shown in Figure 4-18. The figure can be used to identify desirable camera heights to minimize errors. The trends in this figure are directly applicable to cameras mounted approximately in the center of the approach traffic lane or on its right side. The values obtained from the figure should be multiplied by 1.2 when the camera is mounted behind the curb on the left side of the approach.

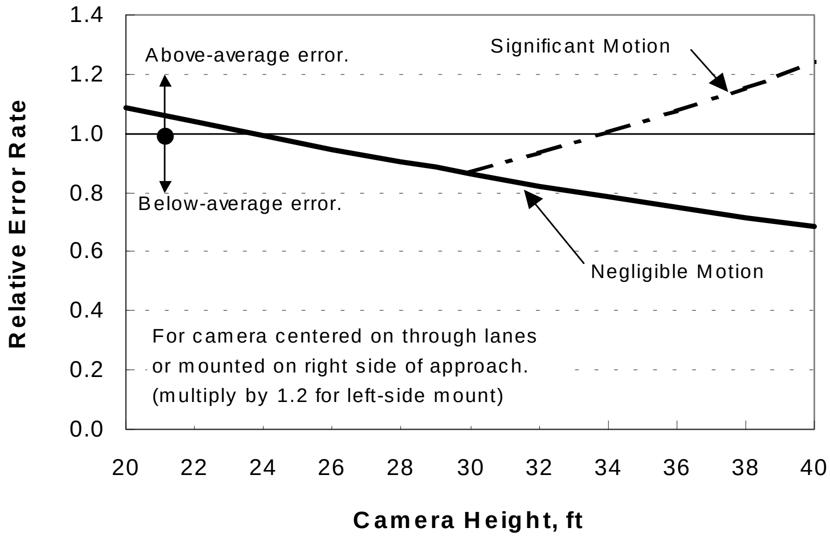


**Figure 4-18. Effect of Camera Height, Motion, and Offset on Error Rate.**

The *y*-axis is defined in Figure 4-18 as "relative error rate." It is computed as the observed error rate divided by the average error rate of 1.83 discrepant calls per true call. The resulting relative error rate can be interpreted as the relative increase (or decrease) in discrepant calls due to a change in camera height. For example, the trends in Figure 4-17 indicate that a camera height of 24 ft yields a relative error rate of 1.0 (i.e., the error rate at this height is expected to be equivalent to the average rate). However, if a camera height of 30 ft is used, the relative error rate is 0.86. This factor indicates that the error rate will be reduced by 14 percent if the camera is raised from 24 to 30 ft.

The trends in Figure 4-18 indicate that error rate *decreases* with increasing height. However, if camera motion is present, this benefit of height is eliminated when camera height exceeds 30 ft. The trend in Figure 4-18 indicates that significant motion causes the error rate to *increase* with increasing height above 30 ft. Fortunately, for the intersections studied, the error rate is still below average at heights up to 34 ft.

**Minimum Camera Height Guidelines.** As noted in the section titled "Study Site Characteristics," 70 percent of the study sites (28 of 40) were in compliance with the applicable minimum height recommendations. The error rate associated with the sites that were in compliance was compared with the sites not in compliance. This comparison revealed that the sites not in compliance had an above average error rate of 2.03 discrepant calls per true call (the average rate is 1.83). The sites in compliance had a below average error rate of 1.78 discrepant calls per true call. The difference between rates is of practical significance (with a statistical significance $p$ of 0.18) and is evidence of the benefit of the minimum height guidelines.

### *Evaluation of Alternatives*

This section describes an evaluation of the VIVDS alternatives that were implemented at each of the study sites. These alternatives were previously identified in Table 4-10. In brief, the sites in the Atlanta District (i.e., Sites 1, 2, 3, and 4) underwent changes to the hardware, detection design, and detection layout. The sites in the other districts underwent changes only to their detection layout only.

The results of the evaluation are listed in Table 4-14. The data in this table illustrate the changes in max-out frequency and delay that resulted from the changes in hardware, detection design, or detection layout.

Overall, the changes at Sites 1, 2, 3, and 4 reduced the max-out frequency and the delay. However, these reductions were not experienced at all four sites. In fact, max-out frequency increased at Site 2 (Marshall), and delay increased at Site 3 (Linden). The reductions were very large at Site 4 (Domino). The reduction in max-out frequency was sufficiently large that it was statistically significant at a 90-percent level of confidence.

It is difficult to interpret the changes to max-out frequency and delay at Sites 1, 2, 3, and 4 because several changes were made at each site. The trends suggest that some combinations of change in hardware, detection design, and detection layout are more effective than others. However, it is not possible to quantify the improvement due to each type of change. In fact, it is possible that improvements resulting from a hardware change were offset by poor performance from a detection design change (or vice versa).

The changes in performance at Sites 5, 6, 7, 8, and 10 are listed in the last two rows of Table 4-14. The performance measures for these sites are combined because all sites had similar modifications to their detection design. No other changes were implemented at these sites. The measures listed in Table 4-14 indicate that the proposed detection design procedure has the ability to reduce both max-out frequency and delay. Both reductions are statistically significant at a 90-percent level of confidence.

## Table 4-14. Effectiveness of Alternative Improvements.

| Alter-native | Measure | Site No.[1] | Before[2] | | | | After[2] | | | | Change[3] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Observation | | Average | | Observation | | Average | | |
| VIVDS hardware, design, and layout changes | Max-out frequency | 1 | 60 | cycles | **18** | % | 60 | cycles | **8** | % | -10 |
| | | 2 | 53 | cycles | **21** | % | 60 | cycles | **27** | % | 6 |
| | | 3 | 30 | cycles | **0** | % | 60 | cycles | **0** | % | 0 |
| | | 4 | 30 | cycles | **47** | % | 50 | cycles | **0** | % | -47 |
| | | Overall | 173 | cycles | **21** | % | 230 | cycles | **9** | % | -12 |
| | Control delay | 1 | 8 | 15-min | **33** | s/veh | 8 | 15-min | **26** | s/veh | -7 |
| | | 2 | 7 | 15-min | **19** | s/veh | 7 | 15-min | **16** | s/veh | -3 |
| | | 3 | 8 | 15-min | **10** | s/veh | 8 | 15-min | **15** | s/veh | 5 |
| | | 4 | 2 | 15-min | **42** | s/veh | 2 | 15-min | **32** | s/veh | -10 |
| | | Overall | 25 | 15-min | **23** | s/veh | 25 | 15-min | **20** | s/veh | -3 |
| Detection layout changes | Max-out frequency | 5, 6, 7, 8, 10 | 300 | cycles | **27** | % | 300 | cycles | **7** | % | -20 |
| | Control delay | 5, 6, 7, 8, 10 | 40 | 15-min | **26** | s/veh | 40 | 15-min | **23** | s/veh | -3 |

Notes:

1 - Site numbers coincide with intersection locations identified in Table 4-6.

2 - Statistics represent the combined data for all intersection approaches.

3 - Change computed as “After - Before.” An underlined value represents a statistically significant change (10-percent chance of error).

# CHAPTER 5. CONCLUSIONS

## OVERVIEW

The objective of this research project was to develop guidelines for planning, designing, installing, and maintaining a VIVDS at an intersection or interchange. The guideline development process included a review of the literature, a survey of practice in Texas, the development of guidelines, and the evaluation of these guidelines using field data. The guidelines developed for this project address the use of a VIVDS to provide vehicle presence detection at a signalized intersection or interchange in Texas.

This chapter highlights the most important information obtained during this research and offers some recommendations for additional research. Initially, key findings from the literature review and survey of practitioners are summarized. Then, the conclusions reached as a result of this research are described. Finally, several unresolved issues are identified and the nature of the research needed to address these issues is identified.

## SUMMARY OF FINDINGS

### Application Considerations

For signalized intersection applications, a VIVDS is most often used to provide vehicle presence detection in the vicinity of the stop line. The VIVDS cameras are mounted on the mast arm, or on the mast-arm pole, located across the intersection from the approach being monitored. A VIVDS provides reliable presence detection when the detection zone is relatively long (say, 40 ft or more). However, its limited ability to measure gaps between vehicles compromises the usefulness of several controller features that rely on such information (e.g., volume-density control, adaptive protected-permissive left-turn phasing) (*1*, *2*).

A VIVDS is sometimes used to provide advance detection on high-speed intersection approaches. However, some agencies are cautious about this use because of difficulties associated with the accurate detection of vehicles that are distant from the camera (*3*). Of those agencies that use a VIVDS for advance detection, the most conservative position is that it should not be used to monitor vehicle presence at distances more than 300 ft from the stop line. A “10 ft to 1 ft” rule is commonly used to identify the maximum VIVDS monitoring distance. This rule states that the maximum distance increases 10 ft for every 1-ft increase in camera height (i.e., a 10 to 1 ratio). Experience with VIVDSs in Texas indicates that a ratio of 17 to 1 can yield acceptable presence-mode operation.

A VIVDS is primarily used in situations where its high initial cost is offset by that associated with installing and maintaining inductive loop detectors. VIVDSs have been generally recognized as cost-effective, relative to alternative detection systems, in the following situations:

- when more than 12 stop-line detectors are needed at the intersection or interchange,
- when inductive loop life is short due to poor pavement or poor soil conditions,
- when extensive intersection reconstruction will last for one or more years,
- when the loop installation is physically impractical due to the presence of a bridge deck, railroad tracks, or underground utilities, and
- when the pavement in which the loop is placed will be reconstructed in less than three years or during overlay projects at large intersections where the cost of replacing all loops exceeds the cost of installing the VIVDS.

Justification of a four-camera VIVDS at an existing intersection is sometimes complicated by the fact that the existing inductive loop system is often in place and providing some service. Under these circumstances, the wholesale replacement of the loops with a VIVDS is sometimes difficult to justify. This complication can be overcome by incrementally installing single-camera VIVDS products as the existing loops fail on a given intersection approach.

### Design Issues

Detection design includes considerations of camera location and field-of-view calibration. Camera location is specified as the distance between the camera and stop line, the offset of the camera from the approach, and the height of the camera. Field-of-view calibration is specified as the rationale for defining camera pitch angle and camera lens focal length.

Camera location has been noted to be an important factor influencing detection accuracy (*8*). Guidance provided by several VIVDS product manuals consistently describes an optimal location as one that provides a stable, unobstructed view of each traffic lane on the intersection approach (*4, 9*). Moreover, the view must include the stop line and extend back along the approach for a distance equal to that needed for the desired detection layout.

The VIVDS product manuals indicate that detection accuracy will improve as camera height increases within the range of 20 to 40 ft (*4, 9, 10*). This height improves the camera's view of each approach traffic lane by minimizing the adverse effects of occlusion. Occlusion refers to a situation where one vehicle blocks or obscures the camera's view of a second vehicle.

Desirable camera heights and offsets are often limited by the availability of structures that can provide a stable camera mount. Considerations of height, offset, and stability often require a compromise location that is subjectively determined to provide the best performance. Camera mounting locations vary widely with the specific application and include luminaire arms, signal head mast arms, and signal poles.

Calibration of the camera field of view is based on a one-time adjustment to the camera pitch angle and the lens focal length. Guidance provided in several VIVDS product manuals consistently describes an optimal field of view as one that has the stop line parallel to the bottom edge of the view and in the bottom one-half of this view (*4, 9*). The optimal view also includes all approach traffic lanes. The focal length would be adjusted such that the approach width, as measured at the stop line, equates to 90 to 100 percent of the horizontal width of the view. Finally, the view must exclude the horizon.

In addition to pitch angle and focal length, the VIVDS manuals describe several additional factors that should be considered when establishing the field of view. These factors include light sources and power lines. If the pitch angle or focal length cannot be adjusted to avoid these factors then alternative camera locations should be considered. If such locations cannot be found, then careful detection zone layout can minimize the effect of light sources or power lines on detection accuracy.

### Operation Issues

Once installed, the performance of the VIVDS is highly dependent on the manner in which its detection zones are defined and operated. In this regard, decisions regarding zone layout and operations include zone location, detection mode, detector settings, controller settings, and verification of daytime and nighttime performance.

Detection zone layout is an important factor influencing the performance of the intersection. Guidance provided by several VIVDS product manuals indicates that there are several factors to consider including: zone location relative to the stop line, the number of VIVDS detectors used to constitute the detection zone, whether to link the detectors using Boolean logic functions, whether to have the detector monitor travel in a specified direction, and whether the detector's call is delayed or extended (*4, 9, 10*). However, these manuals do not provide sufficient guidance to ensure their products adequately serve intersection traffic.

Unlike inductive loops, the performance of a VIVDS is adversely affected by environmental and temporal conditions. Environmental conditions include fog, rain, wind, and snow. Temporal conditions refer to the effects of changes in light level and reflected light that occur during a 24-hour period and during the course of a year. In recognition of the wide range of factors that can influence VIVDS performance, at least one VIVDS manual encourages an initial check of the detector layout and operation during the "morning, evening, and at night" (*4, p. 109*) to verify the operation is as intended. Recommendations for periodic checks at specified time intervals (e.g., every six months) are not offered by the manufacturers.

## CONCLUSIONS

VIVDSs are becoming an increasingly common means of detecting traffic at intersections and interchanges. This interest stems from the recognition that video detection is often cheaper to install and maintain than inductive loop detectors at larger intersections. It is also recognized that video detection is more adaptable to changing conditions at the intersection (e.g., lane reassignment, temporary lane closure for work zone activities). The benefits of VIVDSs have become more substantial as the technology matures, its initial cost drops, and experience with it grows.

It is estimated that about 10 percent of the intersections in Texas currently use VIVDSs. The collective experience with the operation of these intersections has generally been positive; however, this experience is limited to a short amount of time (relative to the life of such systems). Moreover, experience with the design and installation of a VIVDS for intersection control has been limited. This limitation is due to the fact that most intersection control applications have been "turnkey" arrangements with the product vendors. Further increases in VIVDS application will require greater participation by TxDOT engineers in the planning, design, operation, and installation stages.

## Applications

A life-cycle cost analysis comparing a four-camera VIVDS and an inductive loop system indicated that a VIVDS is more cost-effective than a loop system under certain conditions. These conditions relate to the number of inductive loops needed at the intersection and the expected life of these loops. In general, a four-camera VIVDS is cost-effective at intersections requiring 12 or more stop-line loop detectors, regardless of loop life. However, in areas where the average loop life is only four years, a VIVDS is found to be cost-effective when only five loops are needed.

## Design Guidelines

Adjacent-lane occlusion results when a tall vehicle in one lane blocks the camera's view of a more distant, adjacent lane. This type of occlusion occurs when the camera is too low, offset too far from the traffic lanes, or both. Minimum camera heights that minimize occlusion vary from 20 to 50 ft, depending on the width of the approach and camera offset. The minimum height for a camera mounted in the center of the approach is 20 ft. Larger minimums are needed as the camera is moved left or right from this central position.

A minimum camera height is required when the VIVDS is used to monitor sections of the approach that are well in advance of the stop line. This minimum height is based on a 17 to 1 ratio (distance to height) that has been found to yield acceptable detection accuracy. The minimum height needed for advance detection ranges from 24 to 36 ft, depending on the distance between the camera and stop line and on the approach speed limit. The higher distances are needed for higher speeds or greater distances.

About 70 percent of the intersection approaches studied are in compliance with the applicable minimum height guidelines developed for this research. The error rate associated with the approaches that are in compliance was compared with the rate for the approaches not in compliance. This comparison revealed that the approaches not in compliance had an above average error rate of 2.03 discrepant calls per true call. The approaches in compliance had a below average error rate of 1.78 discrepant calls per true call. The relatively large difference between rates is evidence of the benefit of the minimum height guidelines.

The examination of discrepant call frequency revealed that camera height and camera motion have an effect on detection accuracy. Specifically, the data indicate that increasing camera height tends to improve accuracy, provided that there is no camera motion. However, there is a "point of diminishing returns" with respect to camera height when the camera support structure is susceptible to instability. Data indicate that camera heights of 34 ft or more may be associated with above-average errors *unless* the camera is mounted on a stable pole.

## Operations Guidelines

Both simulation and field data indicate that the detection zone layout guidelines developed for this research can be used to reduce delay and improve intersection operation. These guidelines are developed for stop-line-only detection applications and for stop-line plus advance detection applications. The guidelines account for the effective increase in vehicle length as a result of the vehicle's transformation from a three-dimensional object to a two-dimensional video image. The guidelines for stop-line-only detection are based on the use of a long detection zone and a 0.0-s passage time. The guidelines for stop-line plus advance detection are based on a 1.0-s passage time and two advance detectors.

Alternative improvements were implemented at eight intersections and two interchanges. At four intersections, the alternative consisted of changes to the VIVDS hardware, detection design, and detection layout. At the remaining four intersections and two interchanges, the alternative consisted of changes only to the detection layout. These improvements were based on the detection layout procedure developed for this research.

The changes in VIVDS hardware at four sites reduced the overall max-out frequency and delay and, thereby, improved overall operation. However, this improvement was not experienced at all four sites. Some sites experienced significantly improved performance while others experienced degraded performance.

The sites at which the only the detection layout was changed demonstrated reductions in both max-out frequency and delay. These findings suggest that the proposed detection layout procedure has the ability to improve intersection operations.

## On-Site Performance Checks

In the days following the VIVDS installation, the engineer or technician should return to the intersection on one or more occasions and reevaluate the VIVDS performance. The purpose of each visit is to verify that the intersection is operating in an acceptable manner and that the VIVDS detectors are detecting vehicles with reasonable accuracy. In general, operation and accuracy should be checked at midday and during the late afternoon, nighttime, and early morning hours.

A periodic check (say, every six months) of the camera field-of-view and detection layout is encouraged. During this check, the engineer or technician should: (1) verify that the detection zones are still in the proper location relative to the traffic lanes, (2) assess the impact of seasonal changes in the sun's position on detection accuracy, (3) verify that the VIVDS is using the latest software version and upgrade it if needed, and (4) check the camera lens for moisture or dirt buildup and clean if needed. In areas with high humidity and extended concentrations of smoke, dust, or other airborne particles, the camera lens may need to be cleaned as frequently as every six weeks.

## RECOMMENDATIONS

The research literature and the VIVDS product manuals offer relatively little guidance regarding procedures for installing and maintaining a VIVDS in an effective and efficient manner. The absence of this information is testament to the "youth" of the technology, relative to the inductive loop detector. The limited amount of research that has been conducted in this area is also a consequence of the proprietary nature of the products and the reluctance of the VIVDS developers to disclose the means by which their systems function. As a result, the only means by which guidelines can be developed is through field application and testing of VIVDS products by the VIVDS customers. One drawback of this approach is that the resulting guidelines take several years to develop. This development time lag ensures that the customer will be unable to use the technology to its maximum potential, especially when the technology is changing rapidly.

Several areas of further research are recommended in light of the limited information currently available. These areas are briefly identified in the following paragraphs.

Observation of several VIVDS installations suggests that satisfactory performance is realized when the camera is mounted on the signal head mast arm. However, VIVDS detection accuracy can be degraded by excessive motion. Unfortunately, there is no published information available that describes the motion tolerance of the VIVDS products. Moreover, information about mast arm stability is not well known as it relates to the distance between the camera and the mast-arm pole, the length of the mast arm, the number of heads supported on the mast arm, and the use of back plates on the signal heads. Research is needed to evaluate both VIVDS motion sensitivity and the stability of a mast arm camera mount.

This research was limited to VIVDS applications that use only one camera to monitor each intersection approach. Experience indicates that the maximum distance that a single camera can accurately monitor is about 500 ft, which limits the use of these systems to approach speeds of 55 mph or less. At least one TxDOT district uses a two-camera system to provide advance detection on intersection approaches with speeds in excess of 55 mph. One camera is centrally mounted on the mast arm. It has a wide-angle lens and is used to monitor vehicles near the stop line. The second camera is mounted high (say, 32 ft or more) on the mast-arm pole or a nearby luminaire pole. Its lens is adjusted to "zoom in" on the location of the distant upstream detection zones. At this time, the performance of this system is reported to be good; however, research is needed to quantify this performance. Moreover, research is needed to evaluate other techniques for using a VIVDS (and possibly other, non-intrusive detection systems) to provide optimal stop-line plus advance detection.

Routine service checks of a VIVDS operation have been found to take more time than similar checks at an intersection with inductive loop detectors. This added time stems from the VIVDS's inability to provide an electronic report that records the detection zone layout and detector feature settings. Additional time is also required by those VIVDS products that require a field setup computer. In spite of the additional time required, periodic on-site service checks have been found to be beneficial. Further investigation is needed (perhaps conducted by TxDOT engineers) to identify the optimal maintenance program for VIVDS applications. This investigation should identify: the VIVDS elements that need to be routinely checked, the manner in which the existing detection layout can be most effectively archived and retrieved, whether the check should be made during the day or night, and a desirable frequency for routine checks.

This research has defined detection accuracy in a generic manner that could be applied to any type of presence-mode detector used for intersection control. Specifically, two measures have been quantified: discrepant call frequency (in calls per cycle) and error rate (in discrepant calls per true call). The use of a common measure for all types of detectors will facilitate comparison of alternative detection devices. It is recommended that future research on detector performance consider the use of these measures.

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