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16. Abstract <b>Traffic engineers are often faced with operational and safety problems at rural, high-speed signalized intersections. Vehicle-actuated control (combined with multiple advance detectors) is often used to minimize these problems. However, this type of detection-control system has not been as successful as intended. Rear-end crashes continue to occur in significant numbers at these intersections and delays to traffic movements are often unnecessarily long. The objective of this project is to develop and test an economical detection-control system that is capable of minimizing both delay and crash frequency at rural intersections.</b>  <b>This report describes findings from the first year of a two-year project. During the first year, a concept detection-control system was developed and evaluated. The development consisted of defining the system's functionality and the hardware needed to implement it in the field. The evaluation consisted of using simulation software to exercise the algorithm for a range of traffic and geometric conditions. The results of the evaluation indicate that the concept system is able to provide equal or lower delays for a reasonable range of speeds, volumes, and turn percentages. The results also indicate that the concept system will significantly reduce the number of vehicles caught in the dilemma zone at the onset of the yellow indication.</b>					
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# **DEVELOPMENT AND EVALUATION OF A DETECTION-CONTROL SYSTEM FOR RURAL INTERSECTIONS**

by

James Bonneson, P.E.  
Associate Research Engineer  
Texas Transportation Institute

Dan Middleton, P.E.  
Program Manager  
Texas Transportation Institute

Karl Zimmerman  
Graduate Research Assistant  
Texas Transportation Institute

Hassan Charara  
Associate Research Scientist  
Texas Transportation Institute

and

Montasir Abbas  
Assistant Research Scientist  
Texas Transportation Institute

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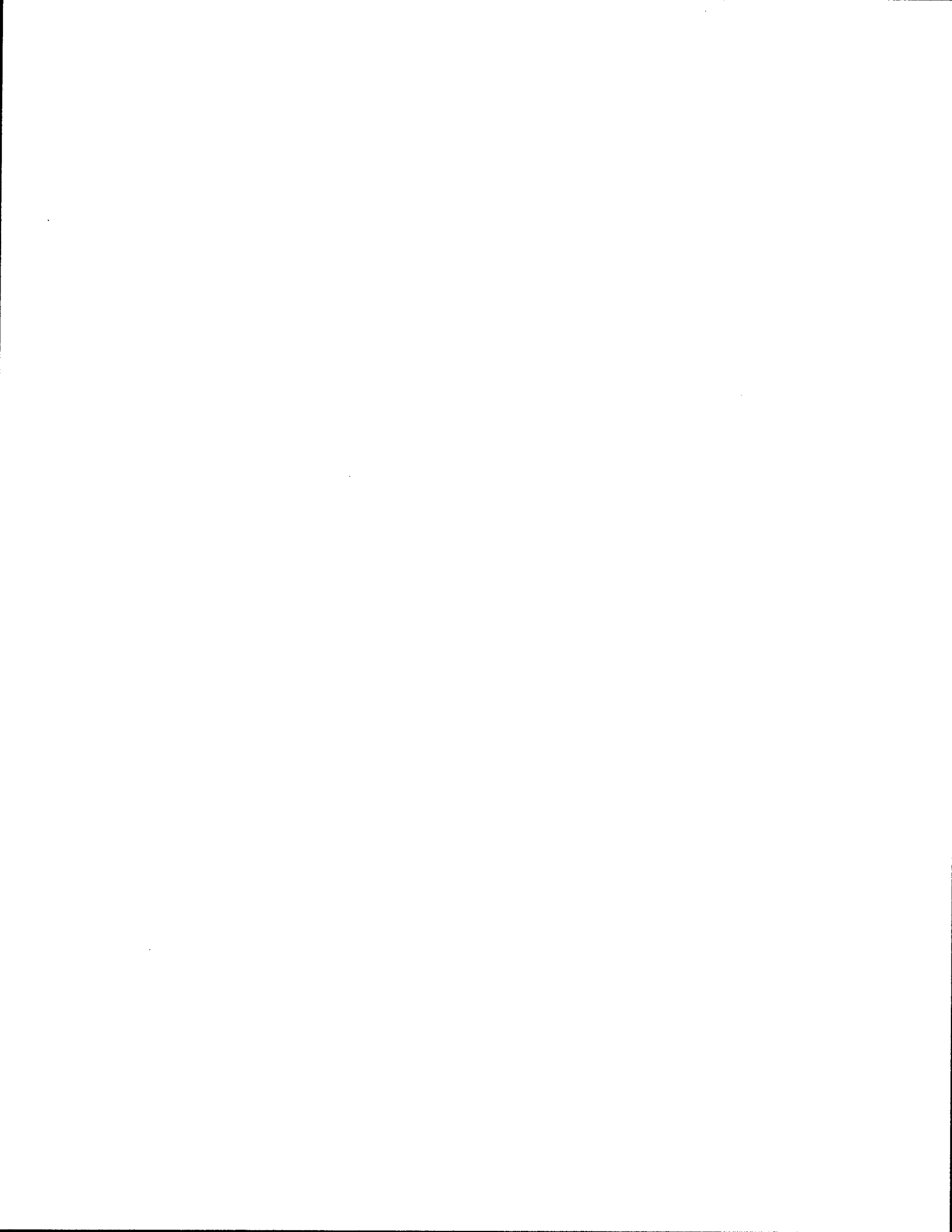
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## **NOTICE**

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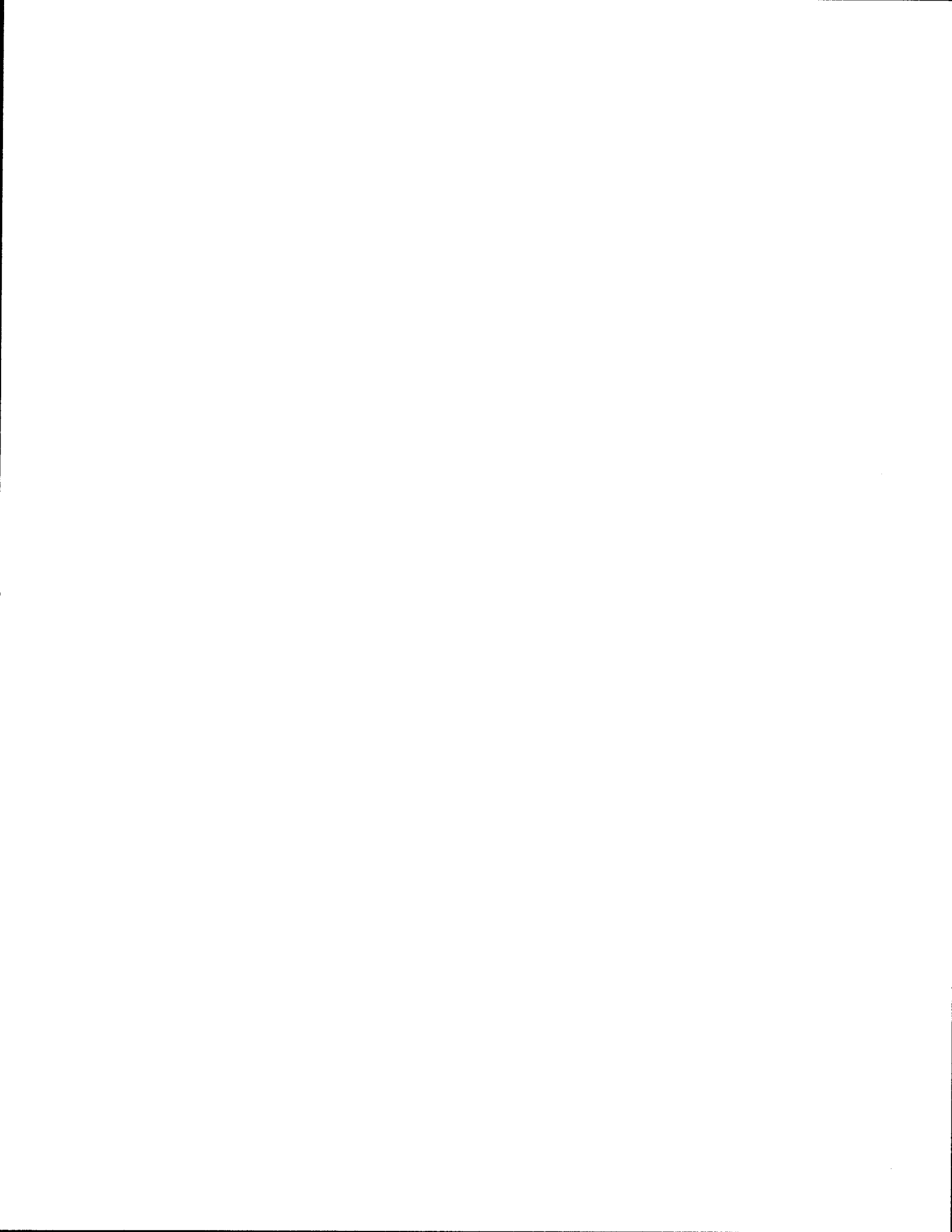
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# CHAPTER 1. INTRODUCTION

## OVERVIEW

Traffic engineers are often faced with operational and safety problems at rural, high-speed signalized intersections. Vehicle-actuated control (combined with multiple advance detectors) is often used to minimize these problems. However, this type of detection-control system has not been as successful as intended. Rear-end crashes continue to occur in significant numbers at these intersections and delays to traffic movements are often unnecessarily long.

The traditional, multiple advance detector system holds the green until a suitably large gap occurs in the traffic stream being served. Through this action, the detection-control system ends the phase safely because the approach is empty. However, this gap occurs infrequently on high-volume approaches and often causes the corresponding signal phase to extend to its maximum limit (i.e., max-out). When the phase reaches this limit, it ends without regard to the number of vehicles on the approach and increases the potential for a rear-end crash. If the maximum green setting is large, then the resulting delays may also be large. The high-speed nature of most rural intersections heightens concerns about phase termination by max-out because crash severity increases significantly with speed.

Other problems exist with the traditional, multiple advance detector system. They include: (1) the system operation is not sensitive to the type of vehicle in the dilemma zone (i.e., car or truck), (2) the system operation is not sensitive to the amount of delay experienced by motorists desiring service via a conflicting phase, and (3) the system is often costly in terms of the number of advance detectors needed along the major-road approaches.

This report describes the development and evaluation of an intelligent detection-control system for isolated rural intersections. Initially, there is a review of the various types of detection-control systems currently in use throughout the world. Then, the capability of relevant off-the-shelf detection and control equipment is identified and evaluated for the purpose of developing a concept system. Next, a plan for deploying and evaluating the concept system is described. Then, the detection-control system algorithm is described and some simulation-based evidence is offered to demonstrate its potential to reduce delays and improve intersection safety. Finally, the findings of the research are summarized in the last chapter of this report.

## RESEARCH OBJECTIVE

The objective of this research project is to develop and test an economical detection-control system that is capable of minimizing both delay and crash frequency at rural intersections. This objective will be achieved through satisfaction of the following goals:

- Design a detection-control system that monitors cars and trucks at a rural intersection and makes decisions in real time regarding the “optimal” time to allow termination of a phase.
- Develop a software algorithm for the system that can determine the optimal time to allow phase termination based on consideration of the potential for a crash on the approaches in service as well as the current and future delay to all vehicles.
- Make the system economical by minimizing the number of detectors per intersection.
- Field demonstrate the feasibility and integrity of the system at two intersections.
- Facilitate implementation of the recommended system by providing specifications that describe its parameters, functions, and performance requirements.

This report documents the findings from the first year of research and the fulfillment of the first three goals.

## **RESEARCH SCOPE**

The detection-control system described in this report is developed for use at rural intersections in Texas. In this regard, it is applicable to isolated, full-actuated intersections with high-speed approaches. One of the intersecting roadways is assumed to be a major road; the other is assumed to be a minor road. The detection-control system is designed to function in under-saturated conditions. It is sensitive to vehicle type to the extent that it is unlikely to end a major-road through movement phase if this phase is serving one or more trucks. The system is designed to work with the type of controllers and detectors currently used by TxDOT. It is also designed to work at intersections with two-lane or four-lane approaches. Each major-road approach is assumed to have an exclusive left-turn bay and no driveway activity.

## **RESEARCH APPROACH**

The research approach is based on a two-year program of development and evaluation that will ultimately yield an efficient and economical detection-control system. During the first year of the research, a concept detection-control system was developed to monitor vehicles on the high-speed, major-road approaches to an isolated intersection. This system is programmed to search for the “best” time to end the major-road through phase (i.e., the fewest vehicles on the through approaches in service and the smallest number of vehicles waiting for service). In the second year, the concept detection-control system will be tested at two rural intersections in Texas.

The main products of this research will be a design guideline and a specification document. The former product will describe the design procedures and controls for designing and operating the recommended detection-control system. The latter product will describe the parameters, features, and performance specifications for the recommended system.

## CHAPTER 2. LITERATURE REVIEW

### OVERVIEW

This chapter provides a review of the literature on detection-control systems for signalized rural intersections. This review describes the safety and operational problems associated with rural intersections and the various detection-control methods used to solve these problems.

Several different detection-control system types have been used at isolated intersections. These systems have a range of operational features and objectives; however, the one objective they have in common is to minimize the potential for crashes resulting from green interval termination. They accomplish this objective by not allowing the green interval to end until all approaches in service are unoccupied or until a present time limit is reached. By waiting until the approach is unoccupied, crashes associated with green interval termination are minimized.

Detection-control systems can be categorized by the components they use to determine the need for and extent of green extension. Three broad categories have been defined for this report. They are:

- Basic Green-Extension Systems: These systems use multiple advance detectors along each high-speed approach and standard controller functions to determine when the corresponding phase should remain green. The system is designed to let both phases end when there are no vehicles on either approach or when the maximum green setting is reached.
- Enhanced Green-Extension Systems: These systems are essentially the same as the basic green-extension systems, except these systems add one or more features. Such features include giving higher priority to trucks or letting the two major-road through phases end at different times.
- Green-Termination Systems: Unlike the green-extension systems, green-termination systems determine the best (or least intrusive) time to explicitly *end* the phase. This decision is based on an assessment of safety to the major-road through movements and delay to all conflicting movements.

The operation of each system is more fully described in a subsequent section of this chapter.

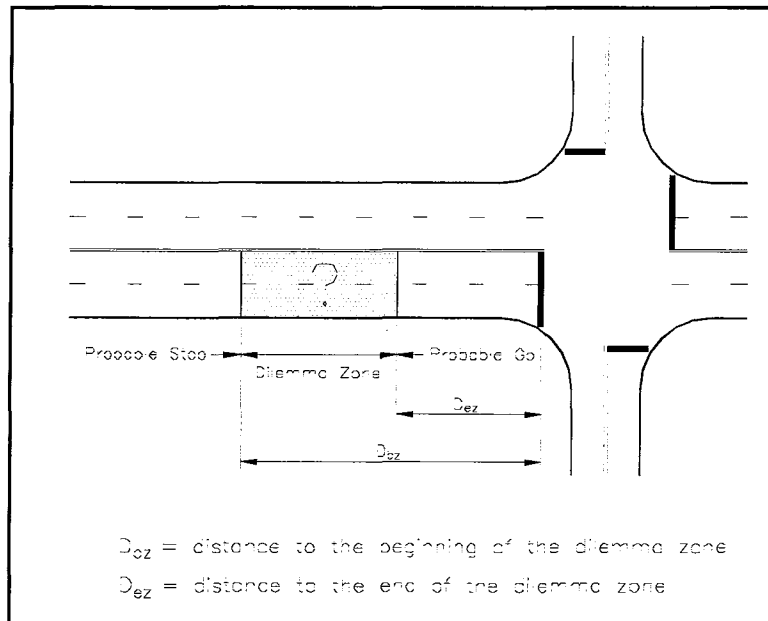
### DILEMMA ZONE

This section characterizes the nature of the safety problem that results when vehicles are on the intersection approach and the green interval is terminated. As a group, drivers within a few seconds travel time of the intersection tend to be indecisive about their ability to stop at the onset of the yellow indication. This behavior yields a “zone of indecision” in advance of the stop line

wherein some drivers may proceed and others may stop. The nature and location of this zone (commonly referred to as the “dilemma zone”) is more fully described in this section.

### Dilemma-Zone Concept

The dilemma zone (or zone of indecision) is that portion of the intersection approach within which drivers exhibit distinct differences in their desire (or ability) to stop when presented the yellow indication. The location of the dilemma zone on a typical approach is shown in Figure 2-1.



**Figure 2-1. Dilemma-Zone Boundaries on a Typical Intersection Approach.**

Some researchers have defined the dilemma zone in terms of the driver’s probability of stopping (1, 2). Zegeer and Deen (1) defined the beginning of the zone as the distance (from the stop line) within which 90 percent of all drivers would stop if presented a yellow indication. They defined the end of the zone as the distance within which only 10 percent of drivers would attempt a stop.

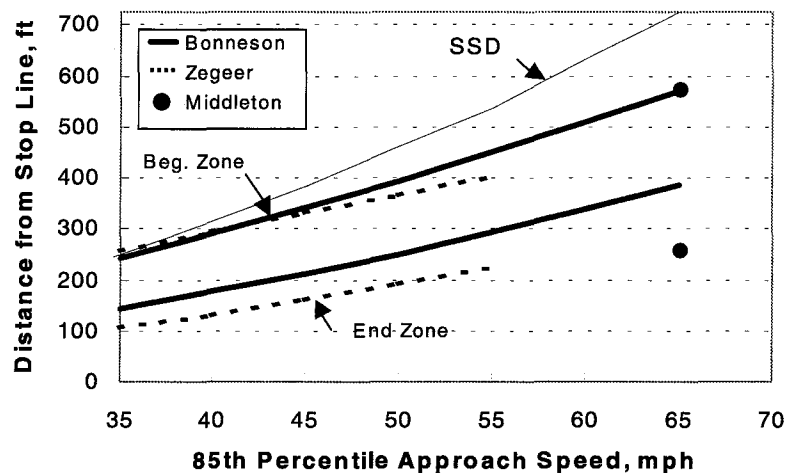
### Dilemma-Zone Boundaries

Several researchers have attempted to define the dilemma-zone boundaries relative to the intersection stop line (1, 2, 3). Dilemma-zone measurements reported by Parsonson (2) and by Zegeer and Deen (1) indicate that the zone boundaries are approximately equal to a constant travel time. Although they do not fully agree, these two studies suggest that the beginning of the dilemma

zone is about five seconds travel time upstream of the intersection. They also suggest that the end of the dilemma zone is about two to three seconds travel time upstream of the intersection. More recent measurements by Bonneson et al. (3) indicate that the beginning is about five to six seconds upstream of the intersection and the end is about three to four seconds upstream. Bonneson et al. suggested that the trend toward an increase in travel time (over the 17 years separating these studies) could be attributed to decreasing driver respect for the meaning of the change interval.

Most recently, Middleton et al. (4) estimated the dilemma-zone boundaries for both passenger cars and trucks. Their study sites had 85<sup>th</sup> percentile approach speeds of about 65 mph. They found that the dilemma zone started at 575 ft and ended at 260 ft for passenger cars. The corresponding distances for trucks were only about 3 percent smaller than for passenger cars. The distance to the beginning of the zone reported by Middleton et al. is consistent with that found by Bonneson et al. (3) while the distance to the end of the zone is consistent with that reported by Zegeer and Deen (1).

The reported distances to the beginning and end of the dilemma zone are compared in Figure 2-2. For comparative purposes, the relationship between speed and the stopping sight distance (SSD) used for street and highway design is also shown in this figure.



**Figure 2-2. Dilemma-Zone Boundaries Reported in the Literature.**

## DETECTION-CONTROL SYSTEMS

The systems described in this section share a common objective of minimizing the potential for crashes that result from green interval termination. This objective is accomplished by using detectors to monitor vehicle presence in the dilemma zone and extending the green interval until the dilemma zone is clear or until a maximum green limit is reached. Some of the systems described in this section have additional objectives intended to provide other safety or operational benefits.

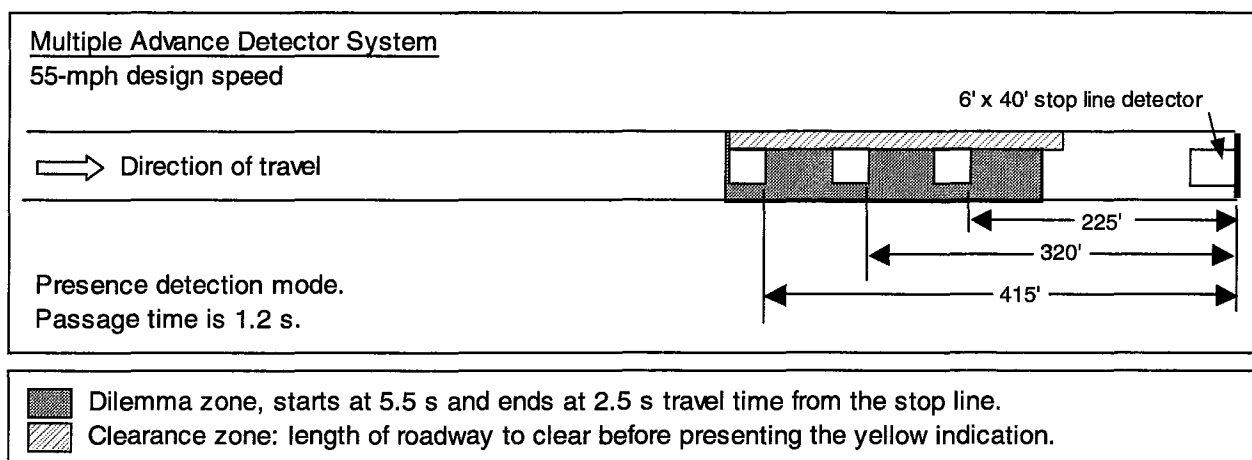
However, the discussion in this section will focus on the method used to provide dilemma-zone protection.

### Basic Green-Extension Systems

Applications and evaluations of basic green-extension systems have been documented since the mid-1970s. These systems have been proven to offer safety benefits and have found greatest use at rural intersections due to the higher speeds and isolated conditions at these intersections. All forms of this system use an upstream detector (or detectors) to extend the green until there are no vehicles in the detection zone or until the maximum green setting is reached. The multiple advance detector system, described in this section, is the most commonly used type of green-extension system.

#### *Multiple Advance Detector System*

The typical basic green-extension system uses multiple advance detectors located along the intersection approach. The first detector is located just in advance of the dilemma zone. A second, third, and sometimes fourth detector is then located between the first detector and the stop line. The location of these intermediate detectors is determined through consideration of the vehicle speed distribution and the controller passage-time setting. The objective of this multiple detector design is to “carry” all but the slowest vehicles through their respective dilemma zones before allowing the phase to end. Figure 2-3 shows a typical design for an 85<sup>th</sup> percentile approach speed of 55 mph.



**Figure 2-3. Multiple Advance Detector System.**

In the basic system, the detector at each upstream location is used to monitor vehicle presence, vehicle speed and length are not measured. However, some discrimination of slower vehicles is possible through detector placement and the call-extension or passage-time settings. On



multilane approaches, the detectors at each location typically monitor all lanes as one detection zone (i.e., there is no indication as to which lane is reporting vehicle presence). The system consists of a controller, detector amplifiers, and detectors (typically inductive loops).

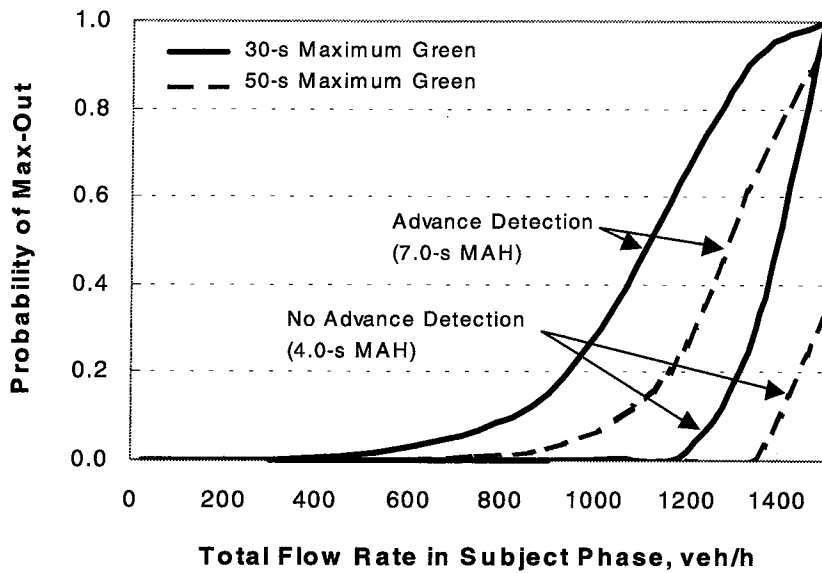
In operation, the controller extends the green interval until it determines that the clearance zone is clear of vehicles or until a preset maximum green limit is reached. For high-speed through movements, the clearance zone may be longer than the dilemma zone. The green intervals for both through movements end together due to the "ring-and-barrier" structure of the controller. In addition, the controller seeks to find a point in time when *both* major-road approaches are clear of vehicles due to its "simultaneous gap-out" mode of operation. More detail on the design and operation of basic green-extension systems is provided by Bonneson and McCoy (5).

### *Safety Benefits*

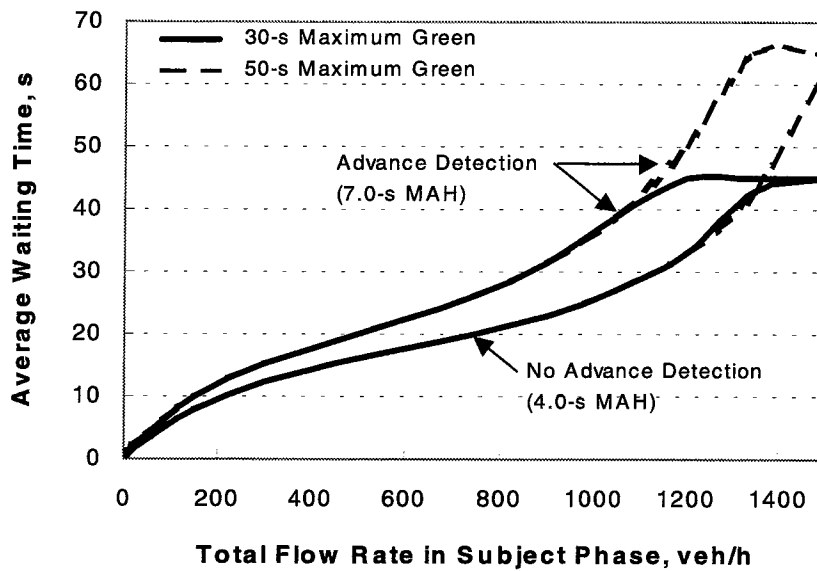
The safety benefits of basic green-extension systems have been reported by Zegeer and Deen (1) and, more recently, by Wu et al. (6). Zegeer and Deen found crash frequency was reduced by 54 percent due to the use of a green-extension system, based on about four years' crash data (three years before and one year after) at three sites. A study of traffic conflicts (e.g., "run red light," "abrupt stop," etc.) at two sites revealed a 70 percent reduction in the overall conflict rate for both cars and trucks.

Wu et al. (6) studied crash data for 10 isolated intersections in Texas. Each intersection had been modified to include multiple advance detectors for the purpose of green extension. The crash rates reported by Wu et al. indicate that the crash rate is reduced 35 percent for intersections with approach speeds of 55 mph. Their analysis indicated that this reduction was statistically significant. There was some variability in the crash data for lower-speed sites and no conclusion could be drawn about safety impact. It is possible that this variability is due to differences in the maximum green setting at the study sites. This issue is described in the following paragraphs.

The safety benefit of green extension can be negated if the phase is extended to its maximum duration (i.e., maximum green setting). The probability for this type of green interval termination (i.e., "max-out") is dependent on flow rate in the subject phase and the "maximum allowable headway," as dictated by the detector design. The maximum allowable headway (MAH) is the largest headway in the traffic stream that can occur and still sustain a continuous extension of the green interval. The relationship between max-out probability, MAH, maximum green, and flow rate is illustrated in Figure 2-4.



**a. Probability of Max-Out.**



**b. Average Waiting Time.**

**Figure 2-4. Effect of Flow Rate and Detection Design on Max-Out Probability and Waiting Time.**

Bonneson and McCoy (7) indicate that the MAH values shown in Figure 2-4 (i.e., 4.0 and 7.0 s) represent the range of values for most detection designs. To illustrate the implications of alternative MAH values, consider the following example. If a phase has a flow rate of 1200 veh/h, a maximum green duration of 30 seconds, and no advance detection (i.e., only a stop-line loop) yielding a MAH of only 4.0 s, then its probability of max-out will be about 0.05 (1 out of 20 cycles). However, if advance detection is used, then the MAH will likely be about 7.0 s and the resulting max-out probability will increase to 0.7 (7 out of 10 cycles). One option available to reduce this probability and the crash potential of the system is to increase the maximum green setting; however, this increase may also increase the delay to waiting vehicles.

### *Operational Benefits*

The operational benefits of basic green-extension systems are less certain than the safety benefits. Intuitively, this system should increase delay to vehicles waiting on conflicting phases as the multiple detectors associated with such systems increase the size of the maximum allowable headway. The magnitude of the waiting time (for the first arriving driver) is shown in Figure 2-4b as a function of flow rate, maximum green, and MAH. As the trends in this figure indicate, the difference in average waiting time between stop-line-only detection and multiple advance detection is about 15 s or less, depending on flow rate. The increase in delay associated with an increase in MAH has also been reported by Tarnoff and Parsonson (8).

In contrast to the findings reported above, the study by Wu et al. (6) indicates that *overall* intersection delay does not increase significantly when multiple advance detection is used. This finding implies that any delay increase to the minor movements is offset by a delay reduction to the major movement (typically, green extension is used only for major-road through movements).

### **Enhanced Green-Extension Systems**

Applications and evaluations of enhanced green-extension systems have been documented since the mid-1980s. These systems operate like the basic green-extension system, but also have the ability to hold the major-road through green interval past the maximum green setting. This helps alleviate the problem of the green phase “maxing out” while vehicles are in the dilemma zone. Two systems are discussed in this section. They are the TTI Truck Priority system and the Swedish LHOVRA system.

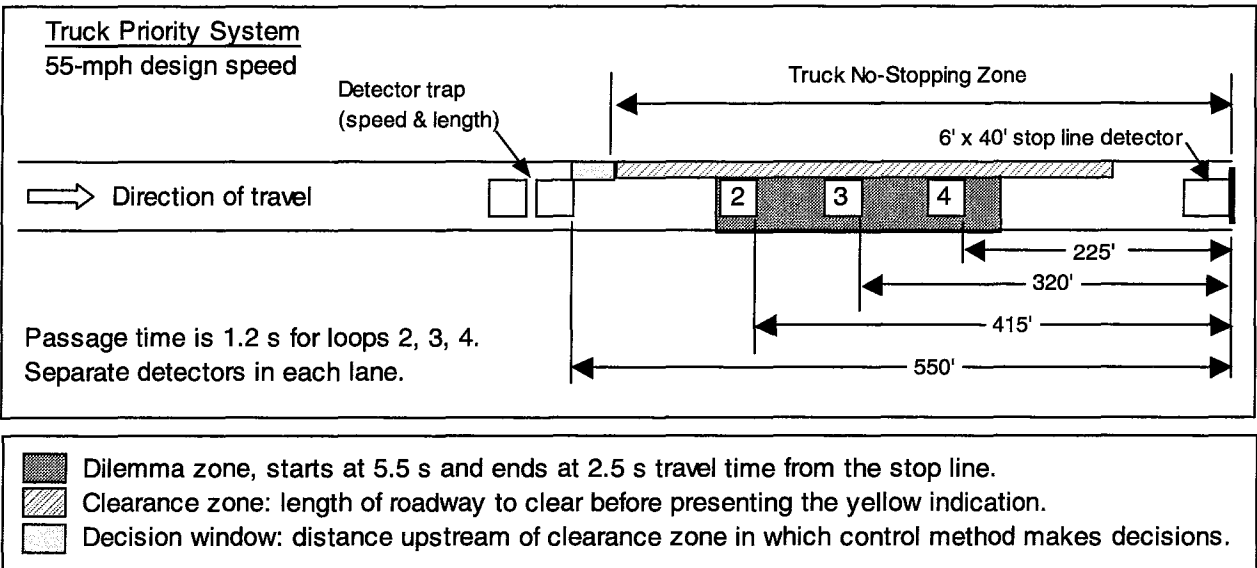
#### *TTI Truck Priority System*

**System Components.** The TTI Truck Priority system was designed specifically to reduce the number of trucks stopping on high-speed rural intersection approaches. A recent report by Middleton et al. (9) indicates that the truck priority system includes the following four components:

- one detector speed trap (i.e., two detectors spaced 18 ft apart in the lane) in each approach lane located about 7.0 s upstream of the intersection,

- a vehicle classifier that determines vehicle speed and classification from the detector trap,
- a microcomputer that analyzes the speed and classification data to determine when a green extension is appropriate, and
- a basic green-extension system (as described in the previous section).

This system has two objectives. The first is the same as for the basic green-extension system. The second objective is to hold the green interval whenever a truck is within the “clearance zone” (i.e., within about 500 ft of the stop line) and thereby minimize the frequency of truck stops on the major-road approaches. A typical design is shown in Figure 2-5 for an 85<sup>th</sup> percentile approach speed of 55 mph.



**Figure 2-5. Truck Priority System.**

In the truck priority system, the upstream detectors in the dilemma zone operate in a manner similar to the basic green-extension system. The detector trap located 550 ft (7.0 s) in advance of the stop line is used to measure the speed and classification of individual vehicles. On multilane approaches, a separate detector trap is located in each traffic lane.

The operation of the truck priority system requires a vehicle classifier and a microcomputer. The classifier is used to identify trucks (i.e., vehicles longer than 30 ft) on the intersection approach. When a truck is identified, the microcomputer queries the signal controller to determine if the signal is green. If the signal is green, the microcomputer directs the controller to hold the phase until the truck reaches the end of the clearance zone, based on its measured speed. This system has the potential to override the controller’s maximum green setting to clear a truck, if needed. In this manner, it does not forfeit clearance zone protection for trucks as a result of phase max-out.

**Safety Benefits.** There appear to be significant safety benefits associated with the truck priority system. However, it is relatively new and long-term safety analyses have not been performed. In a preliminary evaluation of the truck priority system at one intersection in Texas, Sunkari and Middleton (10) found that about 4 percent of trucks benefit by not having to stop as a result of active green extension. The small size of this percentage may suggest minimal system benefit; however, it is due primarily to the small number of trucks that arrive during the end of the green interval. In fact, the system was found to extend the green for all trucks that were in need of clearance zone protection.

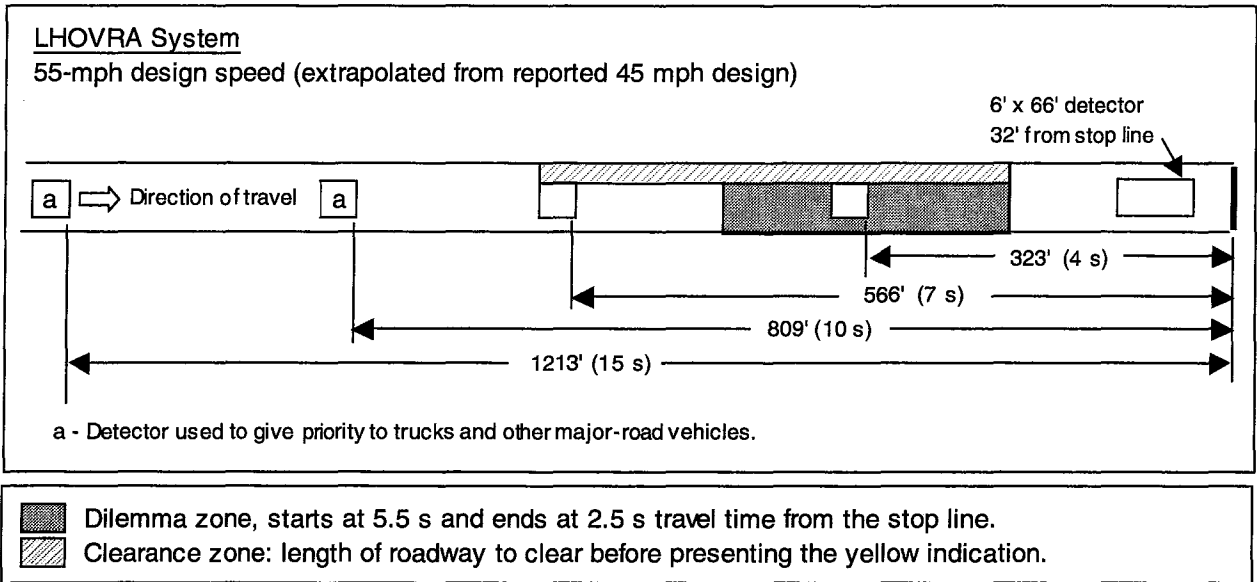
**Operational Benefits.** The benefits of the truck priority system include: (1) reduced frequency of stops (and resulting pavement damage) and (2) reduced delay to trucks. Sunkari and Middleton (10) estimate that the truck priority system will save \$6,300 annually at an intersection where the major road has 14,000 veh/day and 8 percent trucks. Small reductions in delay to passenger cars were also observed but not quantified.

### *LHOVRA System*

**System Components.** LHOVRA was initiated in 1979 by the Swedish National Road Administration to reduce crash frequency and delays at intersections on high-speed roads (11). LHOVRA is a modular collection of traffic control functions implemented within the controller. The engineer may choose the best combination of functions based on the safety problems present at a given intersection. As of 1993, LHOVRA was reported to be in use at about 800 of Sweden's 1500 isolated intersections (12).

The acronym LHOVRA comes from its six system functions. One letter stands for each function. The L-function is intended to give trucks priority when they are approaching the intersection during a red signal indication. When this function is used, the green interval is returned to the approach with the truck sooner than it might otherwise have been had the "normal" cyclic phase sequence been followed. The H-function is like the L-function; however, it provides priority to all major-road vehicles. The O-function is intended to provide dilemma-zone protection. The V-function provides variable yellow times. The R-function provides detection for permitted left-turn vehicles and prevents the "left-turn trap" (see Orcutt [13] for a discussion of this trap). The A-function provides a responsive all-red dwell state. The O-function is the subject of discussion in the remainder of this section.

LHOVRA intersections require three "base" detectors per approach. Two additional detectors are provided if the priority (i.e., L and H) functions are used. The three "base" detectors are located at the stop line, at four seconds travel time from the stop line, and at seven seconds from the stop line. The two upstream detectors define the clearance zone for the system (this zone exceeds the length of the typical dilemma zone found at U.S. intersections). The LHOVRA design is described in the literature for a 45-mph approach speed; however, it is implied that other speeds are possible provided that the detectors are located at travel times of 4, 7, 10, and 15 s. A LHOVRA design is shown in Figure 2-6 for a design speed of 55 mph.



**Figure 2-6. LHOVRA System.**

In the LHOVRA system, the “base” detectors are used to monitor presence only; vehicle speed and length are not measured. On multilane approaches, the detectors at each location monitor all lanes as one detection zone (i.e., there is no indication as to which lane is reporting vehicle presence). The system consists of a controller, detector amplifiers, and detectors.

In operation, the LHOVRA O-function works like the basic green-extension system in terms of extending the green to vehicles in the clearance zone. However, the LHOVRA system allows for the separate termination of the green for each major-road phase by separately monitoring the detectors on each approach. After the first phase gaps out, its detectors are temporarily ignored and the green indication is sustained. When the second phase gaps out or maxes out, the controller directs this phase to end its green interval. The detectors on the first approach are polled and, if a vehicle is in the clearance zone, the corresponding phase is allowed to remain green until the clearance zone is clear or 12 s elapses, at which time its green interval is ended.

The “past-end-green” enhancement described in the preceding paragraph has the potential to increase the frequency of green interval termination by gap-out and reduce phase duration relative to the basic green-extension system. The former attribute should reduce crash frequency and the latter attribute should reduce delay. This scheme can be implemented in standard controllers; however, there are no reports in the literature indicating that it has been tried or tested.

**Safety and Operational Benefits.** Evaluations of LHOVRA’s O-function at several intersections have found significant safety benefits. Peterson et al. (11) found that the crash rate is reduced by 30 percent. The number of vehicles entering the intersection during the yellow interval was reduced from 7 to 1 percent and the number of red light runners was reduced from 2 to

1 percent. The same study also noted that delays to major-road through vehicles were reduced by 3.0 to 5.0 s/veh; delays to the minor movements were reduced by 2.0 to 3.0 s/veh. The number of major-road through vehicles that stop was reduced by 50 percent. Peterson et al. estimated that the LHOVRA system had a benefit-cost ratio of 16:1.

### **Green-Termination Systems**

Unlike the green-extension systems described previously, green-termination systems determine the best time to *end* a green phase. Applications and evaluations of these systems have been documented since the mid-1980s. These systems have been proven to offer both safety and operational benefits. The system that is most relevant to this research project is the Self Optimizing Signal (SOS) system. This system is described in this section.

#### *SOS System*

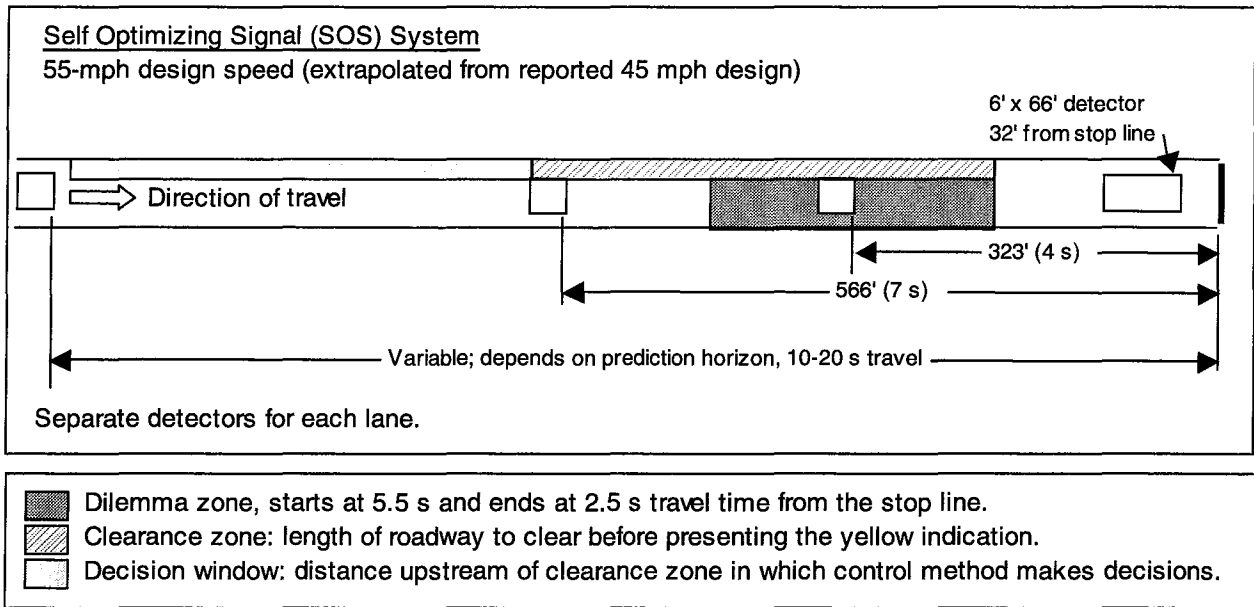
The SOS system was developed by the Transport Research Institute for the Swedish National Road Administration. The system was developed as an extension to the LHOVRA system. The main addition was a phase-length-optimization function intended to minimize overall delay. A report by Kronborg et al. (14) indicates that the system includes the following three components:

- a detection design that is similar to that used for LHOVRA (see Figure 2-6),
- a microcomputer that monitors the location and lane (i.e., inside or outside lane) of each vehicle on the approach, and
- a full-actuated controller with stop-line presence detection.

The objective of the SOS system is to determine the optimal time to end a phase based on considerations of safety to vehicles served by the major-road through phases and delay to vehicles served by conflicting phases. The SOS design is described in the literature for a 45-mph approach speed; however, it is implied that other speeds are possible provided that the detectors are located at travel times of 4, 7, and 15 s. An SOS detector layout is shown in Figure 2-7 for a design speed of 55 mph.

In the SOS system, the detector at each upstream location is used to monitor vehicle presence, vehicle speed and length are not measured. On multilane approaches, a separate detector is installed in each lane at each upstream location. Each detector and corresponding lane is individually monitored by the SOS system.

The SOS system replaces LHOVRA's O-function with an algorithm that decides the optimum time to end the green phase (14). The algorithm receives presence data from the detectors and then predicts where each vehicle will be in the surveillance zone (i.e., decision window plus clearance zone) at each of the decision points in the "time horizon." Decision points are defined to occur at 0.5-s intervals (i.e., 0.5, 1.0, 1.5 . . .) in the future. Thus, 40 decision points exist for a time horizon of 20 s.

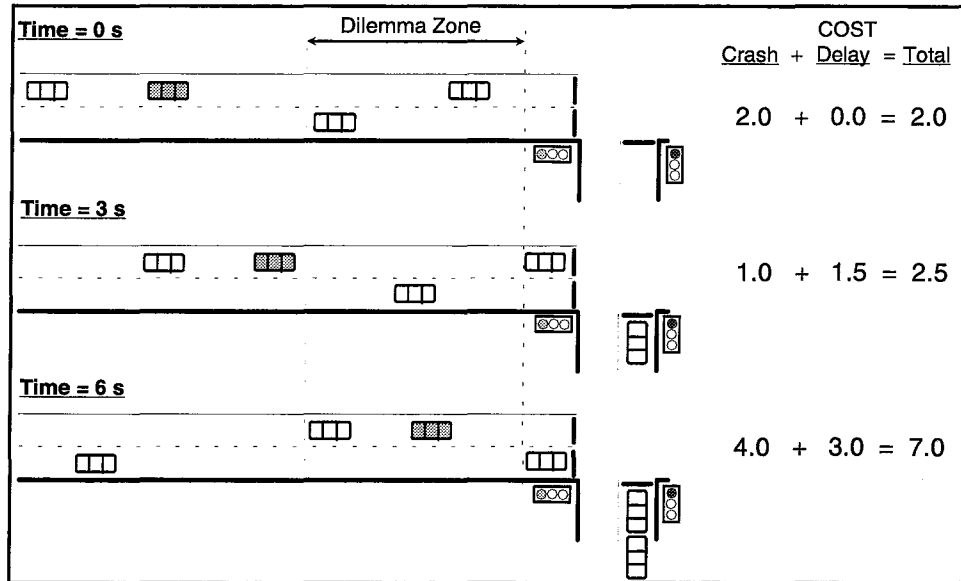


**Figure 2-7. SOS System.**

The SOS system assigns a cost for terminating the green phase to each decision point. This cost includes the delay to waiting vehicles and the expected number of crashes due to phase termination at that point. The SOS system then determines which decision point represents the “least-cost” time to end the green phase. As this “end-time” approaches, the cost estimate for all 40 decision points is updated using a rolling horizon (i.e., the points representing time past are deleted and new future points are added). If, as the selected end-time is neared, a lower cost end-time is identified then the end-time is changed to reflect this new time. This process continues until the end-time is reached or the system extends to a maximum green limit. Once the end-time is reached (or max-out occurs), a “past-end-green” function is invoked to maximize the likelihood that both major-road approaches end by gap-out.

Figure 2-8 illustrates the consideration of dilemma-zone activity at three decision points (separated by 3 s). At time “ $t = 0.0$  s,” two cars are in the dilemma zone for a collision cost of 2.0 units, the delay cost is 0.0 units, and the total cost of ending the green is 2.0 units. At time “ $t = 3.0$  s,” only one car is forecast to be in the zone so the cost is 1.0 unit; however, the delay cost is expected to increase to 1.5 units and the total cost of ending the phase is expected to be 2.5 units. At time “ $t = 6$  s,” there are also two cars in the zone but, because they are in the same lane, the potential for a rear-end crash is higher and the cost is expected to be 4.0 units. The delay cost has increased to 3.0 units and the total cost is now 7.0 units. In this example, the SOS system would determine that time “ $t = 0$  s” is the optimum time to end the phase. However, if just the cost of crashes were considered, the optimum time to end the phase would be “ $t = 3$  s.”





**Figure 2-8. Cost Strategy Used by the SOS System.**

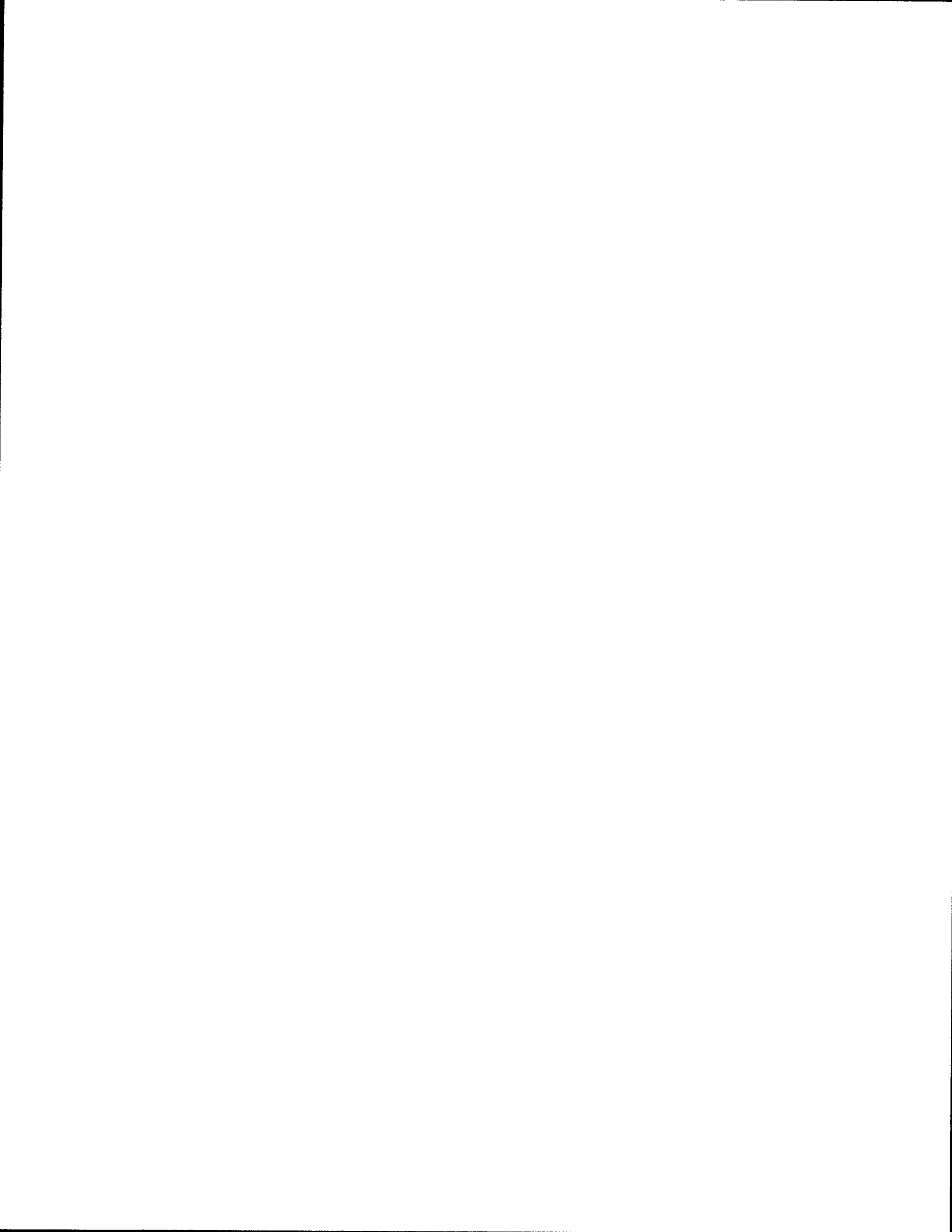
Unlike the basic green-extension system, the SOS system does not necessarily wait until the dilemma zone is fully clear (i.e., gaps out) to permit green interval termination; rather, it identifies the “best” time to end the green within a reasonable time horizon. In this case, the “best” time is dependent on how many vehicles will be in the dilemma zone and how much delay will be incurred by waiting motorists at each 0.5-s time interval in the next 20 s.

#### *Safety Benefits*

Kronborg et al. (14) found that the test installation of SOS performed dramatically better than LHOVRA when comparing their safety benefits. The SOS system was found to reduce the number of vehicles in the dilemma zone by 38 percent. It also reduced the number of vehicles “at risk” (i.e., a second or third vehicle in the dilemma zone) by about 58 percent. Finally, SOS was found to reduce red light running by about 16 percent. Reductions in collisions due to the SOS system have not been reported.

#### *Operational Benefits*

Kronborg et al. (14) also evaluated the operational benefits of the SOS system relative to those of the LHOVRA system. They found that the queue lengths were about the same for both systems during the peak and off-peak hours; however, the cycle length for the SOS system was more variable than that for LHOVRA. During the peak hours, the variation was greatest with SOS having cycle lengths 20 percent longer than LHOVRA.

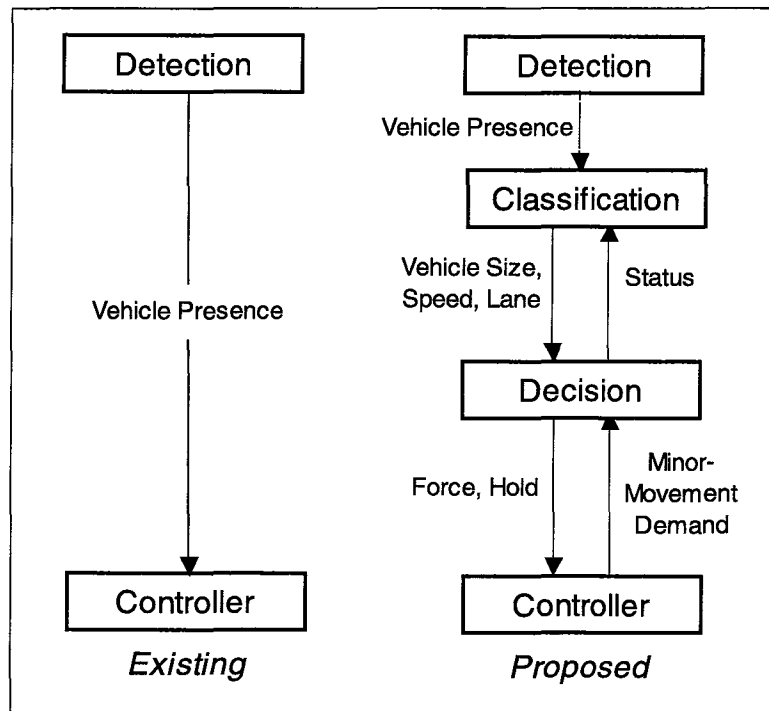


## CHAPTER 3. CONCEPT SYSTEM COMPONENTS

### OVERVIEW

This research proposes a new concept for vehicle detection and control at rural signalized intersections. The concept detection-control system is similar to a green-termination system because it uses vehicle speed and length information to predict the "best" time to end the phase. A computer processing system utilizes the speed information to predict the arrival of the vehicle in the dilemma zone. It uses vehicle length to provide a sensitivity to trucks.

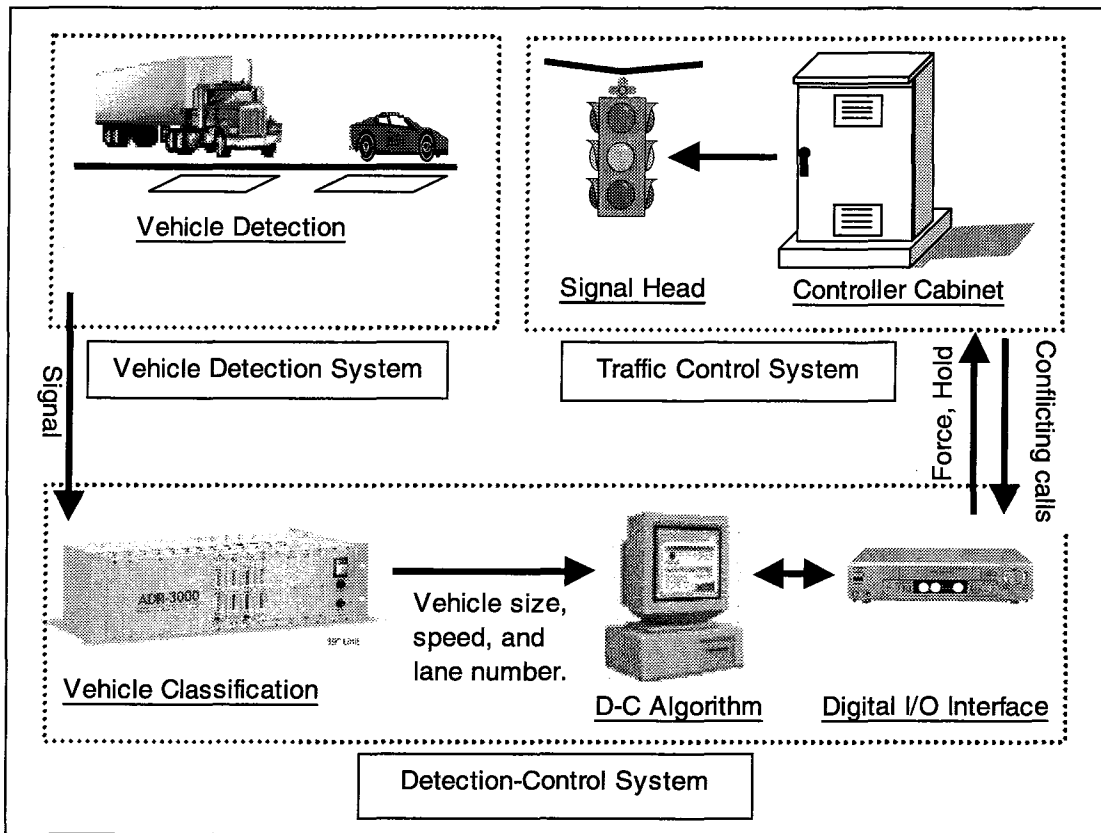
The objective of the concept system is to identify the best time to end the major-road through phase based on consideration of the number of vehicles in the dilemma zone, the number of trucks in the dilemma zone, and the waiting time of vehicles in conflicting phases. The concept system requires two detectors per lane (in a speed trap configuration) on each major-road approach to the intersection. Stop-line detection is desirable although, it is not required. Figure 3-1 shows a side-by-side comparison of the flow of information for traditional green-extension systems and the proposed concept detection-control system.



**Figure 3-1. Existing Versus Proposed Detection-Control System.**

The discussion contained in this chapter relates to specific components that comprise the concept system. This research project will produce a specification for manufactured systems that is based on the concept system developed in this research project. It is anticipated that this specification will facilitate the implementation of the concept system in standard traffic signal controllers.

Figure 3-2 is a flowchart showing the concept detection-control system and its relationship to the detection and the traffic control systems. The concept system consists of a vehicle classifier, a computer to process the detection-control (D-C) algorithm, and an input/output (I/O) device to provide a two-way communications interface between the computer and the signal controller.



**Figure 3-2. Concept System Components.**

The detection-control system communicates with both the vehicle detection system and the traffic control system. It uses the information provided by both systems to make decisions about holding the current phase in green or terminating it. It receives information about waiting vehicles from the stop-line detectors of conflicting movements. It receives vehicle length, speed, and lane location from the upstream major-road detectors.

## VEHICLE DETECTION SYSTEM

The vehicle detection system includes the detection equipment and the communications hardware that convey the detected signal to the traffic signal controller. Equipment applicable to the concept detection-control system is described in this section.

### Detection Equipment

Both intrusive and non-intrusive vehicle detection equipment can provide the information needed by the detection-control system to determine vehicle speed and length. Intrusive detectors involve sensing elements mounted either on top of or within the upper pavement layer. These detectors require significant traffic disruption for installation and maintenance activities. In contrast, non-intrusive detectors do not require mounting within the pavement surface. The following sections describe the intrusive and non-intrusive detection equipment that could be used with the concept detection-control system.

#### *Intrusive Detectors*

At the present time, most vehicle detectors fit the "intrusive" category. Detectors in this category include: inductive loop detectors, magnetometers, and piezoelectric cables. Of these detectors, the piezoelectric cables are typically used when the vehicle classification scheme is based on axle counts, vehicle weight, or both. For this research, classification based on length is adequate so piezoelectric cables are not needed. The following sections briefly describe the capabilities of inductive loop detectors and magnetometers.

**Inductive Loop Detector.** The inductive loop detector consists of a coil of wire installed in the pavement surface, a lead-in cable, and an amplifier located in the controller cabinet. The coil is composed of one or more turns of insulated loop wire installed in a shallow slot that is sawed in the pavement, a lead-in cable, and a detector electronic unit. Typical loops have a square, 6 ft by 6 ft, shape that is centered laterally in the traffic lane. The amplifier can be adjusted to record vehicle passage in pulse or presence mode. The disadvantages of the inductive loop detector include a propensity to double-count trucks and a low likelihood of detecting motorcycles (due to their small detection zone).

**Magnetometer Detector.** A magnetometer typically consists of an intrusive sensor about the size and shape of a small can, a lead-in cable, and an amplifier located in the controller cabinet. The cylinder portion of the magnetometer contains sensor coils that operate in a manner similar to inductive loops. These coils are installed in a small circular hole centered laterally in the lane and communicate with the controller by wire or radio transmission. Magnetometers function by detecting increased density of vertical flux lines of the earth's magnetic field caused by the passage of a mass of ferrous metals, such as a motorized vehicle. They operate in either presence or pulse mode. Magnetometers require less cutting of the pavement than inductive loop sensors, are easier

to install, and can be installed underneath bridge decks without damage to the deck. The disadvantages of the magnetometer are similar to those of the inductive loop detector.

### *Non-Intrusive Detectors*

Only a few non-intrusive detectors have the potential to be used with the concept detection-control system. The detectors that warrant consideration are: active infrared sensing systems, passive acoustic detectors, microloop detectors, and video image vehicle detection systems. The following sections briefly describe each of these detectors.

**Active Infrared Detector.** Active infrared detectors operate by focusing a narrow beam of energy and either measuring its reflection or measuring the direct energy disruption by an infrared-sensitive cell. In the first case, one device both sends and receives energy, and interprets the reflected pattern. In the second, energy disruption represents vehicle presence such that detection occurs when a vehicle passes through the beam and disrupts the signal. The infrared beam can be transmitted from overhead or from one side of the road to the other. Infrared systems can provide information on vehicle speed and length, in addition to simple passage of vehicles.

Preliminary testing of active infrared detectors indicates very promising results. Tests of the Autosense II by Schwartz Electro-Optics found it to operate during day/night transitions and other lighting conditions without significant problems (15). However, its cost of \$10,000 per lane is an obvious disadvantage. A second disadvantage of this detector is its requirement to be placed directly over each lane. This requirement translates into a lengthy lane closure during installation and removal. A third disadvantage of this detector is that some weather conditions (e.g., heavy fog, heavy dust, and heavy rain) appear to be problematic. Advantages of this detector include its ease of setup and its generation of data protocols for interpreting its output.

**Passive Acoustic Detector.** Passive acoustic detectors are generally composed of an array of microphones that are aimed at traffic to "listen" for passing vehicles. Two vendors currently market passive acoustic detectors. One vendor mounts a detector over each lane. The other vendor mounts one detector along the side of the intersection approach and uses it to monitor up to five lanes. Neither of these two devices is currently deemed accurate enough to meet the needs of this project.

**Microloop Detector.** The microloop detector is a transducer that converts changes in the vertical component of the earth's magnetic field into changes in inductance. Vehicles passing over the microloop increase the magnetic field, resulting in detections. The installation process for the microloop utilizes a horizontally bored conduit that is a fixed depth (18 to 24 inches) below the pavement surface. Sensors are installed by inserting from the shoulder end of the conduit via a ground box and sliding along the conduit until they are underneath the lane to be monitored.

The microloop provides speed, count, occupancy, and vehicle classification by length when connected to a ©3M Canoga vehicle detector and a PC running 3M software. A single probe

centered under each lane is expected to detect most vehicles, but two or more probes would be needed to detect small motorcycles or bicycles. Initial tests indicate that the 3M microloop detector is a promising addition to the list of non-intrusive detectors (15).

Microloop detectors are less likely to be affected by pavement weakness or other surface problems when compared to inductive loop detectors. Concerns related to this detector include its relatively high initial cost (where boring is required) and the shallow depth of the horizontal bore.

**Video Image Vehicle Detector.** A video image detection system consists of one or more cameras providing a digitized view of the detection area and a microcomputer to process the digitized image. Advanced video image vehicle detectors can collect, analyze, and record traditional traffic data; detect and verify incidents; classify vehicles by length; and monitor intersections. These detectors provide vehicle counts with  $\pm 5$  percent precision as long as weather and lighting conditions are favorable. However, their ability to classify vehicles is generally limited to daylight hours because their nighttime detection algorithms depend only on the detection of headlights.

### **Communication Equipment**

There are generally two options for communicating from the detectors to the controller cabinet. They are copper wire communication and wireless communication. Copper wire communication represents an economical and tested technology. Typical wire costs are about \$0.25 per linear foot while trenching costs approximately \$3.00 per linear foot of trench. At this rate, copper wire would cost about \$8,000 per intersection for the concept detection-control system.

A search of product literature revealed that at least one product is available for wireless communication applications. The company that sells this product line is ENCOM Wireless Data Solutions, Inc. The product is a spread spectrum system specifically designed for traffic monitoring applications. It has a range of up to 20 miles. Each transmitter accepts up to four inputs. The basic equipment includes a transmitter at each detection point and a receiver in the cabinet. The system requires a clear line-of-sight between the detection points and the cabinet. The initial cost of installing this system for two approaches with up to two lanes per approach is approximately \$10,000 per intersection.

### **DETECTION-CONTROL SYSTEM**

The detection-control system includes a vehicle classifier, a computer for processing the detection-control algorithm, and a digital I/O controller interface. This section discusses the types of classification equipment and algorithm processing equipment needed for the detection-control system. The digital I/O is a fairly simple device that provides an electronic interface between the processing equipment and the traffic signal controller and will not be discussed further.

## **Classification Equipment**

The classification equipment that is selected for inclusion in the concept detection-control system should satisfy the following criteria:

- be cost-effective and have a reasonably fast processing speed;
- be accurate for both vehicle length ( $\pm 3$  ft) and speed ( $\pm 1$  mph) measurements;
- be reliable and accurate in all weather and lighting conditions;
- provide remote communication with an external computer through an I/O port; and
- have a user-interface accessible via laptop or front-panel keypad and display.

Classifiers that satisfy these criteria include the Peek ADR-3000, IVS-2000, and TraffiCard.

### *Peek ADR-3000 Classifier*

The Peek ADR-3000 classifier is available from Peek Traffic, Inc. It can accommodate up to 64 loop inputs or 32 speed traps. Speed accuracy is reported to be  $\pm 1$  mph with a 95-percent level of confidence. It has a 19,200 baud RS 232 communications port to facilitate set-up and remote communications with an external computer. The cost of this classifier is \$3,000.

### *IVS-2000 Classifier*

The IVS-2000 classifier by Orincon Industries, Inc. evaluates the complete loop “signature.” This signature contains more information than just an “on” or “off” indication of vehicle presence. Its shape and magnitude provide information on vehicle type and speed. The classification accuracy is reported to be 85 to 90 percent. Speed accuracy is reported to be  $\pm 5$  mph.

### *TraffiCard Classifier*

The TraffiCard by StreetCom is a microprocessor plug-in device that works in conjunction with inductive loop detectors, microloops, or video vehicle imaging detectors. Its basic functionality is to store the exact time and duration of each vehicle passage for up to 100,000 vehicles. It accommodates up to four detection inputs or two speed traps. It measures both vehicle length and speed. The TraffiCard plugs into a standard card rack configured for a two- or four-channel vehicle detector amplifier. Preliminary results from the use of this device (to detect trucks traveling faster than a site-specific safe speed) indicate fairly good results. The cost of one system is \$1,800. This includes the TraffiCard, its software, some adapters, and the necessary cables.

## **Algorithm Processing Equipment**

This section covers the general architecture of the computer processing associated with the detection-control system. Computer processing for this system requires a housing that is hardened for the environment found at most roadside signal controller cabinets. In other words, it must



withstand temperature and humidity extremes as well as dust and perhaps other airborne elements that can accumulate over time. For the concept system, the processing will likely occur in a stand-alone housing such as an industrial computer; however, it may ultimately reside in a 2070 controller or a detector amplifier unit. The space in a signal controller cabinet is limited, so the space required by the detection-control system must be kept to a minimum.

Besides the functionality and characteristics described above, the concept system used must also have sufficient memory for storing data to verify the adequacy of the prototype system. There may also be data storage needs in future systems for longer-term monitoring or for special site-specific conditions that could not be monitored in this research.

## **RECOMMENDED CONCEPT SYSTEM COMPONENTS**

This section identifies the recommended components for the concept detection-control system and the associated vehicle detection system. As noted previously, it is anticipated that the detection-control system developed in this research project will ultimately reside in the traffic signal controller.

### **Vehicle Detection System**

Based on a comparison of cost and reliability, it was determined that the inductive loop detector combined with a copper wire lead-in were the preferred components for the vehicle detection system. The copper wire option is less expensive than the wireless option. It also has a high degree of reliability relative to the newer wireless technologies. The relatively long, 1000-ft detector lead-in length associated with the detection-control system required a detector amplifier with an ability to detect small inductance changes. A two-channel amplifier from Reno A&E (Model DS70-S1200) was selected for this project. It is able to detect inductance changes as small as 0.0025 percent and has a cost of \$325.

### **Detection-Control System**

The detection-control system consists of three components: the vehicle classifier, the detection-control algorithm processor, and the digital I/O controller interface. A description of the recommended hardware for each component is provided in the following sections.

#### *Classification Equipment*

The Peek ADR-3000 classifier was determined to be the preferred vehicle classifier for the detection-control system. It was selected for three reasons. The first reason was the willingness of Peek Traffic, Inc. to provide serial data protocols. These protocols are essential to facilitate communications between the classifier and the algorithm processor. The second reason was the classifier's ability to provide the desired speed measurement precision of  $\pm 1.0$  mph. A third reason

was the classifier's ability to accommodate all of the inductive loops required by the detection-control system at one intersection. The ADR-3000 has a cost of \$3,000.

### *Algorithm Processing Equipment*

An ICS Advent industrial computer was determined to be the preferred processing platform for the concept system. The classifier information is provided to the computer through a serial communications port. The minor-movement detector status and major-road phase status is obtained from the signal controller and is provided to the computer through a digital I/O controller interface device (described in the next section). The computer has an Omnix 400 series housing with a Pentium II processor, 260 MB random-access memory, Windows NT operating system, and a 40 GB hard drive. The housing has a rugged design that can withstand 122° F temperatures and a 20-g shock (1 g = an acceleration equivalent to gravity). It has a cost of \$2,300.

### *Digital I/O Controller Interface*

Two-way communication between the traffic signal controller and the microcomputer is via a bus-mounted, digital I/O device connected directly to the controller cabinet back-panel. This device provides the detection-control algorithm with information about the status of all signal phases and corresponding calls for service. When the algorithm selects a time to either terminate or hold the major-road phase(s), an appropriate signal is sent to the signal controller via the I/O device. A National Instruments digital I/O interface card (PCI-6527) was determined to be the preferred device for the concept detection-control system. This device has 24 isolated digital data input channels, 24 digital output channels and a cost of \$600 (including I/O connector bus and cable wiring harness).

## CHAPTER 4. FIELD EVALUATION PLAN

### OVERVIEW

This chapter describes a plan for the field evaluation of the concept detection-control system. The plan allows for collection of data needed to assess the safety and operational impacts of the concept system. Initially, a process is described for selecting suitable intersections to test and evaluate the concept system. Then, a data collection plan is described that identifies the field study schedule and the types of data to be collected.

### SITE SELECTION PROCESS

The objective of the site selection process was to identify two rural intersections that would provide suitable test environments for the concept detection-control system. Five criteria were used to identify the candidate study sites. These criteria include: (1) adequate intersection approach site distance, (2) approach speeds in excess of 40 mph, (3) left-turn bays on the major-road approaches, (4) availability of crash data for the previous two years, and (5) a minimum of 8 percent heavy vehicles. The cooperation of the agency responsible for the intersection was also essential with regard to granting access to the controller cabinet and permission to install the concept system.

A list of candidate study sites was developed using information from a variety of sources. These sources included the project advisory committee and TxDOT's Bryan District. The Bryan District was contacted because of its close proximity to research staff's headquarters in College Station, Texas. Based on this input, five sites were identified in TxDOT's Waco and Bryan Districts. Figure 4-1 is a map that shows all five sites and the local road network.

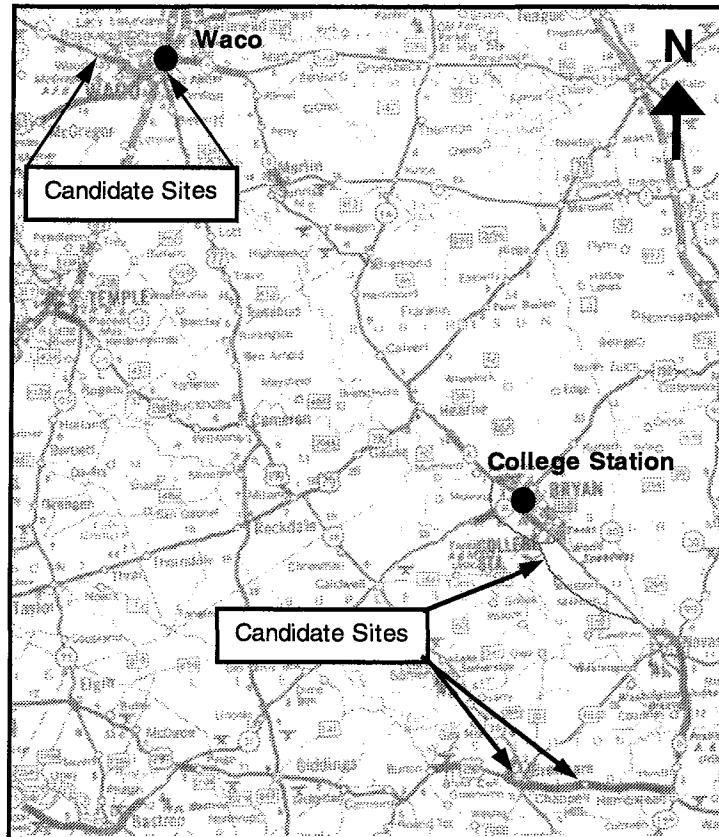
The research team made visits to each of the candidate study sites. Information gathered during and subsequent to these visits included: geometry, traffic volumes, truck percentages, crash rates, and forthcoming intersection improvement projects. Identification of scheduled intersection improvement projects was important because of the potential to modify such projects to facilitate the needs of the concept system without a significant increase in cost.

### Description of the Candidate Sites

#### *U.S. 290 at F.M. 577*

U.S. 290 is a major east-west through route for trucks and other vehicles traveling between Houston and Austin. There are no other signalized intersections on U.S. 290 in either direction for several miles. F.M. 577 is a local connector route on both the north and south sides of the intersection. On the north side, it serves local traffic for residential, commercial, and industrial land uses. On the south side, the road connects an industrial park that has limited traffic activity. There

is significant truck traffic between U.S. 290 and the north leg of F.M. 577 partly due to the Blue Bell Creamery located nearby on F.M. 577.



**Figure 4-1. Candidate Study Site Locations.**

**Geometric Characteristics.** U.S. 290 is a four-lane roadway at its intersection with F.M. 577. It has left-turn bays on each approach. Both approaches also have right-turn bays that form turning roadways at the intersection. U.S. 290 has an unusually wide median of approximately 130 ft. F.M. 577 also has separate left- and right-turn lanes at the intersection. The southbound right-turn lane on F.M. 577 is flared to resemble the two turning roadways on U.S. 290.

Terrain is rolling hills through this section of U.S. 290, forming a fairly steep downgrade for eastbound vehicles approaching the signal. Sight distance to the intersection is limited for westbound drivers due to a crest curve about 1000 ft from the intersection. The grades are also significant for southbound vehicles from F.M. 577 entering and turning either left or right onto U.S. 290. Outside shoulders along U.S. 290 are approximately 10 ft wide, although turn lanes utilize most of this width near the intersection. Photographs of the intersection approach geometry are included in the Appendix.

**Traffic Control Characteristics.** The speed limit on U.S. 290 is 65 mph. The traffic signal was installed in 1999 and turned on in November 2000. The intersection has overhead lighting and flashing warning lights on both major-road approaches. The warning signs are located 1000 ft from the intersection. Underground conduit exists for the flashing warning lights, but its diameter is only 1 inch. The U.S. 290 approaches include both stop-line and advance detectors. The most distant advance detectors are located 600 ft from the stop line on the eastbound approach and 635 ft back on the westbound approach.

**Traffic Volume Characteristics.** U.S. 290 traffic in 1999 consisted of 18,240 veh/day near the F.M. 577 intersection. Of these vehicles, 2788 were trucks (pickups and panels excluded) and 1815 were combination trucks. The proportions of all trucks and combination trucks are estimated at 15 percent and 10 percent of the traffic stream, respectively.

**Crash History.** Table 4-1 shows the crash history for the intersection of U.S. 290 and F.M. 577 during 1998 and 1999. These data were obtained from the Texas Department of Public Safety. During the two-year period noted, there were 16 crashes. Two involved fatalities, eleven involved injuries, and three were property-damage-only. All crashes involved two vehicles except the one that involved a fixed object.

**Table 4-1. Crash History for the Intersection of U.S. 290 and F.M. 577.**

Crash Number	Crash Date	Crash Type	Crash Severity
8011562	01/16/1998	Vehicle with Vehicle	Type C Injury (claimed)
8090649	04/22/1998	Vehicle with Vehicle	Type C Injury (claimed)
8137353	06/18/1998	Vehicle with Vehicle	Type B Injury (non-incapacitating)
8153639	07/08/1998	Vehicle with Vehicle	Type C Injury (claimed)
8204342	09/06/1998	Vehicle with Vehicle	Type C Injury (claimed)
8281346	10/29/1998	Vehicle with Vehicle	Property-Damage-Only
8281347	10/30/1998	Vehicle with Vehicle	Type A Injury (incapacitating)
9061171	03/18/1999	Vehicle with Fixed Object	Property-Damage-Only
9065633	03/23/1999	Vehicle with Vehicle	Type B Injury (non-incapacitating)
9073911	04/02/1999	Vehicle with Vehicle	Type K Fatal
9110869	05/14/1999	Vehicle with Vehicle	Type B Injury (non-incapacitating)
9164589	07/15/1999	Vehicle with Vehicle	Type B Injury (non-incapacitating)
9178740	07/31/1999	Vehicle with Vehicle	Type K Fatal
9197209	08/23/1999	Vehicle with Vehicle	Type C Injury (claimed)
9213222	09/11/1999	Vehicle with Vehicle	Property-Damage-Only
9213957	09/12/1999	Vehicle with Vehicle	Type B Injury (non-incapacitating)

**Related Findings.** The intersection contains several geometric elements that would challenge the performance of the concept detection-control system (e.g., steep grade and restricted

sight distance). However, the intersection could also benefit from an improved advance detection design.

Conduit installed under the traffic signal contract is located in the median on both U.S. 290 approaches. Unfortunately, the conduit for the detector lead-ins and the conduit for the AC power to the advance flashing lights is 1 inch in diameter. As a result, it is not large enough for the lead-in wires that are required for the concept system. TxDOT plans an overlay for the pavement in the near future but there was no interest expressed in adding additional loops to accommodate the needs of this project. In January 2001, the Bryan District was considering reducing the speed limit on the intersection approaches to improve safety.

#### *U.S. 290 at F.M. 1155 in Chappell Hill*

U.S. 290 is a major east-west through route for trucks and other vehicles traveling between Houston and Austin. The intersection of U.S. 290 at F.M. 1155 in Chappell Hill is very isolated, with several miles separating it from the nearest signalized intersections on U.S. 290. This site is approximately 10 miles east of the intersection described in the preceding section. The traffic mix has a significant number of through trucks. F.M. 1155 serves mostly local traffic on both the north and south sides of the intersection. The community of Chappell Hill, located just north of the intersection, attracts a significant number of tourists during certain times of the year. A small commercial center on the south side of the intersection contains a restaurant, convenience stores, and fuel.

**Geometric Characteristics.** Both approaches on U.S. 290 are relatively flat with a 1 percent upgrade on the westbound approach. The westbound approach also has a horizontal curve to the left when approaching this intersection but the sight distance is still well more than 1000 ft. Both approaches on U.S. 290 have two through lanes, one right-turn lane, and one left-turn lane. Shoulders are approximately 10 ft wide, but near the intersection the shoulder becomes the right-turn lane. F.M. 1155 is a two-lane roadway with a widened section on the southbound approach for a right-turn lane. Photographs of the intersection approach geometry are included in the Appendix.

**Traffic Control Characteristics.** The speed limit on U.S. 290 near this intersection is 65 mph. The traffic signal was installed in 1995 and turned on in June 1997. There is a single pole supporting lighting for the intersection. This pole is located in the median at the intersection. There are also intersection warning signs with flashing lights 1000 ft from the intersection along both major-road approaches. Underground conduit exists for the flashing lights, but its diameter is only 1 inch. The first advance detector is located 490 ft from the stop line on the westbound approach and 484 ft on the eastbound approach. The eastbound approach has several driveways associated with the commercial development at the intersection.

**Traffic Volume Characteristics.** The average annual daily traffic on U.S. 290 in 1999 (10 miles west of this intersection) was 17,254 veh/day. Of these vehicles, 2659 were trucks (pickups

and panels excluded) and 1768 of these were combination trucks. The proportions of all trucks and combination trucks were 15 percent and 10 percent of the traffic stream, respectively.

**Crash History.** Table 4-2 shows the crash history at the intersection of U.S. 290 and F.M. 1155. According to these data, there were 10 crashes at the intersection during 1998 and 1999. There were no fatalities, but there were nine injury crashes and one property-damage-only crash.

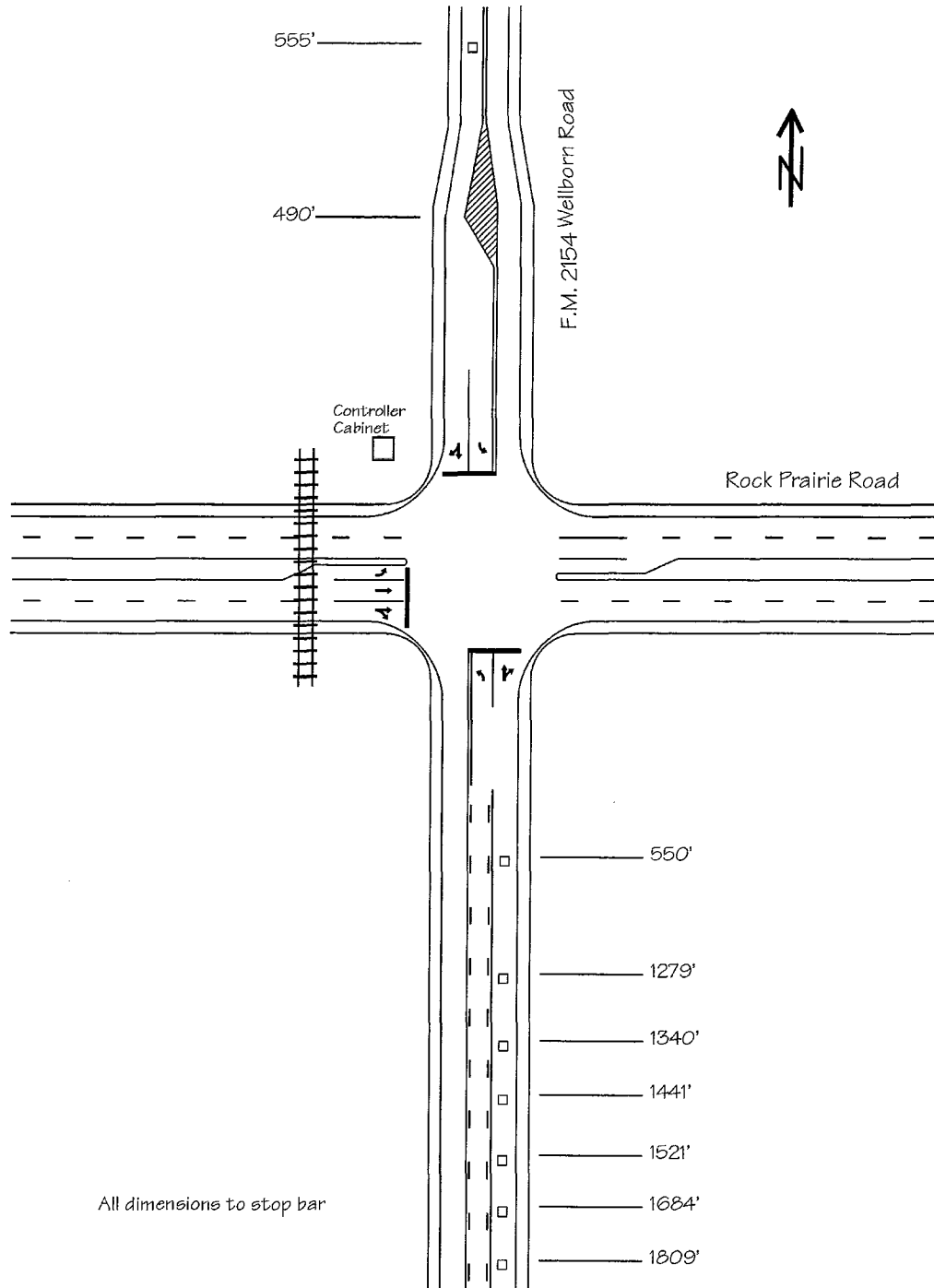
**Table 4-2. Crash History for the Intersection of U.S. 290 and F.M. 1155.**

Crash Number	Crash Date	Crash Type	Crash Severity
8063192	03/20/1999	Vehicle with Vehicle	Type A Injury (incapacitating)
9011090	01/16/1999	Vehicle with Vehicle	Type A Injury (incapacitating)
9016497	01/23/1999	Vehicle with Vehicle	Property-Damage-Only
9019139	01/27/1999	Vehicle with Vehicle	Type C Injury (claimed)
9049572	03/05/1999	Vehicle with Vehicle	Type C Injury (claimed)
9080213	04/09/1999	Vehicle with Vehicle	Type B Injury (non-incapacitating)
9142504	06/19/1999	Vehicle with Vehicle	Type C Injury (claimed)
9173793	07/26/1999	Vehicle with Vehicle	Type B Injury (non-incapacitating)
9179720	08/02/1999	Vehicle with Vehicle	Type C Injury (claimed)
9301454	12/19/1999	Vehicle with Vehicle	Type B Injury (non-incapacitating)

*F.M. 2154 and Rock Prairie Road in College Station*

F.M. 2154 (Wellborn Road) is a north-south roadway that connects College Station with the communities of Wellborn and Millican to the south. It also serves long-distance traffic by its connection with S.H. 6 near Navasota. Much of the traffic at this site, especially during peak periods, is commuter traffic oriented to and from College Station. There is a parallel railroad track on the west side of F.M. 2154 and an Exxon convenience center on the southeast quadrant of the intersection. The two west-side quadrants are blocked by the railroad and the fourth (northeast) quadrant is vacant.

**Geometric Characteristics.** F.M. 2154 has a two-lane cross section to the south of the intersection with Rock Prairie Road. The north leg of F.M. 2154 has a three-lane cross section with a center two-way left-turn lane. Both approaches on F.M. 2154 are on a slight upgrade (1 percent or less) with the intersection at the crest of a mild vertical curve. Topography is relatively flat and there are no driveways within 1000 ft on either approach. Shoulders are approximately 10 ft wide away from the intersection, with all but about 4 ft of the median used within 500 ft of the intersection for a left-turn lane. Figure 4-2 shows the intersection geometry. Photographs of the intersection approach geometry are included in the Appendix.



**Figure 4-2. Sketch of F.M. 2154 and Rock Prairie Road Intersection.**

**Traffic Control Characteristics.** The speed limit is 65 mph on the F.M. 2154 approaches. The intersection is relatively new, beginning operation in August 1999. Prior to this time, the



intersection was located approximately 1200 ft south of its current location. The intersection has street lighting mounted on two of the signal poles and on another pole near the intersection. Advance detectors are located at the stop line and as far back as 550 ft from the stop line on F.M. 2154.

The signal controller is in the northwest quadrant. For the northbound approach, detectors from the previous intersection are located at distances of 1279 ft, 1340 ft, 1684 ft, and 1809 ft from the new intersection's stop line. Conduit exists for at least part of the distance from the new intersection. However, it may not have enough capacity to handle the wire for the concept system.

**Traffic Volume Characteristics.** Vehicle classification counts for F.M. 2154 were not available, but the number of trucks at this site is relatively small based on visual observation. Trucks account for no more than 10 percent of the traffic. The average annual daily traffic at this site in 1999 was 13,600 veh/day. There are no known plans for intersection improvements in the near future.

**Crash History.** Table 4-3 shows the crash history for the intersection of F.M. 2154 and Rock Prairie Road. Three crashes occurred in the two-year period from 1998 through 1999. There were no fatalities but there was one injury crash and two property-damage-only crashes. All three crashes involved two vehicles. The first two crashes listed in Table 4-3 occurred before the current intersection was constructed.

**Table 4-3. Crash History for the Intersection of F.M. 2154 and Rock Prairie Road.**

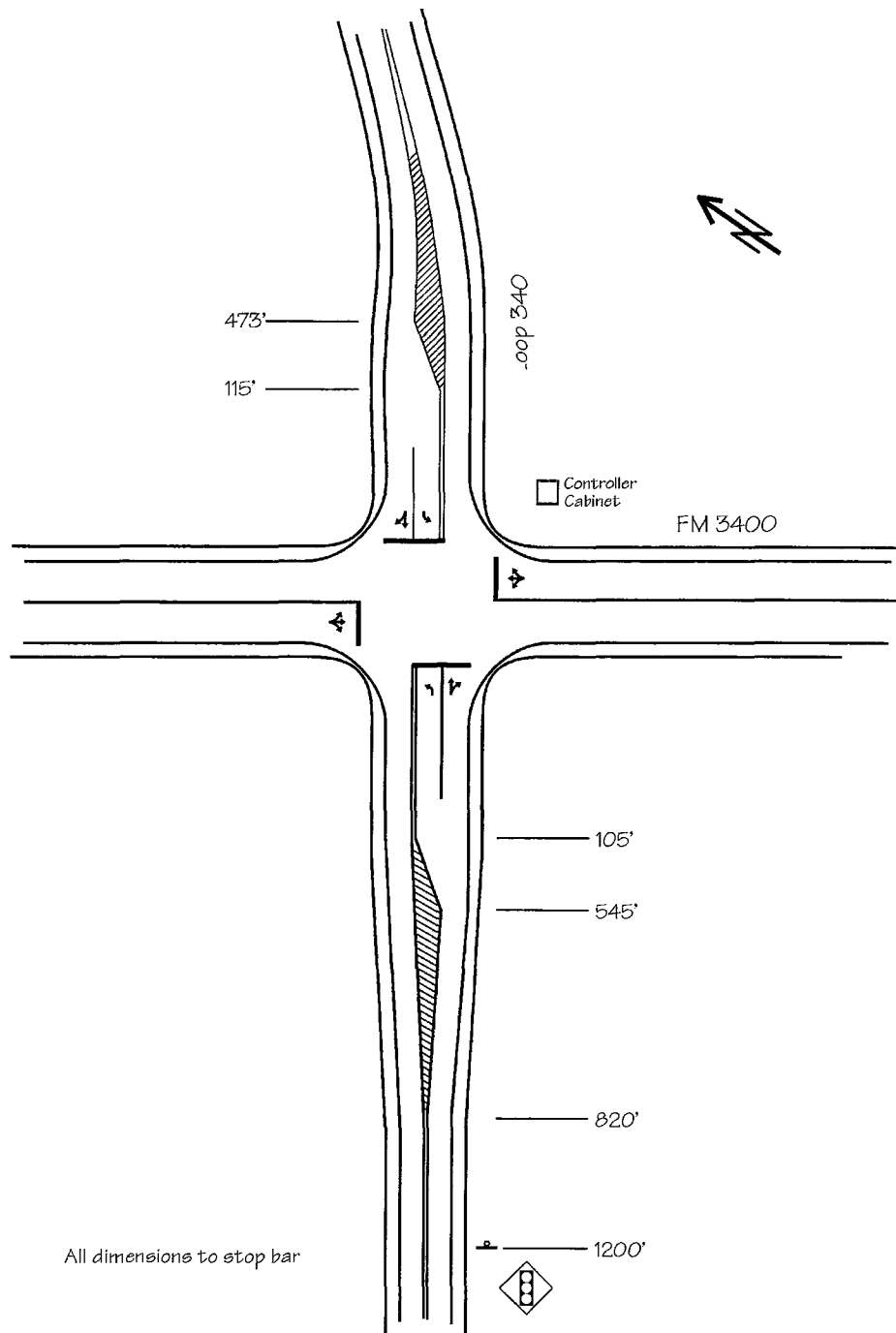
Crash Number	Crash Date	Crash Type	Crash Severity
8216178	09/19/1998	Vehicle with Vehicle	Property-Damage-Only
9122368	05/27/1999	Vehicle with Vehicle	Property-Damage-Only
9196377	08/22/1999	Vehicle with Vehicle	Type C Injury (claimed)

*S.H. 6/Loop 340 and F.M. 3400 near Waco*

Loop 340 is oriented in a northeast-to-southwest direction at its intersection with F.M. 3400. Loop 340 is both a bypass route and a major through route for traffic on the east side of Waco. It connects to I-35 on the north and the south. The land surrounding the intersection is undeveloped. Much of the turning traffic includes trucks going to and from the surface mining operation south of the intersection on F.M. 3400.

**Geometric Characteristics.** Both Loop 340 and F.M. 3400 are two-lane roadways. Loop 340 has a left-turn lane on each approach to the intersection and a shoulder that is approximately 10 ft wide in the vicinity of the intersection. No right-turn lanes are marked on any approach, although traffic can conveniently use the paved shoulders as separate turning lanes. There is excellent sight distance on Loop 340 in both directions. There is a gentle horizontal curve to the

right on the southbound approach and the topography is flat. Figure 4-3 shows the intersection geometry. Photographs of the intersection approach geometry are included in the Appendix.



**Figure 4-3. Sketch of Loop 340 and F.M. 3400 Intersection.**

**Traffic Control Characteristics.** The speed limit on Loop 340 is 60 mph. There is intersection lighting on the poles that also support the span-wire-mounted signal heads.

**Traffic Volume Characteristics.** The average annual daily traffic on Loop 340 is 12,900 veh/day north of the intersection and 15,600 veh/day south of the intersection. Recent truck counts were not available for Loop 340, but visual observation indicates approximately 20 percent trucks. Driveway activity along Loop 340 is insignificant in the vicinity of the intersection.

**Crash History.** Table 4-4 shows the crash history for the intersection of Loop 340 and F.M. 3400. A total of 10 crashes occurred in the two-year period from 1998 through 1999. There were no fatalities, but there were seven injury crashes and three property-damage-only crashes. All crashes involved two motor vehicles.

**Related Findings.** The Waco District plans on improving this intersection soon because it does not currently have advance detectors on Loop 340. When the signal was installed, the district anticipated a widening project along Loop 340, so detectors were not included in the design. However, the widening project has been delayed and the district plans to proceed with the installation of advance detectors on Loop 340. It is possible that the scope of this installation could be expanded to include installation of additional conduit and detectors for the concept detection-control system.

**Table 4-4. Crash History for the Intersection of Loop 340 and F.M. 3400.**

Crash Number	Crash Date	Crash Type	Crash Severity
8072908	04/01/1998	Vehicle with Vehicle	Type B Injury (non-incapacitating)
8132303	06/12/1998	Vehicle with Vehicle	Type B Injury (non-incapacitating)
8137296	06/18/1998	Vehicle with Vehicle	Type C Injury (claimed)
8140712	06/22/1998	Vehicle with Vehicle	Type B Injury (non-incapacitating)
8167401	07/25/1998	Vehicle with Vehicle	Type A Injury (incapacitating)
8186119	08/15/1998	Vehicle with Vehicle	Type C Injury (claimed)
8277277	11/29/1998	Vehicle with Vehicle	Type C Injury (claimed)
8286306	12/08/1998	Vehicle with Vehicle	Property-Damage-Only
9045161	02/27/1999	Vehicle with Vehicle	Property-Damage-Only
9070179	03/28/1999	Vehicle with Vehicle	Property-Damage-Only

*S.H. 6 and F.M. 185 near Waco*

The intersection of S.H. 6 and F.M. 185 is located to the southwest of Waco, serving traffic between I-35 and the rural areas to the west. The area around the intersection has development on three quadrants with two convenience centers and a small bank. The northeast quadrant is vacant.

**Geometric Characteristics.** S.H. 6 is a two-lane highway that is oriented in an east-west direction. F.M. 185 is also a two-lane highway; it is oriented in the north-south direction. The approaches on S.H. 6 flare near the intersection to accommodate both a right-turn and a left-turn lane. The right-turn lane occupies a portion of the full width of the paved shoulders. Three of the four intersection legs have large radius turning roadways for right-turning traffic. The exception is the eastbound-to-southbound right-turn movement. The eastbound approach has several driveways. The topography is almost flat on all approaches, with excellent sight distance. There are no known plans for intersection improvements in the near future. Photographs of the intersection approach geometry are included in the Appendix.

**Traffic Control Characteristics.** The speed limit on S.H. 6 is 70 mph. The signal at this intersection began operation in October 2000. Inductive loop detectors are located as far back as 480 ft from the stop line on S.H. 6.

**Traffic Volume Characteristics.** There are no automatic vehicle classification stations nearby, so accurate truck percentages were unavailable. However, visual observation indicates that total trucks are approximately 10 to 15 percent of the traffic stream. S.H. 6 has higher volume than F.M. 181 and is considered the major roadway at this intersection.

**Crash History.** There were no crashes recorded at the intersection of S.H. 6 and F.M. 185 during 1998 and 1999.

### **Recommended Study Sites**

Researchers used the selection criteria described at the start of this chapter to decide which two of the five candidate sites would best serve the needs of the research project. The degree to which each site satisfied the stated criteria is indicated in Table 4-5.

The following observations guided the site selection process. First, the performance of the detection-control system is anticipated to be the same for either a two-lane roadway or a four-lane roadway. Therefore, research staff will use two of the three two-lane intersections in order to minimize system installation costs. Second, the intersection of S.H. 6 and F.M. 185 is not desirable because it has large-radius turning roadways. These roadways introduce a geometric complication that should be avoided at this stage of the project. Based on these considerations, the two sites recommended for field data collection are the F.M. 2154 and Rock Prairie Road intersection in the Bryan District and the Loop 340 and F.M. 3400 intersection in the Waco District.

**Table 4-5. Summary of Site Characteristics.**

Characteristic	Intersection Location				
	TxDOT Bryan District			TxDOT Waco District	
	U.S. 290 & F.M. 577	U.S. 290 & F.M. 1155	F.M. 2154 & Rock Prairie Rd.	S.H. 6/Loop 340 & F.M. 3400	S.H. 6 & F.M. 185
Good sight distance*	No	Yes	Yes	Yes	Yes
Number of through lanes	4	4	2	2	2
Posted speed exceeds 40 mph*	Yes	Yes	Yes	Yes	Yes
Left-turn bay on major road*	Yes	Yes	Yes	Yes	Yes
Right-turn bay	Yes	Yes	No	No	Yes
Right-turning roadways	No	No	No	No	Yes
Total crashes (two-year total)*	16	10	3	10	0
Estimated percent trucks*	12	10	5	15	10
Peak period volume	Moderate	Low	Moderate	Moderate	Low
Est. percent trucks turning	15	12	10	30	10
Est. percent cars turning	10	10	12	5	10
Proximity to TTI, miles	40	50	5	80	95
Typical driver: repeat/new	New	New	Repeat	Repeat	Repeat
Intersection lighting	Yes	Yes	Yes	Yes	Yes

Note:

\* - Denotes one of the predefined site selection criteria.

## DATA COLLECTION PLAN

This section describes a plan for collecting the data needed to calibrate and validate the concept detection-control system. Initially, a schedule of data collection activities is described. Then the data needed for the calibration and validation activities are identified. Finally, the methods used for each data collection activity are defined.

### Data Collection Schedule

A series of data collection activities are planned. These activities are designed to calibrate the detection-control system and then validate it. They are scheduled to take place near the end of the first fiscal year and throughout the second fiscal year. The data collection schedule is listed in Table 4-6.

**Table 4-6. Data Collection Schedule.**

<b>Task</b>	<b>FY<sup>1</sup></b>	<b>Data Collection Activity</b>	<b>Location</b>	<b>Data Types Collected<sup>3</sup></b>
6	01	Test and refine software algorithm using HITL <sup>2</sup>	TTI/Office	Traffic operation
8	02	Controlled field tests of software and hardware	TTI/S.H. 6 Test Site	System function
9	02	Before-and-after study of installed system	Two intersections	Operation & safety
10	02	Safety study	Two intersections	Traffic safety
		System reliability study	Two intersections	System function

Notes:

1 - FY: fiscal year.

2 - HITL: Hardware-in-the-Loop. Uses Eagle signal controller to provide real-time control of the simulator.

3 - Specific performance measures are identified in Table 4-7.

The first data collection activity will take place near the end of FY 2001. It will focus on the software algorithm for the detection-control system. The data collection activity will center around an assessment of the algorithm, as facilitated by a traffic simulator. To provide a suitable basis of comparison, the simulated intersection will be evaluated with both the concept detection-control system and the traditional, multiple advance detector system.

The second data collection activity will take place at the start of FY 2002. It will focus on a test of the combined algorithm and detection-control system hardware components, as described in Chapter 3. The data collection activity will take place at TTI's Highway 6 detection system test site.

The third data collection activity will take place in the second quarter of FY 2002, following implementation of the system at one of the two recommended intersection study sites. Data will be collected before and again after the system is installed. The objective of the field studies is to assess the system's operational impact and make a preliminary assessment of its safety impact. Once this assessment has been completed, the detection-control system will be installed at the second study site and the before-and-after study process repeated. The control system at the first intersection site will be restored to its original operation after the detection-control system is removed.

The fourth data collection activity will take place in the third quarter of FY 2002. It will consist of an assessment of the long-term performance of the detection-control system. Performance measures will include traffic safety and system reliability. This activity will take place at the second intersection study site at which the system is installed.

**Database Elements**

A wide range of traffic and system-function data will be collected to facilitate the calibration and validation of the detection-control system. These data can be categorized as traffic operation, traffic safety, or system-function related. Within each category, several characteristics will be

measured to facilitate the assessment of system performance and reliability. Table 4-7 shows the specific data categories and associated performance measures to be collected.

**Table 4-7. Database Elements.**

Task	Operation Data		Safety Data		System Function Data	
	Performance Measure	Period <sup>1</sup>	Performance Measure	Period <sup>1</sup>	Performance Measure	Period <sup>1</sup>
6	Control delay	PM, Off				
	Percent stopping	PM, Off				
	No. vehicles in zone	PM, Off				
8					Speed & class accuracy	PM, Off
					Travel time accuracy	PM, Off
					Percent correct response	PM, Off
9	Control delay	6 hours	Abrupt stop conflict	2 days		
	Percent stopping	6 hours	Run-red conflict	2 days		
	No. vehicles in zone	6 hours	Other conflicts	2 days		
10			Crash rate (all)	6 mo.	Time between failure	6 mo.
			Rear-end crash rate	6 mo.	Average time off line	6 mo.
			Rt.-angle crash rate	6 mo.	Average repair time	6 mo.

Note:

1 - Period: Minimum duration of data collection for “after” study. Duration of “before” study will equal or exceed this amount. PM- afternoon peak hour. Off-representative off-peak hour.

The database elements listed in Table 4-7 are categorized by research task to facilitate their cross reference with the data collection schedule identified in Table 4-6. For example, the software testing and refinement activities that take place in Task 6 are based on traffic operations data that include delay, percent stopping, and the average number of vehicles in the dilemma zone at the onset of the yellow indication. This latter measure will provide some indication of the effectiveness of the concept system in reducing the number of vehicles exposed to phase-termination-related conflicts, relative to the multiple advance detection design.

The controlled field tests that take place during Task 8 will focus on: (1) the ability of the hardware to accurately measure vehicle speed and length, (2) the ability of the algorithm to use this information to estimate vehicle travel time along the approach, and (3) the ability of the algorithm to make the correct control decision (i.e., extend green or terminate the phase).

The before-and-after studies conducted during Task 9 will focus on an assessment of both the traffic operations and safety impacts of the system. The traffic operations data will be similar to that obtained during Task 6. The safety data will focus on vehicle conflicts that may occur on the major-road approaches to each intersection study site.

As noted previously, the data collected during Task 10 will focus on the long-term performance of the detection-control system. In this regard, long-term is limited to a six-month study window during which crash records and system service records will be collected. The latter records will be used to describe the reliability of the system in terms of the time-between-system-failure, average-time-off-line, and average-repair-time. These data will be recorded only for the detection-control system components and will not include any time the system is off-line because of initial set-up activities.

The focus of the reliability study will be on the longevity of the system hardware components, especially those in and adjacent to the roadway (i.e., loop detectors and wire lead-ins). The reliability of the hardware located in the controller cabinet will also be recorded; however, this data will be qualified by the fact that these system components are “temporary” as they are intended only to demonstrate the feasibility of the concept system. More robust systems will likely be available from control manufacturers for permanent applications of the detection-control system. It should be noted that the existing controller and detection circuitry will remain operational if the concept detection-control system unexpectedly stops functioning.

**Data Collection Methods**

Table 4-8 identifies the data collection method to be used for each research task and corresponding study. For example, during the simulation study in Task 6, the delay and percent-stopping data will be obtained directly from the simulation output. The number-of-vehicles-in-the-dilemma-zone data will be obtained from a log of events generated by the simulation software (and saved in an electronic log file).

**Table 4-8. Data Collection Method.**

Task	Performance Measure	Period <sup>1</sup>	Data Collection Method
6	Delay, stops, & no. veh. in zone	PM, Off	Simulation model output.
8	Accuracy & correct response	PM, Off	Videotape record of events supplemented with speed measurement from a second microwave detector.
9	Delay, stops, & no. veh. in zone	6 hours	Videotape record of queue counts and volume on major road.
	Vehicle conflicts	2 days	Videotape record of conflicts on the major-road approaches.
10	Crash records	6 mo.	Request crash records from Dept. of Public Safety.
	Failure rate & repair time	6 mo.	Detection-control system output and staff maintenance logs.

Note:

1 - Period: Minimum duration of data collection for “after” study. Duration of “before” study will equal or exceed this amount. PM- afternoon peak hour. Off-representative off-peak hour.

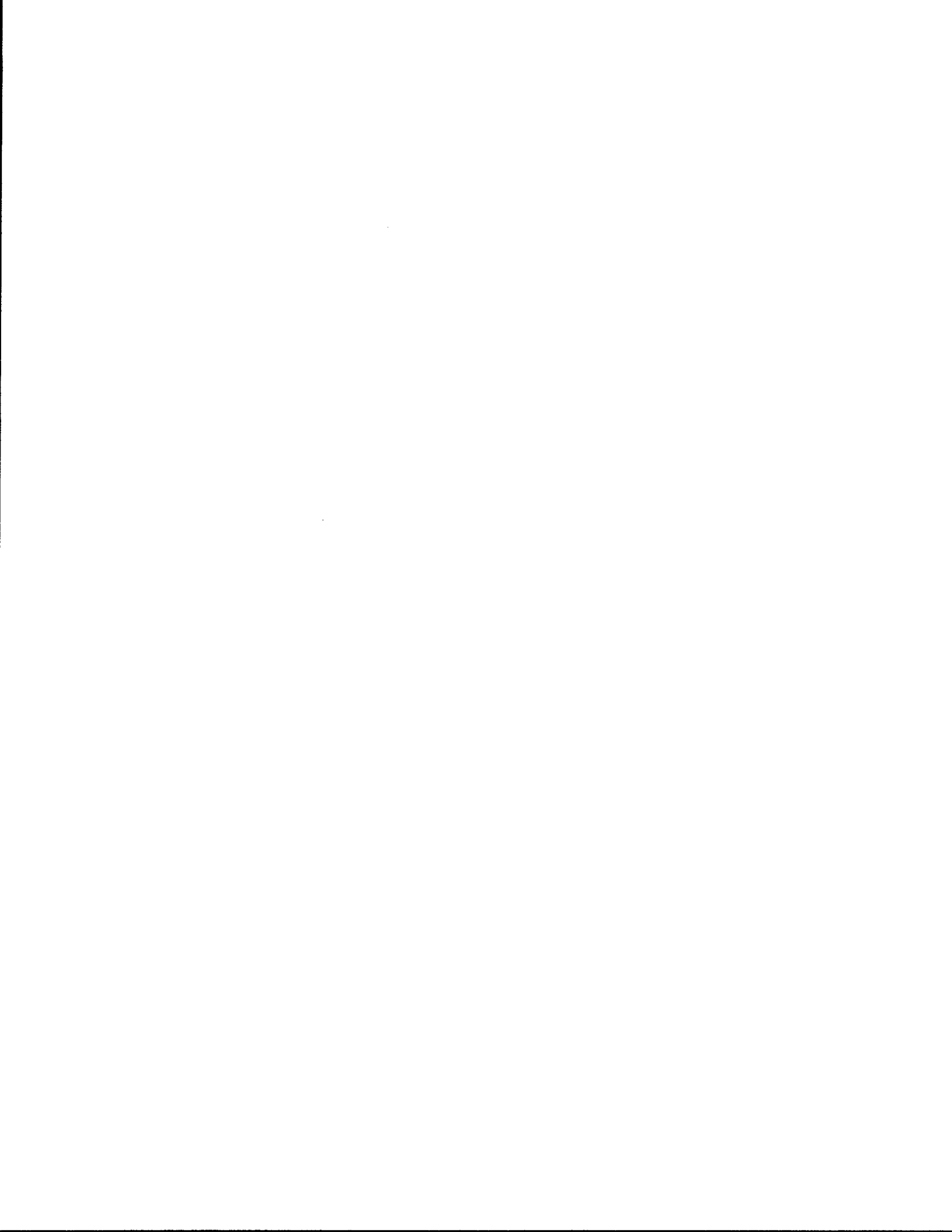
Videotape recordings of both major-road intersection approaches will be used to extract the data needed to assess the performance of the detection-control system. During the study in Task 8,



the videotape record will be used to extract vehicle travel time data. This data will be supplemented with individual speed and length data obtained from the detection-control system classifier and from a microwave detector (available at TTI's Highway 6 test site). Data from the latter detector will be used as a "ground-truth" for comparison purposes. During the study in Task 9, videotape records will be used to extract delay, stop, and conflict data.

Separate data collection activities will be undertaken during Task 10 to gather safety and reliability data. Specifically, safety data for the study site intersections will be requested from the Texas Department of Public Safety. These data will be requested for a period covering two years before the detection-control system was installed and for the six-month period during which the system was operational.

Reliability data will also be collected during the six-month study period in Task 10. Data regarding the system's time-of-operation will be generated automatically and saved in an electronic log file. A maintenance log will also be kept by the research staff and used to categorize the types of problems encountered and their average repair times.



## CHAPTER 5. ALGORITHM DESCRIPTION AND EVALUATION

### OVERVIEW

This chapter describes the concept detection-control algorithm and its evaluation. The algorithm is one component of the detection-control system that is intended to improve the safety and operation of rural signalized intersections. The other components of this system are described in Chapter 3 and illustrated in Figure 3-2.

Subsequent sections of this chapter provide a description of the algorithm and the findings from its laboratory evaluation. The first section to follow includes: a review of the system objectives, a discussion of issues related to the location of the upstream detection zone, and an overview of the control logic incorporated into the algorithm. The second section describes an evaluation of the algorithm. This evaluation is based on a laboratory simulation of intersection operations where a variety of factors (including volume, turn percentage, and speed) were varied and the effects noted. The evaluation section includes a description of the levels considered for each factor and a summary of the simulation results.

### ALGORITHM DESCRIPTION

#### Objective and Goals

The objective of the concept detection-control system is to effectively and efficiently control high-speed signalized intersections. Effectiveness is measured in terms of overall motorist delay and the number of vehicles in the dilemma zone at the onset of the yellow indication. Efficiency is measured in terms of the number of detection loops needed for each lane of the major-road approach and the ease with which the detection-control system can be installed and operated. The traditional, multiple advance detector system serves as a baseline for assessing the relative merit of the concept system.

The objective of the concept detection-control system was achieved by accomplishing the following goals (relative to the traditional, multiple advance detector system):

- reduce the frequency of vehicles caught in the dilemma zone at the onset of yellow;
- reduce the cost of design, installation, and maintenance of advance detection;
- provide a sensitivity to the presence of trucks in the dilemma zone with the potential to eliminate the possibility of catching a truck in the dilemma zone; and
- maintain or reduce overall delays.

The first goal was achieved by predicting the time *every* driver is in his or her dilemma zone and by searching for a time in the near future where the total number of drivers in their respective dilemma zones is at a minimum. This future time is defined as the “best-time-to-end-the-phase.”

The concept detection-control system approach represents a “dynamic” dilemma-zone monitoring process because it determines the dilemma zone for *each* vehicle, in *real-time*, and *prior* to when the information is needed. It differs from the operation of the traditional system because the traditional system searches for a time when a segment of each approach is effectively clear of vehicles. The traditional system does not guarantee that the slowest and fastest vehicles are clear of their respective dilemma zones at the onset of yellow (this point is described more fully in a later section). In contrast to the detection-control system, the traditional system can be described as having a “static” monitoring process.

The second goal is achieved in three ways. First, the detection-control system requires the measurement of vehicle speed and length at one point in advance of the intersection. This measurement can be accomplished with two inductive loop detectors per lane (although non-intrusive detection is also available). In contrast, the traditional, multiple advance detector system requires three or four loop detectors per lane for design speeds of 55 mph or more.

Second, the detection-control system has a “one-size-fits-all” design such that its detection design, controller settings, and algorithm operation is the same for all design speeds. In contrast, the traditional system requires engineering oversight during its design and installation as several key design elements and controller settings are dependent on design speed.

Third, the detection-control system is robust in terms of its ability to adapt (without manual intervention) to changes in speed over its design life (e.g., due to a change in the posted speed limit) and, thereby, maintain a high level of safety and efficiency over time. In contrast, the detectors would have to be reinstalled for the traditional system if the approach speed is permanently changed.

The third goal is achieved by measuring the length of the approaching vehicles and using this information to postpone phase determination whenever “long” vehicles (e.g., trucks) are in the dilemma zone. The traditional system does not provide this sensitivity.

The fourth goal is achieved as an indirect result of the detection-control algorithm’s dynamic dilemma-zone monitoring process. This process is often able to find the “best-time-to-end-the-phase” sooner than the traditional system. This behavior can translate into lower delays.

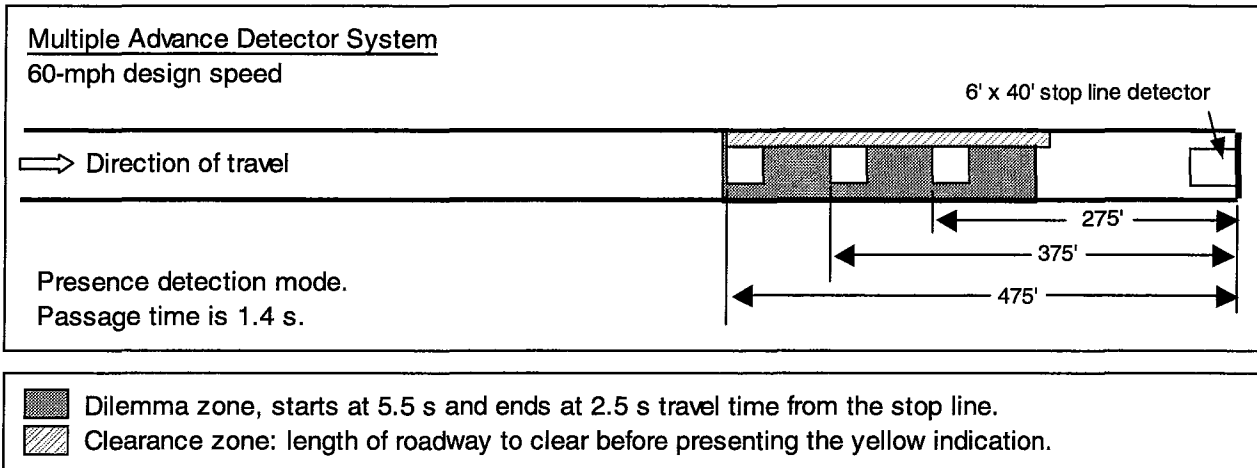
## **System Description**

This section describes the traditional, multiple advance detector system and the concept detection-control system. The focus of this section is on the latter system; however, the former system is also described to facilitate a comparison between the two systems.

### *Multiple Advance Detector System*

**Description.** As discussed in Chapter 2, the traditional multiple advance detector system is one of several systems that can be categorized as a “basic green-extension system.” A multiple

advance detector system is illustrated in Figure 5-1. The layout shown is based on a 60-mph design speed (where the design speed is defined as the 85<sup>th</sup> percentile speed). The design specifications for other design speeds are listed in Table 5-1. Details on the methods used to develop these specifications are available in a report by Middleton et al. (4). The values in Column 6 of Table 5-1 are discussed in the next section.



**Figure 5-1. Detector Layout for the Multiple Advance Detector System.**

**Table 5-1. Multiple Advance Detector Design Specifications.<sup>1</sup>**

85% Approach Speed, mph	Distance to 3 <sup>rd</sup> Loop, ft	Distance to 2 <sup>nd</sup> Loop, ft	Distance to 1 <sup>st</sup> Loop, ft	Passage Time, s	Max. Allowable Headway, s <sup>2</sup>
45	210	330		2.0	4.5
50	220	350		2.0	4.4
55	225	320	415	1.2	4.2
60	275	375	475	1.4	4.3
65	320	430	540	1.2	4.1
70	350	475	600	1.2	4.2

Notes:

- 1 - A 6' x 40' stop-line detector may be provided if it is set in the controller to be inactive during the green interval, after the first gap-out is detected.
- 2 - Maximum allowable headways are computed using the following assumptions: (1) advance detectors have presence-mode operation, and (2) the average approach speed is 88 percent of the 85<sup>th</sup> percentile approach speed.

During normal operation, the traditional system searches for a time when a segment of each approach lane is effectively clear of vehicles. The boundaries of this “clearance zone” are typically

based on the beginning of the dilemma zone for a vehicle traveling at the design speed and the end of the dilemma zone for a vehicle traveling at some specified speed slower than the design speed. Many traditional systems use the 85<sup>th</sup> percentile speed for the design speed and the 15<sup>th</sup> percentile speed to define the end of the clearance zone. This zone is illustrated in Figure 5-1.

The stop-line detector shown in Figure 5-1 is not included in some variations of the traditional design. If it is not provided, the recall-to-minimum setting in the controller is used for the corresponding phase. In this case, the minimum green setting is set long enough to clear the queue of vehicles waiting at the start of the phase. If the stop-line detector is provided, the controller operation for this phase would be set such that the detector is disabled during the green interval but only after the stop-line detector “gaps out” for the first time.

By design, the traditional system seeks to find a time during the green indication when no vehicle, traveling at a speed *in the design speed range*, is in its dilemma zone. In operation, the clearance zone is almost always clear of vehicles when the phase terminates by gap-out. Two points can be made from these characterizations. First, the traditional system does not guarantee that the slowest and fastest vehicles are clear of their respective dilemma zones (in fact, if the 85<sup>th</sup> and 15<sup>th</sup> percentile speeds are used to design the system, up to 30 percent of the traffic stream may not be provided dilemma-zone protection). Second, a fairly lengthy time between vehicles is needed in the traffic stream before the phase can terminate by gap-out. At higher volumes, the search for this “maximum allowable headway” is often unsuccessful and the phase terminates by reaching the maximum green setting (i.e., it maxes out) at which time no dilemma-zone protection is provided to any vehicle.

**Maximum Allowable Headway.** The maximum allowable headway represents the largest time interval between detector calls that can still extend the green indication for the subject phase. A larger time between vehicle calls would result in gap-out of the phase. A shorter time between calls will extend the phase. If the phase extends until the maximum green setting duration is reached, a max-out occurs.

Both long and short maximum allowable headways are undesirable. Long values increase the likelihood of max-out which defeats dilemma-zone protection and effectively converts the controller to pretimed operation. Short values of the maximum allowable headway can result in premature termination of the phase (i.e., phase gap-out before the waiting queue is served).

The maximum allowable headway is a random variable because of the variation of speeds in a given lane, the numerous detectors located in a given lane, and the number of lanes served by a given phase. However, it can be estimated for a given lane using the following equation (5):

$$MAH = PT + \frac{D_1 - D_n + L_d + L_{pc}}{V_a} \quad (1)$$

where:

$MAH$  = maximum allowable headway, s;

$PT$  = passage-time setting, s;

$D_l$  = distance to the leading edge of the advance detector furthest from the stop line, ft;

$D_n$  = distance to the leading edge of the advance detector nearest the stop line, ft;

$L_d$  = length of an advance loop detector (typically, 6 ft), ft;

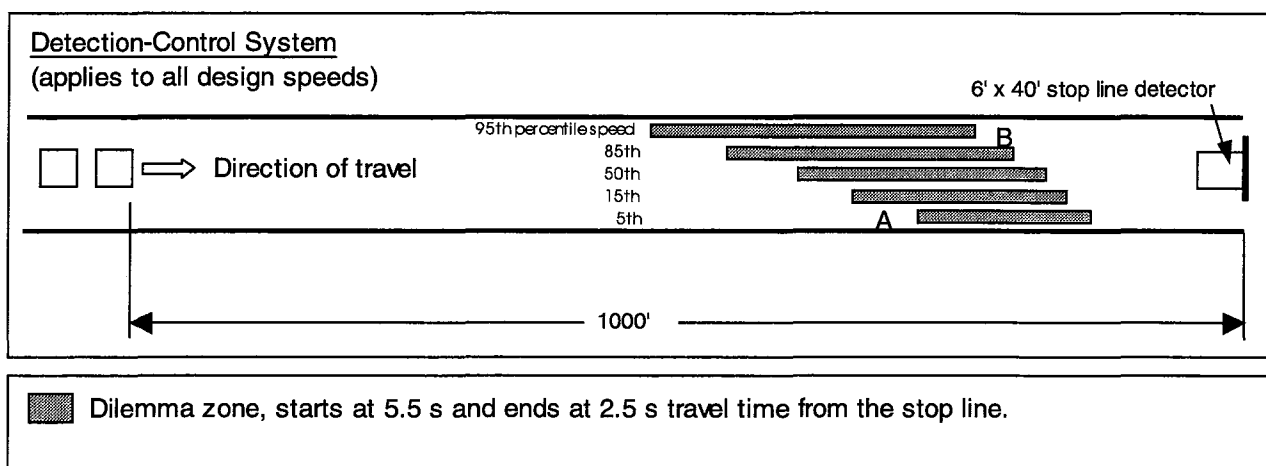
$L_{pc}$  = detected passenger-car length (typically, 18 ft), ft; and

$V_a$  = average running speed on the intersection approach of the subject lane group, as measured during the nonqueued portion of the green, fps.

Equation 1 was used to compute the maximum allowable headway for the detector designs listed in Table 5-1. The results are shown in Column 6 of this table. These values illustrate a consistent trend in the design to search for a headway of about 4.0 to 4.5 s or more in all lanes served by the subject phase. With this maximum allowable headway, a phase serving a flow rate of 1000 veh/h would extend an average of eight seconds before gapping out. In contrast, if the stop-line detector is provided but not disabled during the green indication, then the maximum allowable headway is likely to increase to 7.0 s and a phase serving a flow rate of 1000 veh/h would extend about 20 s before gapping out.

#### Detection-Control System

**Description.** The concept detection-control system consists of one detection zone (probably with two inductive loops) located several seconds in advance of the dilemma zone. The location of this detection zone is based on a desire to “look ahead” into the future of vehicle arrivals to the dilemma zone. Unfortunately, the benefit of an increased look-ahead time is offset by reduced travel time prediction accuracy. These points are discussed in more detail in a subsequent section. The detection-control system detection layout and control strategy is illustrated in Figure 5-2.



**Figure 5-2. Detector Layout for the Concept Detection-Control System.**

As noted previously, the concept detection-control system searches for a time when *each* vehicle served by the subject phase is outside of its respective dilemma zone. In the event that this time cannot be found, the detection-control system seeks a time when the fewest vehicles will be in the dilemma zone, relative to the duration of the look-ahead time window.

Like the multiple advance detector system, the stop-line detector for the concept detection-control system is not required. If it is not provided, the recall-to-minimum setting in the controller is used for the corresponding phase and its minimum green setting is set long enough to clear the queue of vehicles waiting at the start of this phase. On the other hand, if this detector is provided, the controller operation for this phase should be set such that the detector is disabled during the green interval but only after the stop-line detector gaps out for the first time.

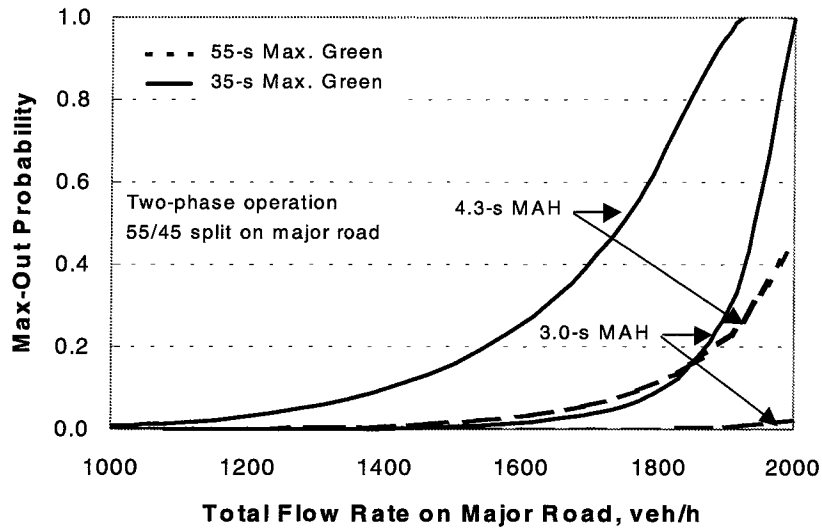
Unlike the multiple advance detector design, the concept detection-control system does not monitor, and attempt to clear, a physical zone in the approach lane. Instead, it uses the speed and length information measured for each vehicle to dynamically define that vehicle's dilemma zone in advance of its arrival to that zone. Figure 5-2 illustrates five dilemma zones for vehicles traveling at the 5<sup>th</sup>, 15<sup>th</sup>, 50<sup>th</sup>, 85<sup>th</sup>, and 95<sup>th</sup> percentile speeds. Limited space within the figure precludes showing additional zones but a unique zone exists for each possible speed with the concept system.

To illustrate the implications of the dynamic dilemma-zone monitoring process, consider the following example. A vehicle traveling at the 5<sup>th</sup> percentile speed is at point A in Figure 5-2; a vehicle traveling at the 95<sup>th</sup> percentile speed is at point B. Neither of these vehicles is in their respective dilemma zone, so the detection-control system could terminate the phase at this instant in time. However, a traditional multiple advance detector system would likely have a clearance zone that extends from the leading edge of the 85<sup>th</sup> percentile speed zone to the trailing edge of the 15<sup>th</sup> percentile speed zone. With this system, both vehicles would be in the clearance zone which would extend the green indication. The implications of this operation are that the detection-control system should: (1) end a phase sooner, (2) operate with less delay, and (3) catch fewer vehicles in the dilemma zone than the traditional system.

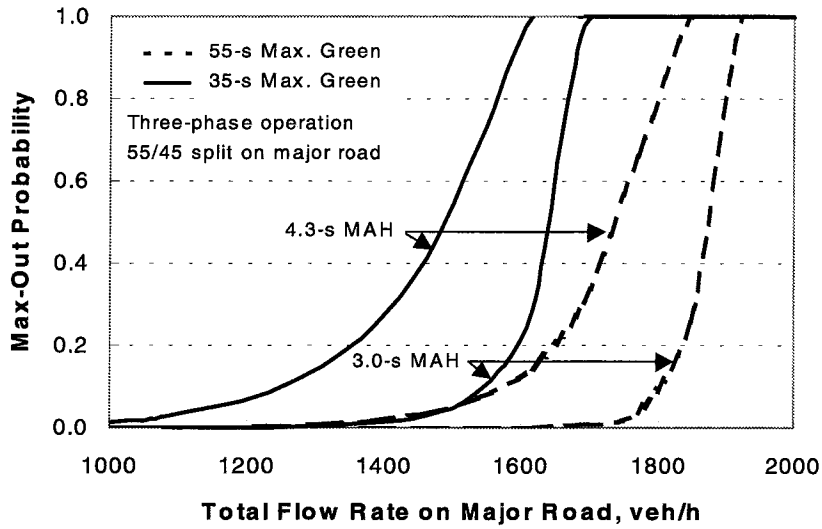
**Probability of Max-Out.** Through the dynamic dilemma-zone monitoring process, the concept detection-control system can be shown to have an effective maximum allowable headway that is equal to the time duration of the dilemma zone. If the dilemma zone is defined to begin and end at 5.5 and 2.5 s travel time, respectively, from the stop line, then the maximum allowable headway for the concept system is effectively 3.0 s.

As noted in the previous section, the concept detection-control system can reduce the number of vehicles caught in the dilemma zone by two methods. The first is by providing coverage for all approach vehicles. The second is by reducing the frequency of max-out. This latter advantage is illustrated in Figure 5-3. The trends provided in this figure were developed using a max-out prediction equation developed by Bonneson and McCoy (5).





**a. Two-Phase Operation.**



**b. Three-Phase Operation.**

**Figure 5-3. Probability of Max-Out.**

The trends in Figure 5-3 illustrate the effect of major-road flow rate, maximum green setting, and number-of-phases for two MAHs. The 4.3-s MAH corresponds to the traditional system and the 3.0-s MAH corresponds to the concept detection-control system. In Figures 5-3a and 5-3b, the

shorter MAH is associated with a much lower likelihood of max-out for the same volume and maximum green setting. The trends confirm that, by increasing the maximum green setting, the frequency of max-out can be reduced; however, this approach can have a significant negative impact on delay. It should be noted that the probability of max-out is negligible for flow rates less than 1000 veh/h, regardless of the MAH.

### Detector Location

This section discusses the issues associated with the location of the concept system's advance detection zone. In this regard, the zone's "location" is defined as the distance between its trailing edge and the stop line (see Figure 5-2). The factors that must be considered when determining this distance include: speed, dilemma-zone boundaries, system processing time, speed measurement precision, look-ahead time, and tolerable error in specification of a vehicle's time-of-arrival to (and departure from) the dilemma zone. Each of these factors is addressed in the following paragraphs.

#### *Minimum Detector Location Distance*

The closest distance between the detector and the stop line is based on the following equation:

$$D_{\min} = L_{tk} + V_{85} (T_{bz} + T_{lag}) \quad (2)$$

where:

- $D_{\min}$  = minimum distance between the trailing edge of the detection zone and the stop line, ft;
- $L_{tk}$  = detected truck length (use 65 ft), ft;
- $V_{85}$  = 85<sup>th</sup> percentile speed on the intersection approach of the subject lane group, as measured during the nonqueued portion of the green, ft/s;
- $T_{bz}$  = time to the beginning of the dilemma zone (use 5.5 s), s; and
- $T_{lag}$  = system processing time (use 0.25 s), s.

The minimum distances for a range of approach speeds are listed in column 2 of Table 5-2. The maximum distances shown are the subject of discussion in the next section.

The minimum distance obtained from Equation 2 will provide the algorithm with sufficient time to identify the presence of about 85 to 90 percent of all vehicles and to record these vehicles' arrival to the dilemma zone. This minimum distance does not allow for any look-ahead time; hence, the system will only be able to determine if any vehicles are in their dilemma zone at the current time. Greater distances would allow for some look-ahead time. This extra time would offer an advantage during high-volume conditions when it is rare that there are no vehicles in the dilemma zone. In this situation, a few seconds of look-ahead time would allow the algorithm to identify the time in the near future where there are the fewest vehicles in the dilemma zone.

**Table 5-2. Minimum and Maximum Detector Location Distances.**

85% Approach Speed, mph	Minimum Distance, ft <sup>1</sup>	Maximum Distance, ft <sup>2</sup>
45	445	1011
50	488	1008
55	530	1107
60	572	1206
65	614	1305
70	657	1405

Notes:

1 - Based on a 65-ft truck length, 5.5 s to the beginning of the dilemma zone, and 0.25-s processor time lag.

2 - Based on an 18-ft passenger-car length, 2.5 s to the end of the dilemma zone, and a 15-s minimum green (17-s minimum green for 45-mph approach speed).

### *Maximum Detector Location Distance*

The furthest distance between the detector and the stop line is based on the following equation:

$$D_{\max} = L_{pc} + V_{15} (G_{\min} + T_{ez}) \quad (3)$$

where:

$D_{\max}$  = maximum distance between the trailing edge of the detection zone and the stop line, ft;

$L_{pc}$  = detected passenger-car length (use 18 ft), ft;

$V_{15}$  = 15<sup>th</sup> percentile speed on the intersection approach of the subject lane group, as measured during the nonqueued portion of the green, ft/s;

$G_{\min}$  = minimum green setting for the subject phase, s; and

$T_{ez}$  = time to the end of the dilemma zone (use 2.5 s), s.

The maximum distances for a range of approach speeds are listed in column 3 of Table 5-2.

The maximum distance is dictated by the desire to locate all vehicles on the approach before the minimum green times out. It is at this point in time where the detection-control system takes control and makes a decision to continue (or end) the subject phase. If the detection zone is located at a distance in excess of that obtained from Equation 3, the detection-control system may not have complete knowledge of all approach vehicles when the minimum green times out.

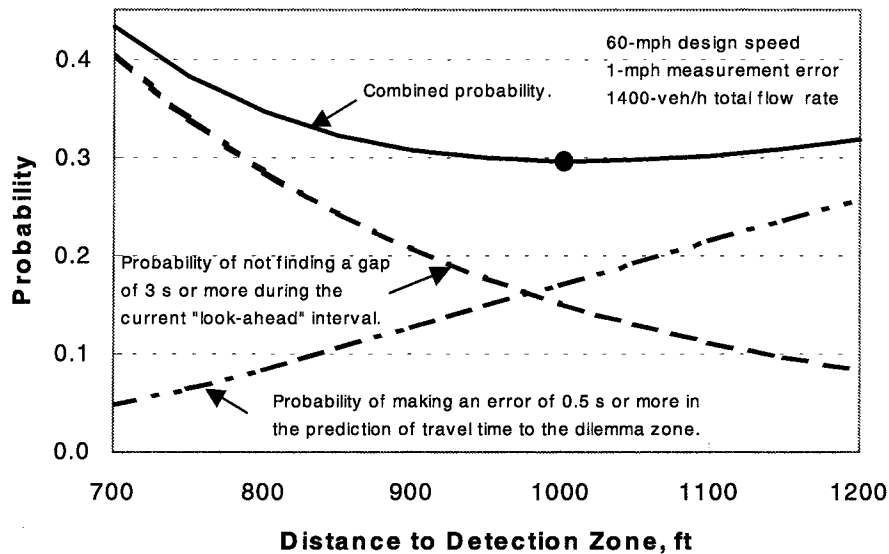
### *Optimum Detector Location Distance*

As discussed in a preceding section, a nominal look-ahead time is needed to provide some dilemma-zone protection during high-volume conditions (i.e., when the total major-road volume exceeds 1000 veh/h). In theory, the concept detection-control system's ability to find the best-time-

to-end-the-phase increases as the look-ahead time increases. In this regard, a longer look-ahead time increases the likelihood of finding an “empty” (or near empty) dilemma zone in the near future.

Lengthy look-ahead times (and corresponding distances) also have some disadvantages. Specifically, they increase the possibility of error in predicting a given vehicle’s time of arrival to (and departure from) the dilemma zone. This error stems from two sources. First, the concept system’s classifier is able to measure speed only to a precision of  $\pm 1.0$  mph. Second, vehicle interactions on the approach can cause some drivers to change speed, relative to that measured at the detection zone. As a result, the error of arrival time and departure time prediction increases with increasing distance to the detection zone.

The effect of distance on the detection-control system’s travel time prediction accuracy is illustrated in Figure 5-4. The downward sloping dashed line shows the probability of *not* finding an “empty” approach (i.e., a 3-s gap) in the current look-ahead interval, as afforded by the corresponding distance. This probability decreases with increasing distance (i.e., it is more likely that an empty approach can be found as the look-ahead interval and distance increases).



**Figure 5-4. Effect of Detection Zone Location on System Accuracy.**

The upward sloping dashed line shows the probability of making an error of 0.5 s or more in the estimate of a vehicle’s time of arrival to (or departure from) the dilemma zone. This trend line is based on a  $\pm 1$ -mph speed measurement error from the classifier and a  $\pm 1.7$ -mph variation in speed on the approach due to vehicle interactions. The upward slope indicates that the probability of a “large” (i.e., 0.5-s or more) error increases with distance.

The solid line indicates the combined probability of making an arrival time prediction error or not finding an empty approach in the current look-ahead interval. This line shows that a minimum point is reached at about 1000 ft. Thus, this distance offers the best compromise between the two problems associated with detection zone location.

Further examination of this process revealed that the optimum distance varies with both speed and volume. In general, the analysis indicates that the distance decreases with decreasing speed or volume. At 45 mph and a total flow rate of 300 veh/h, the optimum distance was found to be 500 ft. At 70 mph and a total flow rate of 1800 veh/h, the optimum distance was found to be 1350 ft. The “combined probability” trend line tends to have very gentle curvature suggesting that deviations of  $\pm 150$  ft from the minimum value are not likely to have a significant effect on system accuracy.

### Algorithm Logic

#### Overview

This section describes the logic used in the detection-control algorithm. This logic is presented in the form of three flow charts. The first flow chart is shown in Figure 5-5. It provides an overview of the algorithm logic. The second and third flow charts provide additional details of the operation of the algorithm’s two main components.

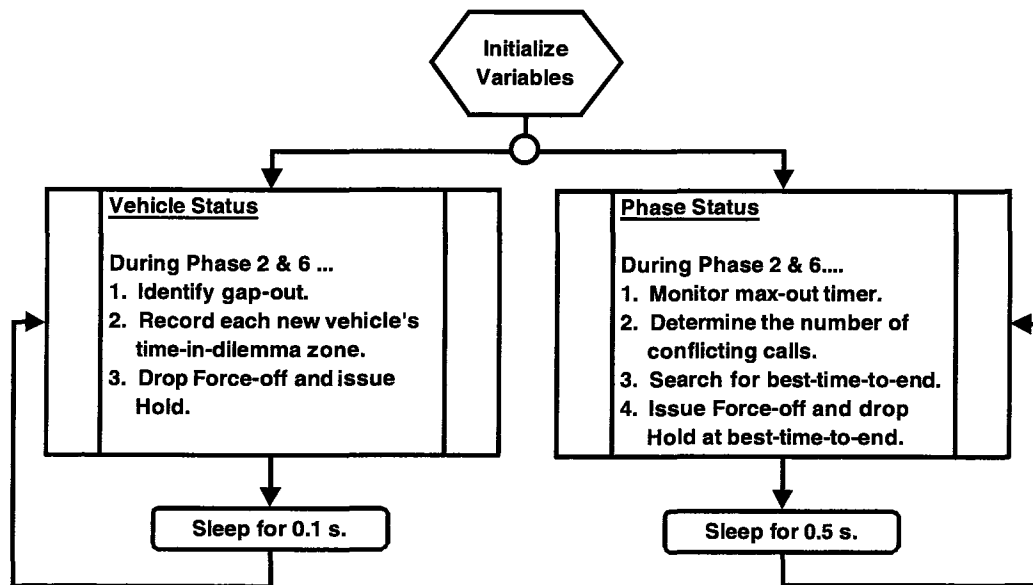


Figure 5-5. Detection-Control System Flow Chart.

As indicated in Figure 5-5, the algorithm consists of two components: a vehicle-status component and a phase-status component. The primary duty of the vehicle-status component is to monitor the output from the classifier and record each vehicle's time of arrival to (and departure from) the dilemma zone at the instant it first becomes available. This component repeats its checks every 0.1 s. The primary duty of the phase-status component is to determine the best time to end the phase and then send the appropriate instructions to the signal controller. This component repeats its duties every 0.5 s. Each component is described in more detail in the next sections.

### *Vehicle-Status Component*

The flow chart of the vehicle-status component of the detection-control algorithm is illustrated in Figure 5-6. This component algorithm sequentially checks the detector output (via the classifier) for each approach lane served during the major-road signal phases (i.e., phases 2 and 6). Action by the algorithm is only taken when the subject phase is in service (i.e., showing a green indication). At the start of each phase, the system variables are reset to zero and a Phase Hold command is issued to the controller. While the phase is green, vehicles measured by the classifier are processed and added to a "dilemma-zone matrix" representing the number and length of vehicles present during each second within the look-ahead time interval.

If a vehicle is determined to have a speed sufficiently high as to cause it to arrive behind a slower vehicle, its speed is adjusted to equal that of the slower vehicle. Its arrival time to (and departure time from) the dilemma zone is then set to lag that of the slower vehicle by 1.5 s. This algorithm is most applicable to single-lane intersection approaches and high-volume multilane approaches. Its use at low-to-moderate volume multilane approaches is generally conservative as it will always assume a car-following mode when, in fact, faster drivers will often pass slower drivers. The function of this component of the algorithm is illustrated in Figure 5-7.

Figure 5-7 shows the time-space trajectory of three vehicles on an intersection approach. Vehicle 1 is a slow vehicle and crosses the detection zone speed trap first. The beginning and end of its dilemma zone are identified by an open circle and square, respectively. Vehicle 2 crosses next but travels at a higher speed. The dilemma zone for this vehicle, based on its measured speed, is also identified by an open circle and square. However, it will reach the back of Vehicle 1 before it reaches the stop line, so it slows to the speed of Vehicle 1. Its dilemma zone is changed to reflect its ultimately slower speed (i.e., the solid circle and square). Similarly, a third vehicle arrives to the back of slowed Vehicle 2 which requires its dilemma-zone boundaries to be adjusted as well (using a solid circle and square).

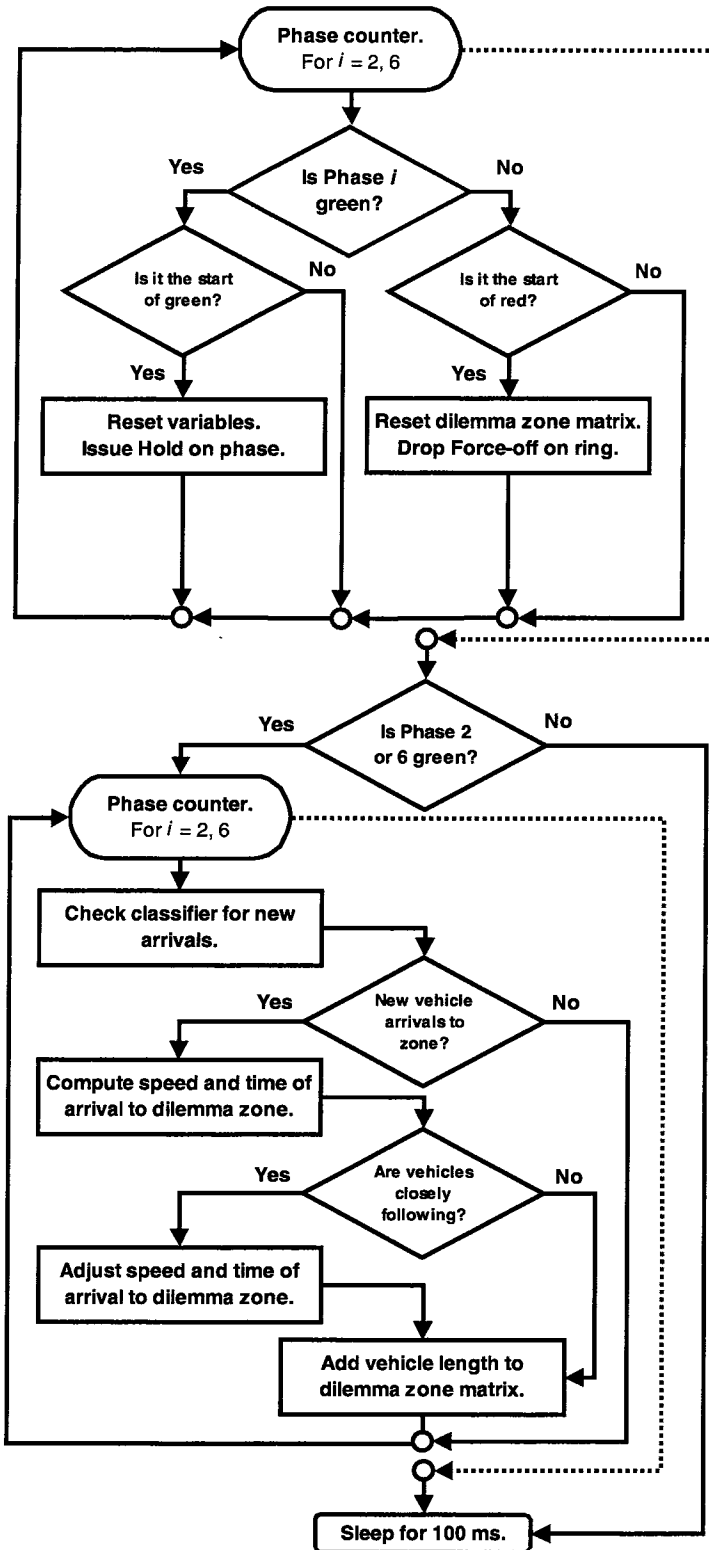
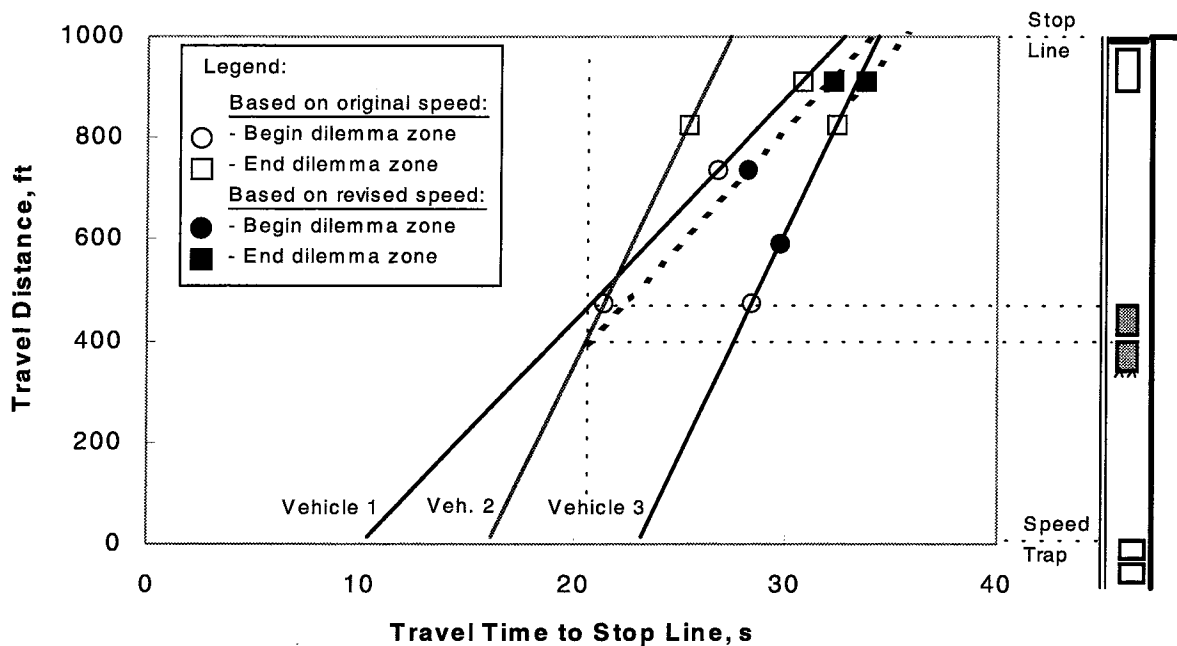


Figure 5-6. Vehicle-Status Component Algorithm Flow Chart.



**Figure 5-7. Illustration of Algorithm Adaptation to Speed Differentials.**

*Phase-Status Component*

The flow chart of the phase-status component of the detection-control algorithm is illustrated in Figure 5-8. This component algorithm sequentially checks the dilemma-zone matrix during the major-road signal phases. Action by the algorithm is only taken when the subject phase is in service (i.e., showing the green indication). While the phase is green, the algorithm monitors a maximum green setting internal to the algorithm (currently set at 70 s). If this maximum is reached, the phase is terminated immediately by dropping all Phase Hold commands and issuing a Ring Force-Off for both rings.

The phase-status component is primarily concerned with monitoring the dilemma-zone matrix and finding the best-time-to-end-the-phase (BTTE) based on the current look-ahead interval. This interval is defined as the travel time between the detection zone and the beginning of the dilemma zone for a vehicle traveling at the 99<sup>th</sup> percentile speed. When the detection zone is located 1000 ft from the stop line and the 99<sup>th</sup> percentile speed is 70 mph, the look-ahead time is about 4.2 s.



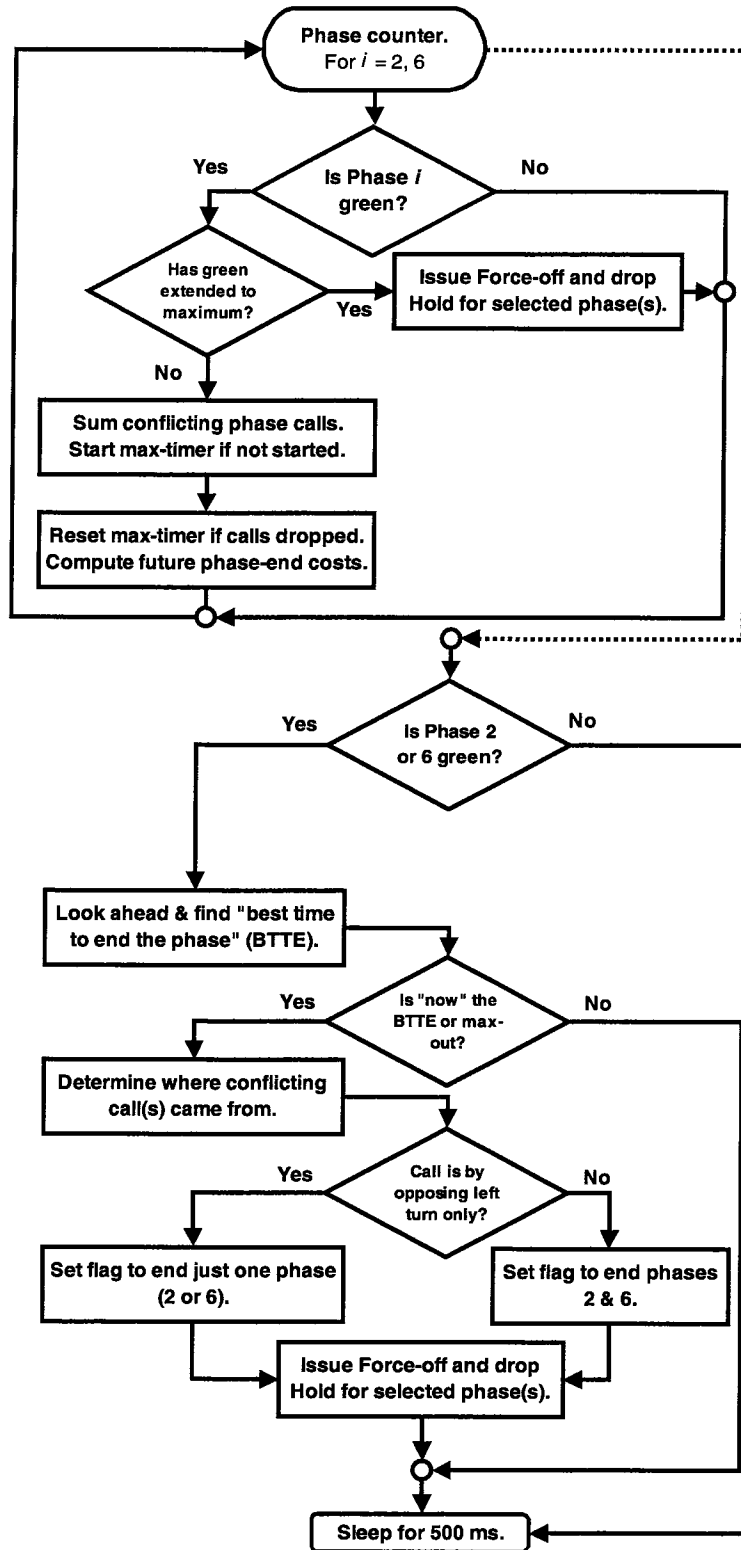


Figure 5-8. Phase-Status Component Algorithm Flow Chart.

Determination of the BTTE is based on two checks. The first check requires that the dilemma zone contain fewer vehicles than a specified maximum value for any current or future time interval. All intervals that have the same (or fewer) number of vehicles than the maximum value are candidates to be the BTTE. The maximum value is established at zero for the initial 70 percent of the maximum green duration. For the last 30 percent of the maximum green duration, the maximum value is relaxed to allow up to one passenger car per lane in the dilemma zone (no trucks). This relaxed maximum value is used to prevent the phase from maxing-out because, at max-out, any number of vehicles can be caught in the dilemma zone.

The second check evaluates the End Green Weight (EGW) for each of the candidate times. The EGW is computed as:

$$EGW_t = \sum_{i=1}^n \left[ \left( \frac{L_{v,t}}{L_{pc}} \right)^{W_{ik}} + t N_c W_d \right] \quad (4)$$

where:

$EGW_t$  = end green weight for time  $t$  ( $0 \leq t \leq T_{la}$ );

$T_{la}$  = look-ahead time interval, s;

$n$  = number of lanes serving the major-road through phase(s);

$L_{v,t}$  = total length of all vehicles in their dilemma zone at time  $t$ , ft;

$L_{pc}$  = detected passenger-car length (typically, 18 ft), ft;

$W_{ik}$  = weight factor to give emphasis to trucks in the dilemma zone (= 1.2);

$N_c$  = number of conflicting phases currently calling for service; and

$W_d$  = weight factor to give small sensitivity to the number of vehicles waiting for service (= 0.1).

The first term of Equation 4 sums, over all lanes, the equivalent number of passenger-car vehicles in the dilemma zone at each point in time. The exponential weighting factor is added to give a sensitivity to longer vehicles (i.e., trucks) that are in the dilemma zone. The second component of Equation 4 is intended to give a preference to ending the phase as soon as possible by adding value to the EGW for each additional second that the system waits to end the phase. In operation, the candidate time interval having the lowest EGW is selected as the BTTE.

If the BTTE is the current time, several checks are made to determine the type of phase termination needed. If the call is only from the opposing major-road left-turn movement, then only one major-road through movement phase needs to be terminated. Otherwise, a Force-Off is issued and the Phase Hold Command is dropped for both phases 2 and 6.

If the BTTE is a future time, then the algorithm waits for 0.5 s and restarts the evaluation process. Eventually, the identified "future time" becomes the current time and, if it is still the BTTE, the appropriate phase (or phases) are terminated.

## ALGORITHM EVALUATION

### Experimental Design

The detection-control algorithm was evaluated using a microscopic, traffic simulation model. The simulation was accomplished using a “hardware-in-the-loop” system that consists of the CORSIM simulation software, an Eagle EPAC 300 TS-2 signal controller, and a Naztec TS-2 controller interface device. This system was used to simulate an isolated signalized intersection with a high-speed, major-road approach and a low-speed, minor-road approach. The advantage of the hardware-in-the-loop system is that it allows the algorithm and controller to interact with each other in real time. The disadvantage of this system is that one second of simulation time is equal to one second of real time. In other words, a hardware-in-the-loop-based simulation is time intensive.

For the simulation experiments, the detection-control algorithm was executed on the same computer as the CORSIM simulation software. As such, vehicle speed and length were available in real-time from the CORSIM software and the vehicle classifier component of the concept system was not used. The trailing edge of the detection zone was located at a point 1000 ft from the stop line. For each traffic movement, a 40-ft stop-line loop detector was used to serve the queue at the start of green. For the major-road through movements, the controller was set to disable this detector after the first gap-out was detected. The algorithm operated with a 70-s maximum green setting.

A traditional multiple advance detection system was also simulated to facilitate the evaluation of the concept detection-control system. The design features of this system are listed in Table 5-1. The stop-line detector was not used in this design. Rather, the major-road through movement phases were set to operate with “recall-to-minimum.” A 35-s maximum green setting was used for the major-road through movement phases. The controller logic contained within the CORSIM software was determined to be capable of simulating the controller operation for the traditional system. As a result, the time required to simulate the traditional system was a fraction of the time required to simulate the concept system using hardware-in-the-loop.

Several elements of the detection and control design were the same for both the concept detection-control system and the multiple advance detector system. Specifically, the through phases were set for dual entry. The major-road approaches have both a left-turn and a through phase; the minor-road approaches have one phase for all movements. The minimum green setting for each of the through phases was set at 15 s; that for the left-turn phases was set at 10 s. The maximum green setting for each of the minor-road through phases was set at 35 s. The maximum green setting for the left-turn phase was set at 25 s. Arrival headways were randomized to reflect isolated operation.

Table 5-3 identifies the factors considered in the simulation experiments. In the first stage of the simulation experiment, the speed, volume, and turn percentage were varied in a full-factorial design. In this design, all 12 factor combinations ( $= 2 \text{ speeds} \times 2 \text{ volumes} \times 3 \text{ turn percentages}$ ) were evaluated during a simulation run. The left- and right-turn volumes were varied by adjusting their percentage of the approach volume. Also, both turn volumes were adjusted together; they were

not considered to be separate factors. The values of directional distribution, approach lanes, truck volume, and maximum green setting used for the Stage I runs are denoted by underline in Table 5-3.

**Table 5-3. Factors Considered in the Simulation Experiments.**

Stage	Factor	Level <sup>1</sup>		
		1	2	3
I	Major-Road Approach Speed (85 <sup>th</sup> percentile), mph	45	60	
	Major-Road Volume (total of both directions), veh/h	800	1400	
	Minor-Road Volume (total of both directions), veh/h	200	400	
	Major-Road Left-Turn Volume, percent	0	10	20
	Major-Road Right-Turn Volume, percent	0	10	20
II	Major-Road Directional Distribution, percent	<u>51</u>	65	
	Major-Road Approach Lanes (1 direction)	<u>1</u>	2	
	Major-Road Truck Volume, percent	<u>10</u>	20	
	Major-Road Maximum Green Setting for all Through Phases, s <sup>2</sup>	<u>35</u>	60	

Notes:

1 - Underlined values were used for the Stage I simulations.

2 - The maximum green setting was varied only for the multiple advance detector design; the detection-control algorithm used a 70-s maximum green setting for all simulations.

In the second stage of the experiment, the directional distribution, number of approach lanes, truck volume, and maximum green setting for the major-road movements were varied in a single-variable factorial design. In this design, a second value for each Stage II factor was examined in isolation of changes to other factors. This one factor was set to the Level 2 value and all 12 Stage I factor combinations were simulated again.

Each simulation run was programmed to simulate 1 hour of operation at the intersection. Each factor combination was simulated using three replications.

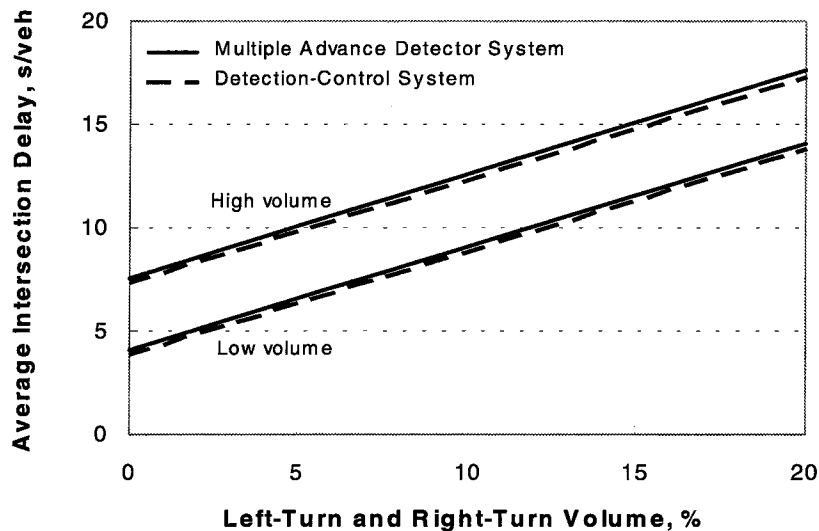
**Measures of Performance**

The effectiveness of the detection-control algorithm was assessed in terms of both operations and safety. Operational effectiveness was assessed using overall intersection delay. The level of safety provided was indirectly assessed by quantifying the number of vehicles in the dilemma zone at the onset of the yellow indication (i.e., dilemma-zone vehicles). It is rationalized that the number of rear-end and right-angle crashes on an intersection approach is directly related to the number of "dilemma-zone vehicles." The probability of max-out was also extracted from the simulation output. This measure offered some insight as to the reason some vehicles were caught in the dilemma zone.

## Evaluation Results

The results of the simulation runs are summarized in Figures 5-9, 5-10, and 5-11. The “low volume” scenario shown in these figures coincides with two-way volumes of 800 veh/h on the major road and 200 veh/h on the minor road. In contrast, the “high volume” scenario coincides with two-way volumes of 1400 veh/h and 400 veh/h for the major and minor road, respectively.

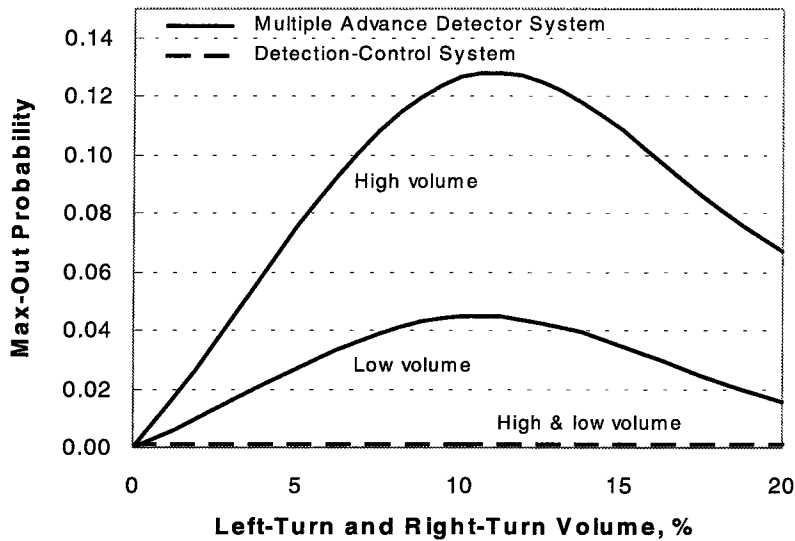
Figure 5-9 illustrates the effect of volume, turn percentage, and detection system on intersection delay. The turn percentages shown correspond to both turn movements (e.g., the “10 percent” level corresponds to 10 percent left turns and 10 percent right turns). The trend lines indicate that delays increase with increasing turn percentage and volume. They also indicate that the concept detection-control system operates with slightly less delay than the multiple advance detector system. Delay is not influenced by directional distribution or truck volume.



**Figure 5-9. Effect of Various Factors on Delay.**

The effect of volume, turn percentage, and detection system on the probability of phase termination by max-out is shown in Figure 5-10. The trends in this figure indicate that the probability of max-out is negligible for the concept detection-control system, regardless of turn percentage or volume. The trend in Figure 5-3b agrees with this trend given that the concept system has a relatively small MAH of 3.0 s. In contrast, this probability varies with turn percentage and volume for the multiple advance detector system. This trend is partly due to the differences in MAH and in maximum green setting used for both systems (i.e., 70 s for the concept system and 35 s for the multiple advance detector system). Examination of Figure 5-3b confirms this influence of

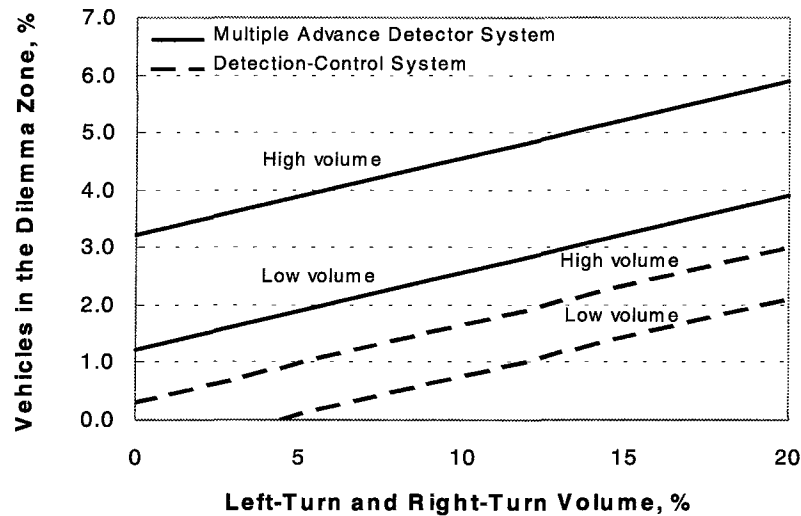
maximum green setting. The Stage II investigation of the maximum green setting for the multiple advance detector system indicated that a 60-s maximum green will eliminate phase max-outs.



**Figure 5-10. Effect of Various Factors on Max-Out Frequency.**

The trends in Figure 5-10 suggest that the probability of max-out increases as the left-turn percentage increases to 10 percent and then decreases to a much smaller value. This trend stems from the frequent occurrence of only one left-turn phase at the 10 percent level. Higher turn percentages tend to have both left-turn phases come on and smaller left-turn percentages rarely have either left-turn phase come on. When one left-turn phase comes on, it is paired in service by the adjacent through-movement phase. This adjacent through phase times its minimum green interval concurrently with that of the left-turn phase. When the left-turn phase ends, the opposing through phase starts and times its minimum green. The combined left-turn and opposing-through minimums total about 30 s which leaves only 5 s before the adjacent through phase reaches its 35-s maximum. Green extension times for nominal flow rates often exceed 5 s and, when they do, the phase maxes out. As noted in the previous paragraph, larger maximum green settings overcome this problem.

The effect of volume, turn percentage, and detection system on the percentage of vehicles caught in the dilemma zone at the onset of the yellow indication is shown in Figure 5-11. The percentage shown in this figure represents the ratio of “through vehicles caught in the dilemma zone” to “all through vehicles.” Turning vehicles are not included in the numerator or the denominator of this ratio. The trend lines in this figure indicate that the percentage of dilemma-zone vehicles increases with increasing turn percentage and volume. Similar trends were found when the major-road speed was 45 mph. The number of vehicles in the dilemma zone is not influenced by directional distribution or the truck volume.



**Figure 5-11. Effect of Various Factors on Percent of Vehicles in the Dilemma Zone.**

In general, the multiple advance detector system catches more vehicles in the dilemma zone than the concept detection-control system. This trend is due primarily to the fact that, by design, the multiple detector system provides dilemma-zone protection for about 70 percent of all vehicles (i.e., it excludes the fastest and slowest 15 percent of vehicles). The data indicate that only about 0.2 percent of the vehicles caught by the multiple detector system are due to phase termination by max-out. The trends in Figure 5-11 apply to an intersection with one lane on each approach. The percentages are reduced by one-half for two-lane major-road approaches.

A comparison of the relative percentages in Figure 5-11 indicates that the concept system reduces the percent of vehicles caught in the dilemma zone by 2 to 3 percent. For an intersection with 1400 veh/h (total for both major-road approaches, each with one lane) and 10 percent turns to the left and right, this translates into a reduction from 41 to 14 veh/h caught in the dilemma zone. For a two-lane approach, it translates into a reduction from 23 to 8 veh/h in the dilemma zone.

The reason for the increase in dilemma-zone vehicles with increasing turn percentage is tied to the slowing speeds associated with turning vehicles. Turning vehicles that slow to turn often cause following through vehicles to slow and get caught in the dilemma zone. For the multiple advance detector system, slowing vehicles are less able to hold a call for green as they travel from one advance detector to another. They often get caught between detectors or caught after clearing the last advance detector. For the concept detection-control system, the problem stems from the system's inability to track vehicles along the approach. Once a vehicle leaves the upstream detection zone, it is assumed that it will sustain the measured speed until it clears the intersection. If this vehicle is slowed by a turning vehicle, it is possible that it will still be in the dilemma zone when the concept system ends the phase.





## **CHAPTER 6. SUMMARY OF FINDINGS**

### **OVERVIEW**

Traffic engineers are often faced with operational and safety problems at rural, high-speed signalized intersections. Vehicle-actuated control with multiple advance detectors is often used to minimize these problems. However, rear-end crashes continue to occur in significant numbers at these intersections and delays to traffic movements are often unnecessarily long.

The traditional, multiple advance detector system is designed to hold the green until a suitably large gap occurs in the traffic stream being served. Through this action, the detection-control system ends the phase safely because the approach is empty. However, this gap occurs infrequently on high-volume approaches and often causes the corresponding signal phase to extend to its maximum limit (i.e., max-out). When the phase maxes out, it ends without regard to the number of vehicles on the approach and increases the potential for a rear-end crash. If the maximum green setting is large, then the resulting delays may also be large.

Other problems exist with the traditional, multiple advance detector system. They include: (1) the system operation is not sensitive to the type of vehicle in the dilemma zone (i.e., car or truck), (2) the system operation is not sensitive to the amount of delay experienced by motorists desiring service via a conflicting phase, and (3) the system is often costly in terms of the number of advance detectors needed along the major-road approaches.

The objective of this research project is to develop and test an economical detection-control system that is capable of minimizing both delay and crash frequency at rural intersections. This chapter documents the findings from the first year of research and the partial fulfillment of the research objective.

### **REVIEW OF EXISTING DETECTION-CONTROL SYSTEMS**

Several types of detection-control systems have been used at rural signalized intersections. These systems include: (1) basic green-extension systems (the most common configuration is based on multiple advance detectors in each approach lane), (2) enhanced green-extension systems (e.g., the TTI Truck Priority System and the LHOVRA System), and (3) green-termination systems (e.g., the SOS system).

All detection-control systems have the potential to reduce both crash frequency and overall intersection delay at rural intersections. However, the safety benefits appear to be more significant than the delay benefits. The enhanced green-extension systems and the green-termination systems have the potential to achieve these reductions in a more cost-effective manner, relative to basic green-extension systems. The enhanced green-extension and green-termination systems are relatively new and evolving in their structure. As a result, the magnitude of their delay and crash

frequency reduction potential is not well known. Table 6-1 summarizes the characteristics of the detection-control systems discussed in this report.

**Table 6-1. Comparison of Alternative Detection-Control Systems.**

Operating Characteristic		Detection-Control System			
		Multiple Advance Detector	Truck Priority	LHOVRA	SOS
FUNCTION					
Dilemma (or clearance) zone protection.	For passenger cars.	✓	✓	✓	✓
	For trucks.	--	✓	--	--
Delay reduction capability.	For major movements.	✓	✓	✓	✓
	For minor movements. <sup>1</sup>	--	--	--	✓
CONTROL LOGIC					
Goal: End green when...	...clearance zone empty.	✓	✓	✓	--
	...least delay+crash cost.	--	--	--	✓
Meaning of maximum green.	Absolute end of green.	✓	--	--	--
	Can be exceeded.	--	✓	✓	✓
Ability to end green on opposing approaches at separate times.		--	--	✓	✓
External computer.		--	✓	--	✓
DETECTOR LOGIC					
Typical number of detectors (for 55-mph design).	One-lane approach.	4	6	3	4
	Two-lane approach.	4	8	3	8
Separate detectors for each lane.		--	✓ <sup>2</sup>	--	✓

Notes:

✓ = yes, "--" = no.

1 - Assumes that only the major-road through movements are provided advance detection.

2 - Only for the first upstream detection zone.

The multiple advance detector system is the most commonly used system at rural intersections. In uses two to four detectors located upstream of the intersection on each major-road approach (more detectors are used for higher speeds). In operation, it monitors a segment of the approach (i.e., the dilemma zone). It holds the green for the major-road through phase whenever there are one or more vehicles in its approach dilemma zone. In operation, the controller searches for the first time that both approaches are empty because the through phases are required to end simultaneously.

The TTI Truck Priority system was designed to reduce the number of trucks stopping on high-speed intersection approaches. It represents an enhanced multiple advance detector system because it provides the same functionality as that system plus it adds an additional upstream detector trap that identifies the speed and length of trucks. A computer monitoring these detectors places a Hold on the corresponding signal phase whenever a truck is detected during green. This Hold command is sustained until all trucks are clear of the intersection approach. In its current, concept system configuration, the TTI-Truck Priority system requires an external computer to process the control algorithm and a detection system that can measure vehicle speed and length.

The LHOVRA system was developed in Sweden and is currently operational at 800 intersections in that country. It operates like the multiple advance detector system by extending the green to vehicles in the approach dilemma zone. However, LHOVRA also provides an optional sensitivity to trucks like that provided by the TTI Truck Priority system and it has the ability to end the green for each major-road through phase at different times, if necessary.

Unlike the other systems, the SOS system determines the best time to explicitly *end* the phase. The objective of this system is to determine the optimal time to end the major-road through phases (separately, if necessary) based on consideration of delay to conflicting movements and crash potential for the major-road through movements. The SOS system requires an external computer to process the control algorithm and separate detectors in each approach lane.

## **ALGORITHM DESCRIPTION AND EVALUATION**

### **System Description**

The objective of the concept detection-control system is to effectively and efficiently control high-speed signalized intersections. This objective is achieved by accomplishing the following goals (relative to the traditional multiple advance detector system):

- reduce the frequency of vehicles caught in the dilemma zone at the onset of yellow;
- reduce the cost of design, installation, and maintenance of advance detection;
- provide a sensitivity to the presence of trucks in the dilemma zone with the potential to eliminate the possibility of catching a truck in the dilemma zone; and
- maintain or reduce overall delays.

The concept detection-control system consists of one detection zone per lane (probably consisting of two inductive loops) located several seconds travel time in advance of the dilemma zone. The location of this detection is based on a desire to have the algorithm “look” into the future of vehicle arrivals to the dilemma zone. The detection-control system searches for a time when each vehicle served by the subject phase is outside of its respective dilemma zone. It uses a dynamic dilemma-zone monitoring process that enables it to safely end the phase and to do so with a relatively short maximum allowable headway. The implications of this operation are that the

concept system will operate with less delay (through shorter phase durations) and with fewer vehicles caught in the dilemma zone than the traditional, multiple advance detector system.

### **Detector Location**

The location of the detection zone used with the concept detection-control system was evaluated in terms of its effect on system accuracy. This evaluation considered the travel time prediction error and the ability of the system to identify an “empty” approach within a given look-ahead time. Based on this analysis, a distance of 1000 ft was found to be appropriate for use with the concept system. This distance should work well for speeds between 45 and 70 mph and for a full range of traffic volumes. The use of one distance for all speeds and volumes is attractive from the standpoint of “one size fits all” and from the standpoint of providing a robust system that can adapt to permanent changes in speed during the system’s design life.

### **Algorithm Logic**

The detection-control algorithm consists of two components: a vehicle-status component and a phase-status component. Both component algorithms operate only when the major-road through phase is green. The primary duty of the vehicle-status component is to monitor vehicle speed and length at the upstream detection zone and record each vehicle’s time of arrival to (and departure from) the dilemma zone at the instant it first becomes available. The vehicle-status component has the ability to determine when a vehicle arrives behind a low-speed vehicle. When this event occurs, the algorithm adjusts the faster vehicle’s time of arrival and departure to the dilemma zone. This component repeats its checks every 0.1 s.

The primary duty of the phase-status component is to determine the best time to end the phase and then send the appropriate instructions to the signal controller. The phase-status component periodically checks for vehicles in the dilemma zone and for the presence of waiting vehicles in conflicting-phase movements. It computes a “cost” associated with ending the phase during the current time interval and for several time intervals in the future. The phase is ended when the lowest cost interval is the current time interval. This component repeats its duties every 0.5 s.

### **Algorithm Evaluation**

Simulation experiments were conducted to evaluate the concept detection-control system performance, relative to the multiple advance detector system. The results of this evaluation indicate that the concept system is able to provide equal or lower delays for a reasonable range of speeds, volumes, and turn percentages. The results also indicate that the concept system will significantly reduce the number of vehicles caught in the dilemma zone at the onset of the yellow indication.

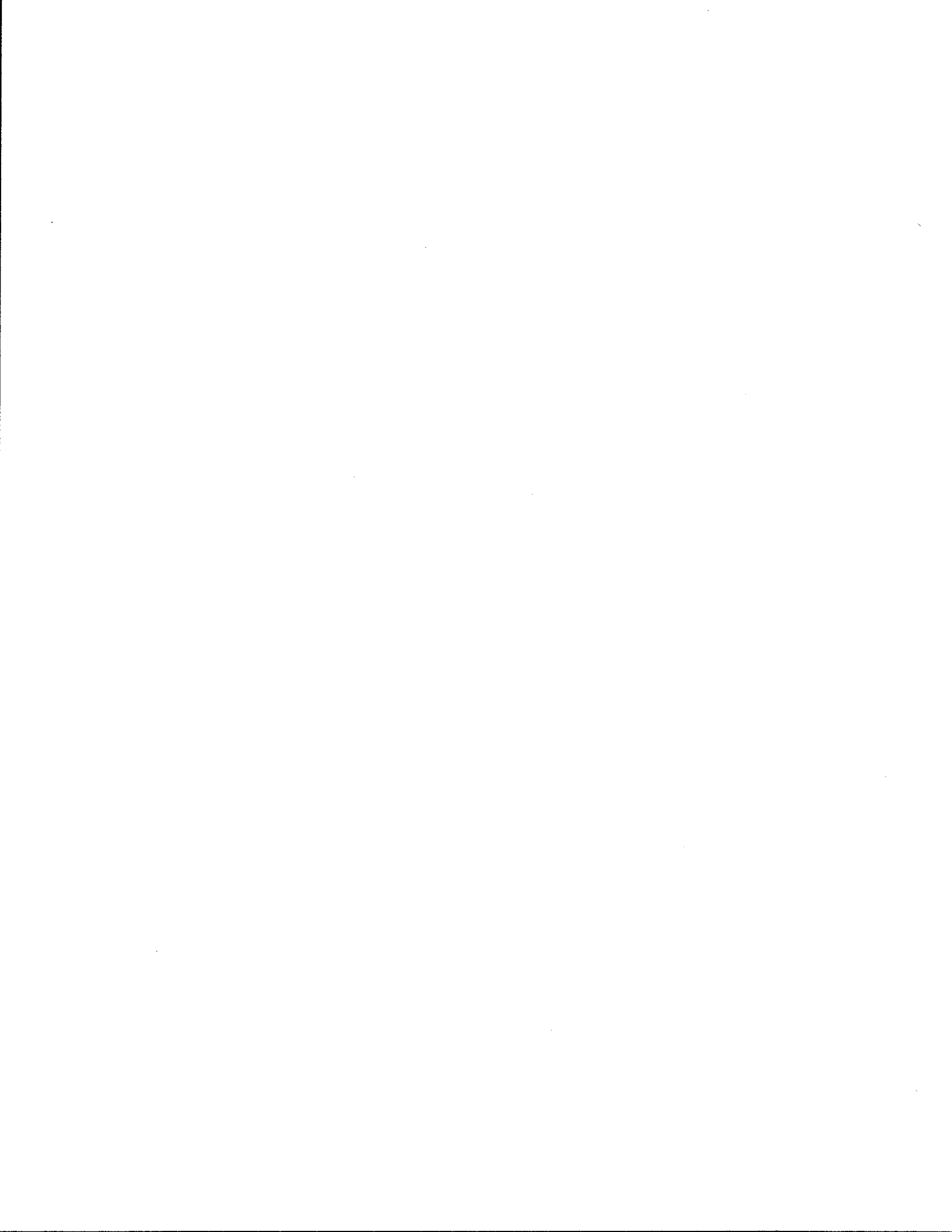
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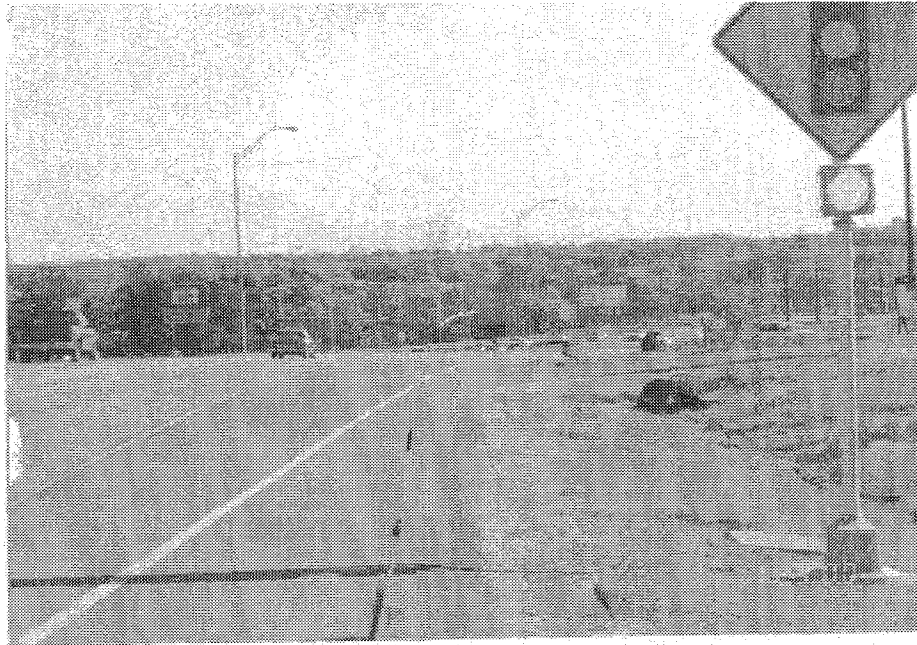
**APPENDIX**

**STUDY SITE PHOTO LOG**

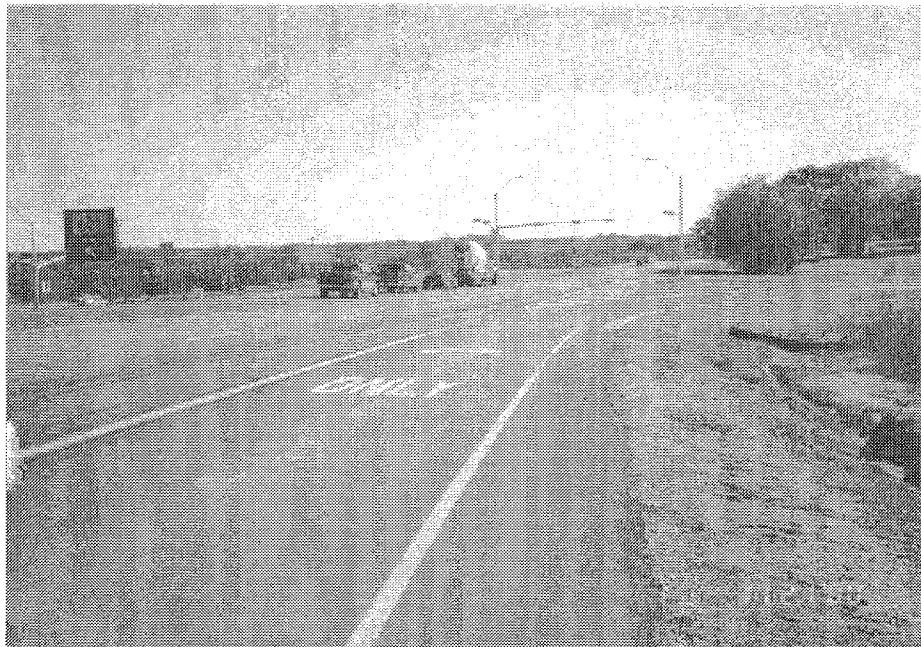




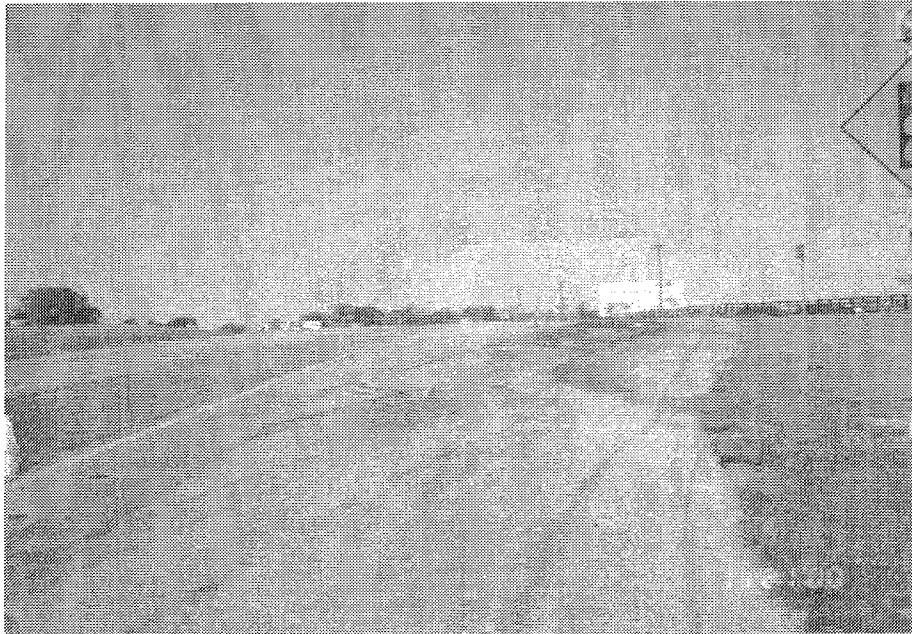
**U.S. 290 AT F.M. 577 IN BRENHAM**



**Figure A-1. U.S. 290 Eastbound at F.M. 577, 1000 ft from the Stop Line.**



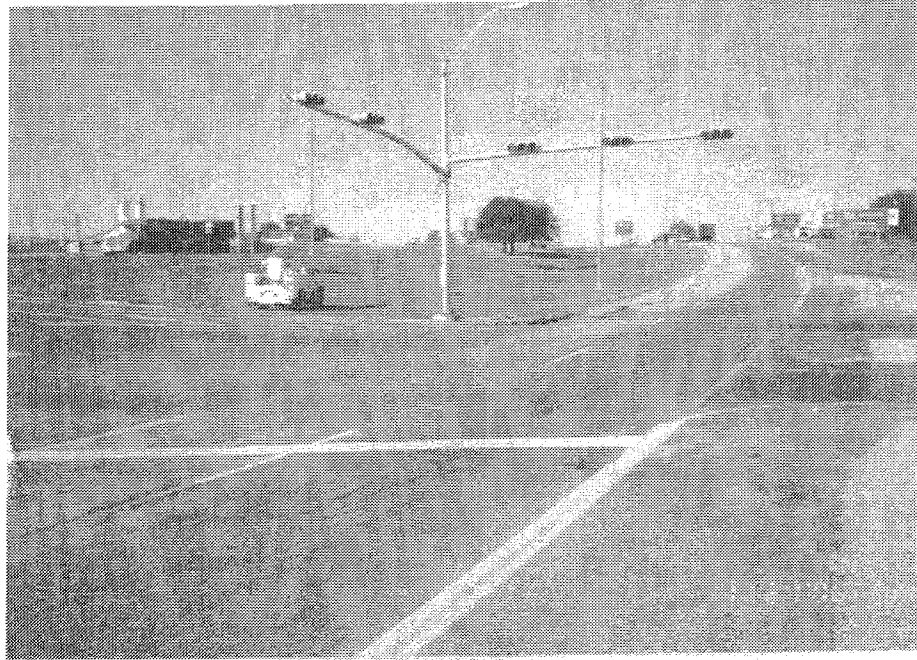
**Figure A-2. U.S. 290 Eastbound at F.M. 577, near the Stop Line.**



**Figure A-3. U.S. 290 Westbound at F.M. 577, 1000 ft from the Stop Line.**

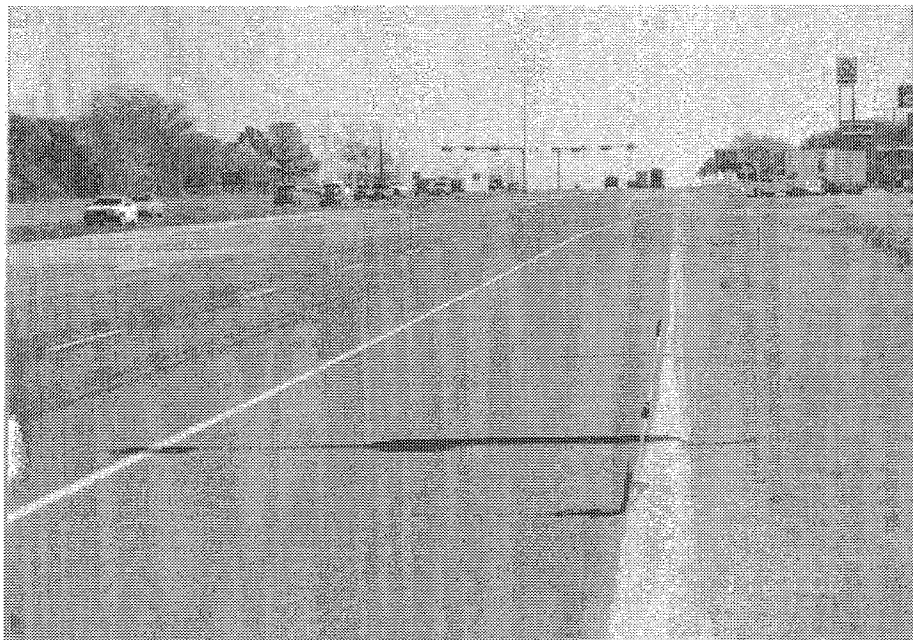


**Figure A-4. U.S. 290 Westbound at F.M. 577, 500 ft from the Stop Line.**

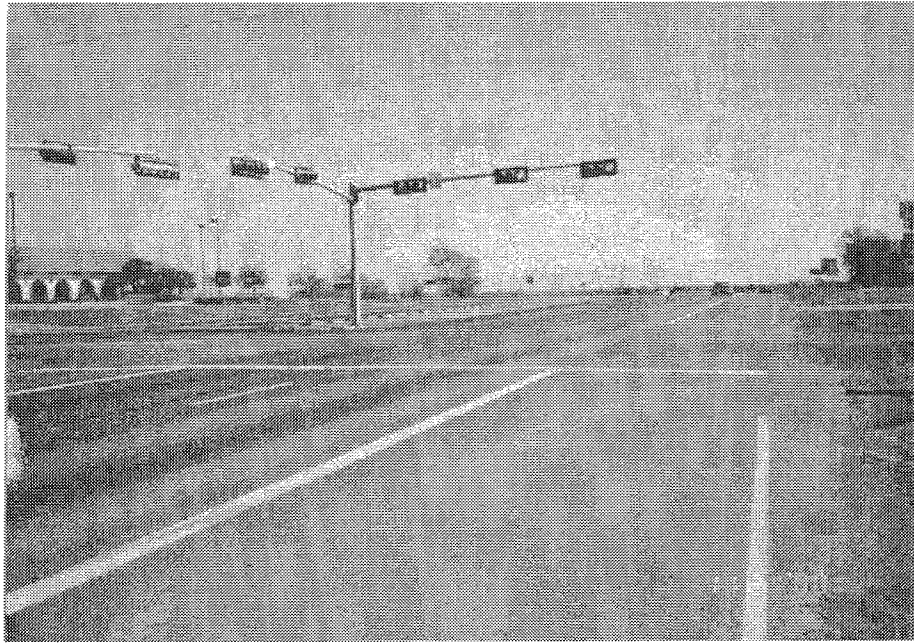


**Figure A-5. U.S. 290 Westbound at F.M. 577, near the Stop Line.**

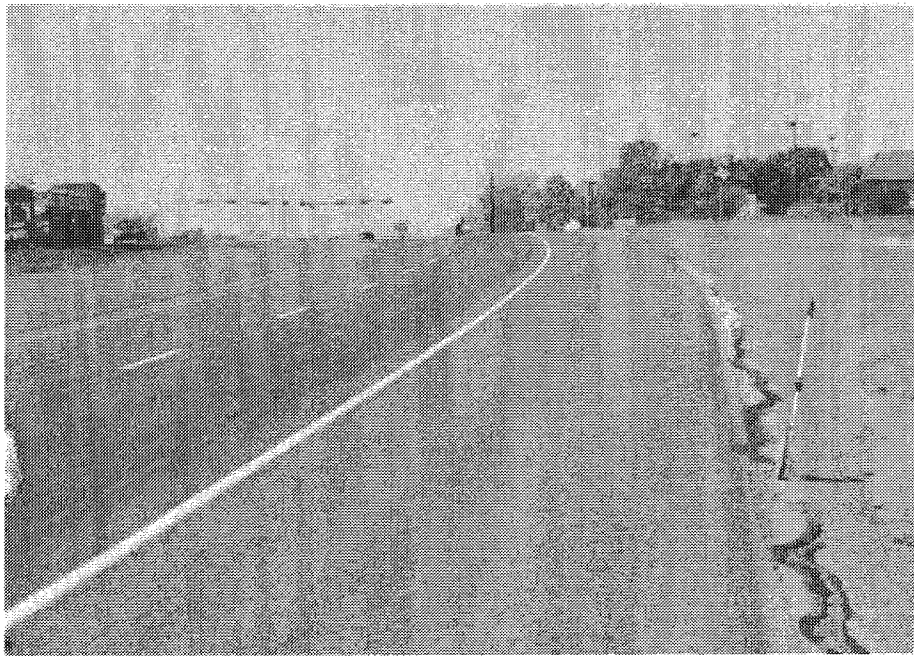
**U.S. 290 AT F.M. 1155 IN CHAPPELL HILL**



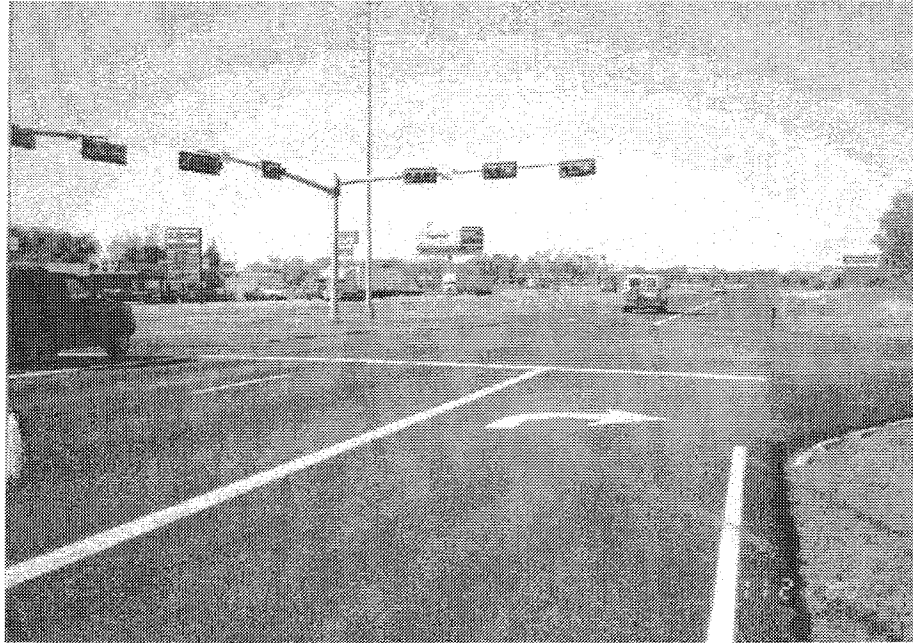
**Figure A-6. U.S. 290 Eastbound at F.M. 1155, 1000 ft from the Stop Line.**



**Figure A-7. U.S. 290 Eastbound at F.M. 1155, near the Stop Line.**

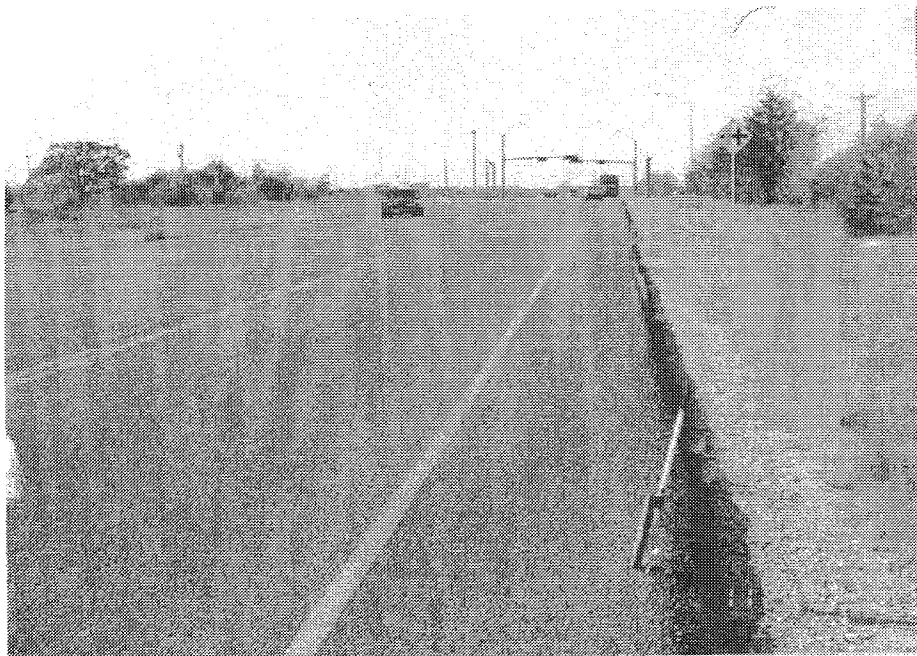


**Figure A-8. U.S. 290 Westbound at F.M. 1155, 1000 ft from the Stop Line.**



**Figure A-9. U.S. 290 Westbound at F.M. 1155, near the Stop Line.**

**F.M. 2154 AND ROCK PRAIRIE ROAD IN COLLEGE STATION**



**Figure A-10. F.M. 2154 Northbound at Rock Prairie Road, 1000 ft from the Stop Line.**



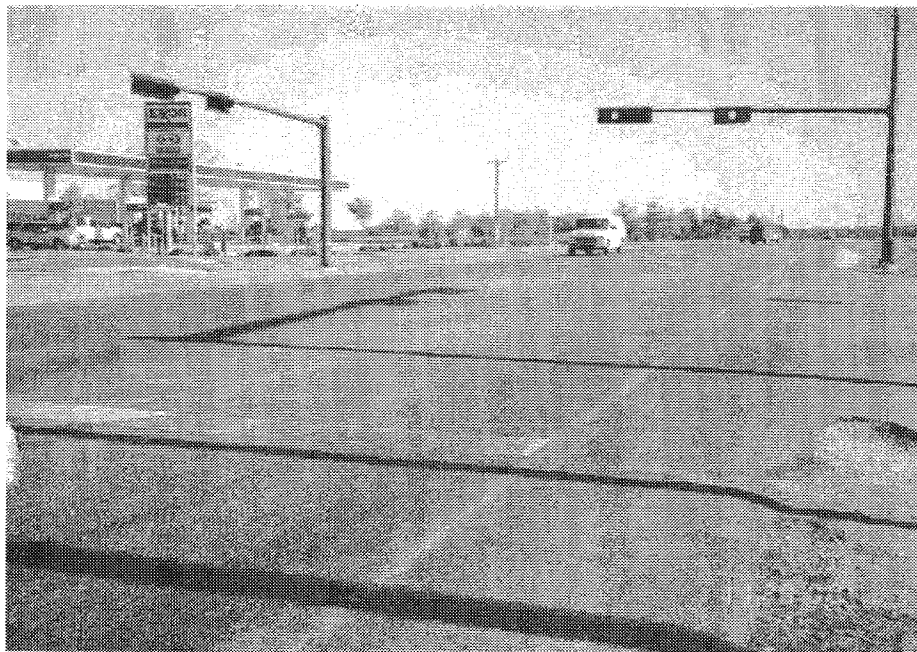
**Figure A-11. F.M. 2154 Northbound at Rock Prairie Road, near the Stop Line.**



**Figure A-12. F.M. 2154 Southbound at Rock Prairie Road, 1000 ft from the Stop Line.**



**Figure A-13. F.M. 2154 Southbound at Rock Prairie Road, 500 ft from the Stop Line.**

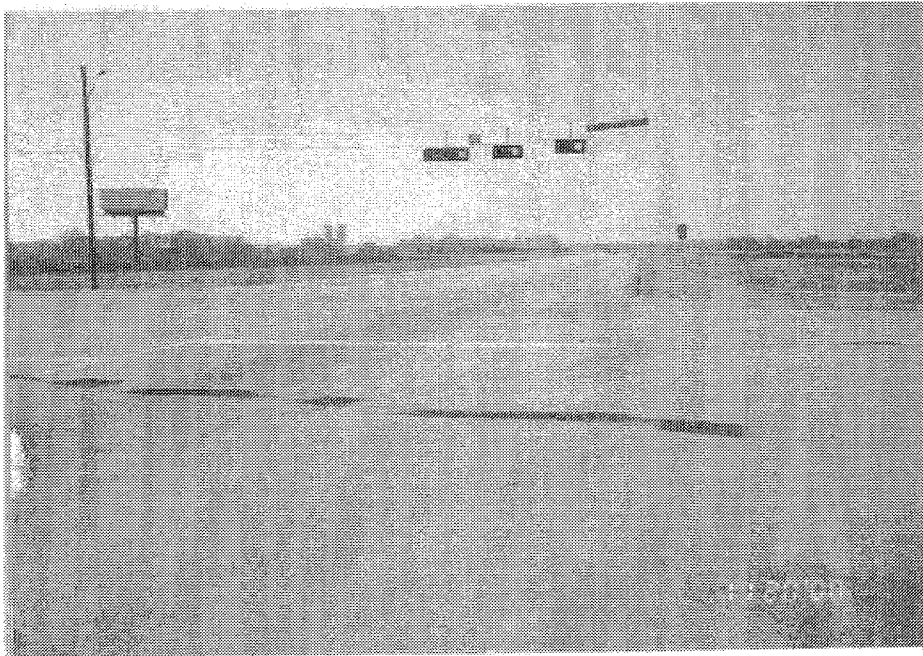


**Figure A-14. F.M. 2154 Southbound at Rock Prairie Road, near the Stop Line.**

**S.H. 6/LOOP 340 AND F.M. 3400 NEAR WACO**



**Figure A-15. Loop 340 Southbound at F.M. 3400, 1000 ft from the Stop Line.**

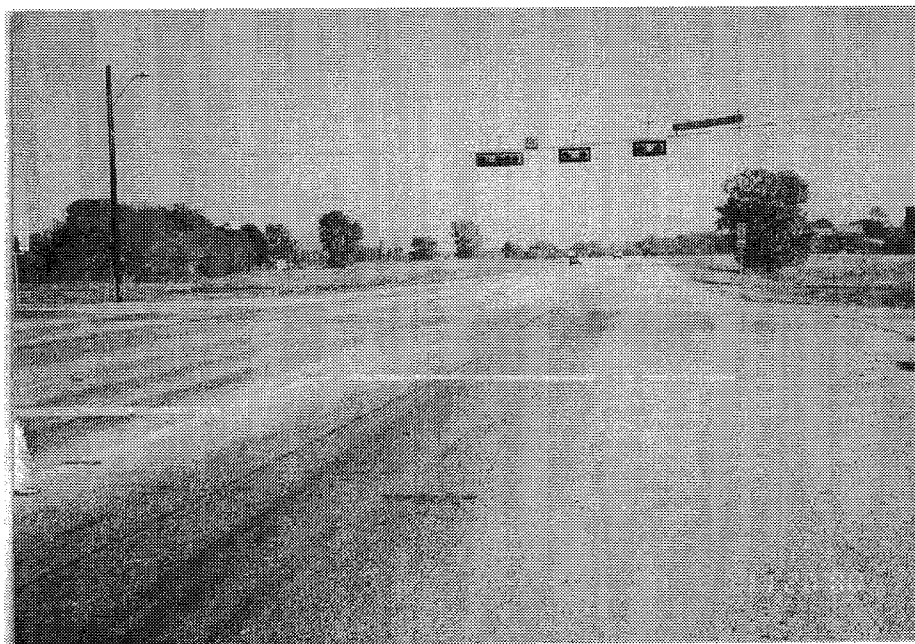


**Figure A-16. Loop 340 Southbound at F.M. 3400, near the Stop Line.**





**Figure A-17. Loop 340 Northbound at F.M. 3400, 1000 ft from the Stop Line.**

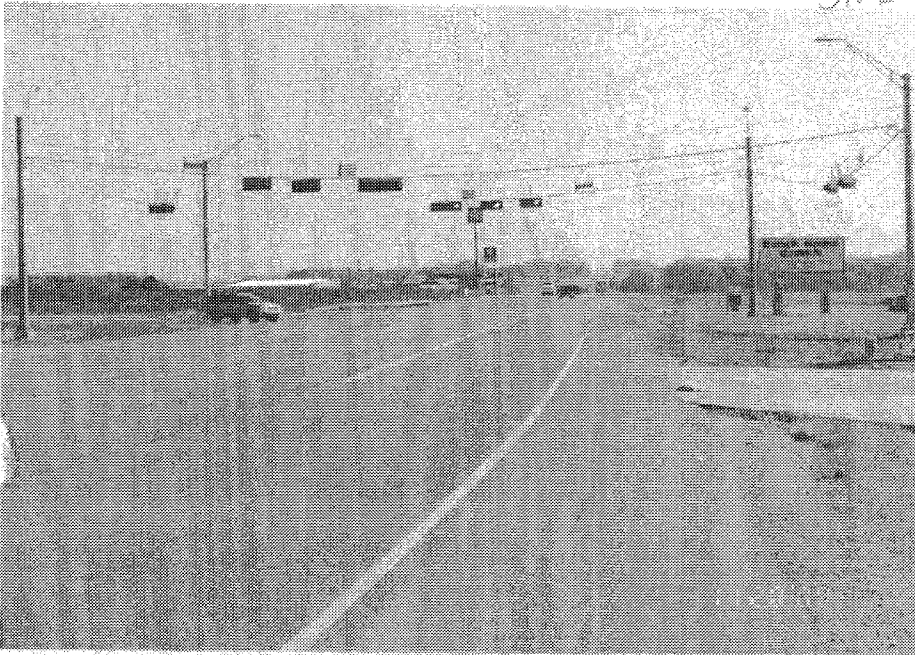


**Figure A-18. Loop 340 Northbound at F.M. 3400, near the Stop Line.**

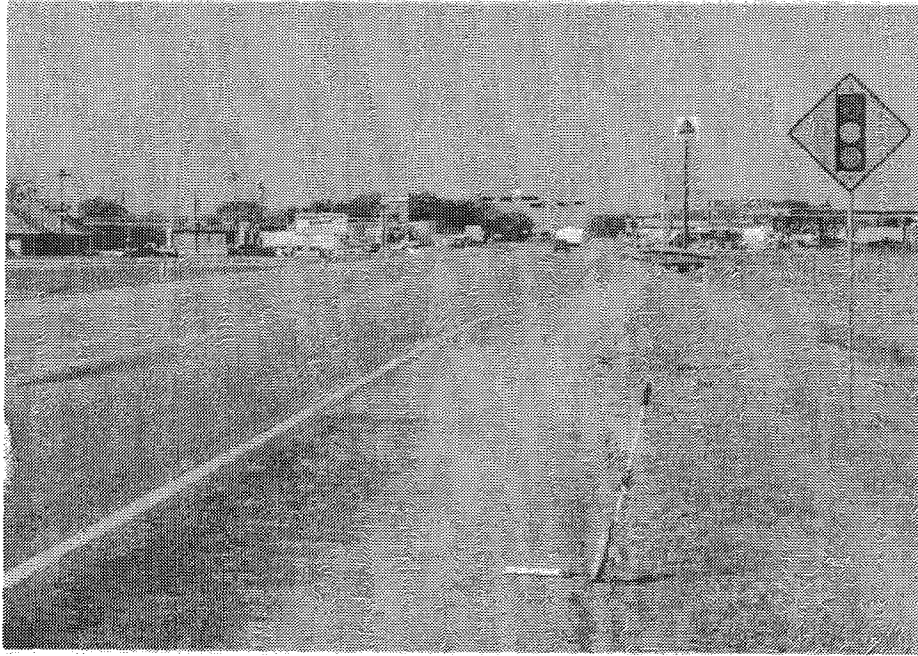
**S.H. 6 AND F.M. 185 NEAR WACO**



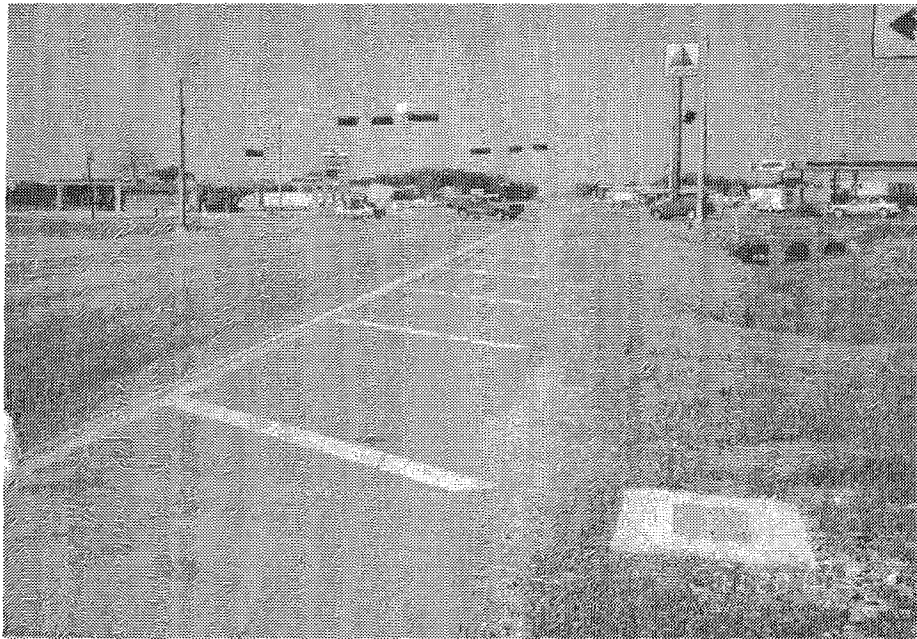
**Figure A-19. S.H. 6 Eastbound at F.M. 185, 1000 ft from the Stop Line.**



**Figure A-20. S.H. 6 Eastbound at F.M. 185, near the Stop Line.**



**Figure A-21. S.H. 6 Westbound at F.M. 185, 1000 ft from the Stop Line.**



**Figure A-22. S.H. 6 Westbound at F.M. 185, near the Stop Line.**