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16. Abstract

Traffic engineers are often faced with operational and safety challenges at rural, high-speed signalized intersections. Vehicle-actuated control, combined with multiple advance detectors, is often used to improve operations and safety. However, this type of detection and control has not always eliminated rear-end or right-angle crashes. Crashes sometimes continue to occur at high-speed intersections, and delays to traffic movements can be unnecessarily long. This project developed and tested a detection-control system that is capable of minimizing both delay and crash frequency at rural intersections.

This report documents the work performed, findings, and conclusions reached as a result of the two-year research project. During the first year, an intelligent 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. During the second year, the system was installed at two intersections and evaluated using field data. The results of this evaluation indicated that the system is able to provide equal or lower delays for a reasonable range of speeds, flow rates, and turn percentages. The results also indicate that the system will reduce the number of drivers running the red indication.

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INTELLIGENT DETECTION-CONTROL SYSTEM FOR RURAL SIGNALIZED INTERSECTIONS

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NOTICE

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

Table **Page**

CHAPTER 1. INTRODUCTION

OVERVIEW

Traffic engineers are often faced with operational and safety challenges at rural, high-speed signalized intersections. Vehicle-actuated control, combined with multiple advance detectors, is often used to improve operations and safety. However, this type of detection and control has not always eliminated rear-end or right-angle crashes. Crashes sometimes continue to occur at high-speed intersections, and delays to traffic movements can be unnecessarily long.

The multiple advance detector system holds the green until a suitably large gap occurs in the traffic stream being served. Through this action, the detection 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 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 a system that provides both detection and intelligent control for isolated rural intersections. Initially, there is a review of the various types of vehicle detection systems currently in use throughout the world. Then, a new detection-control system is described. Next, a plan for deploying and evaluating the system is described. The system is then evaluated and shown to improve intersection safety. Finally, the findings of the research are summarized, and some conclusions are offered.

RESEARCH OBJECTIVE

The objective of this research project was to develop and test an intelligent detection-control system that is capable of minimizing both delay and crash frequency at rural intersections. This objective was 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 terminate the signal phase.

- Develop a software algorithm that can determine the optimal time to terminate the phase based on consideration of crash potential and delay to all traffic movements.

- 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 research and the means by which the aforementioned goals were fulfilled.

RESEARCH SCOPE

The detection-control system described in this report is developed for use at rural signalized intersections. In this regard, it is applicable to isolated, 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 control the major-road through movement phases. It is sensitive to vehicle type to the extent that it is designed to avoid terminating the major-road phase if it 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.

RESEARCH APPROACH

The research approach consisted of a series of tasks that included the development and evaluation of an efficient and economical detection-control system. During the first year of the research, a concept detection-control system was developed. This system was programmed to search for the best time to end the major-road phase. This time was defined to be that with the fewest number of vehicles on both major-road approaches and with the fewest number of vehicles waiting for service. During the second year of research, the concept detection-control system was tested and evaluated at two rural intersections in Texas.

Products of this research include a design guideline and a specification document. The former product describes the design procedures and controls for designing and operating the recommended detection-control system. The latter product describes the parameters, features, and performance specifications for the recommended system. Both products are included as an appendix to this report.

CHAPTER 2. LITERATURE REVIEW

OVERVIEW

This chapter provides a review of the literature as it relates to vehicle detection systems for signalized rural intersections. This review describes the safety and operational problems associated with rural intersections and the various vehicle detection systems used to solve these problems.

Several different vehicle detection systems 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 phase termination. They accomplish this objective by not allowing the phase 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 phase termination are minimized.

Vehicle detection systems can be categorized by the components they use to determine the need for and extent of phase (or "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 time to explicitly *end* the phase. This decision is based on an assessment of safety to the major-road through movements and the delay to 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 phase 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 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.

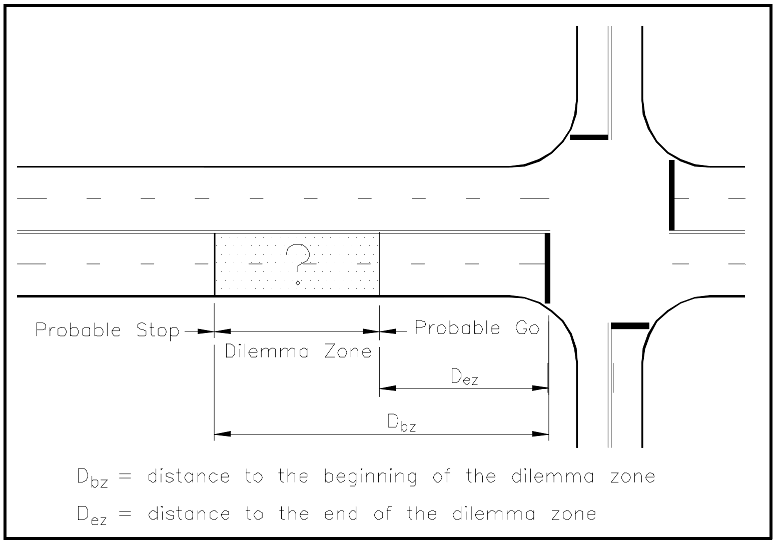


Figure 2-1. Dilemma-Zone Boundaries on a Typical Intersection Approach.

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) at which 90 percent of all drivers would stop if presented a yellow indication. They defined the end of the zone as the distance at 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 5.0 s travel time upstream of the intersection. They also suggest that the end of the dilemma zone is 2.0 to 3.0 s travel time upstream of the intersection. More recent measurements by

Bonneson et al. (*3*) indicate that the beginning is 5.0 to 6.0 s upstream and the end is about 3.0 s upstream.

Most recently, Middleton et al. (*4*) estimated the dilemma-zone boundaries for both passenger cars and trucks. Their study sites had 85th 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.

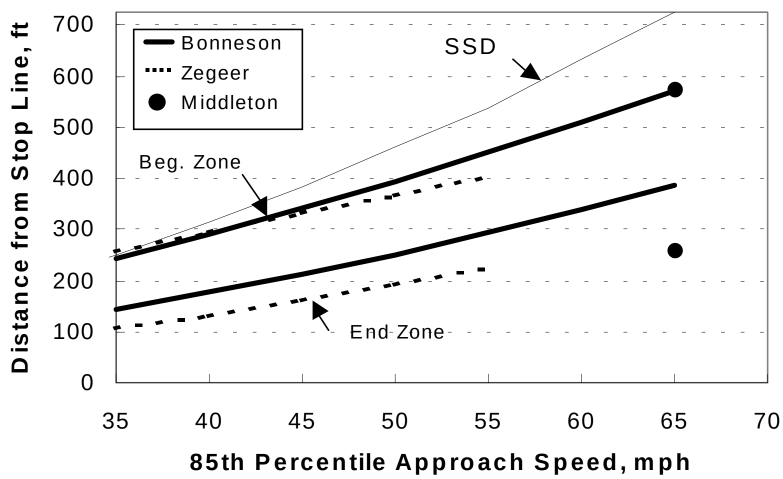


Figure 2-2. Dilemma-Zone Boundaries Reported in the Literature.

Based on this review, it is concluded that the dilemma zone boundaries are most precisely defined using travel time (as opposed to distance) from the stop line. The beginning and end of the zone is practically defined by the 90th and 10th percentile drivers, respectively. The travel time to the beginning and end of the dilemma zone varies slightly among studies (perhaps due to rural vs. urban conditions) but tends to be about 5.5 s and 2.5 s, respectively.

VEHICLE DETECTION SYSTEMS

The systems described in this section share a common objective of minimizing the potential for crashes that result from phase termination. This objective is accomplished by using detectors to monitor vehicle presence in the dilemma zone and then extending the phase until the dilemma zone is clear or until a maximum green is reached. Some of the systems described in this section have additional objectives that are intended to provide other safety or operational benefits. However, the discussion in this section will focus on the methods used to provide dilemma-zone protection.

Basic Green-Extension Systems

Evaluations of basic green-extension systems have been documented since the mid-1970s. These systems have been consistently found to offer safety benefits. They are generally used at rural intersections with relatively high speeds and full-actuated signal operation. 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 multiple advance detector system typically employs two or three detectors per lane in advance of the intersection. 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 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.

The detector at each upstream location is used to monitor vehicle presence in the "clearance zone." The length of the clearance zone is dependent on the design speed range; it tends to be slightly longer than the dilemma zone. The design speed range is typically defined by the 85th and 15th percentile speeds. The clearance zone starts at the leading edge of the first advance detector. It ends at a point beyond the last advance detector that is equal to the distance traveled during the passage time at the 15th percentile speed.

Figure 2-3 shows a typical multiple advance detector design for an 85th percentile approach speed of 55 mph. The design specifications for other design speeds are listed in Table 2-1 (*4*). Additional detail on the design and operation of these systems is provided by Bonneson and McCoy (*5*). The values in columns 6 and 7 of Table 2-1 are discussed in Chapter 3 of this report.

The stop-line detector shown in Figure 2-3 is not included in some variations of this detection design. If it is not included, 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 a stop-line detector is provided, the controller operation for this phase may 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.

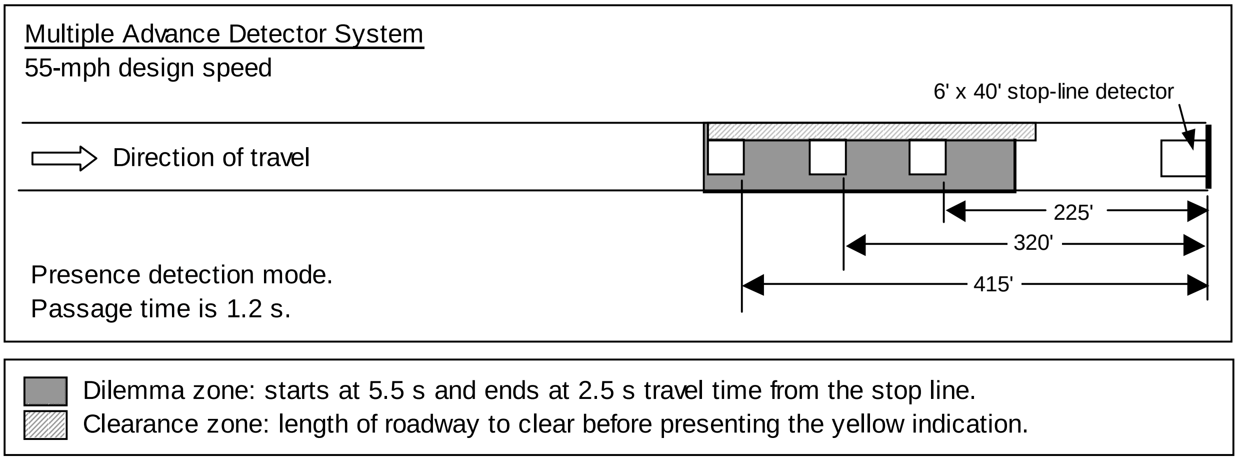


Figure 2-3. Multiple Advance Detector System.

Table 2-1. Multiple Advance Detector Design Specifications.

85% Approach Speed, mph	Distance to 1st Loop, ft	Distance to 2nd Loop, ft	Distance to 3rd Loop, ft	Passage Time, s	Max. Allowable Headway, s[1]	
					Inactive Stop-Line Det.[2]	Active Stop-Line Det.[3]
45	330	210		2.0	4.5	7.6
50	350	220		2.0	4.4	7.4
55	415	320	225	1.2	4.2	6.3
60	475	375	275	1.4	4.3	6.5
65	540	430	320	1.2	4.1	6.1
70	600	475	350	1.2	4.2	6.1

Notes:
1 - 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 85th percentile approach speed.
2 - "Inactive stop-line detector" indicates that either (1) a 6' × 40' detector that is set in the controller to be inactive (after the first gap-out is detected) during the green interval or (2) no detector is provided.
3 - "Active stop-line detector" indicates a 6' x 40' detector that submits calls throughout the green interval.

The multiple advance detector system seeks to find a time during the phase when no vehicle, traveling at a speed *in the design speed range*, is in its dilemma zone. This zone is almost always clear of vehicles when the phase terminates, provided that it terminates by gap-out. Two points can be made from these characterizations. First, this system does not guarantee that the slowest and fastest vehicles are clear of their respective dilemma zones (in fact, if the 85th and 15th percentile speeds are used to design the system, up to 30 percent of the traffic stream may not be guaranteed 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 flow rates, 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.

Safety Benefits

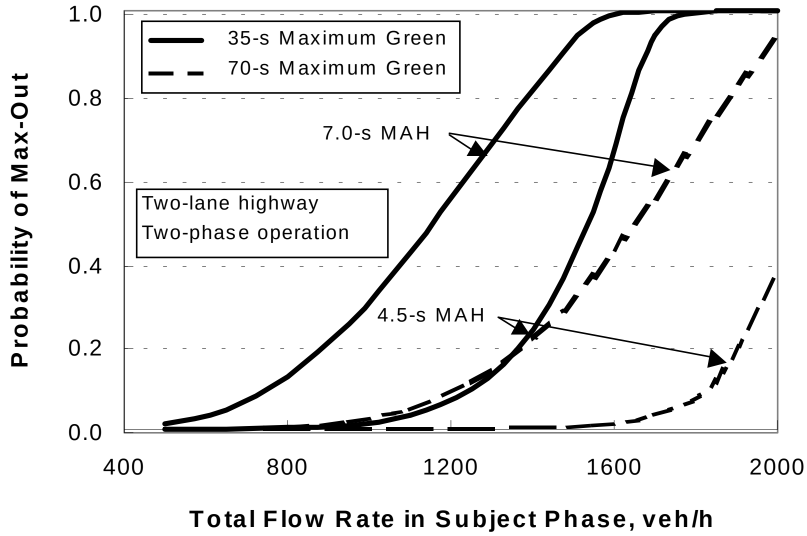
The safety benefits of basic green-extension systems have been reported by Zegeer and Deen (*1*) and, more recently, by Wu et al. (*6*). Zegeer and Deen found crash frequency was reduced by 54 percent due to the use of a green-extension system, based on about four years' crash data (three years before 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 was 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.

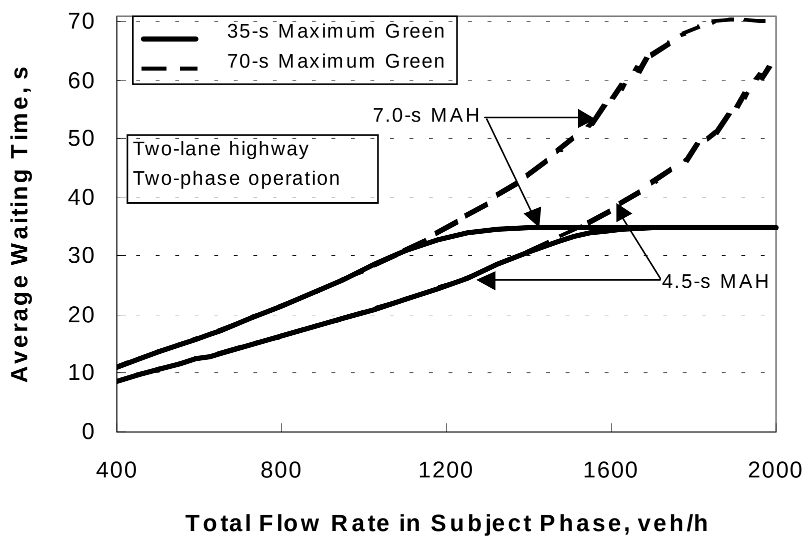
The safety benefit of green extension can be negated if the phase is extended to its maximum duration (i.e., maximum-green setting). The probability of termination by "max-out" is dependent on flow rate in the subject phase and the "maximum allowable headway," as dictated by the detector design. The 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.

Bonneson and McCoy (*7*) suggest that the MAH values shown in Figure 2-4 (i.e., 4.5 and 7.0 s) represent the range of values for most detection designs. More generally, designs with advance detectors *and* stop-line detectors tend to have a MAH of 6.5 to 7.5 s. Designs with only stop-line detectors or those with only advance detectors tend to have a MAH of 4.0 to 5.0 s. In general, designs with smaller MAH values are more efficient in terms of fewer max-outs and less delay.

To illustrate the implications of alternative MAH values, consider an intersection with a major-road phase flow rate of 1200 veh/h, a maximum-green duration of 35 s, and an efficient detection design yielding a MAH of only 4.5 s. Figure 2-4a indicates that the probability of max-out for this phase will be about 0.09 (one out of 11 cycles). However, if the MAH is 7.0 s, the resulting max-out probability will increase to 0.6 (six 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 as suggested by the trends in Figure 2-4b.



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.

Operational Benefits

The operational benefits of a green-extension system vary among the intersection's approaches and the corresponding signal phases. Delays incurred during the major-road through phase (i.e., the phase served by the green-extension system) are likely to decrease because of the additional green time provided by the system. In contrast, delay to vehicles waiting on conflicting phases tends to increase. To illustrate this latter point, consider Figure 2-4b which illustrates the magnitude of the waiting time for the first arriving driver served by a conflicting phase. Relative to a detection design with a MAH of 4.5 s, a design with a MAH of 7.0 s is shown to increase waiting time by 2 s at low flow rates and by as much as 15 s at high flow rates. The increase in delay associated with an increase in MAH has also been reported by Tarnoff and Parsonson (*8*).

The study by Wu et al. (*6*) indicates that *overall* intersection delay does not increase significantly when multiple advance detectors are used. This finding implies that any delay increase to the minor movements is offset by a delay reduction to the major movement.

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 phase past its maximum-green setting. This feature helps alleviate the problem of phase max-out when 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 computer 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 85th percentile approach speed of 55 mph.

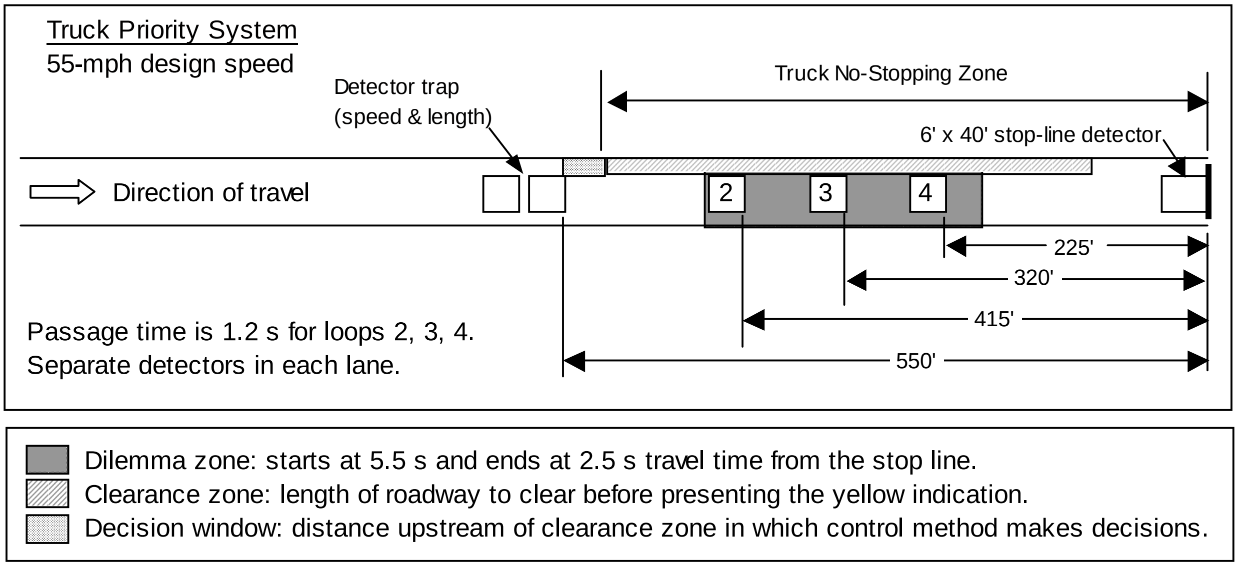


Figure 2-5. Truck Priority System.

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 computer. The classifier is used to identify trucks (i.e., vehicles longer than 30 ft) on the intersection approach. When a truck is identified, the computer queries the signal controller to determine if the signal is green. If the signal is green, the computer 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 4.0 s travel time from the stop line, and at 7.0 s 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 4.0, 7.0, 10, and 15 s. A LHOVRA design is shown in Figure 2-6 for a design speed of 55 mph.

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.

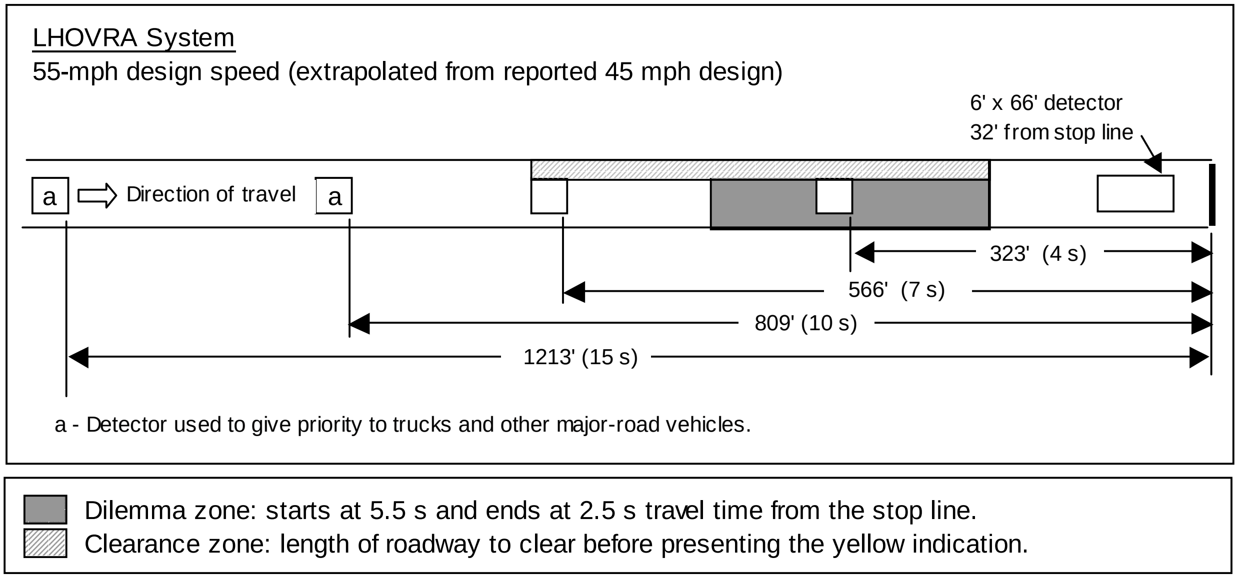


Figure 2-6. LHOVRA System.

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. 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 phase 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 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 computer 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 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.

The SOS system assigns a cost for terminating the 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 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.

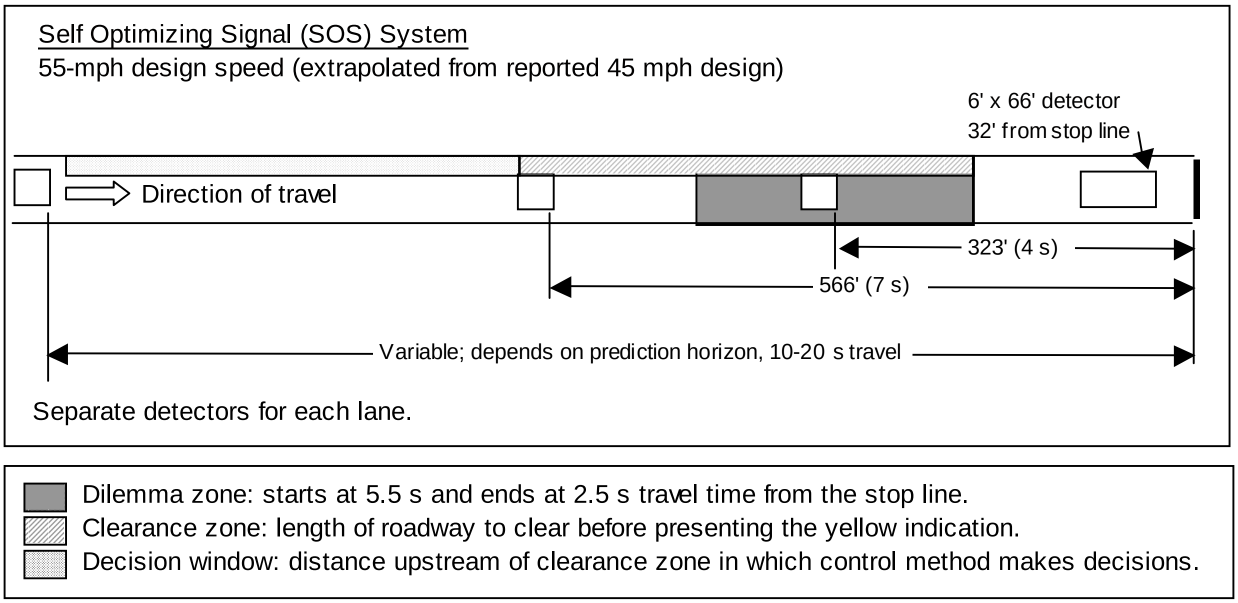


Figure 2-7. SOS System.

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."

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 phase 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.

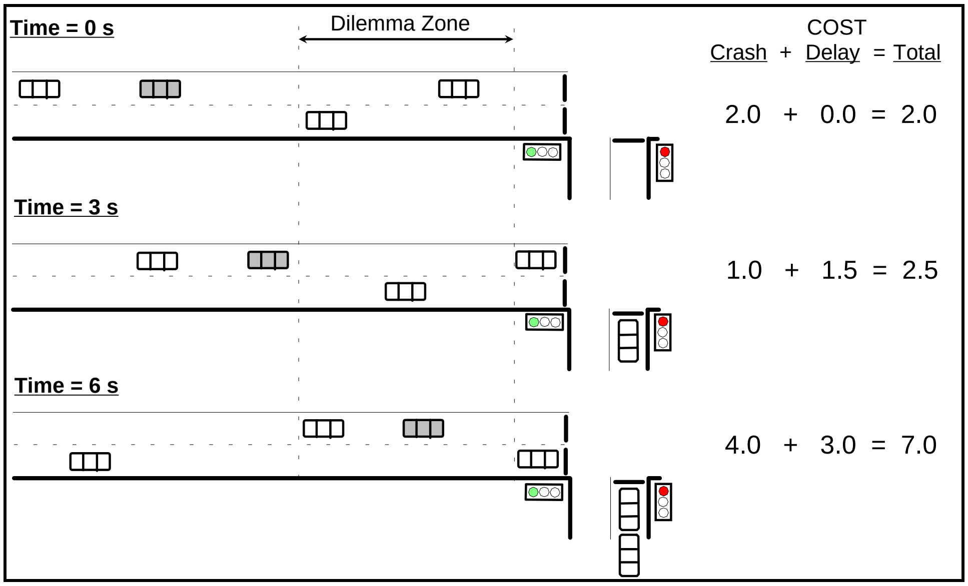


Figure 2-8. Cost Strategy Used by the SOS System.

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. DETECTION-CONTROL SYSTEM

OVERVIEW

A new system for vehicle detection and control at rural signalized intersections is described in this chapter. The new 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 processor utilizes the speed information to predict the arrival of the vehicle in the dilemma zone. It uses the length information to provide a sensitivity to trucks.

The system is designed 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. It uses two detectors per lane (in a speed trap configuration) located 700 to 1000 ft upstream of the intersection on each of its major-road approaches. Figure 3-1 shows a side-by-side comparison of the flow of information for the existing multiple advance detector system and the new detection-control system.

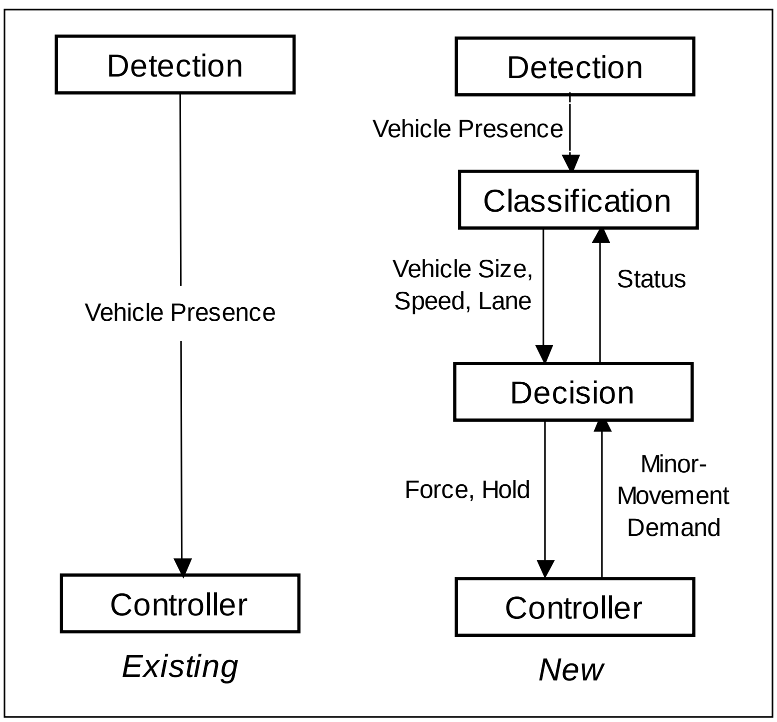


Figure 3-1. Comparison of the Existing System and the New System.

Figure 3-2 is a flowchart showing the new detection-control system and its relationship to the detection and the traffic control systems. The "concept" version of the new 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. It is anticipated that the various components of the new system would be consolidated into the signal controller or into a separate micro-controller for full implementation.

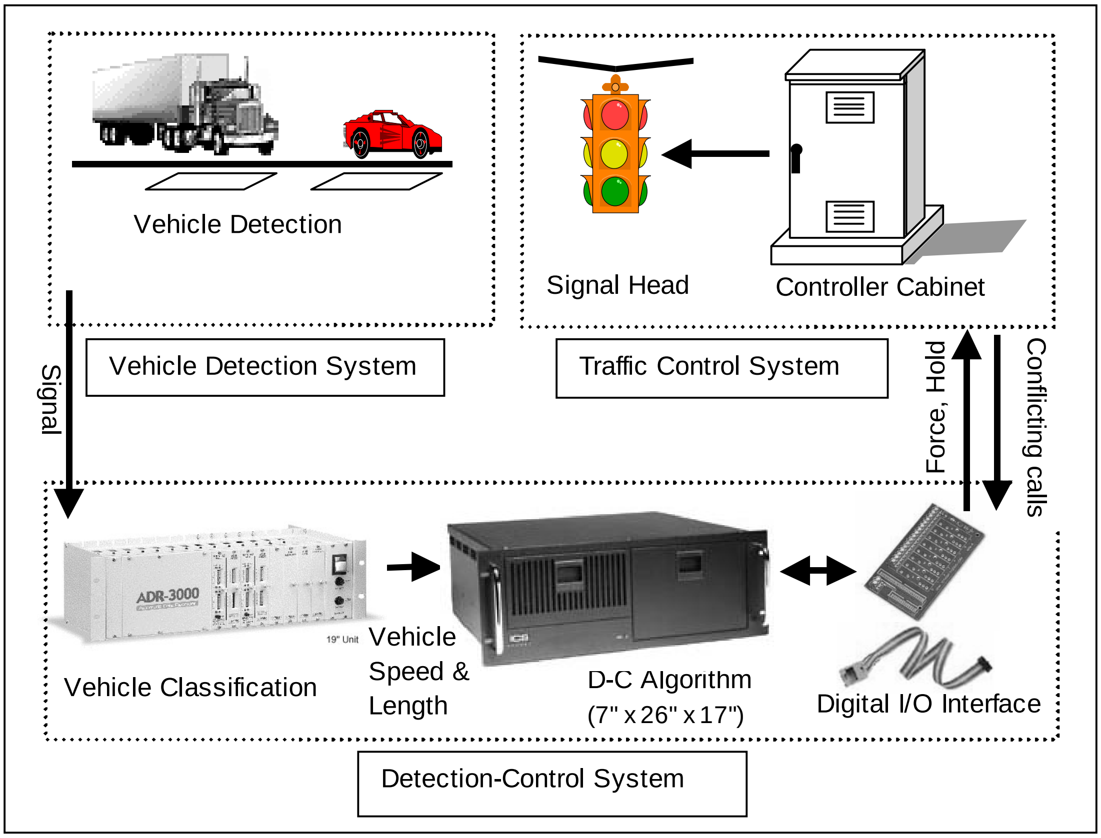


Figure 3-2. Concept System Components.

The new detection-control system communicates continuously 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. The vehicle detection system provides information about vehicle length, speed, and lane location from the upstream major-road detectors. The traffic control system provides information about the presence of vehicles waiting at the stop line of each of the conflicting movements.

SYSTEM OBJECTIVE AND DESCRIPTION

System Objective

The objective of the detection-control system is to effectively and efficiently detect and control the major-road approaches to an isolated signalized intersection. 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 multiple advance detector system serves as a baseline for assessing the relative performance of the detection-control system.

System Description

The detection-control system consists of one detection zone located several seconds in advance of the dilemma zone. The detection zone should be configured to support measurements of vehicle speed and length (e.g., a two-loop speed trap). The distant 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 3-3.

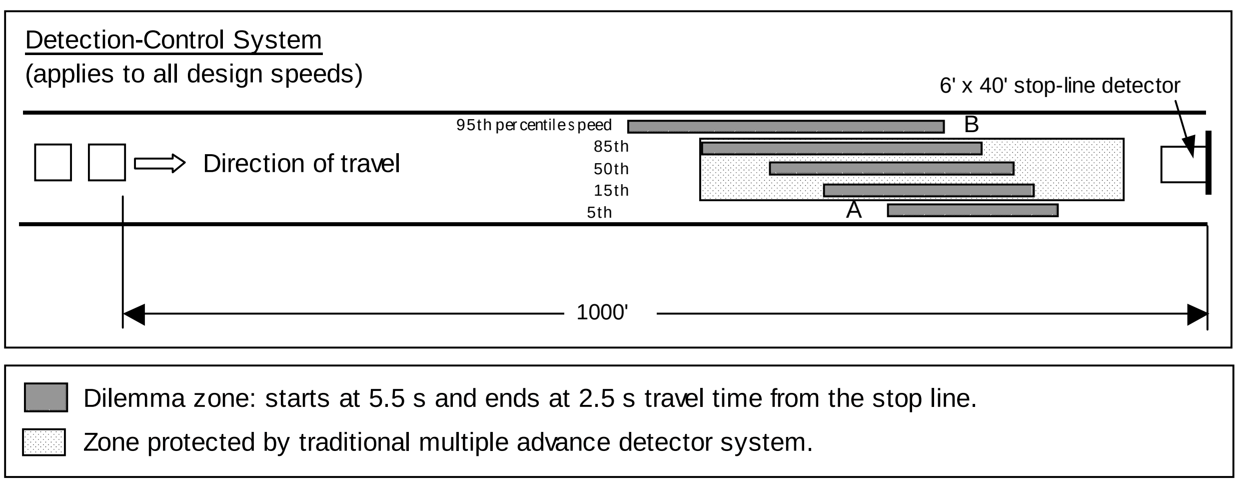


Figure 3-3. Detector Layout for the Detection-Control System.

As noted previously, the 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. A stop-line detector for the detection-control system is required. The dilemma zone is defined to start at a point where the vehicle is 5.5 s travel time from the stop line and end when the vehicle is 2.5 s from the stop line.

Unlike the multiple advance detector design, the 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 prior to its arrival to the zone. Figure 3-3 illustrates five dilemma zones for vehicles traveling at the 5th, 15th, 50th, 85th, and 95th percentile speeds. Limited space within the figure precludes showing additional zones but a unique zone exists for each possible speed with the new system.

To illustrate the implications of the dynamic dilemma-zone monitoring process, consider the following example. A vehicle traveling at the 5th percentile speed is at point A in Figure 3-3; a vehicle traveling at the 95th 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. In contrast, a multiple advance detector system would likely have a clearance zone that extends from the leading edge of the 85th percentile speed zone to the trailing edge of the 15th percentile speed zone. With this system, both vehicles would be in the clearance zone and would extend the phase. The implications of this comparison 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 multiple advance detector system.

ALGORITHM DESCRIPTION

Algorithm Logic

Overview

This section describes the logic used in the detection-control algorithm. This logic is presented in the form of three flowcharts. The first flowchart is shown in Figure 3-4. It provides an overview of the algorithm logic. As indicated in this figure, 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. This component repeats its checks every 0.05 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 flowchart of the vehicle-status component of the detection-control algorithm is illustrated in Figure 3-5. 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.

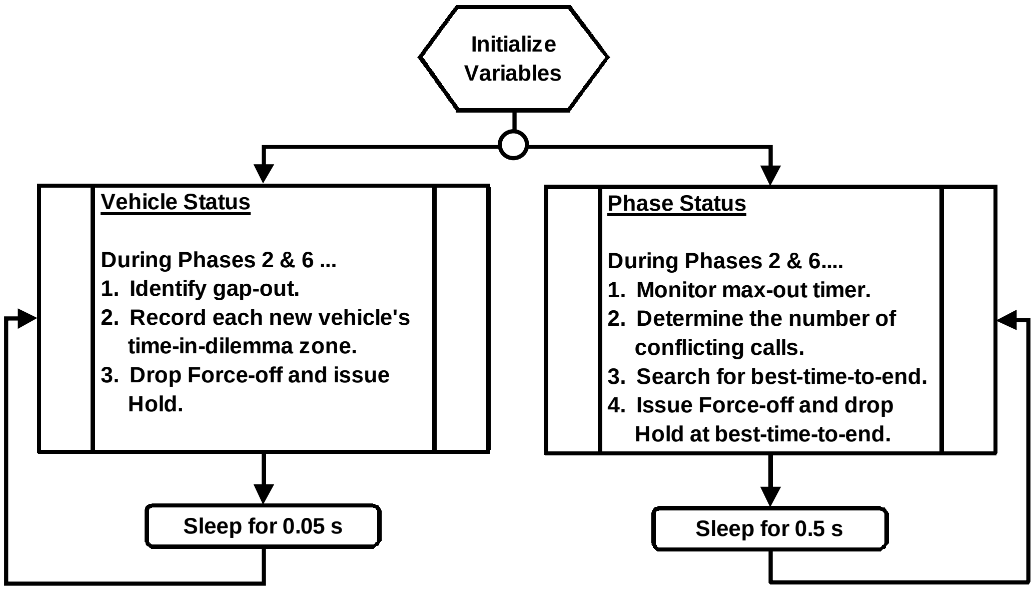


Figure 3-4. Detection-Control Algorithm Flowchart.

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 may pass slower drivers. The function of this component of the algorithm is illustrated in Figure 3-6.

Figure 3-6 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).

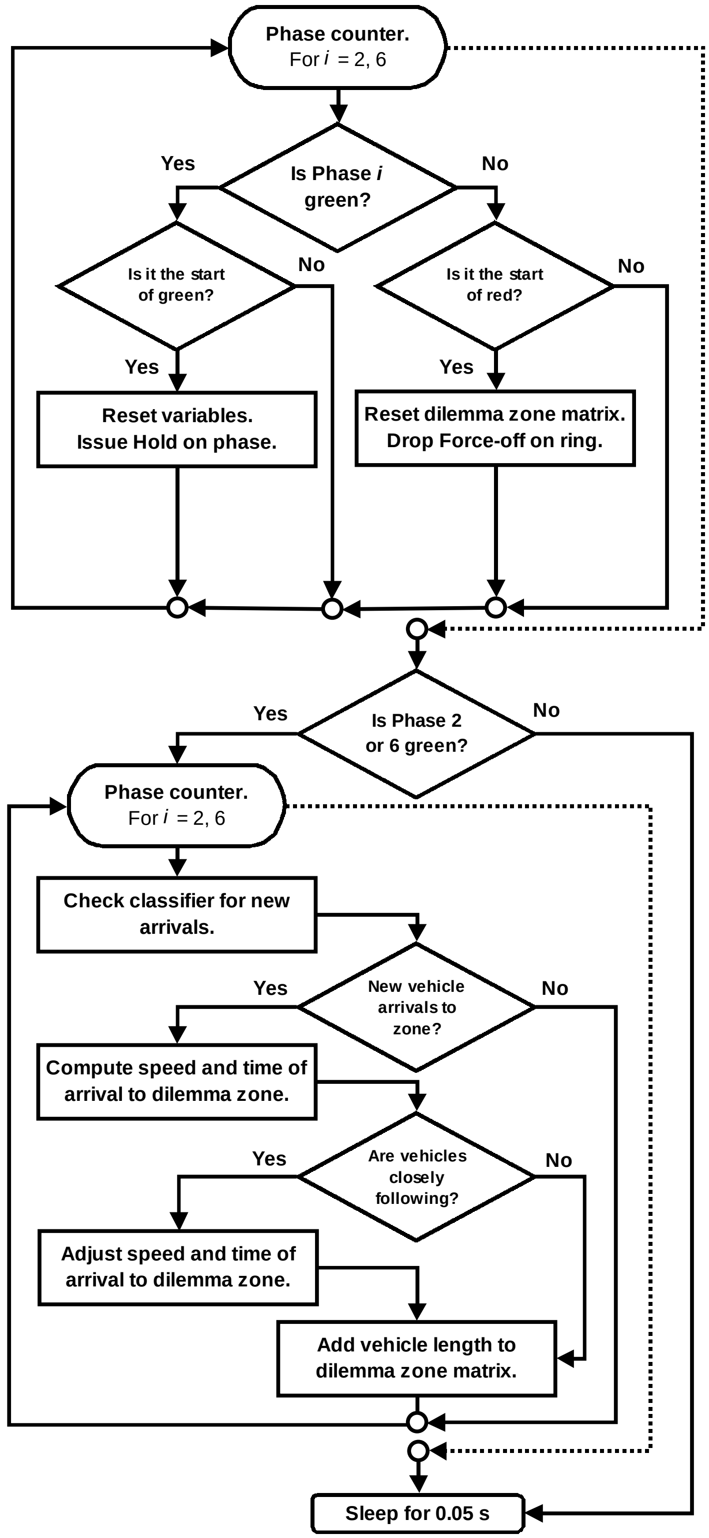


Figure 3-5. Vehicle-Status Component Algorithm Flowchart.

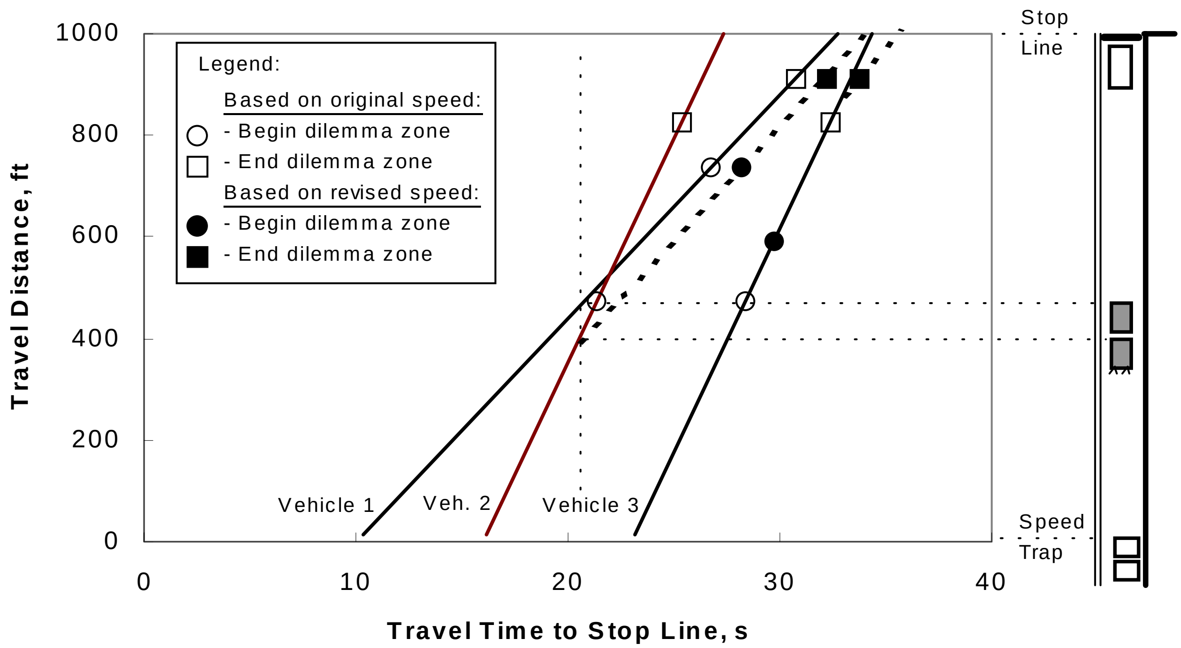


Figure 3-6. Illustration of Algorithm Adaptation to Speed Differentials.

Phase-Status Component

The flowchart of the phase-status component of the detection-control algorithm is illustrated in Figure 3-7. This component algorithm checks the dilemma-zone matrix during the major-road through phase. Action by the algorithm is only taken when the subject phase is in service (i.e., showing a green indication). While the phase is green, the algorithm monitors a maximum-green setting internal to the algorithm. If this maximum is reached, the phase is terminated immediately by dropping all phase Hold commands and issuing a Force-Off command 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 99th percentile speed. When the detection zone is located 1000 ft from the stop line and the 99th percentile speed is 70 mph, the look-ahead time is about 2.8 s.

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.

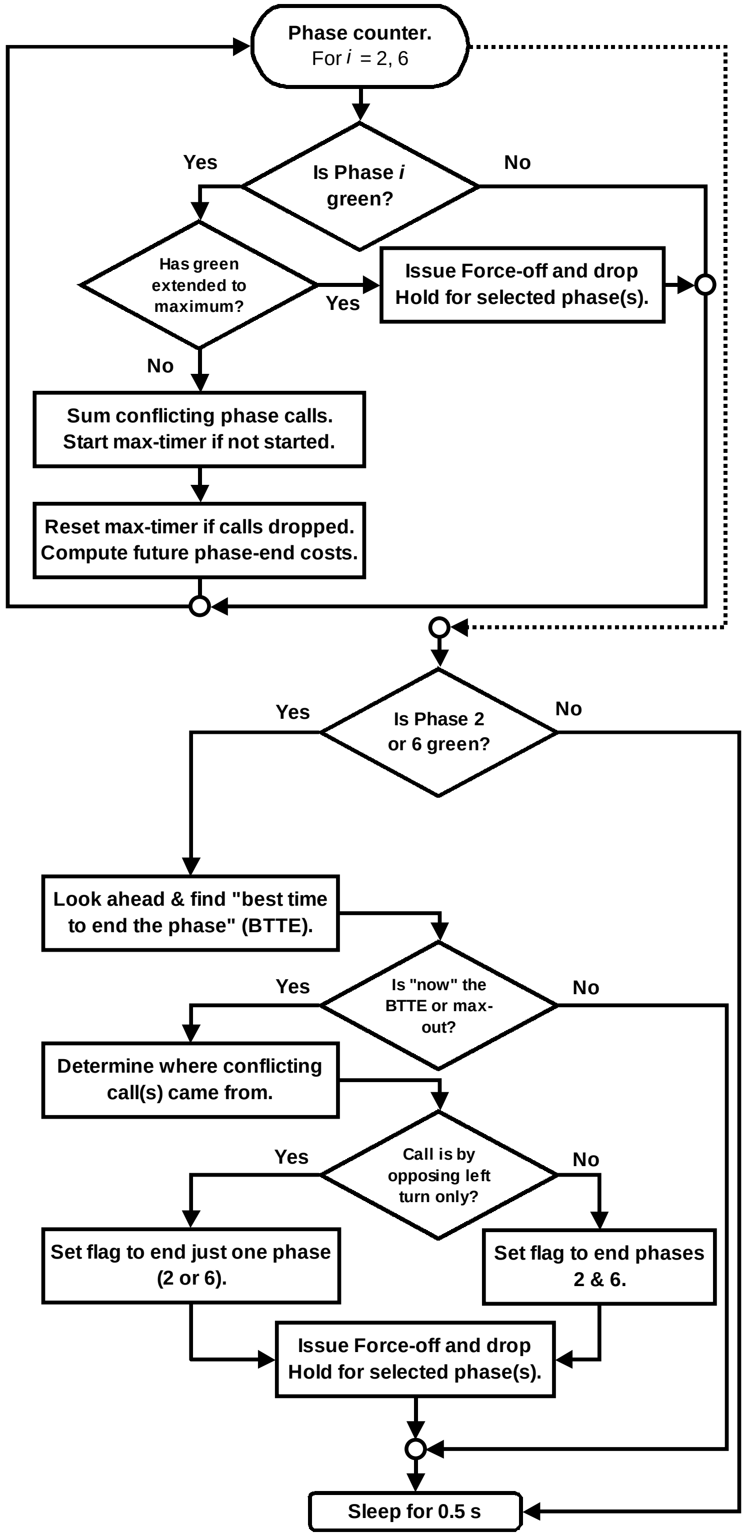


Figure 3-7. Phase-Status Component Algorithm Flowchart.

Two maximum values are used. One maximum value is used for the first portion (or stage) of the phase, and a second value is used for the last stage of the phase. The maximum value is established at zero during the first stage. During the second stage, the maximum value is relaxed to allow up to one passenger car per lane in the dilemma zone (no trucks). This "relaxation" of the maximum value is intended to prevent the phase from maxing-out while still limiting the number of vehicles caught in the dilemma zone to a minimal value. The reason for separating the phase into two stages is described in more detail in the next section.

The second check evaluates the "end green weight" (EGW) for each of the candidate times. The EGW is computed as:

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

where:

EGW_t = end green weight for time t ($0 \le t \le T_{la}$);
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_{tk} = 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 1 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 1 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 ring Force-Off command 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.

Special Features

Two-Stage Gap-Out Feature

As noted in the previous section, the detection-control system has a two-stage gap-out feature that allows it to prevent phase termination by max-out. This feature is illustrated in Figure 3-8. The first stage requires a clear (or empty) dilemma zone to end the phase. During the second stage, the algorithm relaxes its requirement for an "empty" approach by allowing up to one car per lane (but not a truck) to be caught in its dilemma zone at the onset of yellow. If the system cannot satisfy this relaxed criteria during stage two, it will reach its maximum limit and terminate the phase (i.e., max-out).

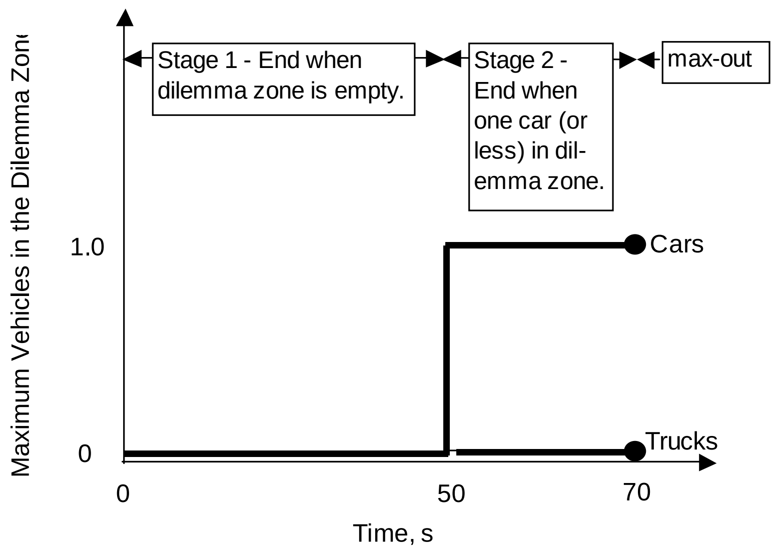


Figure 3-8. Two-Stage Gap-Out Criteria.

The rationale behind the two-stage criteria is that: (1) ending the phase with one car in the dilemma zone is reasonably safe and (2) it avoids the less safe situation of phase termination by max-out. The rear-end crash is the most common crash at signalized intersections; however, this crash is very unlikely when there is only one car in the dilemma zone at yellow onset. When a phase ends by max-out, there are often two or more vehicles in the dilemma zone per lane and a rear-end crash is more likely to occur.

The two-stage feature is unique to the detection-control system. The multiple advance detector system continuously searches for a clear approach. In contrast, the two-stage feature helps to minimize the number of vehicles caught in the dilemma zone (especially at higher flow rates) by finding a relatively safe time to end the phase without requiring all approach lanes to be empty. As a result, the detection-control system is less likely to max-out than the multiple advance detector system.

Look-Ahead Feature

The two-stage feature is further enhanced by the look-ahead feature available with the detection-control system. By locating the detectors in advance of the dilemma zone, the system algorithm can evaluate dilemma zone occupancy several seconds before the vehicles actually arrive. This feature is available only during the second stage. It gives the algorithm a look at both current and future conditions.

The operation of the look-ahead feature is illustrated in Figure 3-9. The "current" time is indicated to be 1.5 s. During the second stage, the algorithm is structured to give preference to ending the phase at the time with the fewest vehicles in the dilemma zone. All half-second intervals during the current look-ahead time are evaluated by the system. Any intervals having one or fewer equivalent passenger cars per lane are candidate times to end the phase. The candidate interval with the fewest total cars (all lanes considered) is identified as the BTTE. If the current interval is identified as the BTTE, the system will end the phase. In the figure, the current time is a candidate time but a time of 4.5 s is expected to be a better time. In this situation, the system will extend the green and reassess all time intervals during the next iteration of the phase status algorithm.

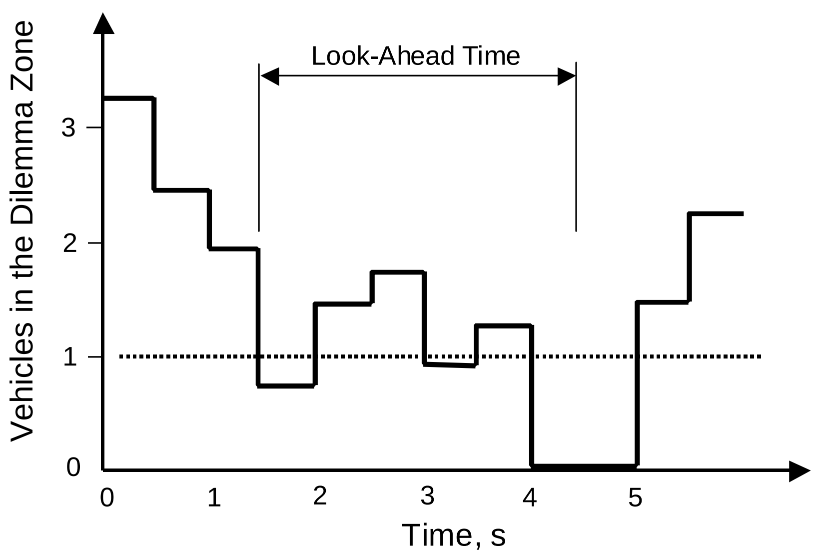


Figure 3-9. Look-Ahead Feature.

The "look-ahead" feature works with the two-stage feature to minimize the number of vehicles caught in the dilemma zone. Its effectiveness increases with increasing look-ahead time. When the 99th percentile speed is 70 mph, detectors located only 700 ft from the stop line do not provide any look-ahead time. However, if the detectors are located 1000 ft from the stop line, the look-ahead time is a more desirable 2.8 s.

SYSTEM PERFORMANCE

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).

For detection systems with multiple advance detectors, the maximum allowable headway is about equal to the sum of four components: (1) the travel time from the first to last advance detector, (2) one passage-time interval, (3) the travel time over the stop-line detector, and (4) a second passage-time interval. Components 3 and 4 can be eliminated if the stop-line detector is set (in the controller) to be inactive during the green interval, after the first gap-out is detected. The maximum allowable headway can be estimated for a given lane using the following equation (*5*):

$$MAH = \left[PT + \frac{D_1 - D_n + L_d + L_{pc}}{V_a} \right] + \left[PT + \frac{D_{sl} + L_d + L_{pc}}{V_a} \right] \qquad \textbf{(2)}$$

where:

MAH = maximum allowable headway, s;
PT = passage-time setting, s;
D_1 = 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;
D_{sl} = length of the stop line detector, 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, ft/s.

Equation 2 was used to compute the MAH for the detector designs listed in Table 2-1. The results are shown in columns 6 and 7 of this table. When the design includes an active stop-line detector, the system searches for a MAH of about 6.1 to 7.6 s before gapping out. The trends in Figure 2-4a indicate that a phase with a MAH of 7.0 s and a flow rate of 1200 veh/h would impose a wait of 35 s for service. When the design includes an inactive stop-line detector, the second term (in brackets “[ ]”) in Equation 2 is not used to compute the MAH. This system searches for a MAH of about 4.1 to 4.5 s before gapping out. In this case, a phase serving a flow rate of 1200 veh/h would impose a wait of only 25 s.

For the detection-control system, the MAH is theoretically equal to the travel time through 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 MAH would be 3.0 s. However, the variation in vehicle speeds combined with uncertainties associated with the system's speed measurement requires a slight increase in the width of the dilemma zone such that the system's effective MAH is about 4.5 s. This issue is discussed in more detail in Chapter 5.

Probability of Max-Out

As noted in the previous section, the detection-control system can reduce the number of vehicles caught in the dilemma zone. This reduction is due to the system's ability to: (1) provide coverage for all vehicles, regardless of their speed; and (2) reduce the frequency of max-out. This latter advantage is illustrated in Figure 3-10. The solid trend lines shown in this figure represent the performance of the multiple advance detector system. They were developed using an equation developed by Bonneson and McCoy (*5*). The dashed line represents the detection-control system and was developed using analytic models of the system's gap-search process.

The trends in Figure 3-10 were developed to illustrate the relationship between probability of max-out and major-road flow rate for both detection systems. Two trend lines are shown for the multiple advance detector system. The values of maximum-green setting and MAH used for these trend lines were selected to be representative of "typical" advance detector systems. The multiple advance detector system with the shorter MAH is associated with an inactive stop-line detector during the green interval. This shorter MAH works well with a shorter (say, 35-s) maximum green because it yields relatively low delay. The trends in Figure 3-10 indicate that the detection-control system is associated with lower probability of max-out than the multiple advance detector system for flow rates in excess of 800 veh/h.

Percent Vehicles in the Dilemma Zone

A new statistic was coined for this research to best illustrate the merits of the detection-control system, relative to other detection systems. This statistic is titled "vehicles in the dilemma zone" and represents the number of through vehicles caught in the dilemma zone at yellow onset divided by the total number of through vehicles. It is expressed as a percentage. This statistic can be computed for each through lane, for an intersection approach, or for the entire intersection. In this research, it is used to describe the performance of both major-road approaches combined. Turning vehicles are not included in the computation of this statistic.

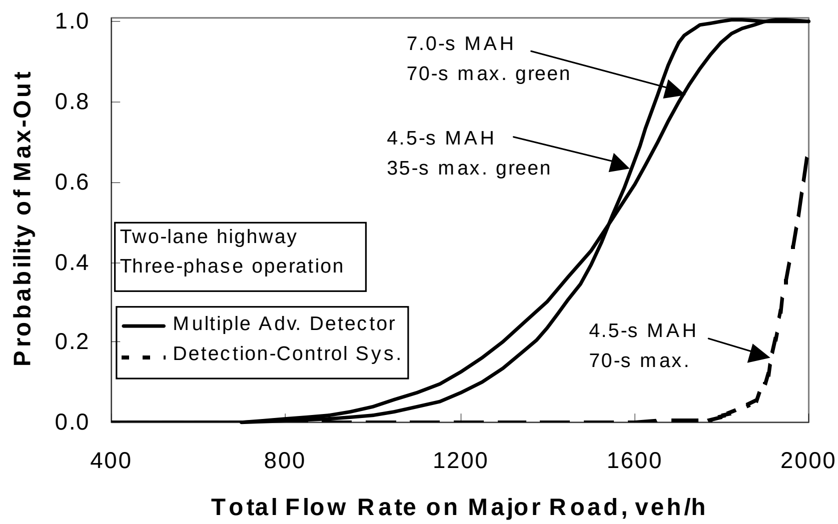


Figure 3-10. Probability of Max-Out.

The indirect benefits of the detection-control system's two-stage gap-out and look-ahead features are illustrated in Figure 3-11. The trends in this figure correspond to the same MAH and maximum-green scenarios portrayed in Figure 3-10. For flow rates below 1200 veh/h, the multiple advance detector system catches 1.3 to 1.7 percent of through vehicles in the dilemma zone, depending on MAH and maximum-green setting. The detection-control system reduces this percentage to about 0.4 percent. To quantify the system's reduction potential, a reduction factor f was defined using the ratio of the dilemma-zone percentages for the detection-control system P_D and the multiple advance detector system P_M (i.e., $f = P_D / P_M$). Values of f are 0.2 and 0.3 for MAH values of 4.5 and 7.0, respectively.

For rates of flow above 1200 veh/h, the percentage of vehicles caught in the dilemma zone by the multiple advance detector system increases rapidly with increasing flow rate. This rapid increase is due to the increasing frequency of max-out with flow rate that is associated with the multiple advance detector system.

SYSTEM COMPONENTS

This section identifies the hardware components used with the detection-control system, as portrayed in Figure 3-2. The specific pieces of hardware identified were selected after a review of the capabilities of several alternative products. This review and its conclusions were previously documented by Bonneson et al. (*15*). As noted previously, it is anticipated that the detection-control system developed in this research project will ultimately reside in a traffic signal controller or a separate microcontroller.

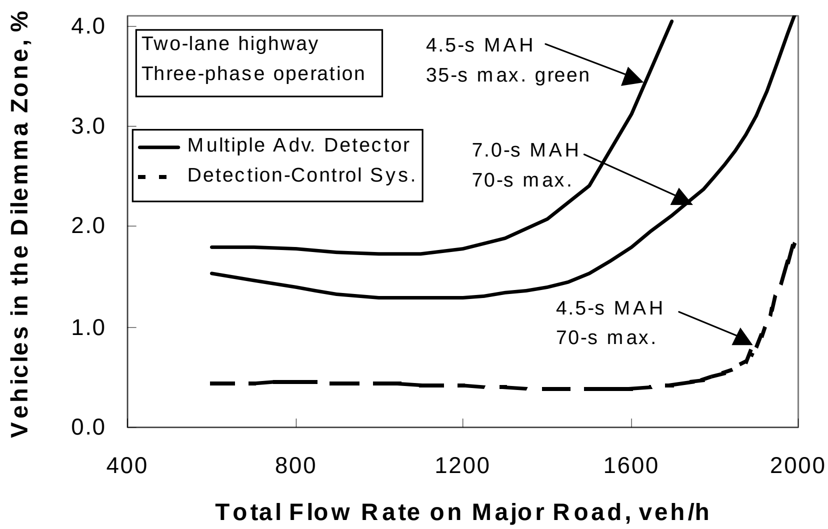


Figure 3-11. Vehicles in the Dilemma Zone.

Vehicle Detection System

Based on a comparison of the cost and reliability of alternative vehicle detectors, 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 communications option was found to be less expensive than the wireless option. It also has a high degree of reliability relative to the newer wireless technologies.

The relatively long (up to 1000 ft) detector lead-in length associated with the detection-control system requires 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 (i.e., a stand-alone computer), and the digital I/O controller interface. 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 to facilitate communications between the algorithm and the classifier. The second reason was the classifier's ability to provide the desired speed measurement precision of ±1.0 mph. A third reason was the classifier's ability to accommodate all of the inductive loops required by the detection-control system for a single-intersection installation. The ADR-3000 has a cost of about $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 algorithm is facilitated via a bus-mounted, digital I/O device wired 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 determines that it is appropriate to hold or to terminate the major-road phase, an appropriate signal is sent to the controller via the I/O device. A National Instruments digital I/O interface card (PCI-6527) was determined to be the preferred device for facilitating this communication. 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).

Traffic Control System

The traffic control system consists of the signal controller and controller cabinet. The only requirement of this system is that it provide access to the controller's input/output connector pins. This access is readily available through the controller interface panel and the detector interface panel in the TS-1 and TS-2 Type 2-supported cabinets. For a TS-2 Type 1-supported cabinet, an auxiliary interface panel is necessary to allow the detection-control system to have access to certain controller functions. This interface panel requires two additional bus interface units (i.e., channels 3 and 4) and a hub to provide for their communication with the cabinet (using synchronous data link control (SDLC) protocols). The cost of these components (including associated rack mounts and cabling) is about $900. This cost is only incurred when the detection-control system is used with a TS-2 Type 1-supported cabinet.

CHAPTER 4. STUDY SITE SELECTION AND DATA COLLECTION

OVERVIEW

This chapter describes a plan for evaluating the performance of the detection-control system. The plan consists of four separate studies. One speed study was conducted for the purpose of verifying the speed measurement accuracy of the detection-control system. A second speed study was also conducted for the purpose of quantifying driver speed-change behavior along the intersection approach. The third study is actually a series of controlled experiments using simulation. This study was intended to facilitate an evaluation of the system's effect on traffic operations. The fourth study was a before-after field study that was conducted at two intersections. This study included the collection of data to evaluate the system's effect on both safety and operations. The first two studies are referred to as the "speed prediction studies," and the last two studies are referred to as the "system evaluation studies."

This chapter consists of two main sections. Initially, the intersections selected for field study are described in terms of their physical, traffic, and signal control characteristics. Then, the data collection plan is discussed in terms of the types and amount of data collected for each of the four studies.

FIELD STUDY SITES

Site Selection Criteria

Five criteria were used to identify candidate study sites (i.e., intersections) for this research project. These criteria include: (1) adequate intersection approach sight 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 trucks. Five candidate study sites were identified as satisfying these criteria. After reviewing these candidate sites, the intersection at F.M. 2154 and Rock Prairie Road in College Station and the intersection at S.H. 6/Loop 340 and F.M. 3400 in Waco were selected for the before-after study. These two sites are described in the next section; additional information about all five sites is provided by Bonneson et al. (*15*).

Site Physical Characteristics

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. A plan view of the intersection is shown in Figure 4-1.

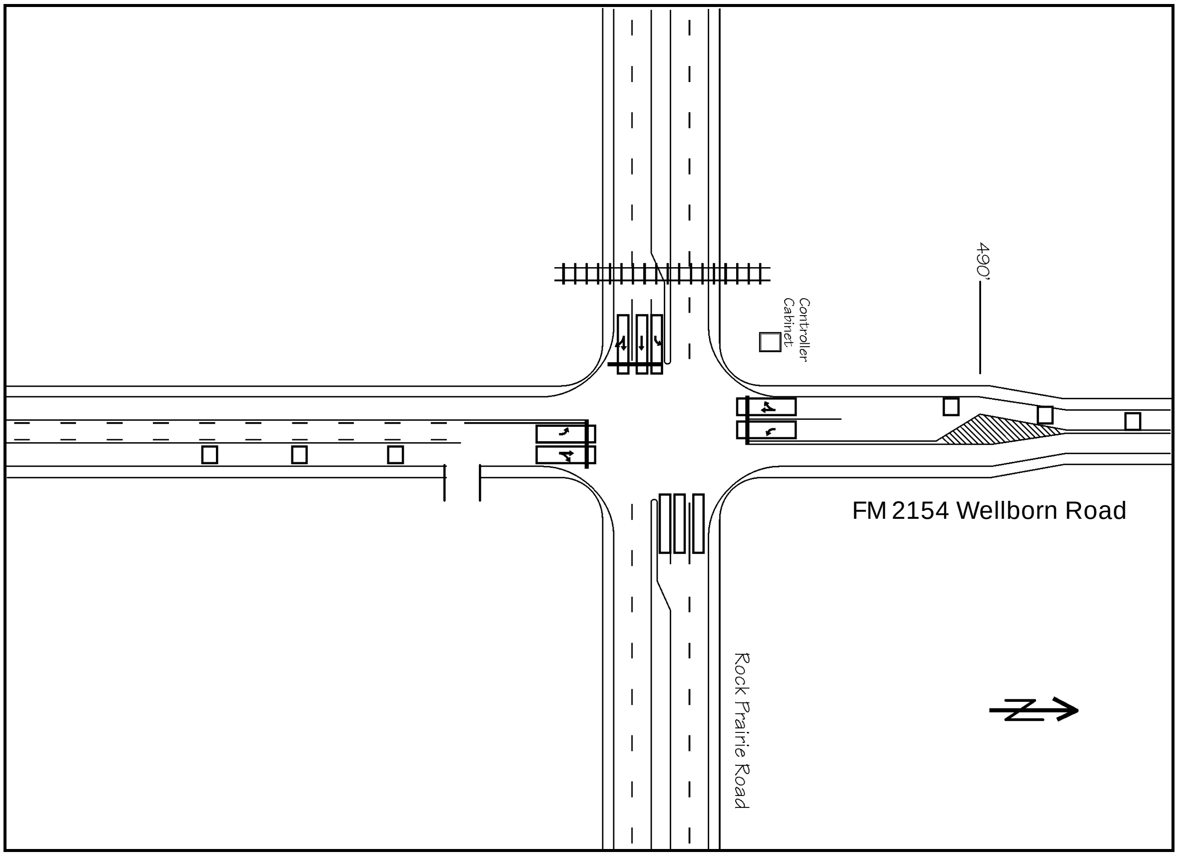


Figure 4-1. Intersection of F.M. 2154 and Rock Prairie Road.

S.H. 6/Loop 340 is oriented in a northeast-to-southwest direction at its intersection with F.M. 3400. S.H. 6/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. A plan view of the intersection is shown in Figure 4-2.

Site Traffic and Traffic Control Characteristics

F.M. 2154 and Rock Prairie Road

F.M. 2154 is the major road at this intersection. It has a speed limit of 65 mph. Prior to installation of the detection-control system, the intersection operated with fully-actuated control. Stop-line detection (40 ft in length) is provided for all traffic lanes. Advance detectors (6 ft in length) are also provided for Wellborn Road. These detectors are located 320, 430, and 540 ft from the stop line.

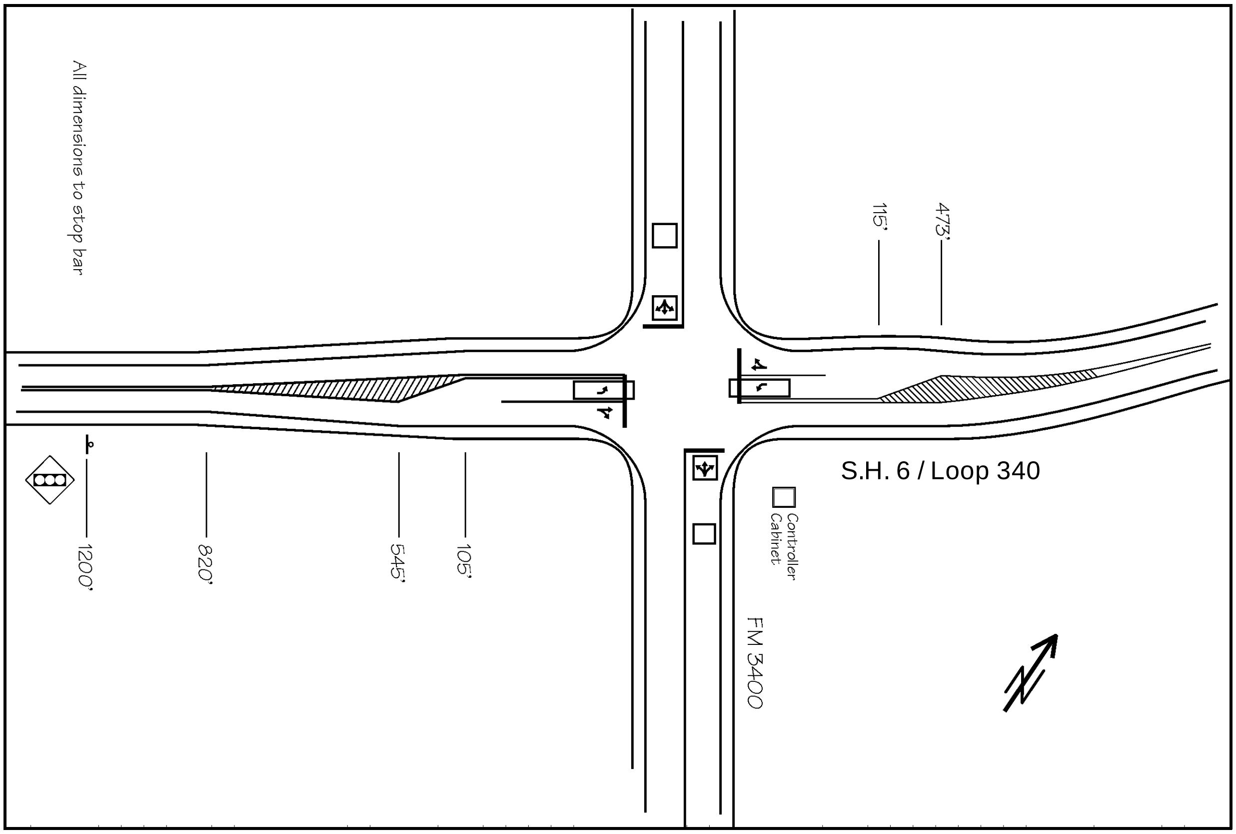


Figure 4-2. Intersection of S.H. 6/Loop 340 and F.M. 3400.

The controller settings for each approach are listed in Table 4-1. Features to note include the use of the "recall-to-minimum" feature for the major-road through phases (i.e., phases 2 and 6), the use of a 60-s maximum for phases 2 and 6, and the use of 3-s passage time for phases 2 and 6. It is estimated that this passage time, combined with the advance detection and active stop-line detector, would cause the controller to routinely seek traffic gaps of about 11 s as a requirement to end the phase (i.e., the design yields an 11-s MAH).

Vehicles turning right from Wellborn Road tend to have a significant adverse effect on approach traffic speeds during the green indication. Specifically, turning vehicles are frequent at this intersection and there is neither a right-turn lane nor a shoulder of adequate width to serve as a "de facto" turn lane. These turning vehicles cause the following through vehicles to slow significantly. A driveway on the northbound approach of Wellborn road is fairly active throughout the day and especially so during the morning peak traffic hour. Vehicles turning right into this driveway have a particularly disruptive effect on the smooth flow of approach traffic.

S.H. 6/Loop 340 and F.M. 3400

S.H. 6/Loop 340 is the major road at this intersection. It has a speed limit of 60 mph. Prior to installation of the detection-control system, the intersection had semi-actuated operation with stop-line detection for each of the minor movements (i.e., minor-road approaches and major-road left-turn movements). The minor-road detection design at the intersection consists of a 6-ft loop at the stop line and a second 6-ft loop approximately 80 ft upstream from the stop line. The left-turn bays each have a 40-ft loop. No stop-line or advance detection is used for the major-road approaches.

Table 4-1. Traffic Control Characteristics.

Field Study Site	Setting	Phase							
		1	2	3	4	5	6	7	8
F.M. 2154 & Rock Prairie Road College Station	Approach [1]	NB	SB	EB	WB	SB	NB	WB	EB
	Movement	Left	Thru	Left	Thru	Left	Thru	Left	Thru
	Yellow, s	4	5	4	4	4	5	4	4
	All Red, s	2	2	2	2	2	2	2	2
	Passage Time, s	2	3	2	2	2	3	2	2
	Minimum Green, s [2]	8	20	8	10	8	20	8	10
	Maximum Green, s	25	60	20	25	25	60	20	25
	Dual Entry	Yes	Yes	Yes	No	Yes	Yes	Yes	No
	Recall	no	Min.	no	no	no	Min	no	no
	Left-Turn Phasing	Lead	--	Lag	--	Lead	--	Lag	--
S.H. 6/Loop 340 & F.M. 3400 Waco	Approach [1]	SB	NB	--	EB	NB	SB	--	WB
	Movement	Left	Thru	--	Thru	Left	Thru	--	Thru
	Yellow, s	3	4	--	3	3	4	--	3
	All Red, s	1.5	1.5	--	1.5	1.5	1.5	--	1.5
	Passage Time, s	3	3	--	2.5	3	3	--	2.5
	Minimum Green, s	4	20	--	8	4	20	--	8
	Max. Green I, s [3]	20	45	--	30	20	45	--	30
	Max. Green II, s [3]	40	60	--	40	40	60	--	40
	Dual Entry	Yes	Yes	--	No	Yes	Yes	--	No
	Recall	no	Max.	--	no	no	Max.	--	no
	Left-Turn Phasing	Lag	--	--	--	Lag	--	--	--

Note:
1 - Approach: NB-northbound, SB-southbound, EB-eastbound, WB-westbound.
2 - Site uses "added initial" feature for phase 6 to add 2.0 s per actuation with maximum initial of 40 s.
3 - Max. Green II in effect from 7:00 to 8:30 a.m. and 4:30 to 5:20 p.m.; Max. Green I at all other times.

The controller settings for each approach are listed in Table 4-1. The major-road through phases (i.e., phases 2 and 6) operate with "recall-to-maximum" where the maximum-green setting varies by time of day. The maximum setting for the major-road phases is 45 s except between the hours of 7:00 am to 8:30 am and 4:30 pm to 5:20 pm when it is 60 s. The maximum setting for the minor-road phases (i.e., phases 4 and 8) is 30 s except between the hours of 7:00 am to 8:30 am and 4:30 pm to 5:20 pm when it is 40 s. Minimum-green settings for the major and minor-road phases are 20 and 8 s, respectively.

The major-road left-turn phases (i.e., phases 1 and 5) have a maximum setting of 20 s except between the hours of 7:00 am to 8:30 am and 4:30 pm to 5:20 pm when it is 40 s. The minimum-green setting for the left-turn phases is 4 s.

When the intersection is controlled by the detection-control system, the maximum-green setting for the major-road through phases is increased to 70 s and the "recall-to-maximum" feature is disabled.

DATA COLLECTION PLAN

Speed Prediction Studies

This section describes the data collection plan for two speed studies. One study collected the data needed to evaluate the speed measurement capability of the classifier component of the detection-control system. The second study collected the data needed to determine the speed-change behavior of drivers between the point of measurement (i.e., the system detectors) and the stop line. This latter study was undertaken to determine if drivers change their speed on the intersection approach and whether any such change might affect the performance of the detection-control system. Both studies were conducted simultaneously on the southbound approach of the intersection at S.H. 6/Loop 340 and F.M. 3400.

For the speed-measurement-error study, vehicle speeds were measured with tapeswitch sensors temporarily adhered to the pavement surface. These sensors were connected to, and monitored by, a portable computer. The tapeswitch speed measurement locations are illustrated in Figure 4-3; also shown are the locations of the detection loops associated with the detection-control system. Speeds measured at the tapeswitch speed trap located 1000 ft from the stop line were used to evaluate the speed accuracy and precision of the detection-classification components. One video camera was set up on the roadside in advance of this trap to provide a visual record of traffic events during the study.

For the speed-change study, vehicle speeds were measured with tapeswitch sensors located at two points on the intersection approach (i.e., at 500 ft and 1000 ft from the stop line). These tapeswitch speed measurement locations are illustrated in Figure 4-3. The measured speeds at each location were paired for common vehicles and then compared to assess driver speed-change behavior. One video camera was set up on the roadside in advance of each tapeswitch trap to provide a visual record of events.

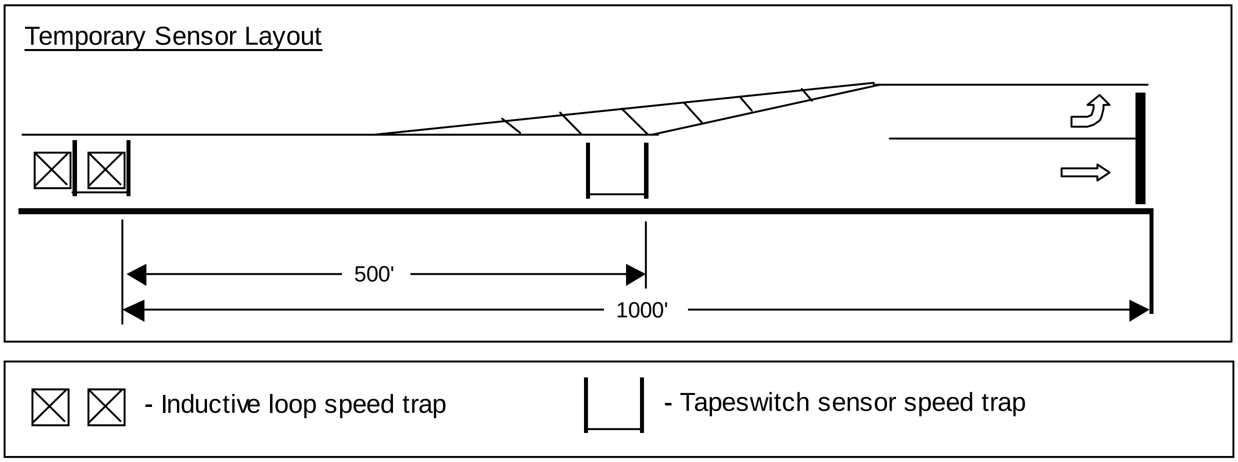


Figure 4-3. Sensor Layout for Pilot Field Study.

System Evaluation Studies

This section describes the data collection plan for two studies of system performance. One study is actually a series of controlled experiments using simulation. This study was intended to facilitate an evaluation of the system's effect on traffic operations. The other study was a before-after field study conducted at two intersections. This study included the collection of data to evaluate the system's effect on both safety and operations.

Evaluation Based on Simulation

The detection-control algorithm was evaluated using a microscopic, traffic simulation software model. The simulation was accomplished using a "hardware-in-the-loop" system that consists of the Corridor Simulation (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 be tested together in a laboratory setting. The disadvantage of this system is that 1.0 s of simulation time is equal to 1.0 s of real time. In other words, a hardware-in-the-loop-based simulation is very 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 (i.e., the vehicle classifier component of the detection-control 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 multiple advance detector system was also simulated to facilitate its comparison with the detection-control system. The design features of this system are listed in Table 2-1. 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 in the CORSIM software is able to simulate controller operation for standard detection systems. As a result, hardware-in-the-loop simulation was not required which resulted in considerable time savings when simulating the multiple advance detector system.

Several elements of the detection and control design were the same for both the detection-control system and the multiple advance detector system. Specifically, the through phases were set for dual entry. The major-road approaches had both a left-turn and a through phase; the minor-road approaches had one phase to serve 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 at10 s. The maximum-green setting for each of the minor-road 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 4-2 identifies the factors considered in the simulation experiments. In the first stage of the simulation experiment, the speed, flow rate, and turn percentage were varied in a full-factorial design. In this design, all 12 factor combinations (= 2 speeds × 2 flow rates × 3 turn percentages) were evaluated in separate simulation runs. The left-turn and right-turn flow rates were varied by adjusting their percentage of the approach flow rate. These turn percentages 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 4-2.

In the second stage of the experiment, the directional distribution, 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 while 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.

Table 4-2. Factors Considered in the Simulation Experiments.

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

Evaluation Based on Field Data

Measures of Effectiveness. Five measures of effectiveness were used to evaluate the performance of the detection-control system. These measures include:

- cycle length;
- control delay;
- percent of vehicles stopping;
- percent of vehicles running the red light; and
- percent of vehicles in dilemma zone at yellow onset.

With the exception cycle length, all of these measures of effectiveness were quantified for the traffic movements served by the detection-control system (i.e., the major-road through movements). The control delay data were collected using the field survey methods described in Chapter 16 of the *2000 Highway Capacity Manual (16)*.

The first three measures listed provide some indication of the operational efficiency provided by the system. A decrease in any (or all) of these measures would be an indication of improved operating conditions. The last two measures provide some indication of the level of safety provided by the system. Again, decreases in any (or all) of these measures would be an indication of increased safety.

Data Collection Approach. The data were collected during a series of "before-after" studies conducted at each of the two study sites (i.e., intersections). For the "before" study, data were collected on each major-road approach for a period of four hours during one day. Thus, at each site, two days were allocated to the collection of "before" data and another two days were allocated to the collection of "after" data. All total, 32 hours of data were collected during eight days of study. The data were collected between the hours of 10:00 a.m. and 5:00 p.m. Data were not collected during inclement weather nor during unusual traffic conditions (e.g., vehicle crash).

The data were collected using both computer-monitored tapeswitch sensors and video camcorders. The tapeswitch sensors were used to measure vehicle speed at a point 510 ft from the stop line on the approach being studied. Two sensors were adhered to the pavement surface to form a 15-ft speed trap. They were monitored by a computer specially equipped for this purpose. During data reduction, the estimated speed and trap-entry time were used to determine if a vehicle on the intersection approach at yellow onset was in its dilemma zone. The location of these tapeswitches on the subject approach is shown in Figure 4-4.

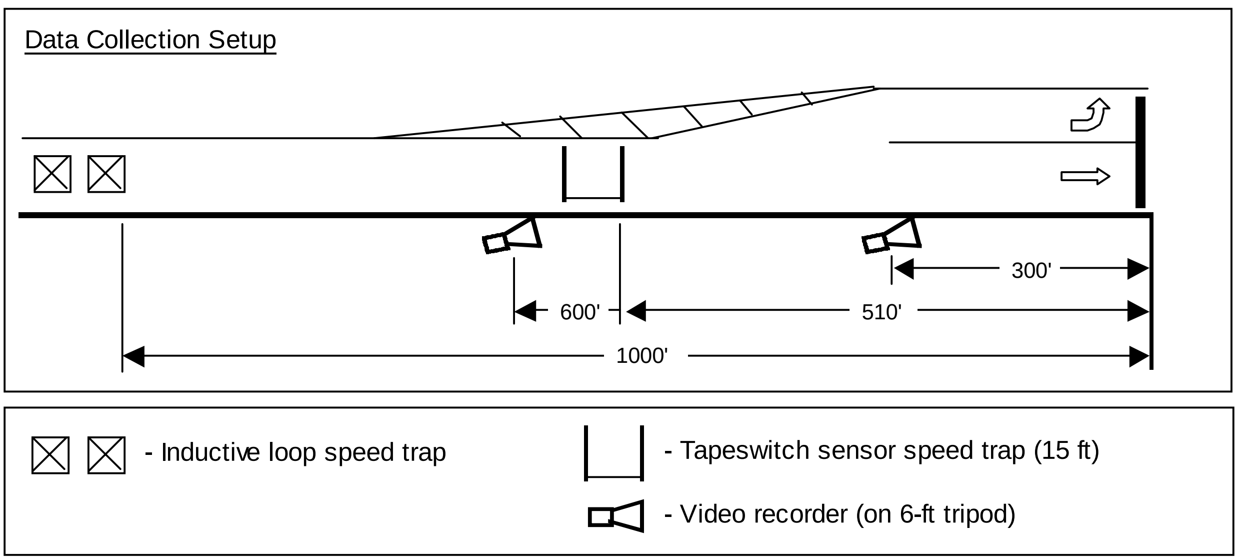


Figure 4-4. Field Study Equipment Locations.

Two camcorders were also located along the approach being studied. One camcorder was located 300 ft upstream of the stop line. This camera was used to determine the average control delay and to identify vehicles that run the red signal indication. The second camera was placed 600 ft upstream and was used to help identify vehicles as they crossed the tapeswitch system, which was placed within the camera's field of view. This camera ensured that the data from the tapeswitch system could be properly interpreted.

In addition to the video and tapeswitch data, the detection-control system was set to "self-record" its behavior during each of the "after" studies at both intersections. Specifically, it generated two output data files. One file logged each vehicle's speed, length, and loop-trap arrival time. This file also logged the time the through-phase indications turned green and the time they turned yellow. A second file logged the conditions underlying each phase termination (i.e., due to gap-out or max-out) and the associated decision logic used by the algorithm. These files could be used together to confirm that the algorithm was making the correct decisions and whether the information provided to it by the classifier were accurate.

CHAPTER 5. SYSTEM EVALUATION AND DESIGN CONSIDERATIONS

OVERVIEW

This chapter describes an evaluation of the detection-control system and the factors that need to be considered when designing the system for a specific intersection. The findings from the field studies were used to evaluate the performance of the system in terms of safety and operation. These findings were also used to identify several design factors and to develop suitable design guidelines.

This chapter consists of two sections. The first section describes the evaluation of the detection-control system based on the analysis of both simulation and field data. The second section describes the findings from the speed prediction studies and their implications on the design of the detection-control system's detector location and controller settings.

SYSTEM EVALUATION

Evaluation Based on Simulation

The results of the simulation runs are described in this section. The evaluation focuses on the effect of various factors (e.g., flow rate, turn percentage, etc.) on delay, probability of max-out, and percent of vehicles in the dilemma zone. As noted in Chapter 4, two flow-rate scenarios were evaluated. The "low flow rate" scenario coincides with two-way flow rates of 800 veh/h on the major road and 200 veh/h on the minor road. In contrast, the "high flow rate" scenario coincides with two-way flow rates of 1400 veh/h and 400 veh/h for the major and minor road, respectively.

Motorist Delay

Figure 5-1 illustrates the effect of flow rate, turn percentage, and detection system type 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 flow rate. They also indicate that the detection-control system operates with slightly less delay than the multiple advance detector system.

Delay was not found to be influenced by directional distribution, truck volume, maximum-green setting, or approach speed for the range of factors considered. The trends shown in Figure 5-1 apply to one-lane approaches. Values obtained from this figure should be multiplied by 0.85 when applied to two-lane approaches.

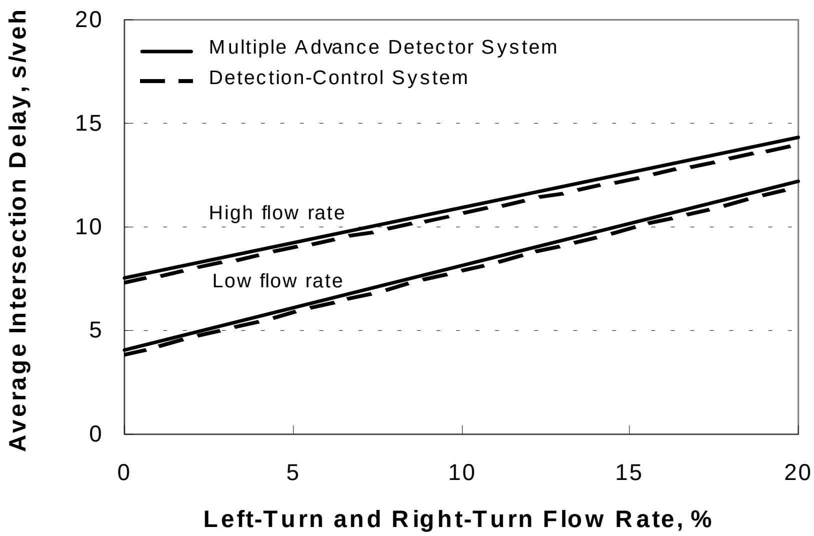


Figure 5-1. Effect of Various Factors on Delay.

Probability of Max-Out

The effect of flow rate, turn percentage, and detection system type on the probability of phase termination by max-out is shown in Figure 5-2. The trends in this figure indicate that the probability of max-out is negligible for the detection-control system, regardless of turn percentage or flow rate. This finding is consistent with the dashed trend line in Figure 3-10 and confirms the effectiveness of the detection-control system.

The trends in Figure 5-2 suggest that the probability of max-out varies with turn percentage and flow rate for the multiple advance detector system (with a 35-s maximum-green setting). The Stage II investigation of maximum-green setting indicated that a 60-s maximum-green eliminates phase max-outs for the multiple advance detector system.

Figure 5-2 indicates that the probability of max-out increases as the left-turn percentage increases to 10 percent and then decreases to a smaller value with increasing turn percentage. This trend stems from the frequent occurrence of only one left-turn phase per cycle at the 10-percent level. Higher turn percentages tend to have both left-turn phases come on together and smaller left-turn percentages rarely have either left-turn phase come on. When only 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.

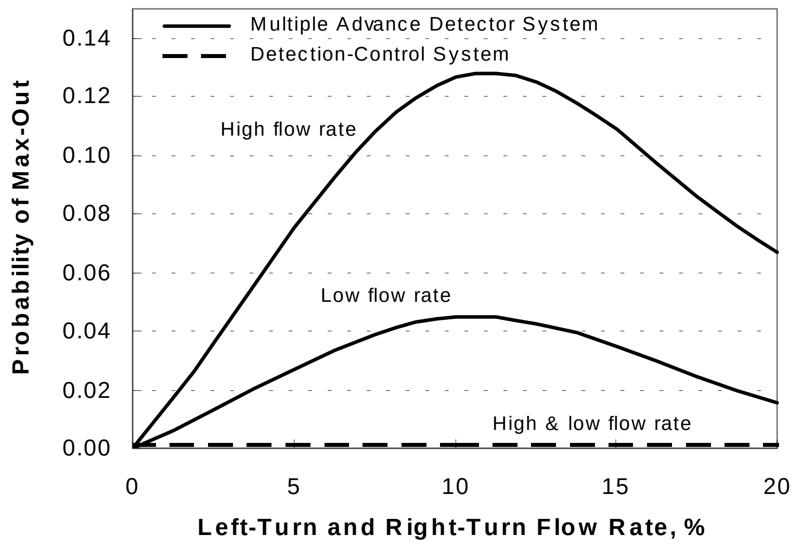


Figure 5-2. Effect of Various Factors on Max-Out Frequency.

Number of Vehicles Caught in the Dilemma Zone

The effect of flow rate, turn percentage, and detection system type on the percentage of vehicles caught in the dilemma zone is shown in Figure 5-3. 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 flow rate.

The trends in Figure 5-3 indicate that the detection-control system catches fewer vehicles in the dilemma zone than the multiple advance detector system. This finding is consistent with the dashed trend line in Figure 3-11 and confirms the effectiveness of the detection-control system. The trend is due primarily to the fact that, by design, the multiple detector system provides dilemma-zone protection for only about 70 percent of all vehicles (i.e., it excludes the fastest and slowest 15 percent of vehicles). Fortunately, typical flow rates limit the exposure of these vehicles such that less than 4.0 percent of all vehicles are actually "caught."

The number of vehicles in the dilemma zone was not found to be influenced by directional distribution, truck volume, or approach speed for the range of factors considered. The trends shown in Figure 5-3 apply to a maximum-green setting of 35 s and one lane on each major-road approach.

About 0.2 percent should be subtracted from any value obtained from the figure if a 60-s maximum-green is used. Values obtained from this figure should be multiplied by 0.5 when applied to two-lane approaches.

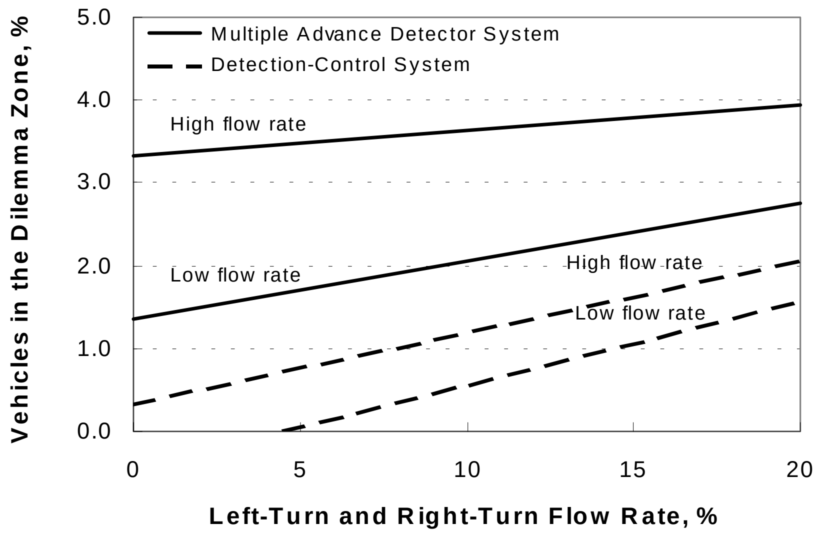


Figure 5-3. Effect of Various Factors on Percent of Vehicles in the Dilemma Zone.

To quantify the system's dilemma-zone reduction potential, a reduction factor f was defined using the ratio of the dilemma-zone percentages for the detection-control system P_D and the multiple advance detector system P_M (i.e., $f = P_D / P_M$). Values of f are 0.0, 0.3, and 0.6 for left and right-turn flow rates of 0, 10, and 20 percent. To illustrate the meaning of this factor, consider an intersection with 1400 veh/h (total for both major-road approaches, each with one lane) and 10 percent turns to the left and to the right. For these conditions, Figure 5-3 indicates that the multiple advance detector system would catch 3.63 percent vehicles in the dilemma zone or 41 veh/h (= [1.0 - 0.1 - 0.1] x 1400 x 3.63/100). In contrast, the detection-control system should only catch 12 veh/h (= 0.3 x 41). For a two-lane approach, these factors translate into a reduction from 21 to 6 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 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 system ends the phase.

Sensitivity to Trucks

The special features of the detection-control system are designed to provide an added sensitivity to truck traffic over a wide range of flow rates. This sensitivity is incorporated during the second stage of the two-stage gap-out feature. The ability of the detection-control system to minimize the number of trucks caught in the dilemma zone is illustrated in Figure 5-4. The trends shown in this figure indicate that the detection-control system reduces the number of trucks caught in the dilemma zone, relative to the multiple advance detector system. A reduction factor *f* of 0.3 is obtained from the data shown (where *f* equals the number of trucks caught by the detection-control system divided by those caught by the multiple advance detector system). This factor is consistent with the factor noted previously with regard to Figure 5-3 (and 10 percent left and right turns).

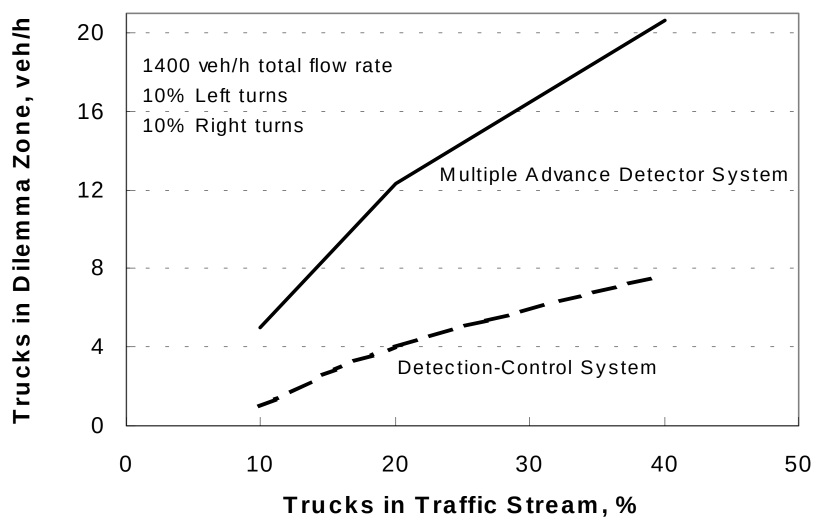


Figure 5-4. Number of Trucks Caught in the Dilemma Zone.

Evaluation Based on Field Data

Summary of Database Characteristics

The database represents the observation of more than 8900 vehicles during the 32 hours of study. These vehicles were fairly evenly divided among the two study sites (i.e., intersections) and exhibited a trend toward slightly reduced rates of flow in the “after” study periods. The count of vehicles for each study, site, and approach is listed in Table 5-1.

Table 5-1. Traffic Counts and Flow Rates During Study Periods.

Field Study Site	Measure	Approach	Study					
			Before		After		Change[3]	
F.M. 2154 & Rock Prairie	Total Vehicles[1,2]	Northbound	810	veh.	691	veh.	-119	veh.
		Southbound	991	veh.	786	veh.	-205	veh.
		Overall	**1801**	**veh.**	**1477**	**veh.**	**-324**	**veh.**
	Hourly Flow Rate[2]	Northbound	214	veh/h	230	veh/h	16	veh/h
		Southbound	262	veh/h	224	veh/h	-38	veh/h
		Overall	**476**	**veh/h**	**454**	**veh/h**	**-22**	**veh/h**
S.H. 6/Loop 340 & F.M. 3400	Total Vehicles[1,2]	Northbound	1503	veh.	1423	veh.	-80	veh.
		Southbound	1411	veh.	1298	veh.	-113	veh.
		Overall	**2914**	**veh.**	**2721**	**veh.**	**-193**	**veh.**
	Hourly Flow Rate[2]	Northbound	376	veh/h	360	veh/h	-16	veh/h
		Southbound	353	veh/h	331	veh/h	-22	veh/h
		Overall	**729**	**veh/h**	**691**	**veh/h**	**-38**	**veh/h**

Notes:
1 - Counts observed during a 4-hour field study.
2 - Through vehicles only (left-turn and right-turn vehicles excluded).
3 - Percent Change computed as “After - Before.”

The average hourly flow rates on each approach are also listed in Table 5-1. These flow rates are fairly typical of intersections on two-lane highways in Texas. From the standpoint of capacity, the flow rates are relatively low and suggest good traffic operations (i.e., Level of Service “A”) during most hours of the day.

The speed and composition of the major-road traffic stream at each site is listed in Table 5-2. Speeds at the intersection of F.M. 2154 and Rock Prairie Road were well below the posted speed limit (65 mph); however, they were also more varied. These two attributes are likely due to the turbulence caused by frequent right-turning vehicles from F.M. 2154, as noted in a previous section. The percentage of trucks was relatively high at both study sites and typical of many rural intersections.

Evaluation Results

This section describes the analysis of the “before-after” data collected at two study sites (i.e., intersections). These data were collected to demonstrate that the detection-control system could provide equal (or better) performance than a multiple advance detector system. The measures of effectiveness computed from the before-after data are summarized in Table 5-3.

Table 5-2. Speed and Traffic Composition During Study Periods.

Field Study Site	Measure	Approach	Statistics					
			Observations [1]		Average		85th Percentile	
F.M. 2154 & Rock Prairie	Speed	Northbound	772	veh.	51	mph	58	mph
		Southbound	1143	veh.	51	mph	58	mph
	Truck Percentage [2]	Northbound	114	trucks	15	%	--	--
		Southbound	151	trucks	13	%	--	--
S.H. 6/Loop 340 & F.M. 3400	Speed	Northbound	1413	veh.	57	mph	62	mph
		Southbound	1179	veh.	56	mph	61	mph
	Truck Percentage [2]	Northbound	227	trucks	16	%	--	--
		Southbound	159	trucks	14	%	--	--

Note:
1 - Observations were recorded during a 5-hour period.
2 - A truck is defined as any vehicle with length in excess of 25 ft.

Table 5-3. Measures of Effectiveness.

Field Study Site	Measure	Before [1]				After [1]				Change [2]
		Observation		Average		Observation		Average		
F.M. 2154 & Rock Prairie	Cycle length	420	cycles	**65**	s	366	cycles	**64**	s	-1
	Control delay [3]	32	15 min	**10**	s/veh	27	15 min	**10**	s/veh	0
	Vehicles stopped	706	veh	**39**	%	647	veh	**44**	%	5
	Red-light runners	0	veh	**0.0**	%	0	veh	**0.0**	%	0
	Veh. in dilemma zone	7	veh	**0.4**	%	8	veh	**0.5**	%	0
S.H. 6/Loop 340 & F.M. 3400	Cycle length	389	cycles	**74**	s	426	cycles	**67**	s	-7
	Control delay [3]	32	15 min	**6**	s/veh	32	15 min	**3**	s/veh	-3
	Vehicles stopped	683	veh	**23**	%	471	veh	**17**	%	-6
	Red-light runners	24	veh	**0.8**	%	1	veh	**0.0**	%	-1
	Veh. in dilemma zone	132	veh	**4.5**	%	21	veh	**0.8**	%	-4

Note:
1 - Statistics represent the combined data for both major-road approaches and reflect only through vehicles.
2 - Change computed as "After - Before." An underlined value represents a statistically significant change (5-percent chance of error).
3 - Delay observations represent 15-minute averages from the 4-hour data set for each major-road approach.

A couple of points need to be remembered when reviewing the data in Table 5-3. First, it must be remembered that the intersection at F.M. 2154 and Rock Prairie Road has a multiple advance detector system and that the other intersection does not have any advance detection. It should also be remembered that both intersections have relatively low major-road flow rates (e.g., 450 to 700 veh/h total both directions) during most hours of the day. Based on these flow rates, the trend lines in Figure 3-10 suggest (by extrapolation) that the intersection at F.M. 2154 and Rock Prairie Road (which has an 11-s MAH) is not likely to max-out often with either detection system. Moreover, the trends in Figure 3-11 suggest that the percent of vehicles caught in the dilemma zone is likely to be about 1.0 percent for the multiple advance detector system and 0.4 percent for the detection-control system.

Based on the aforementioned points, the trends listed in Table 5-3 are fairly logical. The detection-control system was not able to improve operations or safety at the intersection of F.M. 2154 and Rock Prairie Road. This result was expected based on the trends in Figures 3-10 and 3-11. This intersection has a relatively low flow rate throughout the day and adequate advance detection; significant improvement was not possible nor expected.

The detection-control system was able to improve operations and safety at the intersection of S.H. 6 and F.M. 3400. This trend was also expected as there was no advance detection in the "before" case. The change in each measure of effectiveness at this intersection was found to be statistically significant based on a paired *t*-test.

DESIGN CONSIDERATIONS

This section describes several factors that influence the design of the detection-control system. System design considerations include the location of the detectors (relative to the stop line), the maximum-green setting, minimum-green setting, and the dilemma zone boundaries. Extension of these design considerations to design guidelines required field measurements of traffic speeds on the intersection approach. Thus, this section begins with a discussion of the findings from the speed-prediction studies.

Speed Prediction

This section summarizes the analysis of speed data collected during two studies at the intersection of S.H. 6/Loop 340 and F.M. 3400. This analysis considered the speed measurement error of the detection-control system and the speed-change behavior of drivers on the intersection approach. The following two subsections summarize the data collected for each study. A subsequent section discusses their implication on the specification of dilemma zone boundaries.

Speed Measurement Error

During one hour of study, more than 214 vehicles were observed to cross the system detectors and the adjacent tapeswitch speed trap. The average speed of traffic was found to be 54.5 mph, and the standard deviation was 6.0 mph. The speeds of each vehicle, as measured by both the detection-control system and the tapeswitch speed trap, were compared and the differences recorded as the "speed-error" term. The distribution of these speed errors is shown in Figure 5-5.

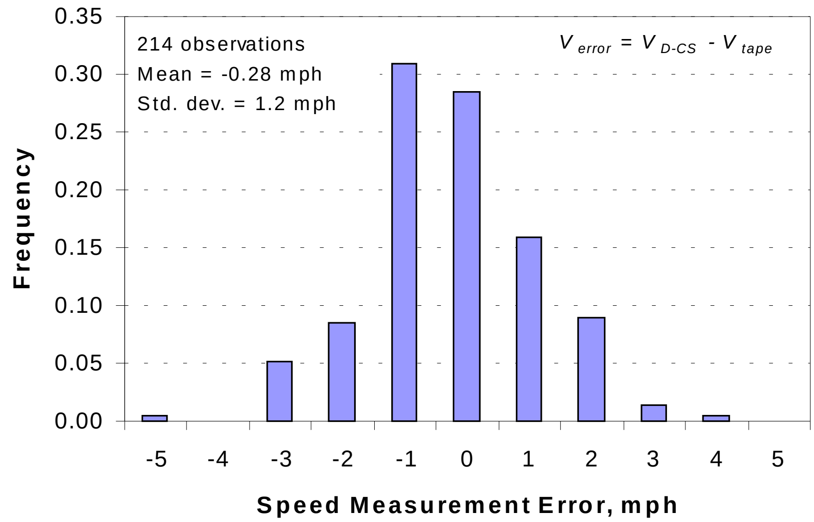


Figure 5-5. Histogram of Speed Error.

The mean speed error was found to be -0.28 mph indicating that the detection-control system was slightly underestimating the true speed. This finding suggests that the average driver arrives slightly *sooner* to his or her dilemma zone than is predicted by the detection-control system. The standard deviation of this error is 1.2 mph.

Speed-Change Behavior

During one hour of study, more than 300 vehicles were observed on the intersection approach. Of these vehicles, many arrived when the signal indication was red and slowed intentionally in preparation of stopping. Others arrived at the start of green, before the waiting queue had cleared, and also slowed intentionally. Finally, some of these vehicles followed turning vehicles and slowed because of the turning vehicle. These intentionally slowing vehicles were removed from the database leaving 118 freely flowing vehicles (104 passenger cars and 14 trucks) that arrived during the green indication. Figure 5-6 illustrates the distribution of speed changes for the 104 passenger cars.

The average speed of the freely flowing passenger cars was 54.1 mph, and the standard deviation was 5.6 mph. The speed distribution for the trucks was very similar to that for passenger cars.

The data shown in Figure 5-6 reflect an average (mean) speed change of -1.0 mph and a standard deviation of 2.6 mph. The negative value indicates that the average driver reduces speed slightly as he or she approaches the intersection. It suggests that drivers will arrive *later* to their dilemma zone than predicted by the detection-control system.

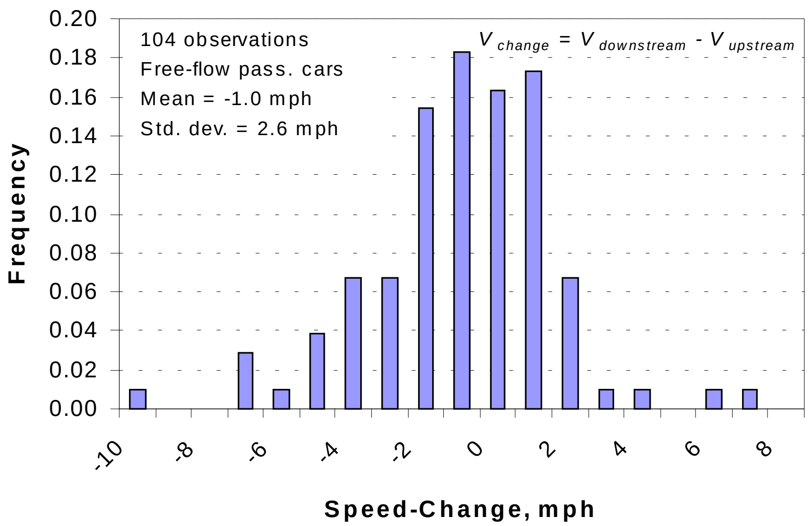


Figure 5-6. Histogram of Speed Change.

Dilemma Zone Boundaries

The implications of the findings described in the previous section are that the detection-control system cannot predict arrivals to the dilemma zone without some error. However, these statistics can be used to adjust the dilemma zone boundaries such that the objective of providing dilemma zone protection to all vehicles can still be achieved.

Bias Due to Error in Speed Prediction

With regard to the bias values of 0.28 and 1.0 mph, these two effects are partially offsetting and result in a net speed bias of 0.7 mph (= 1.0 - 0.28) toward a net average speed reduction. This reduction can be accommodated by shifting (i.e., subtracting) a small amount of time from each of the dilemma zone boundaries. This shift accommodates the net late arrival of the average vehicle. A net bias of 0.7 mph translates into a 0.17 s shift in the zone boundaries for a true average speed of 53 mph (60 mph 85th percentile speed) and a detector distance of 1000 ft. Figure 5-7 is provided to illustrate the amount to be subtracted from the dilemma zone boundaries for other speeds. The 85th percentile speed shown is based on the assumption that the average speed is 88 percent of the 85th percentile speed.

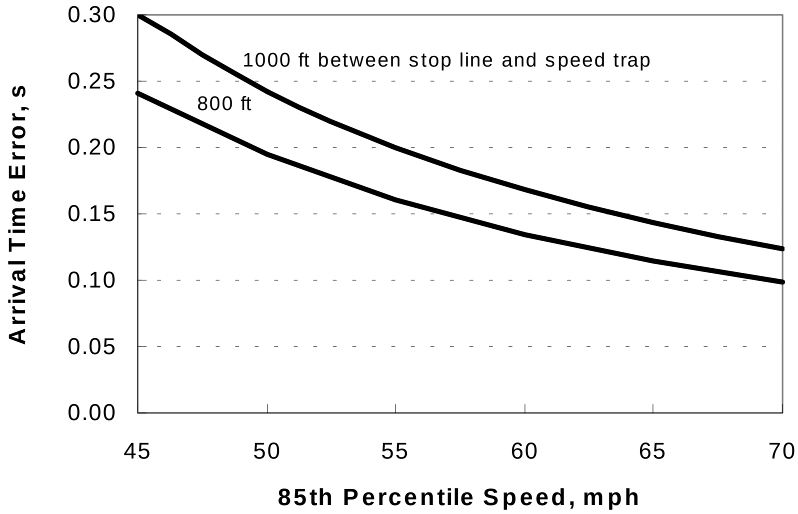


Figure 5-7. Dilemma Zone Shift to Minimize the Effect of Speed Prediction Bias.

Bias Due to Variability in Speed Measurement

The variability in the speed measurement error and in the speed-change data also has implications on the ability of the detection-control system to provide dilemma zone protection for all vehicles. This variability suggests that the actual arrival time to the dilemma zone may vary due to: (1) errors in speed measurement and (2) changes in speed. These two sources of variability add to the amount of uncertainty in the prediction of a vehicle's arrival time to the dilemma zone.

One method of minimizing the effect of speed variability is to increase the width of the dilemma zone (i.e., by adding a small amount of time to the beginning of the actual dilemma zone and by subtracting a small amount of time from the ending of the actual dilemma zone) that is protected by the detection-control system. By increasing the total time duration of the "protected" dilemma zone, it is much more likely that a vehicle will be outside its "true" dilemma zone (i.e., 2.5 to 5.5 s travel time) at yellow onset.

A simulation analysis of the effect of speed variability on arrival time was undertaken to quantify appropriate dilemma zone width adjustments. For this analysis, the total variance of speed prediction S_T^2 was assumed to equal the variance of speed measurement S_m^2 plus that for speed-change S_c^2 (i.e., $S_T^2 = S_m^2 + S_c^2$). The standard deviation of speed measurement S_c was estimated as 1.2 mph. The standard deviation of speed-change S_c was assumed to equal 4.8 percent of the mean speed. The value of 4.8 percent was obtained from the speed-change data shown in Figure 5-6 (i.e., 4.8 = 2.6/54.1 x 100). For an average speed of 54 mph, the total standard deviation S_T was estimated as 2.9 mph (= $[1.2^2 + (54 \times 0.048)^2]^{0.5}$).

The simulation predicted the arrival time of individual vehicles to the dilemma zone where the speed of individual vehicles was normally distributed with a standard deviation of S_T. Four distances were evaluated for each of two average speeds. The four distances were 500, 750, 1000, and 1250 ft. The two speeds simulated were 40 and 60 mph. The results of this simulation analysis are shown in Figure 5-8. Each data point represents the simulation of 500 vehicles for one distance and speed combination.

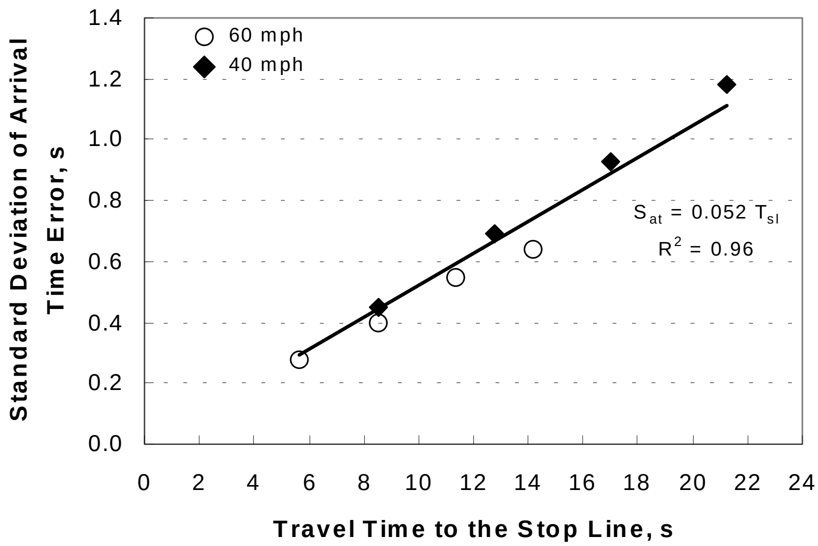


Figure 5-8. Standard Deviation of Arrival Time Error.

The trend line in Figure 5-8 indicates that the standard deviation of arrival time prediction error is linearly related to a vehicle's travel time from the speed trap to the stop line. The best-fit trend line shown indicates the relationship between travel time T_{sl} and standard deviation S_{at} is linear with a slope of 0.052 s/s and an intercept of 0.0 s (i.e., $S_{at} = 0.052\ T_{sl}$).

The relationship shown in Figure 5-8 was converted into a more useful relationship between 85th percentile speed and standard deviation for 800 and 1000-ft distances between the speed trap and the stop line. This relationship is shown in Figure 5-9. The 85th percentile speed shown is based on the assumption that the average speed is 88 percent of the 85th percentile speed.

Figure 5-9 can be used to estimate the necessary increase in width of the dilemma zone to accommodate speed-prediction error. This increase is accommodated by adding a small amount of time to the beginning of the dilemma zone and subtracting a small amount of time from the ending of the zone. An analysis of the effect of the amount of time to be added (and subtracted) indicates that the addition (and subtraction) of 1.5 standard deviations should provide dilemma zone protection for about 97 percent of the approach vehicles.

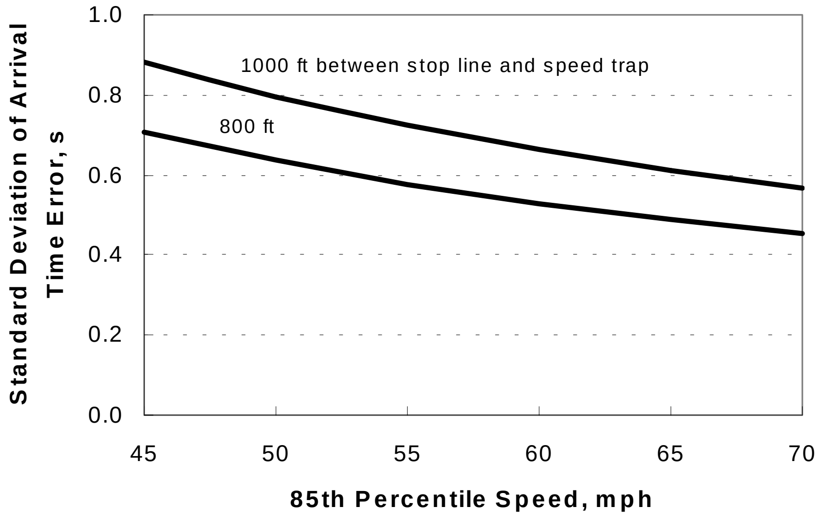


Figure 5-9. Dilemma Zone Increase to Minimize the Effect of Speed Variation.

To illustrate the use of Figure 5-9, consider an intersection approach with a true average speed of 53 mph (60 mph 85th percentile speed) and a detector distance of 1000 ft. Figure 5-9 indicates that the standard deviation of arrival time is 0.67. A multiplier of 1.5 yields a dilemma zone width adjustment factor of 1.0 s (= 1.5 x 0.67). If the beginning of the true dilemma zone is defined to be 5.5 s travel time from the stop line, the adjusted zone boundary would be 6.50 s (= 5.5 + 1.0). Similarly, if the true end of the dilemma zone is defined to be 2.5 s, the adjusted zone boundary would be 1.50 s (= 2.5 - 1.0).

Controller Processing Time and Algorithm Roundoff

Two additional factors influence system performance and can be offset by adjusting the dilemma zone boundaries. The first factor relates to the 0.5-s cycle length of the phase-status component algorithm. The cyclic nature of this component's zone checking process introduces the possibility of missing a vehicle's arrival or departure time by as much as 0.5 s. To eliminate this problem, the algorithm rounds the estimated zone arrival and departure times "outward" (i.e., by rounding the arrival time up to the nearest value evenly divisible by 0.5 s and rounding the departure time down in the same manner). In effect, the dilemma zone boundary is conservatively widened by an average of 0.25 s within the algorithm. To avoid double counting this adjustment, the dilemma zone boundaries entered into the detection-control software should be adjusted "inward" by 0.25 s.

The second factor relates to the time required by the controller to process a phase termination instruction. Specifically, about 0.20 s lapse between the time the controller is instructed to terminate the phase and the yellow is presented. To offset this time lag, the dilemma zone boundaries must be shifted (i.e., increased) by 0.20 s. This lag time would be eliminated if the detection-control system is implemented in a signal controller.

Adjusted Dilemma Zone Boundaries

The findings from the previous sections were combined to determine the net adjustment to the dilemma zone boundaries. Figure 5-10 shows the result of this combination. To illustrate the use of this figure, consider an intersection approach with a true average speed of 53 mph (60 mph 85th percentile speed). The bias of -0.7 mph requires a shift (decrease) in the zone boundaries of 0.17 s. The variability in speeds requires the boundaries to be widened by 1.0 s. The phase-status round-out requires the boundaries to be narrowed by 0.25 s. The controller lag time requires an additional shift (increase) of 0.2 s. Given true dilemma zone boundaries of 5.5 and 2.5 s, the adjusted boundaries are computed as 6.28 s (= 5.50 - 0.17 + 1.0 - 0.25 + 0.20) and 1.78 s (= 2.5 - 0.17 - 1.0 + 0.25 + 0.20).

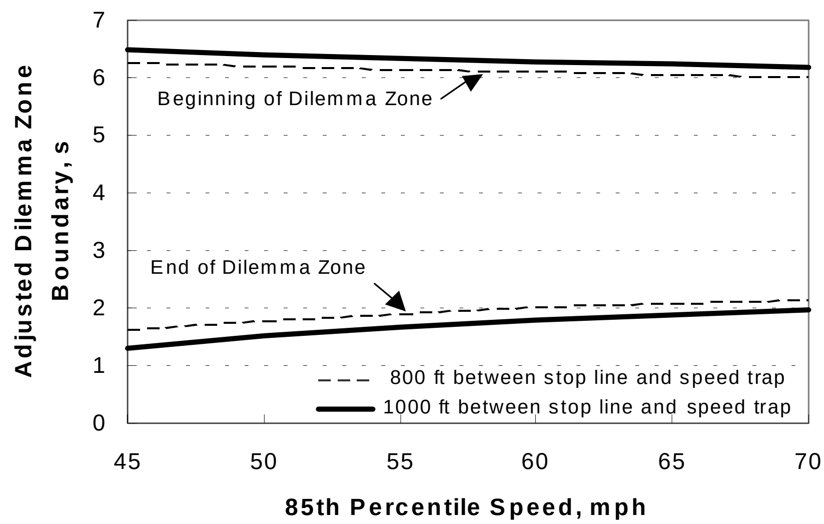


Figure 5-10. Adjusted Dilemma Zone Boundaries.

The trends in Figure 5-10 indicate that the dilemma zone boundaries are insensitive to detector distance and approach speed. Therefore, the beginning and end of the dilemma zone can reasonably be conservatively defined as 6.3 and 1.7 s, respectively, for all applications of the detection-control system. An exception to this definition is described in the next section, as it relates to high-volume four-lane highway intersections.

Detector Location

This section discusses the issues associated with the location of the system's detection zone. In this regard, the zone's "location" is defined as the distance between its trailing edge and the stop line (see Figure 3-3). The factors that must be considered when determining this distance include: speed, dilemma-zone boundaries, classifier processing time, and vehicle length. The effect of each of these factors on detector location is addressed in the following paragraphs.

Minimum Detector Location Distance

The closest distance between the detector and the stop line is computed as:

$$D_{\min} = L_{tk} + V_{85}\,(T_{bz} + T_{lag}) \tag{3}$$

where:

D_{min} = minimum distance between the trailing edge of the detection zone and the stop line, ft;
L_{tk} = maximum truck length (use 65 ft), ft;
V_{85} = 85th 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 6.3 s), s; and
T_{lag} = classifier processing time (use 0.025 s), s.

The minimum distances for a range of approach speeds are listed in column 2 of Table 5-4. The maximum distances shown are the subject of discussion in the next section.

Table 5-4. Minimum and Maximum Detector Location Distances.

85% Approach Speed, mph	Minimum Distance, ft[1]	Maximum Distance, ft[2]
45	483	888
50	530	984
55	576	1081
60	623	1177
65	669	1274
70	716	1370

Notes:
1 - Based on a 65-ft truck length, 6.3 s to the beginning of the dilemma zone, and 0.025-s classifier processing time.
2 - Based on an 20-ft passenger-car length, 1.7 s to the end of the dilemma zone, and a 15-s minimum green.

The minimum distance obtained from Equation 3 will provide the detection-control system with sufficient time to identify the presence of almost 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. A larger distance would allow for some look-ahead time. As noted in Chapter 3, look-ahead time offers an advantage during high-volume conditions. Under these conditions, a few seconds of look-ahead time allows the system to identify the time in the near future where there are the fewest vehicles in the dilemma zone.

Maximum Detector Location Distance

The furthest distance between the detector and the stop line is computed as:

$$D_{\max} = L_{pc} + V_{15}\,(G_{\min} + T_{ez}) \qquad \textbf{(4)}$$

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 20 ft), ft;
V_{15} = 15^{th} 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 1.7 s), s.

The maximum distances for a range of approach speeds are listed in column 3 of Table 5-4.

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 can accurately predict the "best time to end the phase." If the detection zone is located at a distance in excess of that obtained from Equation 4, the detection-control system may not have complete knowledge of all approach vehicles when the minimum green times out.

The range of distances reported in Table 5-4 suggests that detectors located between 750 and 1000 ft should work for any intersection where the 85^{th} percentile approach speed is in the range of 45 to 70 mph. In other words, the detection-control system is able to accommodate a very wide range of speeds with the same detector installation *and* there is a wide range of distances within which these detectors can be installed without compromising system performance.

Optimum Detector Location Distance

As discussed in a preceding section, a nominal look-ahead time is needed to improve the level of dilemma-zone protection during high-volume conditions (i.e., when the total major-road flow rate exceeds 1000 veh/h). In theory, the 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.

The benefit of the look-ahead feature is illustrated in Figure 5-11. The duration of the look-ahead feature is directly related to, and increases with, the distance from the detection zone to the stop line. The dependent variable shown is the "probability of error." It represents the probability that one or more vehicles is in the dilemma zone at the onset of yellow. High-flow-rate conditions are considered in these figures as they tend to be the most challenging for any detection system to serve. As flow rate decreases, the probability of error decreases and tends to be smallest at the shorter distances.

Figure 5-11a illustrates the effect of the look-ahead feature at an intersection on a two-lane highway. Figure 5-11b illustrates its effect at a four-lane highway intersection. In each figure, one trend line illustrates the effect of distance (or look-ahead time) on the probability of intentionally catching one or more vehicles in its dilemma zone. A second line illustrates the effect of distance on the probability of making an error in the prediction of a vehicle's travel time through the dilemma zone such that it is "caught" in the zone at yellow onset. The thick (or "combined probability") line represents the joint probability of making one or both of these errors.

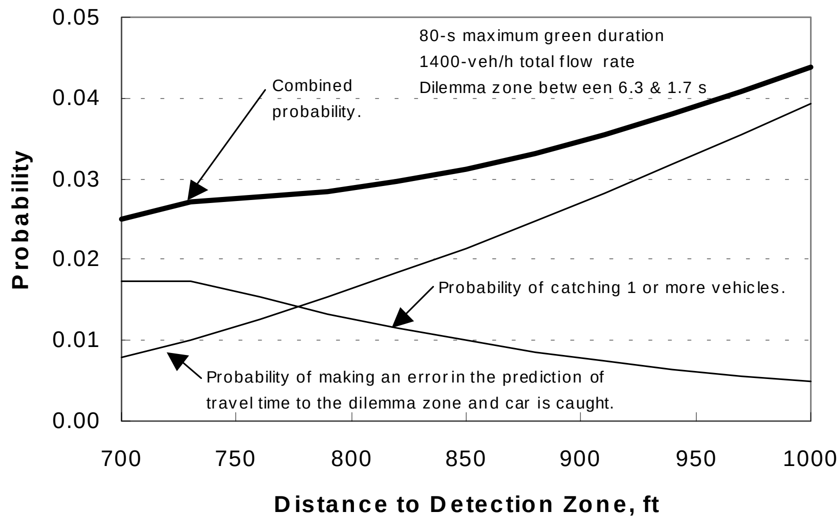
For two-lane highway intersections, the trends in Figure 5-11a indicate that the probability of error is relatively low, regardless of detector location. The probability increases slightly with increasing distance which suggests that the look-ahead feature offers no benefit. Hence, the trend suggests that system detectors could be installed between 700 and 800 ft without loss of performance.

For four-lane highway intersections, the decrease in probability of error with increasing distance indicates that the look-ahead feature offers some benefit. Specifically, it minimizes the frequency of catching a vehicle in the dilemma zone under high-flow-rate conditions. The "combined probability" trend line suggests that system detectors should be installed between 800 and 1000 ft for best performance. It should be noted that the dilemma zone boundaries used for this analysis were defined as 5.8 and 2.2 s (not 6.3 and 1.7 s). These boundaries were used to reduce the probability-of-catching-1-or-more vehicles to acceptable levels. These boundaries should be used for all four-lane highway applications of the detection-control system if the total flow rate on the major-road exceeds 2000 veh/h during peak periods.

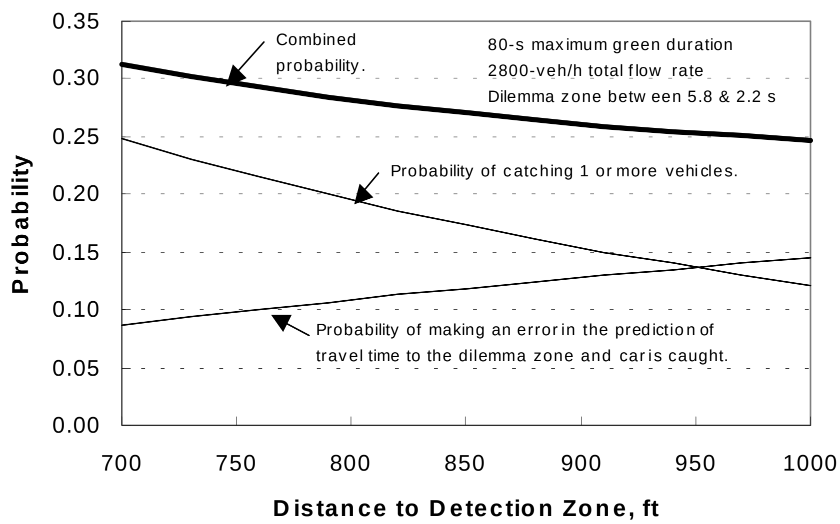
Control Settings

Maximum Green

The maximum-green setting for the detection-control system corresponds to the total time available to the first and second "stages" (as described in Chapter 3). This setting is similar to that used in a signal controller; however, the setting discussed in this section is entered directly into the software for the detection-control system. Also directly entered into the software is the duration of the first stage.



a. Two-Lane Highway.



b. Four-Lane Highway.

Figure 5-11. Probability of Catching Vehicles in the Dilemma Zone.

Limited research has been conducted on the implications of various values of this setting or on its optimal value. Moreover, limited research has been conducted regarding the optimal duration of stage one or stage two. However, preliminary investigations indicate the following rules will yield acceptable operation:

- The first stage should be about equal in duration to the maximum-green setting for the subject phase *if* it were controlled with stop-line-only detection.
- The second stage should be about 40 s.

The first point reflects the fact that the detection-control system functions like any other actuated intersection (with stop-line-only detection) during the first stage. The maximum-green setting for stop-line-only detection typically ranges from 30 to 60 s. Lower values in this range are likely to minimize delays and larger values are likely to minimize the frequency of max-out. Given that max-outs are precluded by the detection-control system's second stage, it is recommended that the duration of the first stage be set to a value in the range of 30 to 40 s. The value selected should be sufficiently long to consistently clear the queue at the start of green during the peak traffic hours.

Once the stage one duration G_1 is established, the maximum-green setting G_{max} is computed as the sum of the stage one and stage two durations. Specifically, it is computed by adding 40 s to the stage one duration (i.e., $G_{max} = 40 + G_1$). This computation yields a stage two duration that is sufficiently long as to preclude max-out under even the highest volume conditions. Although the stage two duration may be longer than the stage one duration, the criteria for stage two "gap-out" (i.e., one or less passenger cars) is much easier to satisfy and tends to be found fairly quickly during all but the highest volume conditions. The resulting phase duration is thereby kept reasonably short such that delays are short to waiting movements. Moreover, the phase is terminated in a relatively safe manner, relative to termination by max-out.

Minimum Green

The detection-control system does not have a minimum-green setting. Rather, it honors the minimum-green setting in the controller and does not impose phase control decisions until after the minimum green has expired (and the passage timer has timed out for the first time). However, the value of the minimum-green setting is important to the safe and efficient operation of the detection-control system. As previously noted with regard to Equation 4, a nominal minimum-green setting is needed by the detection-control system to ensure that the position of all approaching vehicles is "known" when it takes control of the phase.

Figure 5-12 illustrates the relationship between the "shortest" possible minimum-green setting, detector location, and approach speed. The trend lines in this figure indicate that the shortest minimum green increases with the distance between the detection zone and stop line. In contrast, the shortest minimum green decreases with increasing speed. The trends in Figure 5-12 indicate that a minimum-green setting of 15 s is suitable for almost all situations. Slightly longer values should be used if the detection distance exceeds 900 ft and the speed is 45 mph.

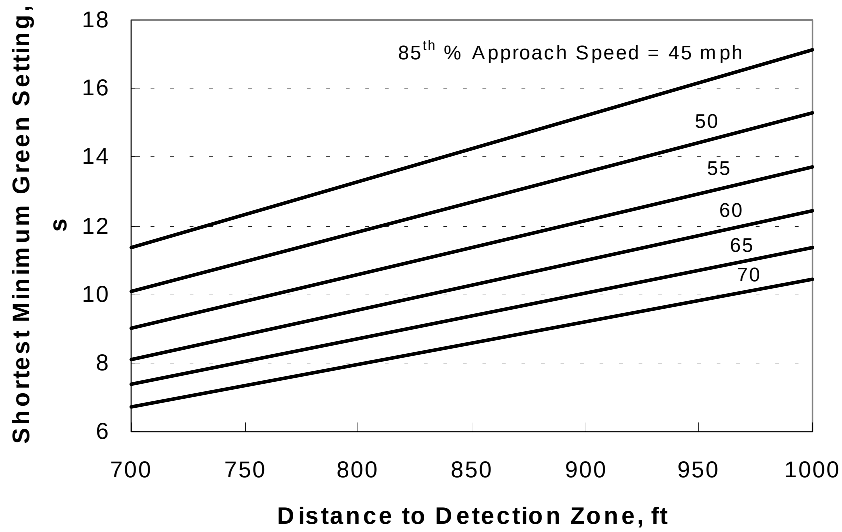


Figure 5-12. Shortest Minimum-Green Setting.

Detection Cost Comparison

An analysis of the initial costs of installing the detection equipment for the detection-control system was conducted. This analysis included the cost of installing the loop detectors needed by the detection-control system (with two loops per lane) and the typical multiple advance detector system (with three loops per lane). The unit costs for the associated wire, trenching, and conduit were obtained from the bid sheets received for the two systems installed for this project. These costs were also compared (and adjusted slightly) to reflect the unit costs paid by TxDOT for the installation of loop detectors at rural intersections. The cost of the stop-line loops is not included. The results of this analysis are illustrated in Figure 5-13 for an intersection on a two-lane highway.

The trend lines in Figure 5-13 recognize the increasing cost of the detection-control system as distance between the detection zone and the stop line increases. The trend lines indicate that the initial cost of a multiple advance detector system is about $13,800 (three loops on each of two approaches). The initial cost for the detection control system varies from $12,600 when the two-loop trap is located at 600 ft to $18,600 when the trap is located at 1000 ft. Both trend lines increase about $4,000 when the highway has four lanes (i.e., two lanes on each intersection approach).

The intersection point of the two lines in Figure 5-13 is at 680 ft. At this point, the initial cost of detection for both systems is about equal. Beyond this point, the cost of trenching associated with the detection-control system exceeds the cost of the third loop detector associated with the multiple advance detector system.

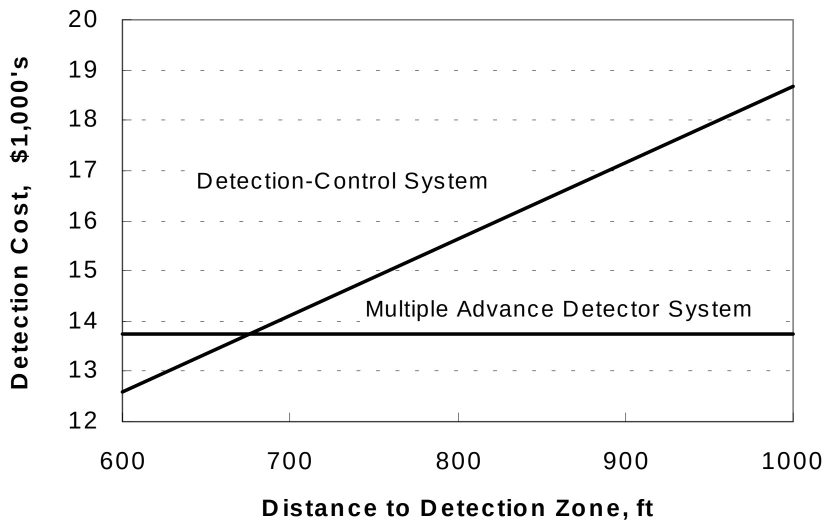


Figure 5-13. Comparison of Initial Costs of Detection Equipment for Two Systems.

CHAPTER 6. CONCLUSIONS

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 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 system ends the phase safely because the approach is empty (i.e., unoccupied). However, this gap occurs infrequently on high-volume approaches and the search for it frequently 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. This type of phase termination increases the potential for a rear-end crash.

Other problems exist with the 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 project was 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 and conclusions from the research conducted for this project.

SUMMARY OF FINDINGS

Alternative Detection Systems

Several types of detection 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 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 systems discussed in this report.

Table 6-1. Comparison of Alternative Detection Systems.

Operating Characteristic		Detection 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.[1]	--	--	--	✔
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.		--	✔[2]	--	✔

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. It 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 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.

Detection-Control System

System Description

A detection-control system was developed for this research to overcome the limitations of existing detection systems. The detection-control system consists of one detection zone per lane (with the ability to measure vehicle speed and length) located several seconds travel time in advance of the dilemma zone. The location of this detection is based on a desire to have the system "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 system will operate with less delay (through shorter phase durations) and with fewer vehicles caught in the dilemma zone than the multiple advance detector system.

System Evaluation

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

The detection-control system was installed and studied at two intersections in Texas. The objectives of this activity were to demonstrate that the detection-control system could: (1) feasibly be installed and operated in the field, and (2) provide equal (or better) performance than a multiple advance detector system. The results of the field studies indicate that the system is able to perform as well as the multiple advance detector system under low-flow-rate conditions. High flow-rate conditions were not studied.

Design Considerations

The location of the detectors used with the detection-control system was evaluated in terms of its effect on system accuracy. This evaluation considered the speed prediction error and the ability of the system to identify a suitable time to end the phase (within a given look-ahead time interval). Detector "location" is defined in terms of the distance between the detection zone and the stop line. The results of this analysis indicate that the detectors for the detection control system should be located 700 to 800 ft from the stop line at two-lane highway intersections (i.e., single-lane approaches) and between 800 and 1000 ft at four-lane highway intersections. These distances are likely to be associated with a minimum number of vehicles being caught in the dilemma zone at the onset of yellow.

An analysis of detector installation costs indicates that the detection-control system is cost-competitive with the multiple advance detector system at distances of less than 750 ft. Hence, it should always be installed at two-lane highway intersections whenever conditions suggest that advance detection is needed. The detection-control system's initial cost is likely to exceed that of the multiple advance detector system at four-lane highway intersections. However, the safety and operational benefits of the detection-control system are likely to offset its added cost at these locations.

CONCLUSIONS

The objective of the detection-control system is to effectively and efficiently detect and control the major-road approaches to an isolated signalized intersection. This objective was achieved by developing a system with the following benefits (relative to the multiple advance detector system):

- reduces the frequency of vehicles being caught in the dilemma zone at the onset of yellow and the frequency of red-light running;
- reduces the cost of design, installation, and maintenance of advance detection;
- provides a sensitivity to the presence of trucks with the potential to eliminate the possibility of catching a truck in the dilemma zone; and
- maintains or reduces overall delays.

The first benefit is realized 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." In short, the detection-control system is a "dynamic" dilemma-zone monitoring process because it identifies the dilemma zone for *each* vehicle, in *real time*, and *prior* to when the information is needed. It differs from the operation of the multiple advance detector system because the latter system searches for a time when a segment of each approach is clear of vehicles.

The detection-control system offers two safety benefits. First, it provides dilemma-zone protection to *all* drivers. The multiple advance detector system does not guarantee that the fastest or slowest 15 percent of vehicles are clear of their respective dilemma zones at the onset of yellow. Second, the detection-control system can relax its "gap-out" selection criteria after trying unsuccessfully to find an empty zone for the first 30 to 40 s of green. In its relaxed state, the detection-control system allows up to one car per lane (but no truck) to be caught in its dilemma zone at the onset of yellow. This feature is especially useful during higher flow rates when a search for a "clear" approach would frequently lead to max-out. It is argued that ending the phase with one car in the dilemma zone is reasonably safe (from a rear-end crash) and preferable to ending with no protection (via max-out).

The second benefit is realized in two ways. First, 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 multiple advance detector system requires engineering oversight during its design and installation as several key design elements and controller settings are dependent on design speed. Second, 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 for the multiple advance detector system would have to be reinstalled if the approach speed is permanently changed.

The third benefit is realized by measuring the length of the approaching vehicles and using this information to postpone phase termination whenever "long" vehicles (e.g., trucks) are in the dilemma zone. The multiple advance detector system does not provide this sensitivity.

The fourth benefit is realized in two ways. First, it is partly achieved by 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 multiple advance detector system which translates into shorter phases and lower overall delay. Second, the detection-control system does not allow the stop-line detector to extend the phase once the queue has been served. This feature reduces wasted green time at the end of the phase and minimizes delay to waiting vehicles. These benefits are most evident at higher flow rates.

CHAPTER 7. REFERENCES

1. Zegeer, C.V. and R.C. Deen. "Green-Extension Systems at High-Speed Intersections." *ITE Journal*, Institute of Transportation Engineers, Washington, D.C., November 1978, pp. 19-24.

2. ITE Technical Committee 18 (P.S. Parsonson, Chairman). "Small-Area Detection at Intersection Approaches." *Traffic Engineering*. Institute of Transportation Engineers, Washington, D.C., February 1974, pp. 8-17.

3. Bonneson, J.A., P.T. McCoy, and B.A. Moen. *Traffic Detector Design and Evaluation Guidelines.* Report No. TRP-02-31-93. Nebraska Dept. of Roads, Lincoln, Nebraska, April 1994.

4. Middleton, D., R. L. Nowlin, M. Shafer, A. H. Parham, and D. Jasek. *Evaluation of Detector Placement for High-Speed Approaches to Signalized Intersections.* Report No. TX-98/3977-1. Texas Department of Transportation, Austin, Texas, September 1997.

5. Bonneson, J.A. and P.T. McCoy. *Manual of Traffic Detector Design*. 1st ed. Institute of Transportation Engineers, Washington, D.C., June 1994, pp. 42-47.

6. Wu, C-S., C. Lee, R. Machemehl, and J. Williams. "Effects of Multiple-Point Detectors on Delay and Accidents." *Transportation Research Record 881*, Transportation Research Board, Washington, D.C., 1982, pp. 1-9.

7. Bonneson, J.A. and P.T. McCoy. "Traffic Detector Designs for Isolated Intersections." *ITE Journal,* Institute of Transportation Engineers, Washington, D.C., August 1996, pp. 42-47.

8. Tarnoff, P.J. and P.S. Parsonson. *NCHRP Report 233: Selecting Traffic Signal Control at Individual Intersections.* National Cooperative Highway Research Board, Washington, D.C., 1981.

9. Middleton, D., D. Jasek, H. Charara, and D. Morris. *Evaluation of Innovative Methods to Reduce Stops to Trucks at Isolated Signalized Intersections.* Report No. TX-97/2972-S. Texas Department of Transportation, Austin, Texas, September 1997.

10. Sunkari, S. and D. Middleton. *Draft Final Report: Evaluation of the Truck Priority Project in Sullivan City.* Project 0-1439. Texas Transportation Institute, College Station, Texas, February 2000.

11. Peterson, A., T. Bergh, and K. Steen. "LHOVRA: A New Traffic Signal Control Strategy for Isolated Junctions." *Traffic Engineering and Control*, vol. 27, no. 7/8, July/August 1986, pp. 388-389.

12. Kronborg, P. and F. Davidsson. "MOVA and LHOVRA: Traffic Signal Control for Isolated Intersections." *Traffic Engineering and Control*, vol. 34, no. 4, April 1993, pp. 195-200.

13. Orcutt, F.L. *The Traffic Signal Book.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1993.

14. Kronborg, P., F. Davidsson, and J. Edholm. *SOS–Self Optimising Signal Control: Development and Field Trials of the SOS Algorithm for Self-Optimising Signal Control at Isolated Intersections*. TFK (Transport Research Institute) Report 1997:2E, Stockholm, Sweden, 1997.

15. J.A. Bonneson, D. Middleton, K. Zimmerman, H. Charara, and M. Abbas. *Development and Evaluation of a Detection-Control System for Rural Intersections.* Report No. FHWA/TX-02/4022-1. Texas Department of Transportation, Austin, Texas, September 2001.

16. *Highway Capacity Manual 2000*. 4th ed. Transportation Research Board, Washington, D.C., 2000.

APPENDIX A:

DESIGN GUIDELINES

INTRODUCTION

This appendix documents guidelines for installing and operating the detection-control system. The installation guidelines address traffic and geometric conditions that are amenable to the use of the detection-control system. These guidelines also address the best location for the system's detection zone (i.e., speed-trap). Guidelines for operating the detection-control system describe the optimum values for three control settings: dilemma zone boundaries, maximum green, and minimum green.

INSTALLATION GUIDELINES

Application Considerations

The detection-control system is intended for use at isolated, full-actuated intersections on high-speed roadways. The intersection should have a major road and a minor road where the major-road approach has an 85^{th} percentile speed (or posted speed limit) of 45 mph or more. Detection zones for the system must be installed in each lane of both major-road approaches. The intersection must operate in isolation of other, adjacent signalized intersections. A left-turn bay is required for each major-road approach, and a right-turn bay (or full-width shoulder) is desirable.

The detection-control system should be considered at new intersections whenever multiple advance detection is being contemplated. At existing intersections with multiple advance detectors, the detection-control system should be considered as a replacement system when the design life of the existing system has been reached.

Extensive simulation and field study have shown that the system is able to function safety and efficiently for all traffic volume levels. However, its performance is degraded by frequent turning activity from the major-road approaches. For this reason, its benefits will be diminished as the total turn percentage (i.e., the sum of the left-turn percentage and the right-turn percentage) increases. Performance has been shown to be very good when the total turn percentage is less than 40 percent.

Detector Location

The detection control system has two requirements regarding intersection detection. First, stop-line detectors are needed for all signalized intersection traffic movements. Second, a detection zone is needed in each through traffic lane of both major-road approaches. Detection zone location is defined as the distance between the trailing edge of the detection zone and the stop line.

An analysis of system accuracy indicates that there is a range of distances within which the detection-control system will operate safely and efficiently. This analysis indicates that system detectors should be installed between 700 and 800 ft at two-lane highway intersections. System detectors should be installed between 800 and 1000 ft at four-lane highway intersections. Detectors located within these ranges will: (1) provide the detection-control system with sufficient time to identify the presence of almost all vehicles and to record these vehicles' arrival to the dilemma zone and (2) allow the system to locate all vehicles on the approach before the minimum green times out and, thereby, accurately predict the "best time to end the phase."

CONTROL SETTINGS

Dilemma Zone Boundaries

The detection-control system software accepts, as input, two values that collectively define the dilemma zone boundaries. One value corresponds to the travel time between the *beginning* of the dilemma zone and the stop line. The second value corresponds to the travel time between the *end* of the dilemma zone and the stop line. The beginning and end of the "true" dilemma zone is generally defined as 5.5 and 2.5 s, respectively.

Studies of driver speed-change behavior and speed-measurement precision indicate that the aforementioned boundaries need to be adjusted slightly for use with the detection-control system. These adjustments are intended to minimize errors associated with the vehicle's predicted arrival to the dilemma zone. The "adjusted" beginning and end of the dilemma zone entered into the detection-control system software should be 6.3 and 1.7 s, respectively. With one exception, these adjusted boundaries are appropriate for all intersections and approach speeds. Adjusted boundaries of 5.8 and 2.2 s should be used at four-lane highway intersections if the total flow rate on the major road exceeds 2000 veh/h during peak traffic periods.

Maximum Green

The maximum-green setting for the detection-control system corresponds to the total time allocated to the first and second stages. This setting is similar to that used in a signal controller; however, the setting discussed in this section is entered directly into the detection-control system software. Also directly entered into the software is the duration of the first stage. The following rules can be used to determine the length of these two settings:

- The first stage should be 30 to 40 s in length with longer values in this range used only if needed to ensure queue clearance during peak traffic hours.
- The second stage should be about 40 s.

Once the stage one duration G_1 is established, the maximum-green setting G_{max} is computed as: $G_{max} = 40 + G_1$.

Minimum Green

The detection-control system software does not have a minimum-green setting. Rather, it honors the minimum-green setting in the controller and does not impose phase control decisions until after the minimum green has expired (and the passage timer has timed out for the first time). However, the value of the minimum-green setting is important to the safe and efficient operation of the detection-control system.

Figure A-1 illustrates the relationship between the "shortest" possible minimum-green setting and detector location for a range of approach speeds. In application, Figure A-1 is consulted after the 85th percentile approach speed is defined and the distance to the detection zone is determined. These two values are then used with Figure A-1 to determine the shortest possible minimum green; any minimum-green setting that exceeds the shortest possible value will allow the detection-control system to operate effectively.

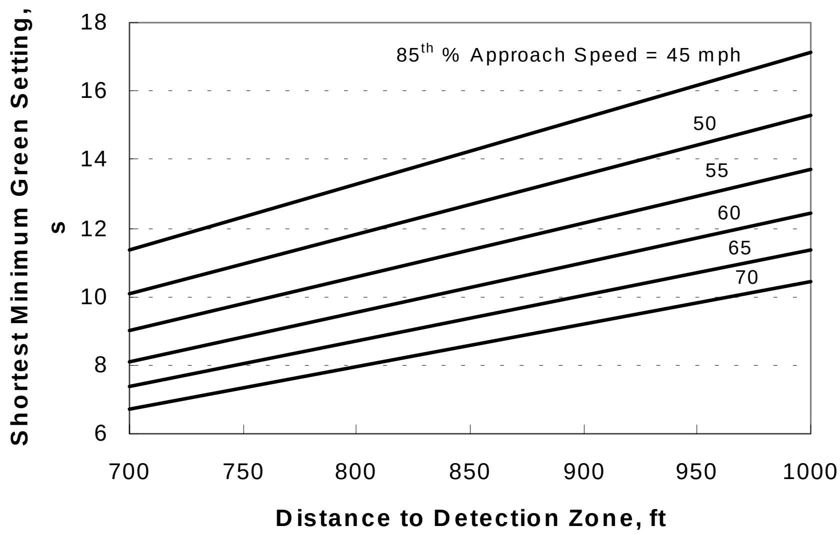


Figure A-1. Shortest Minimum-Green Setting.

As an alternative to the use of Figure A-1, a minimum-green setting of 15 s (or more) can be consistently used for all detection-control system installations. The only exception is when the detection distance exceeds 900 ft and the speed is 45 mph. In this instance, a 17-s minimum-green setting is appropriate.

APPENDIX B:

SYSTEM SPECIFICATIONS

TEXAS DEPARTMENT OF TRANSPORTATION
SPECIAL SPECIFICATION
8XXX
Detection-Control System for Traffic Signals

1.0 GENERAL

This specification sets forth the procurement, installation, and performance requirements for the detection-control system (D-CS) for traffic signals. This system is intended for isolated, full-actuated intersections on high-speed roadways. Its objective is to improve the safety and operation of these intersections. This objective is achieved by controlling the phase length of the major-road through phase. A pair of inductive loop detectors are placed in each major-road traffic lane at least 700 ft upstream of the intersection in a speed-trap configuration. As a vehicle passes over these loops, the detection information is fed into a classifier that determines the vehicle's speed and length. Using this information, the detection-control algorithm, operating within a computer at the intersection, calculates when that vehicle will be in its "dilemma zone" on the intersection approach. It then prevents the phase from ending when one or more vehicles are in the dilemma zone.

The detection-control system can monitor up to two through traffic lanes on each major-road approach. It also monitors all of the minor movement detectors so that these movements can be serviced efficiently. User input to the detection-control algorithm includes maximum green, distance from the stop line to the detector traps, travel time from the beginning of the dilemma zone to the stop line, and travel time from the end of the dilemma zone to the stop line.

1.1 Definitions

1.1.1 <u>Stand-Alone Computer</u>: A stand-alone computer is a Windows®-based computer system capable of multiple functions including service as the algorithm processor. The computer shall be hardened to withstand environmental conditions more extreme than normally encountered indoors.

1.1.2 <u>Microcontroller</u>: A microcontroller is a specialized computer system specifically designed for service as the algorithm processor.

1.1.3 <u>Field Setup Terminal</u>: A field setup terminal is a portable terminal consisting of a monitor and a keyboard. This terminal shall have at least one input for VGA video and one input for standard 128-key keyboard, as provided by the stand-alone computer or microcontroller.

1.1.4 <u>Through Travel Lane</u>: A lane that is continuous on both sides of the intersection and in which traffic is allowed to cross the intersection. Left-turn lanes and right-turn lanes are not considered through travel lanes.

1.1.5 Vehicle Classifier: A stand-alone device used to monitor the upstream detector pairs and compute vehicle speed and length. It is used with the stand-alone computer and is housed in the controller cabinet. If a microcontroller is used to implement the detection-control system, the classifier functionality may be incorporated into the microcontroller software.

2.0 VEHICLE DETECTION SYSTEM COMPONENTS

2.1 Materials and Hardware

2.1.1 Inductive Loop Detectors: The detection-control system uses two 6 ft by 6 ft inductive loops in each through travel lane, placed upstream of the intersection. A special feature of this design is that each loop shall have six (6) turns of wire. Otherwise, the design shall be in conformance with Item 688, "Traffic Signal Detectors." Key features of Item 688 include that detector loop wire shall be stranded copper No. 14 AWG XHHW cross-linked-thermosettting-polyethylene insulated conductor conforming to IMSA 51-3.

2.1.2 Detector Loop Lead-In Cable: One lead-in cable shall be provided from each loop detector. A special feature of this design is that the cable shall be shielded twisted No. 12 AWG. Otherwise, the design shall meet all the requirements of IMSA 50-2, which includes but is not limited to the requirements specified for Type C cable in Item 684, "Traffic Signal Cables."

2.1.3 Loop Amplifier: A two-channel loop amplifier (or detector unit) shall be provided for each pair of inductive loop detectors (i.e., one amplifier per through travel lane). These loop amplifiers may be stand-alone or rack mounted. If rack mounted, the amplifiers must have a rack separate from any other loop amplifiers in the cabinet. Loop amplifier units shall comply with Special Specification 6001, "Digital Loop Vehicle Detector Unit."

2.2 Installation and Testing of D-CS Loop Detectors

There shall be two loops per travel lane. The spacing of the loops shall be 16 ft trailing edge to trailing edge and the loops shall be centered in each through lane. The trailing edge of the trailing loop shall be at a distance from the stop line specified on the plan sheets. A special feature of this design is that each loop shall be provided with its own lead-in cable to the cabinet. Otherwise, the installation of each loop detector shall be in compliance with Item 684, "Traffic Signal Cables."

2.2.1 Inductive Loop Layout: Each loop layout shall be 6.0 ft by 6.0 ft square with 8.5 ft between each pair of diagonally opposite corners. When cutting the pavement, the contractor shall not deviate more than 0.5 inch from the chalk line on leading edges of loops and no more than 1.0 inch on all other sides of the square loops. The contractor shall either cut diagonals on corners or shall round the corners to a minimum 1.0-inch radius for the full depth of the cuts. All sharp edges at corners and elsewhere shall be removed. The contractor shall not create excessive "gaps" at loop corners. All saw cuts shall be filled with loop sealant flush with the pavement surface.

2.2.2 Inductive Loop Saw Cuts: The saw cut depth shall allow six (6) turns of loop wire to be placed such that each turn in the leading edge of each loop is “stacked” on the previous turn. Each successive wire turn shall touch the one installed below it (or before it) and the wire turns shall remain contiguous following application of the loop sealant. Backer rod is not required. The contractor shall install all turns in a clockwise direction and shall mark the beginning end on each loop.

The loop saw cuts shall be vertical and shall be at least wider than the diameter of the loop wire, up to a maximum of 0.25 inch. The top wire may be as much as 1.5 inches below the surface, but not less than 1.0 inch below the surface. The saw cut depth shall be a minimum of 2.5 inches and a maximum of 3.0 inches measured at any point along the loop perimeter.

The width of home-run saw cuts shall be at least 0.25 inch wider than twice the diameter of the loop wire, up to a maximum of 0.5 inch. The top wire in the home-run cut may be as much as 1.5 inches below the surface, but not less than 1.0 inch below the surface.

2.2.3 Wire Twists in Home-Run Cut: A special feature of this design is that the contractor shall twist loop wire leads a minimum of five (5) twists per foot from feeder slot to the first ground box.

2.2.4 Testing Loop Wires: TxDOT (or the contracting agency) will test all loop wires at the first ground box prior to the contractor applying loop sealant. If any failures are discovered in the loop wire conductor, the contractor will be required to replace the loop wire.

2.2.5 Loop Sealant: The contractor shall completely encapsulate the loop conductors with sealant both in the loop proper and along the wire leads. A minimum of 1.0 inch of sealant shall be provided between the top of the conductors and the top of the saw cut. The contractor shall fill saw cuts completely with sealant such that it is flush with the top of the saw cuts. The sealant shall be either 3-M loop sealant or TA-500.

2.3 Installation and Testing of D-CS Lead-In Cable

A special feature of this design is that each loop shall be provided with its own lead-in cable to the cabinet. Otherwise, installation of lead-in cable shall be in compliance with in Item 684, “Traffic Signal Cables.”

2.3.1 Loop Lead-In Cable: A special feature of this design is that the loop lead-in cables shall be long enough to extend from the first ground box to the cabinet without splicing. Some additional length shall be provided to allow sufficient slack to make connections at each end.

The contractor will pull the lead-in cables from the first ground box to the cabinet. The shield shall be left unconnected, insulated at the splice point, and grounded only in the control cabinet until inspected by the contracting agency. If the lead-in cable fails testing, the contractor shall remove the defective cable and replace it.

2.3.2 Cable Splices: A special feature of this design is that there shall be only one (1) splice between the loop and the cabinet. That one splice shall be in the first ground box and connect the loop to the lead-in cable. The contractor will be responsible for soldering and sealing all connections in the first ground box with 3-M Scotchcast.

2.3.3 Ground Boxes: The ground boxes shall be consistent with Standard Plan "Electrical Details - Ground Boxes" ED (3) - 00. The size shall conform to Type A on the standard sheet.

2.3.4 Conduit: The lead-in cable shall be in conduit that is in conformance with Item 618, "Conduit."

2.4 Installation and Testing of D-CS Loop Amplifiers

The loop amplifiers (or detector units) for the detection-control system shall be installed as stand-alone or rack-mount. If installed as rack-mount, the rack shall be separate from any other detection rack in the controller cabinet. Each loop shall be assigned to a separate amplifier channel. The loop amplifiers shall be connected to the vehicle classifier, not to the traffic signal controller.

Loop amplifier function shall be tested by TxDOT (or the contracting agency) to comply with Special Specification 6001, "Digital Loop Vehicle Detector Unit."

3.0 DETECTION-CONTROL SYSTEM COMPONENTS

3.1 Materials and Hardware for D-CS

3.1.1 Vehicle Classifier: The vehicle classifier shall be capable of speed measurement within ±2.0 mph with 95 percent level of confidence and vehicle length measurement within ±3.0 ft with 95 percent level of confidence. The vehicle classifier shall have sufficient input channels to classify vehicles on four through movement lanes at the intersection (two lanes per approach). The vehicle classifier shall also have a display where the classifier's settings can be viewed or modified without the need for any external display devices.

3.1.2 Algorithm Processor: The detection-control system requires a processor capable of operating the algorithm software. The algorithm processor shall be a stand-alone computer or a microcontroller capable of providing the same functionality as the stand-alone computer. Disconnection of the algorithm processor from the traffic controller shall not affect the controller's operation.

3.1.2.1 Stand-Alone Computer: The stand-alone computer's central processing unit (CPU) shall be at least equivalent to a 700-MHz processor. The stand-alone computer shall have at least 1 ISA slot, 2 PCI slots, and a 65-watt AC power supply. The stand-alone computer shall be equipped with a 20 GB hard disk drive, at least 128 MB of RAM, and VGA video. The processor shall be provided with surge protection and an uninterruptible power supply (UPS) capable of operating the D-CS for 15 minutes to allow for occasional, short-term electrical service disruptions.

The stand-alone computer shall have the Windows-2000® operating system and any associated service packs. All peripherals shall be compatible with this hardware and operating system. In addition to the operating system, the computer shall have the control algorithm installed, as well as a remote control software package specified by the contracting agency and any classifier test software.

3.1.2.2 Microcontroller: The microcontroller shall be capable of operating the detection-control algorithm in a manner identical to that obtained when the algorithm is operated on the stand-alone computer. In addition, the microcontroller may incorporate elements of the vehicle classifier.

The microcontroller shall be able to communicate remotely with a computer operating the Windows-2000® operating system and remote control software. The microcontroller shall allow for direct entry of setup parameters via the field setup terminal as well as accepting remote instructions from a Windows-2000®-based computer. The microcontroller shall be capable of serial communications.

The microcontroller shall be shelf or rack mountable. The maximum outside dimension, excluding connectors, shall be 19 in wide by 12 in high by 12 in deep.

The contracting agency shall enter the settings needed by the algorithm as well as those needed by the remote control software. The contractor shall verify that all computer hardware and software functions properly prior to system activation.

3.1.3 Digital I/O Interface: The digital I/O device shall be a 48-bit, parallel, isolated digital I/O interface for PCI bus computers. The device shall offer at least 48 channels of isolated digital data acquisition. Twenty-four of the channels shall be opto-coupler inputs and twenty-four of the channels shall be solid-state relay outputs. The digital I/O device shall allow sensing of digital levels up to 28 VDC and switch currents of up to 120 mA.

3.2 Installation of D-CS Components

All components of the detection-control system (i.e., the vehicle classifier, the algorithm processor, and the digital I/O interface) shall be installed and housed in the traffic signal control cabinet, provided there is sufficient space in the cabinet for all of the equipment. If there is not sufficient space, the contracting agency shall recommend any necessary changes, including a second cabinet for the detection-control system equipment.

3.3 Environmental Requirements

The algorithm processor and vehicle classifier hardware shall reasonably conform to NEMA TS-1 standards and Special Specification 6000, "Traffic Signal Controller Assembly" for temperature, humidity, and other operating factors. In the case of the algorithm processor, it may not be possible to meet these standards with existing stand-alone computer systems. If so, the contracting agency must approve any hardware that does not meet NEMA TS-1 hardware standards or Special Specification 6000.

4.0 TRAFFIC CONTROL SYSTEM COMPONENTS

4.1 Materials and Hardware for Traffic Control System

4.1.1 Signal Controller: The signal controller used with the detection-control system shall be of a type that complies with Special Specification 6000, "Traffic Signal Controller Assembly."

4.1.2 Controller Cabinet: Either type of controller cabinet (TS-1 or TS-2) is acceptable for detection-control system installation. For a TS-1 or TS-2 Type 2 (i.e., a TS-2 controller in a TS-1 cabinet), no additional equipment is necessary, provided that the following controller inputs and outputs are available:

a. Phase On (for the first 8 phases)
b. Phase Check (for the first 8 phases)
c. Phase Hold (for the first 8 phases)
d. Ring Status Bits for Rings 1 and 2
e. Force Off Rings 1 and 2

For a TS-2 Type 1 controller and cabinet, a separate auxiliary BIU interface panel (for BIU channels 3 and 4) is necessary to allow the detection-control system to have access to all of the inputs and outputs listed previously.

A version of this panel designed specifically for the controller in the cabinet shall be obtained from the contractor manufacturer by the contractor.

In either cabinet, the detector inputs for all phases must be available to be monitored by the detection-control system.

4.2 Installation of Traffic Control System Components

Both the signal controller and the controller cabinet shall be installed and inspected in accordance with Special Specification 6000, "Traffic Signal Controller Assembly." The contractor shall check whether all of the specified component parts will fit into the specified cabinet, and notify the contracting agency if they do not, prior to cabinet installation. The additional BIU panel required for the TS-2 Type 1 controller and cabinet must be installed in an easily accessible location within the controller cabinet.

4.3 Environmental Requirements

All signal controller equipment shall have environmental ratings in accordance with Special Specification 6000, "Traffic Signal Controller Assembly."

5.0 TESTING, MAINTENANCE, AND SUPPORT

5.1 Testing

5.1.1 Vehicle Detection System: The vehicle detection system shall be tested as described in Section 2.0.

5.1.2 Detection-Control System: Each component of this system shall be tested individually.

5.1.2.1 Vehicle Classifier: The vehicle classifier shall be tested, in a manner suitable to the contracting agency, to determine speed accuracy before the detection-control system is activated. The vehicle classifier shall be able to determine vehicle speed within ±2.0 mph of its actual speed 95 percent of the time under any traffic or weather condition. The vehicle classifier shall be able to determine vehicle length to within ±3.0 ft of actual vehicle length at least 95 percent of the time under the same conditions.

5.1.2.2 Algorithm Processor: The algorithm processor shall be monitored for at least a four-hour initial test period (to include one hour of peak traffic demand) prior to system activation. During this initial test period, processor and algorithm operation should be monitored to ensure that the algorithm is making the proper decisions to end the phase. The phase hold and force-off controller inputs shall not be connected during this initial test period.

After the algorithm processor has been tested during the initial test period and shown to be making the proper decisions to end the phase, the phase hold and force-off controller inputs shall be connected, and the operation of the complete system monitored for an additional 10 to 20 signal cycles to verify that phase holds and force-offs are being properly issued to the controller by the algorithm processor.

5.1.3 Traffic Control System: Components of the traffic control system shall be tested and approved in accordance with Special Specification 6000, "Traffic Signal Controller Assembly."

5.2 Maintenance

Normal, routine maintenance shall be performed by TxDOT personnel. However, malfunctions which affect overall detection performance and which can be attributed to a specific component of the detection-control system (e.g., algorithm processor, digital I/O interface, etc.) shall be repaired under warranty at no cost to TxDOT.

5.3 Support

During the warranty period, any software upgrades shall be supplied to TxDOT at no charge. In addition, phone consultation as needed shall be provided at no cost during the warranty period for operating questions or problems that arise.

5.4 Future Support

If TxDOT desires, it may enter into a separate agreement with the suppliers for technical support and software upgrades. The supplier shall make available such a program to TxDOT after the original warranty period.