motorcyclist wearing a fluorescent jacket and helmet cover, and (e) motorcycle with low-beam headlight on. Not all of the conditions have as much data as we would like to see or will ultimately collect. The data we have at this time suggest that it may be possible to measure changes in driver behavior by the method described. It must be remembered that the study is in progress and conclusions at this time are tentative. We are encouraged by trends that show changes in the probability of acceptance of short gaps (less than 5 s) as a function of the treatment conditions investigated. However, these trends are only found in the right cross or left turn and center-left turn maneuvers. The maneuver that is most similar to that measured by Ashford, Strond, Kirkby, and Kirk seems to show no differences.

Again, I think this is an excellent paper. It is regrettable that the gap-acceptance methodology provided negative results, but it may be that an expansion of the technique will still prove meaningful.

Publication of this paper sponsored by Committee on Visibility.

Signalization of High-Speed, Isolated Intersections

Peter S. Parsonson, Georgia Institute of Technology

At signalized intersections where approach speeds are 56 km/h (35 mph) or higher, drivers face a "dilemma zone." If the yellow signal comes on while the driver is in this zone, a decision to stop may result in a rear-end collision or a sideswipe. The opposite decision, to go through the intersection, might produce a right-angle accident. For such an intersection, the traffic engineer needs to select a detector-controller configuration that will (a) detect an approaching vehicle before it enters the dilemma zone and either (b) extend the green signal to provide safe passage through the zone or else (c) end the green signal when the vehicle is still upstream of the dilemma zone and thereby provide adequate stopping distance. A major research project examined in detail a number of advanced detector-controller designs. The resulting design manual has systematically integrated into a single publication the available knowledge on the subject. This paper condenses the author's contribution to the design manual, elaborates on certain points incompletely treated by it, and proposes a new configuration. Current knowledge of dilemma-zone boundaries is reviewed, a classification of controllers and detectors and a taxonomy of detector-controller configurations are provided, and research data on the effectiveness of green-extension systems are summarized. The proposed new configuration uses a basic, actuated, nonlocking controller; 25-m (85-ft) long, delayed-call loop detector at the stopline; and two extended-call detectors upstream to give protection to the dilemma zone.

For over a decade, it has been known that at signalized intersections where approach speeds are 56 km/h (35 mph) or higher drivers face a "dilemma zone" or "zone of indecision." If the yellow signal comes on while the driver is in this zone, the decision whether to stop or go through may be difficult. A decision to stop abruptly may result in a rear-end collision. The opposite decision, to go through the intersection, might produce a right-angle accident. If the traffic-signal controller is vehicle-actuated rather than pretimed, the traffic engineer can attempt to design the installation to minimize the problem of the dilemma zone.

The goal of the traffic engineer in tackling this problem is to ensure, if possible, that no vehicle is in the dilemma zone on the display of the yellow interval. The key to the solution is the selection of a cost-effective detector-controller configuration that will (a) detect an approaching vehicle before it enters the dilemma zone and either (b) provide safe passage through the zone or (c) provide adequate stopping distance. Thus, the solution focuses on the placement of vehicle detectors and the coordination of that placement with the timing functions of the controller.

It bears emphasizing that the dilemma zone can be protected only if the green signal is terminated by "gap-out." If the green is extended by heavy traffic (or an overlong unit extension) to the maximum interval, there can be no protection. A vehicle may well be caught in the dilemma zone.

A major research project examined in detail a number of advanced detector-controller designs for use at high-speed, isolated intersections. The resulting design manual (1) systematically integrated into a single publication the available knowledge on this subject. This paper condenses my contribution to the design manual and elaborates on certain points incompletely treated by it. A new configuration is proposed.

The dilemma caused by indecision on the display of the yellow interval is the subject of this paper but is only one of three separate difficulties associated with the termination of the green interval. A second and different dilemma faces the motorist if the length of the yellow interval (plus any all-red clearance interval) is not enough to permit him or her either to clear the intersection or to stop safely (2). A third type of dilemma is the "short green" problem in high-speed signalization (3). A green interval of only 2 to 4 s in length may so conflict with a driver's expectations that he or she may panic and not react to the yellow change interval although there is ample opportunity to stop.

BOUNDARIES OF THE DILEMMA ZONE

Once it has been determined from analysis of accidents or conflicts that the problem of a dilemma zone exists on an approach, despite a rational timing of the yellow-plus-all-red clearance period, an advanced detector-controller configuration is warranted. The first step in the selection of this configuration is the identification of the extent, or boundaries, of the dilemma zone. This can be obtained from the literature and adjusted for gradients (4).

In 1974, Parsonson and others (5) examined research on the probability of stopping from various speeds (6, 7, 8). They characterized the dilemma zone as that ap-

proach area within which the probability of deciding to stop on the display of yellow is within the range of 10 to 90 percent. That is, the upstream boundary of the dilemma zone was located where 90 percent of drivers would decide to stop if the yellow began just as they reached that boundary. At the downstream boundary, closer to the stopline, only 10 percent would decide to stop. These findings are summarized below (1 km/h = 0.62 mph and 1 m = 3.3 ft):

Approach Speed (km/h)	Distance From Intersection for Two Probabilities of Stopping (m)	
	10 Percent	90 Percent
48	27	52
64	33	75
72	50	90
80	66	105
97	78	135

These data agree well with data for 48 and 80 km/h (30 and 50 mph) published by Olson and Rothery in 1972 (9).

Zegeer of the Bureau of Highways, Kentucky Department of Transportation (DOT), recently conducted a thorough study of dilemma-zone boundaries for nine straight and level approaches (4). Responses of about 2100 drivers to the yellow interval were recorded. Figure 1 and the following table summarize Zegeer's findings:

Approach Speed (km/h)	Distance From Intersection for Two Probabilities of Stopping (m)	
	10 Percent	90 Percent
56	31	77
64	37	86
72	46	99
80	52	107
89	71	117

It can be shown that at speeds of 72 to 80 km/h (45 to 50 mph) Zegeer's dilemma zones are 28 to 38 percent longer than those reported by Parsonson and others (5). At lower and higher speeds, the differences are minor. The Zegeer data are extensive and were collected under closely controlled conditions. Most traffic engineers will probably use his findings in Figure 1 and the table above rather than data given in the earlier table.

The Zegeer data show that the upstream boundary of the dilemma zone, at which 90 percent of motorists will decide to stop, is 4.5 to 5 s of passage time from the intersection. The other boundary, for a 10 percent chance of stopping, is 2 to 2.5 s from the intersection. There is a dilemma zone that is typically 2.5 to 3 s in length.

Any solution to the problem of the dilemma zone begins with the detection of an approaching vehicle before it enters the dilemma zone. Therefore, it is axiomatic that there should be a detector approximately 5 s of travel time before the stopline, just upstream of the dilemma zone. In this connection, it is useful to show the dilemma-zone "cloud" (shaded area) on a table of approach speed versus passage time from detector to stop line (Figure 2) (4). The figure shows that 5 s of detector setback is adequate except for speeds of 97 km/h (60 mph) or more. Cell values are distances in meters from the detector to the stopline at that approach speed.

In the years before there was wide circulation of research data on dilemma-zone boundaries, it was common for traffic engineers to derive the boundaries from kinematic analyses of stopping and clearing. The upstream end of the dilemma zone is associated with stopping; therefore, a calculation of safe stopping distance from a certain approach speed should give a satisfactory estimate of the correct location for a detector just upstream of the dilemma zone. The minimum stopping sight distances for wet roads of the American Association of State Highway Officials (AASHO) (9) are shown in Figure 2 (dashed line) to be reasonably close to the upstream boundary of the dilemma zone. Figure 1 indicates a high probability of stopping (96 percent) for 80 km/h (50 mph) and the AASHO safe stopping distance of 111 m (369 ft). A detector placed at this location would lay the groundwork for excellent protection against dilemma.

Some investigators have not used the AASHO safe stopping distances but have instead assumed a 1-s reaction time and an emergency stop on a dry road. Bierele (10), Grimm (11), and, in personal correspondence, Holloman, assistant traffic engineer for the city of Winston-Salem, North Carolina, have reported stopping distances at 80 km/h of approximately 76 m (250 ft) on this basis of calculation. Figure 1 indicates a probability of stopping of only 47 percent for 76 m and 80 km/h. A detector placed at this location would leave over half of the dilemma zone without detection.

DETECTOR-CONTROLLER CONFIGURATIONS

The purposes of this section are (a) to establish a uniform terminology, (b) to organize a taxonomy of advanced detector-controller strategies, and (c) to propose a simple, qualitative flow chart to assist the traffic engineer to sort out the alternative strategies.

Terminology

Sackman and others (1) explain the meaning of many specialized terms, such as stretch detector, locking detection memory, and modified density controller. The distinction between several specialized types of detectors is important to this paper.

Here, the term extended-call detector is used to describe a unit that has a carryover output: When the vehicle leaves the detection area, the extended-call detector "stretches" or prolongs the call for an adjustable period of seconds. An extended-call detector connected to a small loop or single magnetometer probe can essentially mimic the output of a normal detector connected to a very long loop or a series of probes.

By contrast, a delayed-call detector does not issue an output until the detection zone has been occupied for an adjustable number of seconds. Delayed-call detectors are finding extensive use in detecting congestion (5) and in screening out false calls for the green signal (3).

In this paper, a green-extension system is a unit offered by at least two manufacturers to provide protection for the dilemma zone at a semiactuated intersection (5). The unit includes two or more extended-call detectors and also display-monitoring circuits that aid in the control of the end of the green.

Table 1 gives a taxonomy of detector-controller configurations. It systematizes the advanced designs currently in use, or advocated for use, in the United States. Each design is "advanced" in that it uses multiple-point detection or advanced actuated controller or both. Details of the applications of these designs can be found elsewhere (1). Table 1 demonstrates how different agencies and engineers have combined various components of detector-controller hardware in their attempts to achieve safety at high-speed intersections. The table covers all types of controllers and is careful to distinguish between basic and "density" models and locking and nonlocking detection-memory modes. Simi-

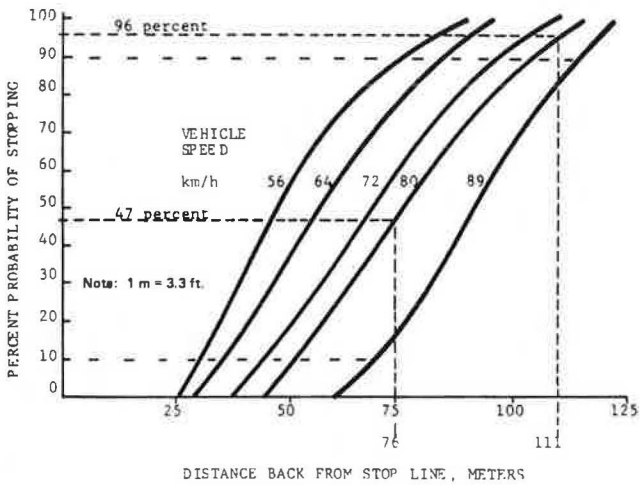
larly, detection is clearly specified as to type.

Figure 3 is a flow chart intended to assist the traffic engineer to make a preliminary selection from the detector-controller configurations given in Table 1. There are several key questions on the flow chart that the traffic engineer needs to be able to answer for purposes of specific application. The first is, Is it important for efficiency that the equipment also be capable of changing the green on detection of a gap no greater than 2 to 4 s? If the answer is no and the traffic engineer is willing to accept a gap of 5 s, then the flow chart leads to relatively simple designs that use basic actuated controllers and detection systems that are comparatively inexpensive. Many traffic engineering agencies in the South and the Southeast, for example, find that these designs are adequate for their needs. If the answer to the question is yes (as, for example, in many jurisdictions in the West Coast states), then the flow chart leads to relatively complex designs that use density controllers or extensive detectorization or both. The degree of complexity and expense in these categories is primarily a function of whether traffic conditions are so variable during a 24-h period that the equipment must be able to measure speed and, in response, change the control logic in real time.

For those engineers who answer no to the question above, the next key question is, Are false calls for the green (as in right turn on red) numerous enough that it is important that the equipment have at least some capability to screen out false calls? Practically every jurisdiction in the United States permits right turn on red in some form. The capability to screen out false calls is so vital to the efficiency of any actuated intersection, urban or rural, that it would seem that most traffic engineers would answer yes to this question. The flow chart will then indicate a basic, fully actuated, nonlocking controller with a long presence loop at the stopline and an extended-call detector to protect the dilemma zone. If the screening out of false calls is of particular importance—a major goal—then a refined design that includes a delayed output from the stopline loop is suggested.

The flow chart does not venture into the area of maintenance of controllers and detectors. It is left to the traffic engineer to factor in such important considerations as the capability of maintenance staff and the difficulty of keeping detection loops in service.

Figure 1. Dilemma-zone curves for Kentucky drivers.

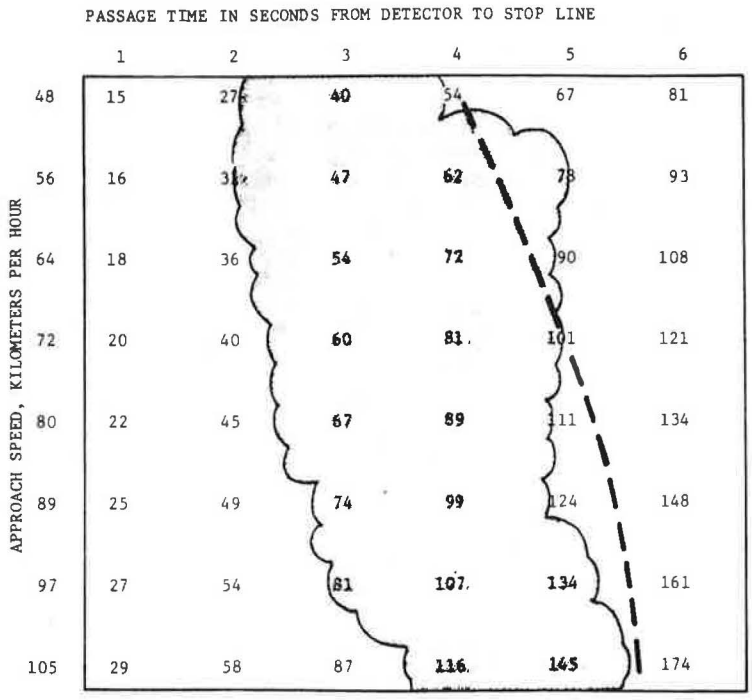


KINEMATIC ANALYSES OF SELECTED CONFIGURATIONS

It is useful to analyze the various designs given in Table 1 by posing certain questions, most of which require kinematic analyses:

1. Does the design detect a vehicle approaching at the design speed before it reaches the dilemma zone?
2. What is the allowable gap imposed by this design? The allowable gap is the maximum time interval between actuations that will cause the green to hold. A short al-

Figure 2. Dilemma-zone boundaries.



Note: 1 km/h = 0.62 mph and 1 m = 3.3 ft.

lowable gap will cause the green to terminate in a "snappy," traffic-responsive manner. A long allowable gap will often prolong a green until it is terminated by the maximum interval setting of the controller. This is highly undesirable because no dilemma-zone protection is provided on "max-out" and a vehicle may well be caught in the dilemma zone.

3. On termination of the green by gap-out, will the vehicles approaching at the design speed be clear of the dilemma zone?

4. On termination of the green by gap-out, will vehicles traveling slower than the design speed be clear of the dilemma zone?

5. Can a queue waiting at the stopline get into motion without a premature gap-out?

6. Can the design screen out false calls for the green (as, for example, in right turn on red)?

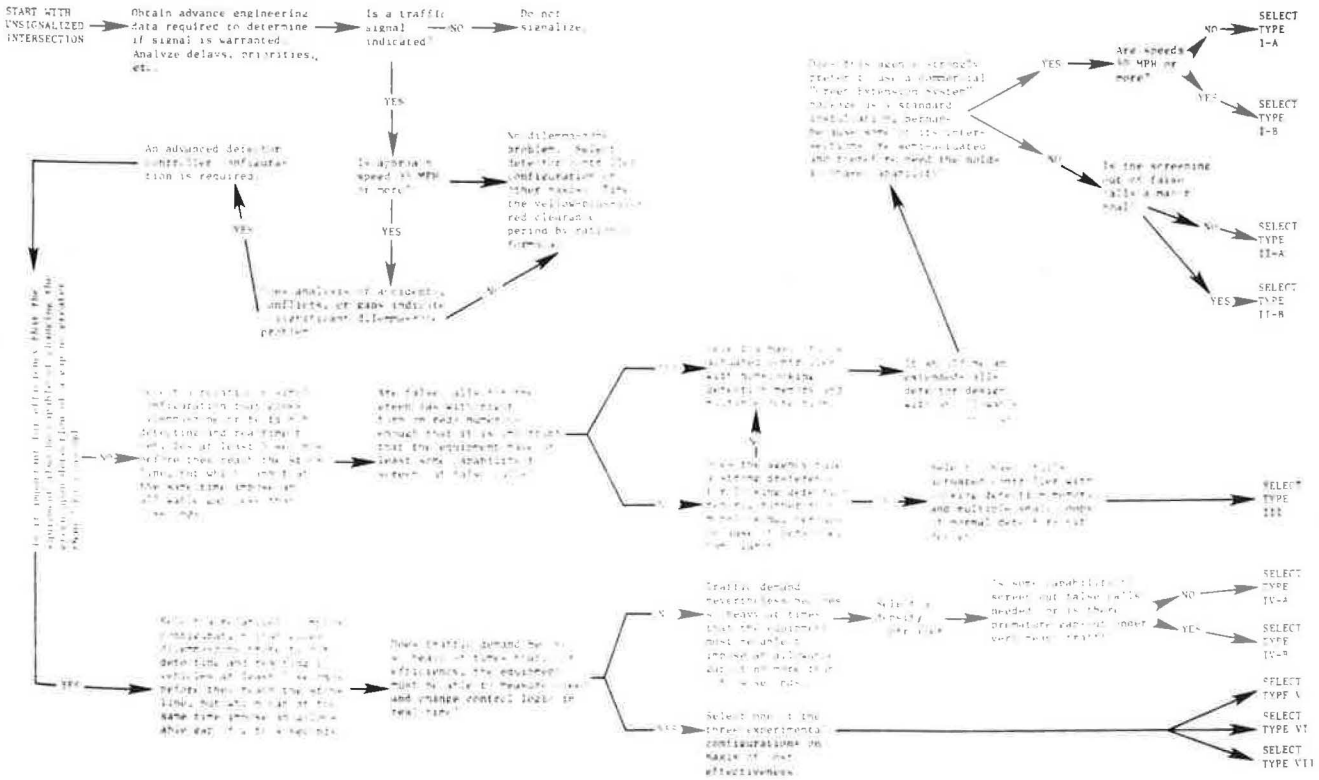
7. During the green interval, can a queue of left-turning vehicles hold the green as they wait to filter through gaps in oncoming traffic? This is important on

Table 1. Taxonomy of detector-controller configurations.

Type	System	Design	Use
1	Green-extension systems for semi-actuated controllers	Two-loop Three-loop	Composed of extended-call detectors and auxiliary logic: controller normally semiactuated with either locking or nonlocking memory; green-extension systems can also be used with basic, fully actuated, nonlocking controllers, in which case auxiliary logic is not needed
2	Extended-call detection systems for basic controllers	21-m loop at stopline (normal detector output) supplemented by extended-call detector 5 s before the stopline 21-m loop at stopline (delayed-call output) supplemented by extended-call detector 5 s before the stopline and a third detector (of normal or extended output) between them	Used with basic, fully actuated, nonlocking controllers
3	Multiple-point detection system for basic controllers		Composed of multiple small-area detectors positioned to take into account vehicles traveling at and under design speed; used with basic, fully actuated, locking controllers
4	Systems for density controllers	Conventional design using one small-area detector located 5 s before the stopline Extended-call detection systems	
5	Shifting-presence zone detection systems		Composed of many hypothetical speed-detection sensors, each sensitive to a narrow speed range and positioned to maintain green for a wide range of approach speeds; intended for use with density controllers
6	Area detection system with volume adjustment		Composed of 18-m presence loop at the stopline, supplemented by multiple-point detection for a distance of 244 m; volume-level indicator disconnects upstream detectors when heavy volumes indicate lower speeds; uses a basic controller
7	Computer controller		Computer measures speed of each vehicle and continuously adjusts the vehicle extension interval to provide dilemma-zone protection at all speeds

Note 1 m = 3.3 ft.

Figure 3. Flow chart for preliminary selection of detector-controller configurations.



two-lane roads, where an occasional left-turning vehicle can cause a queue to form. When a gap in oncoming traffic appears, a gap-out may occur before the queue can get into motion over its detector.

These criteria are applied here to one of the configurations in Table 1 for an example design speed of 72 km/h (45 mph). The table given previously for Zegeer's data (4) gives the dilemma-zone boundaries for this speed as 46 and 99 m (152 and 325 ft) from the stopline, which corresponds to 2.3 and 4.9 s of passage time respectively.

Conventional High-Speed Design

The conventional or most straightforward design for a 72-km/h (45-mph) signalized approach would use a single small-area detector 99 m (325 ft) before the intersection. The controller would be an advanced actuated model (density or volume-density) with the following key timing settings: passage time, 5 s; minimum gap, 3 s; and last-automobile-passage feature, disabled if present. Figure 4 shows the detector location and the dilemma zone.

The answers to the seven questions posed previously are as follows:

1. The design does detect a design-speed vehicle before it reaches the dilemma zone since the upstream detector was located in accordance with Zegeer's data on dilemma-zone boundaries, given previously.
2. The allowable gap imposed by this design reduces, usually on the basis of time waiting on the red, to the setting of the minimum gap (here 3 s). The shortest setting that would pass a 72-km/h (45-mph) vehicle through a 53-m (173-ft) dilemma zone is 2.6 s. The 2.6 s is therefore the minimum desirable allowable gap; a shorter value would give snappier operation but could leave a vehicle in the dilemma zone.
3. On gap-out, the vehicles will be clear of the dilemma zone, and the last automobile to have crossed the detector will be 3 s downstream from it and 2 s from the stopline. The driver will have little difficulty in deciding to go through. The vehicle behind the last automobile (termed here the trailing automobile) will be upstream of the detector on gap-out and will easily decide to come to a stop. A typical positioning of vehicles on gap-out is shown in Figure 5.

If the controller incorporated the feature for last-automobile passage, the signal indication would not change until the last automobile had completed its passage time of 5 s after crossing the detector. Figure 6 shows that in this case the trailing automobile may well be caught in the dilemma zone. The figure explains why California, for example, does not use the last-automobile-passage feature.

4. On termination of the green by gap-out, vehicles traveling slower than the design speed may be caught in the dilemma zone if the allowable gap is set low. For example, a minimum allowable gap of 4.9 - 2.3 = 2.6 s barely permits a vehicle at the design speed of 72 km/h (45 mph) to clear its dilemma zone before gap-out. A slower vehicle would be caught. Figure 7 shows that an allowable gap of 4.3 s would be required to pass a straggler at 56 km/h (35 mph) through its own dilemma zone. It can be seen that there is a trade-off between snappy operation and protection for the slower vehicles in the traffic stream. One can be obtained only at the expense of the other. What is needed is a detector-controller configuration that can measure the speed of the last automobile and tailor an appropriate extension of the green. Computer controllers can do just that (see type 7 in Table 1) and represent one alternative to the conventional design.
5. A queue waiting at the stopline is supposed to be able to get into motion without premature gap-out. A density controller has a "variable initial interval," which is intended to produce a minimum green sufficient to permit motion over the detector in time to extend the green. Thus, the design taken at face value will meet this test. However, in practice it has been observed that premature gap-out can occur when traffic is very heavy. Dense traffic can defeat the purpose of the timing adjustment that controls the number of actuations (on the red) that will cause maximum initial to time. When traffic is dense, traffic stopping at the intersection may arrive at the detector during the green interval and therefore contribute nothing to the timing of the next initial interval. Years ago, the only remedy was to set a value of minimum initial high enough to ensure motion over the detector. Such a high setting resulted in slug-

Figure 4. Conventional detector-controller design for 72-km/h (45-mph) approach speed.

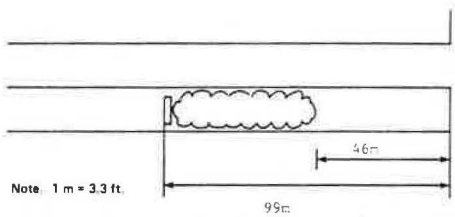


Figure 5. Typical positioning of last automobile and trailing automobile on gap-out without last-automobile-passage feature (conventional high-speed configuration).

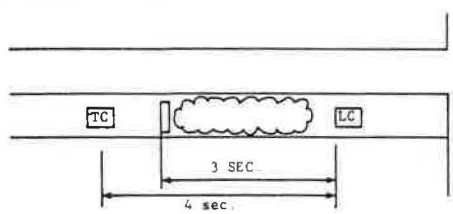


Figure 6. Conventional high-speed detector-controller design with last-automobile-passage feature.

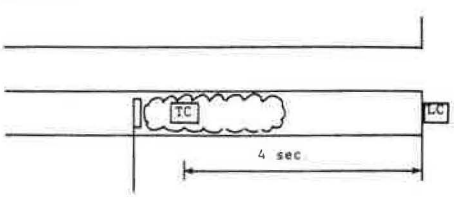
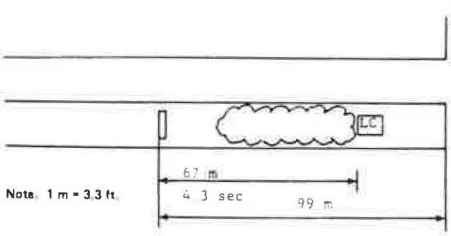


Figure 7. Gap-out of 56-km/h (35-mph) vehicle in the conventional high-speed design for 72 km/h (45 mph).



gish operation during periods of light traffic and a loss of reputation for the sophisticated capability of the density controller. The type 4 extended-call system offers a solution to this problem and is discussed elsewhere (1).

6. The design has no ability to screen out false calls for the green because the controller's detection memory is of the locking type. Once a vehicle crosses a detector, its call will be locked in until satisfied by a display of the green to that approach even if the vehicle has turned into a gas station or turned right on red. Many of the alternative designs in Table 1 provide a degree of screening.

7. A queue of vehicles waiting to turn left cannot hold in a call for the green. Many of the alternative designs in Table 1 overcome this problem by using a stopline loop.

Green-Extension Systems for Semiactuated Controllers

A green-extension system (GES) is a commercially available equipment package consisting of two or more extended-call detectors, one or more auxiliary timers that can disconnect or "force off" the extended-call detectors, and auxiliary electronics that can monitor the signal display, arm or make operational the extended-call detectors, and control the yielding of the green to the side street (by activation of hold-in-phase circuits). The auxiliary timers and electronics are needed only if the controller is semiactuated. If it is fully actuated, then the extended-call detectors do not require any auxiliary logic and the designs are as given for type 2 (Table 1). The semiactuated controller can use either locking or nonlocking memory for the side street depending on whether detection is for a small or large area.

The type 1 two-loop system uses two extended-call detectors and is considered satisfactory for approach speeds up to 72 km/h (45 mph). The three-loop systems are recommended where approach speeds are in excess of 72 km/h or where speeds are lower but traffic densities are quite high. The allowable gap of a GES is typically 4.5 to 5 s.

Inasmuch as Parsonson and others (5) describe GESs in detail, and since semiactuated control is steadily losing favor for use at isolated intersections, no further consideration of such systems is required here.

EFFECTIVENESS OF GREEN-EXTENSION SYSTEMS

There is a substantial amount of before-and-after data on the effectiveness of GESs in Kentucky. Zegeer has prepared an outstanding report on the effectiveness of 5 of 16 GES installations of the Kentucky DOT (4). Extensive accident data for 3 of these sites were combined to give a total of 8.5 years of before data and 3.7 years of after data. Zegeer found a total of 70 accidents before GES and 14 accidents after or 8.2 and 3.8 accidents/year respectively. This was a reduction of about 4.4 accidents/year or 54 percent. Zegeer reported that rear-end accidents were reduced by 75 percent and right-angle accidents by 31 percent. Summaries of property-damage-only, injury, and fatal accidents showed that the number of each type of accident was reduced by approximately 50 percent.

Two new GES sites, at the Kentucky towns of Ashland and Stanford, were selected for before-and-after studies of conflicts, speeds, and delays. Average speed at both intersections is approximately 66 km/h (41 mph), and each uses two-phase, semiactuated control. Figure 8 (4) shows as an example the installation at the Ashland intersection. The five detectors shown on US-23 are GES detectors; they do not actuate the controller. The 4 percent downgrade on the northbound approach determined the need for a third GES detector 125 m (410 ft) from the stopline. The comprehensive evaluation of the two intersections produced a number of significant conclusions, including the following:

1. The six types of yellow-phase conflicts observed were reduced by an average of 62.1 percent.
2. No significant change was found in the number of automobiles stopped or in the total delay of vehicles on side streets after installation of the GES.
3. The initial cost to install a GES to an existing signal is $2750, and maintenance costs for a 10-year period are $500/year. The cost of an average accident to the highway user in Kentucky is $7112. Therefore, if a GES installation were to eliminate only one mainline, rear-end accident per year, the benefit/cost ratio would be 6 and the total net benefit to motorists would be close to $30 000 over a 10-year period.

PROPOSAL FOR A NEW CONFIGURATION

There appears to be an unmet need for a high-speed design that includes loop-occupancy features; a basic, actuated, nonlocking controller; and extended-call detectors and that provides both a short allowable gap and protection over a wide range of speeds. A new configuration of the type 2 delayed-call variety is proposed in this section and is shown to have an allowable gap of 3.3 to 4.0 s and a range of speeds from 56 to 80 km/h (35 to 50 mph).

Figure 9 shows the details of the design. The 26-m (85-ft) long stopline loop is a delayed-call design [with a quadrupole (3) configuration to improve detection of small vehicles]. So great a length is intended to hold the call of discharging vehicles until a 2-s gap in 56-km/h (35-mph) traffic occurs. In this way, the green will be held by start-up traffic until motion over the extended-call detectors is ensured. Premature gap-out is thus avoided.

The following analysis presumes that (a) both extended-call detectors are the type that time the extension from the exit of the vehicle and not its entrance into the detection area, (b) 1.8-m (6-ft) long loops are used, and (c) the vehicle is 4.5 m (15 ft) long.

The upstream detector is set to extend the call by 1.4 s. This is sufficient to carry vehicles at 64 to 80 km/h (40 to 50 mph) to the second extended-call detector (Figures 9 and 10). Slower vehicles at 56 km/h (35 mph) will not reach that detector, thereby losing their green before reaching their own dilemma zone (Figure 11). The second detector is set to extend the call by 1.9 s, to carry vehicles at 64 to 80 km/h through their dilemma zones. A kinematic analysis follows.

1. The design does detect an 80-km/h vehicle before it reaches the dilemma zone since the upstream detector was located in accordance with Zegeer's data.
2. The allowable gap is nominally the sum of the settings of the two extended-call detectors or 3.3 s. More precisely, the allowable gap should be calculated by taking into account the lengths of the loops and vehicles. On this basis, the time headway from front bumper to front bumper that will just hold the green is 3.7 s for 80-km/h traffic and 4.0 s for a 64-km/h stream. The fact that the stopline loops disconnect once discharging traffic is at speed is of great value in ensuring a reasonably short allowable gap.
3. On gap-out, vehicles traveling at the design speed—80 km/h—will be clear of their dilemma zone (Figure 9).

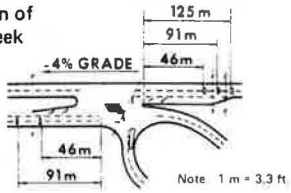


Figure 8. Intersection of US-23 and Hoods Creek Pike in Ashland, Kentucky.

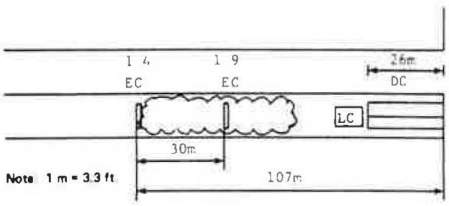


Figure 9. Proposed type 2 delayed-call design for 80-km/h (50-mph) approach speed.

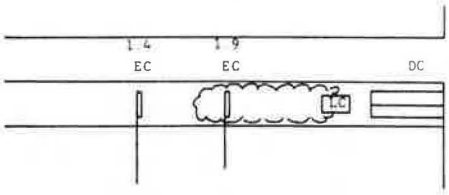


Figure 10. Gap-out of 64-km/h (40-mph) vehicle in the proposed design.

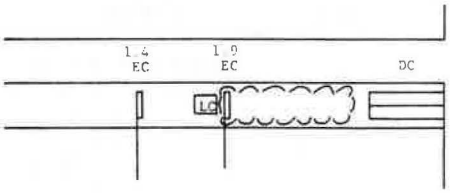
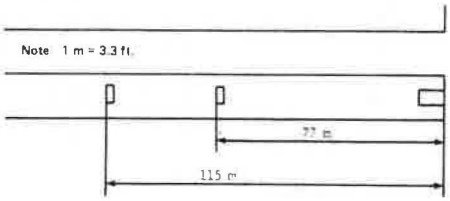


Figure 11. Gap-out of 56-km/h (35-mph) vehicle in the proposed design.

Figure 12. Modification of proposed detector-controller configuration.



4. Slower vehicles, at 56 to 72 km/h (35 to 45 mph), will also be clear of the dilemma zone on gap-out. See Figure 10 for 64 km/h and Figure 12 for 56 km/h.

5. The 26-m (85-ft) long loop at the stopline will allow a queue waiting at the stopline to get into motion without premature gap-out.

6. The delayed-call design of the stopline loop improves the ability of the design to screen out false calls for the green. When the green is at rest on the cross street, however, a false call at either of the extended-call detectors will bring the green unnecessarily.

7. The long loop at the stopline permits a queue of left-turning vehicles to hold the green as they wait to filter through gaps in oncoming traffic.

The next step in the development of this proposed new configuration will be a trial installation in the Atlanta area.

ACKNOWLEDGMENTS

Much of this paper is adapted from my contribution to a Federal Highway Administration research contract. I served as a consultant to the contractor, Urban Interface Group of Laguna Beach, California.

I am grateful to Charles V. Zegeer of the Kentucky DOT for permission to report his research results to the Transportation Research Board. The following individuals offered detailed, constructive, thoughtful comments on the first draft of this paper: James Gawlas of the Gwinnett County, Georgia, Traffic Engineering Division; Donald E. Lepic of the Adams County, Colorado, Community Development Division; Lionel M. Rodgers of Storch Engineers, Wethersfield, Connecticut; and Richard C. Wisler of Sarasota Engineering Company, Sarasota, Florida. Their suggestions are gratefully acknowledged. The manuscript was edited and typed by John C. Whatley of the School of Civil Engineering, Georgia Institute of Technology.

The contents of this paper do not necessarily reflect the official views or policies of the U.S. Department of Transportation.

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Discussion

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Parsonson has provided a very valuable tool to the engineer whose objective is to design a signal system that will provide dilemma-zone protection for high-speed vehicles approaching an isolated signalized intersection. Many jurisdictions, recognizing the dilemma-zone problem, have developed and implemented unique system designs. Quite often these systems were designed on a case-by-case basis, and very little attention was given to standardization.

This paper and the research project design manual referred to by Parsonson (1) have analyzed and classified the various state-of-the-art and classic systems in use today and have provided a taxonomy of advanced detector-controller strategies for the practicing engineer. This taxonomy does provide a means of standardizing design as well as providing a common basis for future discussion for the practicing engineer.

The state of Kentucky uses a standardized design for the 32 dilemma-zone signal systems currently in operation. The system design used would most closely fit Parsonson's type 1 (two-loop and three-loop) green-extension classification even though basic, fully actuated, nonlocking controllers are used. A more complete description of the system design used in Kentucky can be found in the appendixes of the research project design manual (1) and a report by Zegeer (13).

It should be noted that practically all dilemma-zone protection signals in Kentucky are located on major arterials and were installed under the interruption of continuous traffic warrant. Capacity is seldom a major problem even though every effort is made to maintain a high level of operational efficiency. All 32 intersections currently provide dilemma-zone protection to the mainline phase only.

Originally, stop-bar loops were used for all approaches that had dilemma-zone protection. The initial interval was low and the efficiency high; however, from a safety standpoint, this type of operation proved to be less than desirable. This design, during off-peak periods, created unreasonably short mainline green periods, which in turn created an intolerable stopping problem, particularly for commercial vehicles. Time-lapse photography showed that commercial vehicles accelerated just before their arrival at the normal dilemma zone, particularly after they observed that the green phase commenced as they were approaching the intersection [303 m (1000 ft) or more]. Eliminating the presence loops and placing the phases on minimum recall with a 12- to 18-s initial interval, in addition to the advance loop extension time, seemed to satisfy driver expectations and lessen the problem. A second consideration for this minimum recall type of operation was the desire that the signal dwell in the dilemma-zone green phase during periods of rest or vehicle inactivity. This is very important when the dilemma-zone approach is on a significant grade and snow and ice are not uncommon.

Truck (commercial) traffic creates a very severe problem at several locations. This is particularly true at locations that have a significant downgrade approach where truck speed is excessive and sight distance is very good [0.8 km (0.5 mile) or more]. Automobiles share this problem to a lesser degree. The problem of the short green phase mentioned earlier becomes very significant under these conditions. Truck drivers, with their vantage point and experience, probably have a perception-reaction time 50 percent less than that of drivers of passenger vehicles; however, the actual stopping distance for trucks is much greater. For example, a vehicle with a 3-S2 commercial classification would require a 65 percent greater stopping distance than would an average vehicle (13). Excessive weight and poor brake performance can increase the stopping distance even more. Ideally, a truck detection system would be used and trucks would be treated separately. Unfortunately, this type of equipment is not currently available.

The technique used in Kentucky for an intersection with the aforementioned problem is to use the highest observed vehicle speed as the design speed in determining the location of the back loops. This technique has produced very satisfying results. An example is the Ashland (US-23) intersection (4, 12). The northbound steep-grade approach with a two-loop configuration (85th percentile design speed) experienced a much higher incidence of traffic conflicts than did the southbound approach, which was a 0 percent grade that used the same detection scheme. In an attempt to reduce the problem, an additional loop was installed on the northbound approach by using the 99th percentile speed as the design speed. This additional loop in the northbound direction reduced the number of conflicts to the same approximate level as that for the southbound approach. The results of a conflict study conducted at this intersection by Zegeer (4) are given below:

Condition	Conflict Rate per 1000 Opportunities (%)		Conflicts per Hour	
	Northbound	Southbound	Northbound	Southbound
Before	19.1	12.4	10.48	6.9
After				
Loops based on 85th percentile speed	11.2	5.0	7.36	3.2
Northbound loop based on 99th percentile speed, southbound unchanged	6.9	5.8	3.53	3.76

Obviously, the Kentucky approach is a compromise solution. Trial-and-error field work has produced the procedures now in use. It is important that additional research be conducted to determine truck dilemma zones by vehicle classification. The effect of excess grade as it affects the dilemma zone for all vehicles and the effects of short greens should also be the subject of additional research.

The new configuration proposed by Parsonson offers some advantages over most existing systems, particularly types 1 through 4. The 26-m (85-ft) stopline loops with quadrupole design provide much better control of the departing vehicle queue. This is also a far superior design for two-phase intersections with unprotected left-turn movements. To operate efficiently, it is essential that the stop-bar presence loops be deactivated once the waiting queue attains operating speed. Experience in Kentucky has shown that using the presence loop for extension and call will more likely result in a maximum time termination of the green phase rather than a gap termination. This is particularly true on a high-volume approach (12 000 average daily traffic).

It is recommended that the initial vehicle be set at 10 to 15 s to eliminate the problem of the short green, particularly when the signal display is visible for a great distance. It is also desirable that the signal rest or dwell in the dilemma-zone green phase.

Kentucky used and abandoned the stop-bar loop before the advent of the quadrupole configuration and digital self-turning loops. Poor maintenance performance and the short-green problem caused this abandonment. The

large loops would not adequately detect all vehicles, and the analog non-self-turning loop amplifiers tended to detune during temperature changes. This generally resulted in a locked-in call and a maximum time termination of the green phase. It appears that detector technology has now evolved to the point that the maintenance factor can be virtually ignored in the process of selecting a detection scheme. In view of these facts, the quadrupole configuration is highly recommended for greater flexibility and operating efficiency.

Delay detection is considered essential for side-street phases at all times and for the main phases during off-peak, low-volume times.

Parsonson's advance detection strategy would be excellent for most vehicles approaching isolated, high-speed intersections. However, approach speeds in excess of 80 km/h (50 mph) are not rare at most intersections. Very comprehensive data should be collected to determine the existence of higher speeds, truck stopping problems, or excessive grades. If conditions warrant, a supplemental loop or loops should be considered. This loop extension time should be sufficient to allow a vehicle to pass the second loop using 80 km/h as the travel speed. The only deterrent to adding supplemental loops to the proposed configuration is the increased likelihood of maximum time termination of the green phase during periods of high traffic volume.

In conclusion, Parsonson has provided an excellent report that summarizes most known designs for dilemma-zone protection and indicates situations for which they would be most appropriate. It is anticipated that this report will assist in developing standardized designs. The new configuration proposed by Parsonson appears excellent and should provide excellent results when implemented.

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Author's Closure

Clark's discussion of high-speed truck traffic is an important contribution to the literature. He suggests that, where a signal is visible from 300 m (1000 ft) away, a minimum green time of 12 to 18 s is needed to meet the expectations of truck drivers. Heretofore, traffic engineering judgment seemed to center on 8 to 10 s as sufficient. Clark's discussion seems to be the profession's first perception that 8 to 10 s may not be enough in certain situations.

My paper proposes a new configuration intended for speeds of up to 80 km/h (50 mph). Clark points out that higher speeds need to be anticipated by the designer, particularly if trucks or downgrades are a factor. In response, I have modified my proposed configuration to that shown in Figure 12.

The upstream detector has been relocated to 115 m (380 ft) from the intersection, a distance adequate for vehicles approaching at 88.5 km/h (55 mph). The second detector is placed 77 m (254 ft) from the intersection; this is the upstream boundary of the dilemma zone for vehicles approaching at 56 km/h (35 mph). Both of these detectors are of normal design (i.e., not extended-call), and the unit extension of the (digital) controller is set at 1.9 s. It is easy to show that the 1.9-s extensions of the green will carry vehicles approaching at 64 km/h (40 mph) to 88.5 km/h through their respective dilemma zones. The allowable gap of 3.7 s for an 88.5-km/h stream and 3.9 s at 80 km/h (50 mph) is snappy enough to minimize the extension of green to the maximum interval.

The modified configuration could retain the 26-m (85-ft) long stop-bar loop proposed. However, the high cost and questionable durability of so long a detection loop are of concern. As an alternative, I propose a stop-bar loop only 8 to 9 m (25 to 30 ft) in length to be used with a novel hybrid detector. A loop of this length will usually bridge the gap between standing vehicles, ensuring a call. The detector is an extended-call and delayed-call (EC-DC) design with an adjustable timer for each of the two modes. As a queue discharges over the EC-DC stop-bar loop, the detector functions as an extended-call model. The stretch settings are high enough to produce an unbroken call until the vehicles are up to speed, at which point the detector gaps out. On gap-out, the detector becomes a delayed-call unit; the full-speed vehicles do not produce a call, and the detector is in effect disconnected.

In the proposed design, once the minimum green of 15 s has expired, the extended-call feature of the detector will hold in a call to the controller until there is adequate motion over the upstream detectors. Premature gap-out is avoided. Then, the EC-DC stop-bar detector will gap out, leaving only the upstream detectors to give dilemma-zone protection and control the allowable gap. The amount of stretch on the EC-DC stop-bar detector must be high enough to prevent premature gap-out but low enough to ensure that this detector will disconnect before interfering with the assignments of the upstream detectors.

There seems to be no evidence that such a hybrid detector has ever been built. During the spring of 1978, one was to be created by the traffic engineering staff of Gwinnett County, Georgia, in cooperation with the Canoga Controls Corporation. The effectiveness of the proposed design was then to be tested at a Gwinnett County intersection.

Publication of this paper sponsored by Committee on Traffic Control Devices.