Effects of Multiple-Point Detectors on Delay and Accidents

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The number and location of detectors on intersection approaches that have actuated signal controllers and high traffic approach speeds have been studied by various researchers. The relation of detector activity to yellow signal intervals and the presence of dilemma zones has also been investigated. Several procedures for locating multiple detectors on problematic intersection approaches have been proposed as solutions to dilemma zone and other traffic control problems. Four multiple-detector placement methods are compared through computer simulation in a relative evaluation of their effects on vehicular delay. Traffic performance statistics produced through computer simulation are compared with those obtained through field observation. Conventional single-point detection schemes are also compared with multiple detectors through before-and-after field tests at 10 typical field sites. The four methods for placing multiple detectors were not found to produce statistically significant differences in vehicular delay when compared with each other or with single-point detection. Multiple detectors were found to produce statistically significant reductions in accident experience for approach speeds of 50 mph or greater.

Actuated traffic signal controllers use current traffic information to vary signal timing in response to actual traffic demand. The required real-time traffic data are acquired by detectors that are designed and located to fit each particular geometric and traffic situation. The most widely used type of vehicle detector is the inductance loop. This detection system is highly adaptable in that the size and shape of the in-road sensing device can be designed to suit most traffic control needs. Conventional installations generally use a single loop on each inbound intersection approach.

This single-loop (or single-point) detection system has the potential to cause problems for drivers who must respond to the yellow signal indication at intersections where speeds of approaching traffic are greater than approximately 35 mph. Certain combinations of high approach speeds, detector location, and controller timing make it difficult for the driver to determine whether to stop or proceed through the intersection from certain locations in advance of the intersection after the appearance of the yellow indication. These locations constitute a dilemma zone or a zone of complex risk evaluation for the driver. Also, under moderate-to-light traffic conditions, controllers that use the single-point detection scheme and are timed for heavy traffic may allow frequent loss of green due to "gapping out," and thus present more yellow intervals and more opportunities for wrong driver decisions. Erratic signal controller operation associated with premature gapping out is frequently cited as an indication of inefficient operation. Such inefficiency might be responsible for unnecessary vehicular delay and increased accident potential.

Various detector placement and controller timing schemes have been proposed for solving these problems at intersections that have high approach speeds (1). Several detection schemes are mentioned in the following paragraphs, and one series, which is referred to as multiple-point detection, is examined in detail. Results of theoretical analysis, simulation, and field evaluation are presented as bases for evaluating four multiple-point detection methods and the potential that they might provide for reducing accidents and improving signal operating efficiency.

DILEMMA ZONE OR ZONE OF COMPLEX RISK EVALUATION

The principal justification for using multiple detectors and special controller timing on high-speed intersection approaches is to prevent, whenever possible, the yellow signal indication from being initiated when a vehicle is within what has been called the dilemma zone or zone of indecision (1). When the signal indication displayed to traffic approaching an intersection changes from green to yellow, drivers must decide immediately whether to stop before entering the intersection or to continue through the intersection without stopping. This requires that each driver evaluate a number of specific time, distance, velocity, and acceleration parameters during perception-reaction time as the vehicle continues toward the intersection. The driver must weigh the risks associated with stopping against those associated with continuing. The action decided on during perception-reaction time will presumably involve the least overall risk in the judgment of the driver.

For a given approach speed, the relative risk involved with a decision to stop or to continue varies with the distance from the intersection at which the approaching vehicle is located when the yellow indication begins as well as with the duration of the yellow indication. When the distance is large, a stop can be accomplished easily with a low rate of deceleration and therefore low risk of skidding or being hit from the rear, but continuing involves a long travel time to the intersection and a high risk of not being able to clear the intersection during the yellow. The time needed to stop is not important. At locations closer to the intersection, the risks related to stopping increase, and those associated with continuing decrease, thereby making the driver's task of risk evaluation more complex. When the vehicle is near the intersection at the onset of yellow, a decision to stop requires a high rate of deceleration with the associated high risks, but a decision to continue allows the vehicle to enter or clear the intersection during a yellow indication of normal duration with low risk. Outside the zone described by these bounding distances, the low-risk decision is obvious. Most drivers will be able to choose the proper action easily, but within the zone, the problem of choosing the low-risk alternative action is complicated. If the traffic engineering objective of eliminating the need for a driver decision under these difficult and complex circumstances is to be realized, the nature and extent of the zone must be defined in descriptive terms.

In analyzing driver response to the yellow signal, May (2) described the zone in which a vehicle could be located at the onset of yellow whereby it could neither stop safely nor clear the intersection during the yellow interval as a dilemma zone. This is the conventional use of the term dilemma--a situation involving choice between equally unsatisfactory alternatives (3). The term option zone was used to describe situations in which the yellow interval was long enough to allow vehicles to either stop safely or to clear the intersection during the yellow.

In a technical report concerning detector-controller configurations that use small-area detectors, Parsonson and others (4) coined an arbitrary definition of dilemma as a probability of stopping of more than 10 percent but less than 90 percent and described the dilemma zone as the range of distance from the intersection within which drivers are often indecisive. This terminology, which has been used in a number of technical papers since 1974, deviates from the conventional usage of the word dilemma and describes drivers who are forced to respond to a yellow signal indication as often being indecisive. There is little evidence to indicate that drivers are indecisive in this situation. When confronted with the same circumstances drivers may vary in which of the two available alternatives they choose, but every driver makes a decision. The concept of using probabilities to delineate the zone in which risk evaluation is evidently a complex task for drivers to perform when facing a yellow signal is commendable. Zegeer's experimental work (5) extends that of Parsonson and others (4) and interprets the observations of several others in support of the concept. Understanding of this concept would possibly be facilitated if nomenclature other than dilemma zone were used. Descriptive terminology such as zone of complex risk evaluation or zone of varying probability of stopping would be more cumbersome but would probably be more accurately interpreted by traffic engineers.

The zone of concern can be delineated adequately for detector placement purposes in various ways. The special detector placement and signal timing schemes that are evaluated in this report attempt to recognize the existence of areas on intersection approaches where driver decisionmaking is problematic and relieve the problem by controlling the timing of the onset of the yellow signal indication.

DETECTOR PLACEMENT METHODS

Three types of special detector placement methods have been developed in recent years and used at a number of locations around the country (1). Another innovative development is described by Parsonson and others (6), but this new system has not yet been used widely. The three techniques listed below use conventional hardware and have been installed at several sites. These methods include the following:

1. Green extension systems for semiactuated controllers,
2. Extended-call detection systems, and
3. Multiple-point detection systems for basic controllers, such as the Beirele method, Winston-Salem method, and SSITE method.

A comprehensive description of each of these methods is given by Sackman and others (1), and a flow chart to guide in selecting detector-controller configurations for specific situations is included. Detailed examples of calculating proper detector locations and controller settings for various high-approach-speed intersections are presented.

The first two detector placement methods ordinarily use two inductive loop detectors with extended-call timing features and do not directly allow for large variations in approach speed by sensor location. With these systems, higher speeds tend to lengthen the dilemma zone and make the effects of timing much more critical as approach speeds and traffic volumes vary.

A number of multiple-point detector installations have been made at intersections in Texas where approach speeds are high. The Beirele method was used to design most of the systems, but a modification was made to the basic method by the Texas State Department of Highways and Public Transportation (TSDHPT) for some locations. It was desirable to evaluate the relative effectiveness of these installations and compare them with similar multiple-detector methods. The four multiple-detector methods that were included in the study are described elsewhere (1) and are presented in outline form below.

Beirele Method

The Beirele method of multiple detector placement uses a 1-s vehicle interval setting on a basic controller operating in the locking detector memory mode. Each detector is located in advance of the intersection at a distance that is at least adequate for a driver who receives a yellow indication at that point to react and stop safely from an assumed speed. Safe stopping sight distances are based on a 1-s perception-reaction time plus braking distances that result from coefficients of friction between 0.41 and 0.54 for speeds between 55 and 20 mph. The outermost, or first, detector is placed at safe stopping sight distance from the intersection for full approach speed. The next detector is tentatively located at safe stopping sight distance from the intersection for a speed assumed to be 10 mph less than that used for locating the first detector. If the travel time for a passenger car between the two presence-mode loop detectors (6x6-ft size) is greater than 1 s, the downstream detector is relocated to allow the vehicle to reach it during the 1-s vehicle interval set on the controller. This location procedure is repeated for each successive detector until the last loop is 75 ft from the intersection. Minimum assured green time is set on the controller to allow vehicles stored between the last detector and the intersection to enter the intersection. Recommended locations of detectors for different speeds are shown in Table 1. Beirele suggests the addition of special speed detection features for approach speeds above 50 mph.

Winston-Salem Method

The Winston-Salem method was developed by Holloman in 1975. The principles used in the method are basically the same as those used by Beirele; however, the differences between the methods are as follows:

1. This method uses slightly different stopping distances,
2. This detector location procedure starts with placement of the innermost detector and works outward, and
3. This method is suggested for speeds up to 60 mph.

Detector locations for three speeds are shown in Table 1.

SSITE Method

The SSITE method of detector placement was described initially in a report by the Southern Section of the Institute of Traffic Engineers (ITE) in 1976 (7). Basically, this method uses both an iterative process and engineering judgment to locate the inductive loops. Detectors are connected in a series-parallel arrangement and operated in the presence mode with a nonlocking controller. Six detectors are used in an attempt to provide detection along the full length of the approach from the intersection to the outer limit of the dilemma zone as defined by Parsonson and others (4). The outer two detectors provide protection for high approach speeds, and the inner four detectors are positioned to allow for reduced speed nearer the intersection and to provide for queue discharge without premature gap-out. A vehicle interval is set in the con-

Table 1. Detector spacing.

		Detector Spacing (ft)[a]					
Method	Speed (mph)	Stop Line-1st Detector	1st-2nd Detector	2nd-3rd Detector	3rd-4th Detector	4th-5th Detector	5th-6th Detector
Beirele	30	48	39				
	40	48	39	58			
	50	52	48	62	76		
Winston-Salem	30	86					
	40	86	61				
	50	86	61	69			
SSITE	30	0	15	31	43	74	
	40	0	15	25	74	106	
	50	0	15	25	45	105	124

[a] Detector spacing is measured upstream from stop line; loop size is 6x6 ft.

Table 2. Loop layout for TSDHPT modified Beirele method.

	Inductive Loop Layout (ft)[a]						
	Without Optional Detector			With Optional Detector			
Speed (mph)	Stop Line-1st	1st-2nd	2nd-3rd	Stop Line-1st	1st-2nd	2nd-3rd	3rd-4th
30	108			55	47		
40	108	64		55	47	64	
50	108	64	83	55	47	64	83

[a] Inductive loop layout is measured upstream from stop line; loop size is 6x6 ft.

troller to hold the green as vehicles pass between successive detectors. Spacing between the inductive loops is shown in Table 1.

TSDHPT Modified Beirele Method

In addition to the three multiple-point detector placement methods described above, a location technique developed and tested by the TSDHPT was also studied. The concept is similar to the Beirele method. A 1-s perception-reaction time is included in stopping distance calculations, but braking distance computations use American Association of State Highway and Transportation Officials (AASHTO) assumed speeds and coefficients of stopping friction (8). In the basic method the closest detector is located 114 ft from the intersection, but a further modification locates an optional detector 61 ft from the stop line. The addition of the optional detector has the effect of reducing the required initial interval (minimum assured green) and possibly improving operational efficiency. The loop layouts for speeds of 30, 40, and 50 mph by using the TSDHPT modified Beirele method are shown in Table 2.

Differences in Detector Placement Methods

Controller type, detector mode, applicable speed range, loop layouts, and allowable gap for each of the basic multiple-detector placement methods are summarized in Table 3. A look at the table indicates that the major differences among these methods are (a) number of inductive loops used and (b) inductive loop spacings.

The length of the zone of complex risk evaluation, or the dilemma zone, becomes larger as approach speed increases; therefore, more detectors are required to trace a vehicle through the zone. In addition, the longer the spacing between successive loops, the longer the required vehicle interval and the less efficient the controller is likely to be. So, in general, multiple-detection systems are more appropriate for signalized intersections that have high-speed traffic on the approaches.

COMPARISON OF MULTIPLE-POINT DETECTION METHODS BY SIMULATION

Although the theoretical potential of multiple-point detection systems for solving driver-decision problems is fairly clear, the actual effects on vehicular delay and accident experience are not well documented. Field observation is costly and time consuming. In order to study the relative differences in vehicular delay that can result from four detector placement methods, an experiment that used computer simulation was conducted. A factorial experiment design was developed to evaluate each placement method at three volume levels and three speed levels for both diamond interchange and four-leg intersection geometric configurations. A schematic representation of the factorial experiment design is presented in Table 4. The mathematical model to be employed in the analysis of variance is

$$Y_{ijK} = \mu + M_i + S_j + MS_{ij} + V_K + MV_{iK} + SV_{jK} + E_{ijK} \quad (1)$$

where

Y_{ijK} = predicted average delay;
μ = grand mean;
M_i = placement method i = 1, 2, 3;
S_j = approach speed j = 1, 2, 3;
V_K = lane volume K = 1, 2, 3;
MV_{iK} = interaction between M and V;
SV_{jK} = interaction between S and V;
MS_{ij} = interaction between M and S; and
E_{ijK} = error term.

No replication is provided in the basic experiment, therefore, the possible three-way interactions are confounded with the error term. Six slightly different types of vehicular delay were tested separately as the dependent variable in the basic experiment. They include the following:

1. Average total delay for all vehicles,
2. Average queue delay for all vehicles,
3. Average stopped delay for all vehicles,
4. Average total delay per delayed vehicle,
5. Average queue delay per vehicle incurring queue delay, and
6. Average stopped delay per vehicle incurring stopped delay.

Total delay is measured as the difference between actual travel time and the travel time required if the vehicle maintains a prespecified desired speed. Queue delay is accumulated only when a vehicle is part of a queue on the intersection approach. A vehicle is said to be in a queue when it is less

Table 3. Summary of detector placement methods.

Design	Green Extension Systems for Semiactuated Control	Extended Call Detector Systems for Basic Controller	Multiple Detection Systems		
			Beirele Method	Winston-Salem Method	SSITE Method
Controller type	Nonlocking type	Nonlocking type	Locking type	Locking type	Nonlocking type
Detector mode	Presence	Presence	Presence	Pulse	Presence
Speed range	V = 85th percentile speed	V = 85th percentile speed	$V \leq 50$	$V \leq 60$	$V \leq 60$
Loop layout					
Outermost loop[a]	$D = 1.47Vt + (V^2/30f)$	$D = 1.47t + (V^2/30f)$	Use stopping distance from intext driver testing	Use stopping distance from Traffic Engineering Handbook	Use SSITE Report
Innermost loop	$D_1 = 1.47V[(V/30) + 1]$	0	48 or 69 ft	86 ft	0 ft
Spacing between loops[b]	$(D - D_1)/V > 2$ s	$(D - 70)/V_{\text{low limit}} > 2$ s	1 s	1 s	2 s
No. of loops[c]	2 or 3	2	$(V/10) - 1$	$(V/10) - 2$	< 6
Allowable gap	5∿6 s	5∿6 s	2∿5 s	2∿5 s	5∿7 s

[a] Distance is measured from the stop line to the upstream end of the loop.

[b] $V_{\text{low limit}}$ = low speed limit, for example 15th percentile speed.

[c] $(V/10)$ represents the integer part of $V/10$, for example $(3.5) = 3$.

Table 4. Factorial design.

Method	Speed (mph)	Lane Volume [(vehicles/h)/lane]		
		300	500	700
Diamond-interchange and four-leg intersection				
Beirele	30	$A_1B_1C_1$[a]	$A_1B_1C_2$	$A_1B_1C_3$
	40	$A_1B_2C_1$	$A_1B_2C_2$	$A_1B_2C_3$
	50	$A_1B_3C_1$	$A_1B_3C_2$	$A_1B_3C_3$
Winston-Salem	30	$A_2B_1C_1$	$A_2B_1C_2$	$A_2B_1C_3$
	40	$A_2B_2C_1$	$A_2B_2C_2$	$A_2B_2C_3$
	50	$A_2B_3C_1$	$A_2B_3C_2$	$A_2B_3C_3$
SSITE	30	$A_3B_1C_1$	$A_3B_1C_2$	$A_3B_1C_3$
	40	$A_3B_2C_1$	$A_3B_2C_2$	$A_3B_2C_3$
	50	$A_3B_3C_1$	$A_3B_3C_2$	$A_3B_3C_3$
Study of optional detector in TSDHPT modified Beirele method				
Without optional detector	30	$A_1B_1C_1$[a]	$A_1B_1C_2$	$A_1B_1C_3$
	40	$A_1B_2C_1$	$A_1B_2C_2$	$A_1B_2C_3$
	50	$A_1B_3C_1$	$A_1B_3C_2$	$A_1B_3C_3$
With optional detector	30	$A_2B_1C_1$	$A_2B_1C_2$	$A_3B_1C_3$
	40	$A_2B_2C_1$	$A_2B_2C_2$	$A_2B_2C_3$
	50	$A_2B_3C_1$	$A_2B_3C_2$	$A_2B_3C_3$

[a] $A_1B_1C_1$ is method 1 (Beirele) when speed at first level (30 mph) and lane volume at first level [(300 vehicles/h)/lane].

than a specified distance (4-40 ft) from the stop line (for the first driver-vehicle unit in the lane) or from the driver-vehicle unit ahead and is traveling less than 3 ft/s. Stopped delay is accumulated when a driver-vehicle unit is stopped or traveling at a velocity less than 3 ft/s. Each of these types of delay is routinely calculated by the TEXAS computer simulation model.

Computer Simulation

The TEXAS model (9,10) which was developed at the Center of Highway Research, University of Texas at Austin, was selected as the most suitable traffic simulation model for this investigation. This model is comprised of three major component programs:

1. Presimulation geometry processor,
2. Presimulation driver-vehicle processor, and
3. Simulation processor.

Both the geometry processor and the driver-vehicle processor are supportive programs for the simulation processor. The outputs from these two programs serve as the input for the simulation processor. The input for the geometry processor includes a detailed description of intersection geometrics and the inputs for the driver-vehicle processor characterize the individual drivers and vehicles that operate in the traffic stream. The additional inputs for the simulation processor include (a) simulation time parameters, (b) car-following parameters, (c) signal timing parameters, and (d) detector location and operating mode information. In the simulation the program sequentially examines each driver-vehicle unit in the intersection system and allows each to respond to surrounding traffic and traffic control devices and predicts its position, speed, and acceleration in the next increment of simulation time. Each unit is thus stepped through the intersection in small time increments. Delay, speed, and volume statistics are accumulated through the simulation process and reported at the end of a selected time period.

Analysis of Simulation Results

Analysis of variance was used to evaluate the significance of effects on the dependent variables produced by each delay-related factor. The null hypothesis stated that the effect produced by each factor on the delay statistics was not significant at a 5 percent level of significance. If the probability associated with the calculated F-statistics was found to be less than 0.05, then the null hypothesis could be rejected. Table 5 summarizes the values of significance of F from 48 analyses of variance. From this table, the following statements can be made.

In both the diamond-interchange and the four-leg intersection study neither detector placement method nor approach speed has a significant effect on the average delay experience by all vehicles that use the intersection or on the average delay experienced by only the delayed vehicles at the 5 percent level of significance. Lane volume, however, has a significant effect on both types of average delay at a 5 percent level of significance.

Analysis of the TSDHPT modified Beirele method with and without an optional detector at a four-leg intersection produced a basis for the following conclusions:

1. The option does not produce significant effects on either type of average delay at a 5 percent level of significance;
2. Approach speed does not have significant effect on either type of average delay when all approaches are analyzed together; however, it produces significant effects at a 5 percent level of signifi-

cance when individual approaches are tested; and

3. Lane volume produces significant effects on both types of average delay at a 5 percent level of significance.

FIELD INVESTIGATIONS OF SINGLE-POINT AND MULTIPLE-POINT DETECTION

In addition to the simulation-based study of delay associated with various detector placement methods, a series of field observations were used to compare the effects of multiple-point with single-point detection. Ten test sites located in Texas that have actuated signal controllers and relatively high approach speeds were selected.

At each test site existing single detectors were replaced by multiple units on selected approaches that were deemed to be most problematic. The place-

Table 5. Significance of F.

		Intersection Geometry					Optional Detector in TSDHPT Modified Beirele Method		
		Diamond Interchange		Four-Leg Intersections[b]					
Delay Measure	Delay	All Approaches[a]	Major Approaches	All Approaches	Major Approaches 1	Major Approaches 2	All Approaches[a]	Major Approaches 1	Major Approaches 2
Avg total delay	Per approach vehicle								
	Detection method	0.103	0.133	0.091	0.251	0.353	0.828	0.199	0.949
	Speed	0.191	0.433	0.269	0.400	0.473	0.231	0.076	0.002
	Lane volume	0.007	0.001	0.007	0.001	0.001	0.001	0.002	0.001
	Per delayed vehicle								
	Detection method	0.090	0.170	0.08	0.252	0.363	0.799	0.176	0.764
	Speed	0.269	0.471	0.34	0.367	0.442	0.233	0.004	0.002
	Lane volume	0.001	0.001	0.01	0.001	0.001	0.001	0.001	0.001
Avg queue delay	Per approach vehicle								
	Detection method	0.119	0.145	0.080	0.209	0.614	0.219	0.108	0.324
	Speed	0.189	0.430	0.340	0.362	0.384	0.230	0.008	0.001
	Lane volume	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Per delayed vehicle								
	Detection method	0.208	0.427	0.070	0.275	0.259	0.997	0.159	0.945
	Speed	0.843	0.583	0.245	0.161	0.229	0.100	0.004	0.093
	Lane volume	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Avg stop delay	Per approach vehicle								
	Detection method	0.119	0.282	0.089	0.246	0.285	0.878	0.339	0.338
	Speed	0.598	0.459	0.220	0.363	0.353	0.715	0.023	0.001
	Lane volume	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Per delayed vehicle								
	Detection method	0.135	0.578	0.083	0.360	0.270	0.410	0.009	0.001
	Speed	0.968	0.593	0.163	0.195	0.237	0.410	0.009	0.001
	Lane volume	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

[a] Only major street approaches receive multiple detectors. [b] Simulation conducted only for four-leg intersection.

Table 6. Location and spacing of multiple detectors.

	Detector Spacing (ft)			
Intersection Approach	Stop Line-1st Detector	1st-2nd Detector	2nd-3rd Detector	3rd-4th Detector
SH-183 and Roaring Springs				
Northbound SH-183	144	74	91	
Southbound SH-183	108	64	83	
SH-174 and FM-917				
Northbound SH-174	108	64	83	
Southbound SH-174	108	64	83	
FM-1220 and Boat Club Road				
Westbound FM-1220	144	74	91	
Southbound Boat Club	144	74	91	
SH-199 and Fire Hall Drive				
Northbound SH-199	141	73		
Southbound SH-199	141	73		
SH-199 and Roberts cut off				
Westbound SH-361	108	64	83	
Eastbound SH-199	108	64	83	
FM-361 and FM-1069				
Westbound SH-361	108	64	83	
Eastbound SH-361	108	64	83	
US-84 and SH-317				
Westbound US-84	141	73		
Eastbound US-84	141	73		
Southbound US-84	141	73		
US-290 and FM-1960				
Westbound US-290	108	64	83	
Eastbound US-290	108	64	83	
Northbound SH-6	108	64		
Southbound FM-1960	108	64	83	
SH-6 and Jackson				
Westbound SH-6	144	74	91	
Eastbound SH-6	144	74	91	
SH-146 and Crest Lane				
Northbound SH-146	108	64	83	97
Southbound SH-146	144	74	91	

Note: Detector spacing is measured upstream from the stop line; all loop detectors are configured 6x6-ft.

ment method used to locate the multiple detectors was the TSDHPT modified Beirele method. Spacings of multiple detectors on the respective approaches are given in Table 6.

Traffic volume and stopped time delay data were observed and recorded at each field site both before and after the existing single-loop detectors were replaced with multiple detectors on selected approaches. Comparisons of the before and after stopped-time delay and traffic data were used as a means of evaluating the effect of two multiple-detector placement systems.

Field Data Collection

Stopped-time delay and traffic volume data were collected at each test site by using procedures specified by Reilly and others (11). At each location data were acquired during both peak and off-peak traffic volume conditions, with and without multiple-detection systems. Data collection for multiple-detector systems was conducted a minimum of one year after system installations, thus providing time for driver familiarization and signal timing fine tuning.

Table 7. Summary of significance of F-ratio form analysis of variance for single- versus multiple-detector installations.

	Source of Variation[a]			
Test Site	Main Effects	Before versus After[b]	Intersection Approach	Time
SH-174 and FM-917	0.003	0.004	0.007	0.031
FM-1220 and Boat Club Drive	0.214	0.429	0.073	0.128
SH-183 and Roaring Springs	0.062	0.236	0.865	0.015
SH-361 and FM-1069	0.001	0.052	0.001	0.661
SH-6 and Jackson Street	0.001	0.001	0.003	0.001
SH-146 and Crest Lane	0.001	0.084	0.276	0.001
US-290 and FM-1960	0.260	0.222	0.122	0.364
US-84 and SH-317	0.556	0.892	0.326	0.468
SH-199 and Fire Hall Drive	0.001	0.002	0.001	0.034
SH-199 and Roberts cut off	0.042	0.405	0.019	0.089

[a] Numbers in each cell can be interpreted as the proportion of all possible chances that differences of the size observed could have occurred due to chance alone. Minimum cell value is 0.0 and maximum is 1.0.

[b] Single versus multiple-point detection.

Data Analyses

The field data analysis process was designed to test a general hypothesis that multiple-detection systems affect stopped delay when compared with conventional single-detector systems. Conventional parametric analysis of variance testing was used to examine this hypothesis.

By using stopped-time vehicular delay as the dependent variable, three-way analysis of variance testing was applied independently to data from each test site. In order to normalize differences in before-and-after vehicular delay data due to variations in traffic volume, all delay statistics were divided by appropriate intersection approach traffic volume totals. Therefore, the dependent variable was actually mean stopped-time delay per vehicle passing through the intersection approach.

A summary of the analysis of variance testing is presented in Table 7. Probability values that indicate the likelihood that observed effects could be due to chance alone are presented. For example, the probability that the observed effects (presumably) due to the detector scheme at SH-174 and FM-917 could have occurred due to chance alone is almost zero (0.004). On the other hand, the probability is extremely large (0.429) that the observed effects of multiple detectors at FM-1220 and Boat Club are

Table 8. Overview of field comparisons of multiple- versus single-point detection.

	Arithmetic Mean Stopped Vehicular Delay[a]			
Test Site	Before, Single Point	After, Multiple Point	Statistically Significant[b]	Detector Configuration Producing Least Delay
SH-174 and FM-917	5.80	9.12	Yes	Single
FM-1220 and Boat Club Road	16.00	14.42	No	Multiple
SH-183 and Roaring Springs	7.56	5.98	No	Multiple
SH-361 and FM-1069	5.70	5.16	No	Multiple
SH-6 and Jackson Street	16.32	8.14	Yes	Multiple
SH-146 and Crest Lane	11.44	13.71	No	Single
US-290 and FM-1960	19.61	29.24	No	Single
US-84 and SH-317	5.05	4.98	No	Multiple
SH-199 and Fire Hall Drive	16.95	10.43	Yes	Multiple
SH-199 and Roberts cut off	14.58	18.52	No	Single

[a] Includes all approaches. [b] Significant at $\alpha = 0.05$.

Table 9. Accident analysis parameters before and after multiple-detector installation.

	Annual Total Traffic Volume (000 000s vehicles)		Annual Accidents		Annual Accident Rate per million vehicles		
Intersection	Before	After	Before	After	Before	After	Approach Speed (mph)
SH-199 and Firehall Drive	10.2	10.2	12	7	1.18	0.69	45
FM-1220 and Boat Club Road	3.93	4.28	6	3	1.53	0.70	45
SH-199 and Roberts cut off	11.5	11.3	20	27	1.74	2.39	45
SH-183 and Roaring Springs	12.0	11.9	29	22	2.42	1.85	40
SH-174 and FM-917	6.04	7.10	7	7	1.16	0.99	55
US-220 and SH-6 and FM-1960	11.9	16.1	27	31	2.27	1.93	55
SH-6 and Jackson Street	4.94	4.49	5	2	1.01	0.45	55
SH-146 and Crest Lane (Barbours Cut)	8.46	11.6	6	0	0.71	0	55
SH-361 and FM-1069	3.75	4.44	4	6	1.07	1.35	40
US-84 and SH-317	2.74	2.81	13	14	4.80	4.98	45

indeed due to chance alone. Also included are analogous assessments for effects due to intersection approach and times of observation as well as all main effects taken together. A probability value of 0.05 is frequently assumed to be small enough to guarantee acceptable confidence that effects are not chance occurrences. If this policv is adopted, statistically significant differences in stopped-time delay due to detector scheme were observed at 3 of the 10 test sites. This statement does not imply, however, that in all three of these significant cases multiple detectors reduced delay. In fact, Table 8 demonstrates that in one of these three cases, there was a significant increase in vehicular delay under multiple detection.

Another view of the comparison between single and multiple-point detection is presented in Table 8. Arithmetic mean values of stopped-time delay per vehicle, including all observations, both for single- and multiple-point detection schemes are presented. The statistical significance of differences between before and after observations at a confidence level of 0.05 and an indication of which detector scheme produced smaller delay values are included. As already noted, effects attributable to detection scheme were significant in only three cases, and of these only two indicated greater efficiency under multiple-point detection.

A generalized comparison of the before-and-after data means indicates that 6 of the 10 test sites had at least marginal decreases in delay under multiple-detection schemes. Conversely, 4 of 10 performed more efficiently under the original single-point detection schemes. A conventional T-test was performed to evaluate the hypothesis that all means of before-and-after conditions drawn from the same population are equivalent. This test produced a T-statistic of 0.65 with 18 degrees of freedom, which when compared with a table value of 2.10 (for a 0.05 confidence level) is obviously not significant. In fact, this value is not significant at a 0.50 confidence level. Therefore, if stopped-time delay is taken as a measure of operational efficiency, data gathered at these 10 test sites do not demonstrate any significant difference in operational efficiency for the single- and multiple-point detection systems that were studied.

SIMULATION OF FIELD SITE CONDITIONS

In the previous sections, a field experiment that compares multiple-point and single-point detection has been described. Although the TEXAS model for intersection traffic that was used in the simulation study of four multiple-point detector systems described earlier has been previously verified through field studies, additional verification was deemed desirable.

Therefore, a typical field test site was selected for comparing delay statistics produced by the simulation model with those observed under field conditions. The intersection of SH-174 and FM-917 was selected for this experiment, and known geometry, signal timing, detector placement, and traffic characteristics were input to the simulation model. Conditions both before and after installation of multiple detectors were simulated and both peak and off-peak traffic volumes were used.

A factorial experiment was designed to test for statistically significant differences among treatment effects. Three main effects were studied; these included time (either peak or off-peak), intersection approach, and data source (field versus simulation).

Differences among simulation and field delay statistics are not statistically significant at an alpha level of 0.05. Differences due to the other two main effects are also not significant at the corresponding alpha level. Although the results of this limited experiment cannot be completely generalized, the assumption that the simulation technique does a reasonable job of representing real-world delay information is supported.

COMPARISONS OF SINGLE-POINT AND MULTIPLE-POINT DETECTION SCHEMES

A field test of single-point and multiple-point detection schemes has been presented. The test compared the two detection methods in a before versus after format with stopped-time vehicular delay as the response variable. A limited comparison of vehicular delay statistics produced by TEXAS simulation model and those collected through field measurement was also presented.

Based on these data and analyses, the following statements can be made:

1. A statistically significant difference in vehicular delay due to single-point versus multiple-point detection was not found and
2. Differences among vehicular delay data predicted by the TEXAS simulation model and that measured in field tests were not found to be statistically significant at a confidence level of 0.05.

ACCIDENT ANALYSIS

In order to assess the significance of multiple detectors on accident experience, data were acquired for each of the test sites. In all cases accident data were compiled for at least one year following installation of multiple detectors. Data for one to three years preceding installation was used as a basis for comparison.

Traffic volumes were used to convert numbers of accidents to accident rates and thereby produce statistics that were somewhat more comparable. Before and after traffic volumes, accidents, and accident rates are presented in Table 9.

Statistical significance of changes in numbers of accidents and rates was evaluated by using both a Poisson and a chi-square test (12). Two tests were used as a means of bounding possible results since the chi-square test is deemed rather conservative and the Poisson test somewhat liberal. The intersections of US-290 and SH-6 and US-84 and SH-317 were deleted from the analysis because of changes in the traffic environment during the data collection period that could not be controlled and would likely bias results.

The remaining eight intersections were grouped by approach speeds into a 40-45 mph class and a 50-55 mph class. Poisson and chi-square tests were applied to each of the two groups and to the aggregate.

Tests by both procedures indicated that changes in accidents and rates were statistically significant at a 95 percent confidence level for the high approach speed (50-55 mph) group. Changes in numbers of accidents or rates for the low approach speed (40-45 mph) group and the aggregate of all eight intersections did not indicate statistical significance at the 95 percent confidence level.

CONCLUSIONS

A comparative evaluation of vehicle detector systems for use in actuated signal control has been presented. The evaluation has compared vehicular delay and accident experience that result from detection systems by using single and multiple detectors and has compared four techniques for locating multiple detectors. In addition, vehicular delay statistics predicted by the TEXAS simulation model have been compared with those observed at a field site.

Based on these analyses the following conclusions may be stated:

1. Simulation studies indicated that there was no generally significant difference in the vehicular delay that resulted from applying the Beirele, Winston-Salem, or SSITE multiple-detector placement methods,
2. Vehicular delay predicted by the TEXAS traffic simulation model was not shown to be significantly different from that observed at a selected field test site,
3. Comparison of single- and multiple-detector installations at 10 test sites indicated no significant difference in stopped-time vehicular delay, and
4. Statistically significant reductions in accident experience were identified at intersections that had multiple detectors and high approach speeds (50-55 mph). Changes in accident experience attributable to multiple detectors at intersections that had approach speeds less than 50 mph were not statistically significant.

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This paper was prepared in cooperation with the Federal Highway Administration. The contents of this paper reflect our views and we are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. The paper does not constitute a standard, specification, or regulation.

Discussion

Peter S. Parsonson

The yellow interval of a traffic signal is such a familiar part of our everyday lives that most people would assume that its design has been well settled and agreed on by traffic engineers for several decades. On the contrary, the topic remains highly controversial to this day. There is still much discussion of when the yellow should start and for how long it should be shown. Multiple-detector schemes are used to control the beginning of the yellow. The authors of this paper are to be commended for being the first to apply a computer simulation model to multiple-point detection.

Multiple-detector strategies have been offered as solutions to a problem related to a zone of indecision (1,6). If the yellow comes on while a high-speed vehicle is in this zone the driver may have difficulty in deciding whether to stop or to go through, although the yellow is long enough to allow either decision. A safety problem can occur if the driver changes his or her mind. A last-second decision to stop abruptly may result in a rear-end collision or a swerve that produces a side-swipe accident. The zone of indecision has been well defined by Zegeer (5).

The multiple-point detectorization schemes examined by the authors were intended by their originators to help solve the problem of the zone of indecision.

Any multiple-point scheme should be compared with the single-point design that uses a density controller. Density designs were in use prior to any of the multiple-point schemes, which were devised primarily because many traffic engineers and technicians prefer a basic actuated controller to the more complex density machine. The density design is the defender in any discussion of schemes to alleviate the problem of the zone of indecision, because the gap-reduction adjustment permits the allowable gap to be as low as 2.6 s (14).

The authors, with good reason, prefer schemes that are effective over a range of approach speeds. Therefore, they discarded green extension systems and extended-call (EC) detector systems in the belief that designs with only two detectors are not effective over a range of speeds. Actually, the extended-call design as well as the density design can be adapted to a range of speeds by increasing the controller's unit extension (or minimum gap), or the detector's extension timing. This sacrifices allowable gap in favor of speed range. This tradeoff allows the engineer to make the design effective over a wider range of speeds at locations where light traffic poses no threat of extending the green to the maximum interval set on the controller.

The authors state that, at present, the Beirele, Winston-Salem, and SSITE methods are recognized as the most-common multiple-point detector-placement methods. The Beirele method keeps the allowable gap reasonably short by placing the first detector only 261 ft from the intersection for a 50-mph design speed (1). This distance is entirely inadequate, as the zone of indecision begins 350 ft from the intersection at this speed (5). The vehicle must be detected before entering that zone.

The Winston-Salem design has the same defect, as the upstream detector at 246 ft falls short by more than 100 ft. Again, effectiveness in eliminating driver indecision is sacrificed in order to keep the allowable gap reasonably short.

The SSITE method remedies this particular problem by placing the first detector 350 ft from the intersection. However, the allowable gap is so long, at 7 s, that this design would be useful only under the lightest of traffic conditions. The paper that originally presented the design explained that it requires undesirably long allowable gaps, stated specifically to be 7 s (15), "The controller's ability to detect gaps in traffic is substantially impaired.... As a result, moderate traffic will routinely extend the green to the maximum setting--an undesirable situation" because on max-out a vehicle may be caught in the zone of indecision. Sackman and others (1) stated that "This allowable gap is so long as to virtually disqualify the design from further consideration" and added that "the SSITE method will rarely be the design of choice."

It appears, then, that this project applied computer simulation techniques to designs that are unsatisfactory. In many respects they compare unfavorably with the traditional density design.

In 1979, perhaps too recently to have figured in this project, a novel EC-delayed call (DC) detection scheme was proposed (6) in response to a perceived need for a design offering loop-occupancy features; a basic, actuated controller with nonlocking memory; a short allowable gap; and effectiveness over a wide range of speeds. A 6-x25-ft loop at the stopline automatically switches from EC to DC operation at the strategic moment during the green interval. (A new detector unit now on the market makes the switch without any of the external relay logic described in the paper.) Normal-calling small loops 254 and 384 ft from the intersection provide protection against driver indecision at speeds from 40 to 60 mph, and 35 mph or lower (but not from 36 to 39 mph). The allowable gap is 4 s.

The authors found at their field sites that multiple detectors did not significantly reduce accident rates at intersections that have approach speeds less than 50 mph. A test installation of the EC-DC design in the Atlanta area has a median approach speed of 48 mph. The EC-DC scheme was found to reduce abrupt stops from 5 to none over the observation period (6). "Brake before clearing" maneuvers were reduced from 8 to none. Total conflicts were reduced 69 percent from 29 to 9. Overall, the authors rated the design superior to either the density scheme or the extended-call detector system. These observed reductions in erratic maneuvers suggest the potential for a reduction in accidents.

Zegeer (5) gathered accident data in addition to conflict rates. He found that his green-extension systems brought about a 54 percent reduction in total accidents, and rear-end collisions were reduced by 75 percent. At least two of the three locations studied appear to have average speeds of only 45 mph.

The authors found that the Beirele, Winston-Salem, and SSITE detector placement methods produced about the same delay in their computer simulations. This is an unexpected finding, as the allowable gaps vary over a wide range (4-7 s) and it is well established (16,17) that delay is sensitive to the allowable gap. Morris and Pak-Poy (16) found by computer simulation that delay can increase by as much as 45-105 percent if the allowable gap is increased from 4 to 7 s. Similarly, Tarnoff and Parsonson (17, p. 14) found by computer simulation that delay can increase by as much as 50 to 70 percent if the allowable gap is increased from 4 to 7 s.

Possibly the authors used a low setting of the maximum interval, thereby causing the green to change to yellow before gap-out could take place.

It is worth emphasizing that a long allowable gap is objectionable not primarily because of delay but because only moderate volumes can extend the green to the maximum interval. In that case, a vehicle may well be caught in the zone of indecision. A computer simulation could be very helpful in the preparation of guidelines for the maximum volumes that can be tolerated by designs of various allowable gaps.

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Driver Use of All-Red Signal Interval

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The purpose of this study was to investigate the theory that drivers use the red signal interval more frequently at intersections that have all-red intervals (i.e., all approaches to an intersection have a red indication) than at intersections that do not have all-red intervals. Data were collected at 10 intersections in four New England cities, during both peak and off-peak periods. Some 2764 signal cycles were observed, during which 1115 vehicles entered the intersection after the start of the red interval. The data were subjected to statistical analyses that yielded the following conclusions: (a) more drivers ran the red light at intersections that had all-red intervals than at intersections that had no all-red intervals; (b) the length of the all-red interval appeared to be cor-