Jan. 1968, pp. 14-20.
8. J. Behnam. Gap Acceptance as a Criterion for Left-Turn Phasing. Traffic Engineering, June 1972, pp. 40-42.
9. J. Leisch. Capacity Analysis Techniques for Design of Signalized Intersections. Public Roads, Vol. 34, No. 9, Aug. 1967, pp. 171-201; No. 10, Oct. 1967, pp. 211-226.
10. J. C. Glennon and B. A. Torson. Evaluation of the Traffic-Conflicts Technique. Federal Highway Administration, Dec. 1975.
11. W. T. Baker. Evaluating the Traffic-Conflicts Technique. Federal Highway Administration, 1971.
12. P. J. Cooper. Predicting Intersection Accidents. Canadian Ministry of Transport, Ottawa, Sept. 1973.

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

Guidelines for Traffic Control at Isolated Intersections on High-Speed Rural Highways

Ahmed Essam Radwan, Virginia Polytechnic Institute and State University, Blacksburg
Kumares C. Sinha, Department of Transportation Engineering, and Harold L. Michael, School of Civil Engineering, Purdue University, West Lafayette, Indiana

This paper involves the development of guidelines for traffic control warrants at isolated intersections on high-speed rural highways by using both field studies and traffic simulation. Gap-acceptance and delay studies were performed at stop-sign-controlled rural intersections in Indiana, and the resulting data were used to validate and modify the UTCS-1 program (known now as NETSIM). Two-way stop signs, pretimed signals, semiactuated signals, and fully actuated signals were evaluated over a range of traffic volumes on both major and minor approaches. Annual economic cost was used as a basis to develop criteria for selecting the most appropriate control type. The resulting warrants are expressed in chart form.

The control of vehicular traffic at highway intersections has been one of the most studied areas in traffic engineering. Intersections critically affect the efficiency, capacity, and safety of a highway system. Not enough information is available on traffic control alternatives at isolated intersections on high-speed rural highways, in particular at the intersection of a multilane high-speed major highway and a two-lane minor road located in suburban or rural areas.

The Manual on Uniform Traffic Control Devices (MUTCD) (1) provides general guidelines for stop-sign and signal warrants at intersections; however, these guidelines do not distinguish between pretimed (PR) signals and vehicle-actuated (VA) control. Section 4C-3 of the MUTCD states:

> When the 85 percentile speed of the major street traffic exceeds 64 km/h (40 mph), or when the intersection lies within the built-up area of an isolated community having a population of less than 10 000, the maximum vehicular volume warrant is 70 percent of the requirement above (in recognition of differences in the nature and operational characteristics of traffic in urban and rural environments and smaller municipalities).

According to that statement, the minimum vehicular volume warrant for traffic-signal installation for a four-lane major street intersecting with a two-lane minor street is 420 and 105 vehicles/h (total traffic per approach), for the major and minor streets, respectively. For the warrant for the interruption of continuous traffic, the vehicular volumes are 630 and 53 vehicles/h. Section 4C-11 of the MUTCD reviews principal factors that may lead to selecting traffic-actuated control. However, there is a need for a detailed examination of warrants for traffic controls at multilane high-speed intersections.

DEVELOPMENT OF THE ANALYSIS TOOL

In this study, the UTCS-1S simulation model (the smaller version of the UTCS-1 model) was modified and used for the purpose of evaluating alternative traffic control devices. The single-intersection version of the UTCS had been successfully validated by Cohen (2) by using field data collected from two intersections that differed widely in geometry and location.

Hall (3) modified the UTCS-1S computer program to provide the vehicle fuel-economy and air-pollution measurements; careful study of the velocity patterns created by automobiles traversing the intersection made it possible to estimate fuel consumption and air pollution resulting from the use of various traffic controls.

Two-Way Stop-Sign-Controlled Intersection

For undivided major highways, the gap-acceptance distributions developed by Wagner (4) were used to modify the UTCS-1S model. These distributions represent the gap-acceptance behaviors of drivers stopped at the stop sign of a two-lane street intersecting with a four-lane undivided highway.

For the case of divided highways, the gap-acceptance distributions were developed from field observations made in the present study. Six rural intersections in Indiana were selected for this purpose, and they fulfilled

Table 1. Linear regression equations for average delay per vehicle on divided and undivided stop-sign-controlled intersections.

Regression Equation	R^2	F	Significance of F^a
Y = 2.1368 + 0.001 841 (major volume) + 0.002 113 (minor volume)	0.7177	41.9553	0.000 01
Z = 1.5543 + 0.001 054 (major volume) + 0.010 46 (minor volume)	0.8379	100.8126	0.000 01

Note: Y = Naperian logarithm (average delay per vehicle on undivided major highway); and Z = Naperian logarithm (average delay per vehicle on divided major highway).

$^a\alpha = 0.05$.

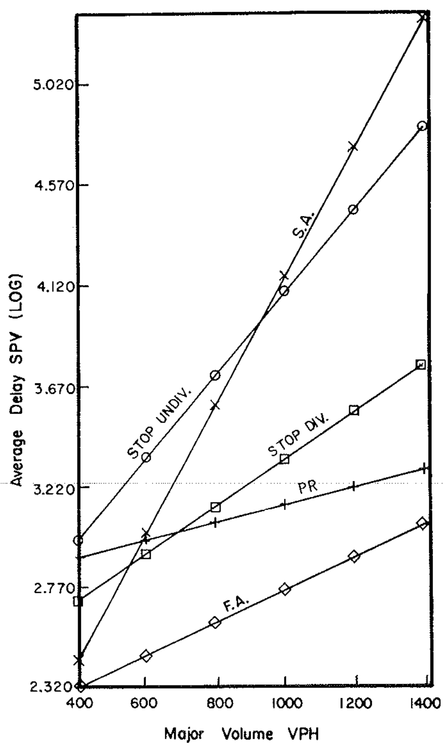
Table 2. Linear regression equations for average delay per vehicle at signalized intersections.

Regression Equation	R^2	F	Significance of F^a
X = 2.6564 + 0.000 386 6 (major volume) + 0.001 861 (minor volume)	0.7453	48.2861	0.000 01
Y = 1.1239 + 0.002 862 (major volume) + 0.003 437 (minor volume)	0.8784	119.2540	0.000 01
Z = 1.8714 + 0.000 724 9 (major volume) + 0.003 175 (minor volume)	0.7365	46.1393	0.000 01

Note: X = Naperian logarithm (average delay for pretimed signals); Y = Naperian logarithm (average delay for semiactuated control); and Z = Naperian logarithm (average delay for fully actuated control).

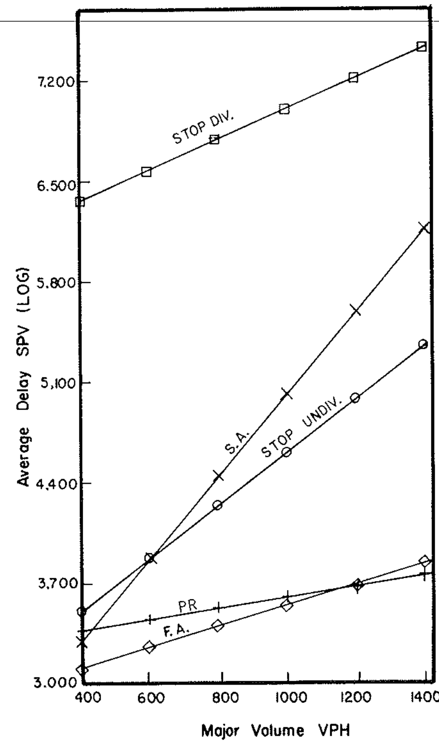
$^a\alpha = 0.05$.

Figure 1. Average delay values for minor-road volume of 50 vehicles/h.



specific requirements. One of these requirements was that the posted speed limit must be 89 km/h (55 mph) for the major road and 64 km/h (40 mph) for the minor road. A slow-motion film technique was adapted for securing the necessary data, and gap-acceptance distributions for different maneuvers were obtained. By using the distribution of driver type embedded in the UTCS program together with the average gap-acceptance values obtained

Figure 2. Average delay values for minor-road volume of 300 vehicles/h.



from the field study, a set of decile distributions of acceptable gaps was developed for various maneuvers. These decile distributions were then embedded in the simulation model.

In order to validate the delay values obtained from the model, stop delays and move-up times were measured from one of the films used in the gap-acceptance field study. Statistical tests showed that there was no significant difference between the simulated and the observed delay values at $\alpha = 0.05$.

After the model was modified and validated, it was used to perform a series of large-scale, two-way stop-sign-controlled intersection simulation runs. Four levels of major traffic volumes (500, 800, 1100, and 1400 vehicles/h), and three levels for minor traffic volumes (100, 200, and 300 vehicles/h), were considered. The purpose of these simulation runs was to develop regression equations for purposes of delay prediction. Three replicate simulation runs were obtained for every major-minor volume combination (400 of simulation time each). Average delay per vehicle measured in seconds for major and minor roads was chosen to be the delay measure for this study. Homogeneity of variances for the replicated data was checked, and it was found that the Naperian logarithm transformation was needed. Test of normality was also checked, and a linear regression equation was fitted to the transformed data for both divided and undivided highways, as shown in Table 1. Velocity profiles developed from the simulation runs were used as an input to an adapted version of the U.S. Environmental Protection Agency's Automobile Exhaust Emission Modal Analysis Model (5). Similar linear regression equations were developed to predict the amount of fuel consumed (per vehicle) within 122 m (400 ft) of either side of the intersection, as a function of major and minor traffic volumes.

Table 3. Costs and estimated lifetimes of control units.

Item	Flasher[a]	Pretimed Signal	Actuated Control
Capital cost ($)	3000-5000	15 000-18 000	(20 000-25 000)[b]
Annual maintenance cost ($)	240	350	550-650
Annual emergency cost ($)	75-100	150	450
Lifetime (years)	15-20	20-25	15-20

[a]Most Indiana rural intersections have both flashers and stop signs.
[b]Two-phase signal.

Table 4. Linear regression equations for annual accidents at signalized and unsignalized intersections.

Regression Equation	R^2	F	Significance of F[a]
X = 2.4613 + 0.000 224 6 (major volume + minor volume)	0.426	5.5738	0.026 0
Y = 1.7235 + 0.000 704 7 (major volume + minor volume)	0.825	85.2934	0.000 01

Note: X = annual number of accidents for stop-controlled intersections; and Y = annual number of accidents for signalized intersections.
[a]α = 0.05.

Signalized Intersection Studies

Signal timing is regarded as a critical variable affecting delay at intersections; for that reason, careful consideration was given to this matter.

Three control alternatives were considered: pretimed (PR), semiactuated (SA), and fully actuated (FA) control systems, each with the same levels of traffic volume. For the PR signal, a cycle length of 80 s was assumed, and the durations of the major- and minor-road phases were timed to minimize delay. For the SA control, a minimum green interval of 36 s was adopted for the major road. Assuming that the detectors are located 55 m (180 ft) back from the stop line on the minor approach, a vehicle extension duration time of 3 s would be sufficient for a vehicle to travel from the detector to the stop line. The initial interval and maximum extension duration times were taken to be 12 s and 24 s for the actuated phase of the minor-road approach. The durations of the initial interval, vehicle extension, and maximum extension were assumed to be 16, 4, and 64 s, respectively, for the major-road phase of the FA control. The corresponding values for the minor-road phase were 12, 3, and 27 s. The time durations of the actuated phases for the SA and FA controls were kept the same under the different levels of traffic demand.

The assumption of a fixed cycle length for all traffic control alternatives might have negated some of the advantages of SA and FA signals, especially at low traffic flow rates. The cycle length assumed for PR signals had a higher value than the optimum cycle length required to minimize traffic delay because the major-road approaches were of the high-speed type and their safety should be incorporated. No information is available regarding the required increase in the optimum cycle length for such intersections; therefore, it was felt that the 80-s cycle duration was a reasonable assumption. Since the initial runs indicated satisfactory results, no changes were made in the signalized logic of the model. Delay regression equations were developed for the three control alternatives, and they are shown in Table 2.

ANALYSIS OF RESULTS

Delay Analysis

After the delay equation for each control alternative was developed, the equations were combined to form composite plots. Figures 1 and 2 show two out of the possible six plots of the average delay values (seconds per vehicle, log scale) versus the major-road volumes (vehicles per hour) for the minor-road volumes of 50 and 300 vehicles/h, respectively. The composite plots indicated that the FA control causes the lowest average delay for the six minor-road traffic volume levels. It can be observed in Figure 1 that the average delay for a divided major highway (one that has a median) is smaller than the average delay for an undivided major highway for a minor-road traffic volume of 50 vehicles/h. As the minor-road volume increases, the delay curve for the divided major highway shifts upward. This can be explained by the fact that the existence of a highway median on the major road allows minor-road vehicles to perform their maneuvers in two movements. This holds for low minor-road volumes; however, an increase in the minor-road volume results in blockage of minor-road vehicles from the median and a consequent spillback occurs. In the case of a spillback, the simulation model randomly assigns a movement decision for a vehicle to determine whether it will join the spillback. This causes disturbance in the major-road flow, resulting in a reduction of speed and a subsequent increase in the average delay for major-road vehicles.

It was noticed that the SA control causes less average delay than the PR control at low minor-road volumes. As the minor-road volume increases, the intersection of the SA control line and the PR control line shifts to the left. Based only on the average delay analysis, the FA control appears to be the best control alternative at any major- or minor-road volume. However, the evaluation of a control alternative must also consider the safety aspects. In addition, the equipment cost should also be considered. It was therefore decided to perform an economic cost analysis that considered the costs of control-unit construction and maintenance, vehicle operation, accidents, and delay.

Economic Cost Analysis

Control-unit construction and emergency and normal maintenance cost data were obtained from the Indiana State Highway Commission. The capital cost, routine maintenance cost, emergency cost, and estimated life for flasher, PR signal, and actuated control signals are shown in Table 3. In the absence of actual information, the SA control costs were assumed to be an average of those for FA and PR controls. In reality, the SA control costs might be higher; however, since the equipment cost is very small compared with the accident and delay costs, this will not affect the results significantly. Assuming that the life of all signals is 20 years and that they have no salvage value, the equivalent uniform annual costs were estimated to be $1587, $5644, $6730, and $13 522 for flasher, PR, SA, and FA controls, respectively.

Vehicle Accident Costs

Accident records for stop-controlled, pretimed signal, and actuated controlled intersections on Indiana state highways were collected for the years 1974, 1975, and 1976. An analysis of variance test was performed, and it was found that the accident rates for stop-controlled intersections are significantly different from those for signalized intersections at α = 0.05. On the other hand, this test showed no significant difference between pretimed signal rates and fully actuated control rates for the same level of significance. Multiple regression equations were developed for stop-controlled and signalized intersections to be used in estimating an annual number of accidents, as shown in Table 4.

One survey of particular relevance to this research was performed by Hejal and Michael (6) to evaluate the direct cost per rural accident in Indiana. By updating the accident cost values to 1978 prices with the aid of the appropriate consumer price indices, the figures were estimated to be $25 954, $5971, and $845 for fatal, personal injury, and property-damage-only accidents, respectively.

In order to determine the average cost of an accident, the study conducted by Abramson (7) was used; in this study, the results of statewide accident information from Illinois, Massachusetts, Utah, and New Mexico were used. By assuming that the results of this study are applicable to the state of Indiana, the fractions of fatal, personal injury, and property-damage-only accidents were estimated to be 0.0041, 0.0826, and 0.9133, respectively.

A recent study by Wuerdemann (8) provided national indirect costs of motor vehicle accidents. An average indirect cost value of $160/accident was adopted from this study. By using the severity fractions, the direct costs, and the indirect-cost value, the weighted average cost per accident was found to be $1595.

Automobile Operating Cost

Knowing the quantity of gasoline consumed in driving a vehicle through an intersection under the four types of control alternatives, as simulated by the UTCS-1S model, permitted gasoline cost calculations. It was assumed that the average cost of gasoline was 17 cents/L (64 cents/gal) in 1978. Federal and state gasoline taxes, which accounted for 3.5 cents/L (13 cents/gal) of this price, are returned to the road user through maintenance benefits. Hence, the actual gasoline operating cost was assumed to be 13.5 cents/L (51 cents/gal).

Winfrey (9) estimated the other automobile operating expenses (tires, oil, maintenance, and depreciation) on the basis of empirical data. By updating these prices to 1978 dollar values, it was found that the other operating costs were 1.980 and 1.806 cents/vehicle for major- and minor-road signalized approaches, respectively. As for

Figure 3. Annual cost for divided major-road intersections controlled by stop sign.

MAJOR VOLUME	MINOR VOLUME	ACCIDENT * COSTS	EQUIPMENT* COSTS	FUEL** MAJOR	FUEL** MINOR	MAJOR ** OTHER	MINOR ** OTHER	DELAY COST**	ANNUAL COST
400.	50.	5941.	1587.	57.	14.	56.	16.	580.	271488.
600.	50.	6837.	1587.	85.	14.	84.	16.	846.	389981.
800.	50.	7732.	1587.	114.	14.	112.	16.	1119.	511121.
1000.	50.	8628.	1587.	142.	14.	141.	16.	1402.	635846.
1200.	50.	9523.	1587.	171.	14.	169.	16.	1698.	765425.
1400.	50.	10419.	1587.	199.	14.	197.	16.	2012.	901579.
400.	100.	6165.	1587.	57.	107.	56.	31.	673.	344913.
600.	100.	7060.	1587.	85.	107.	84.	31.	960.	471254.
800.	100.	7956.	1587.	114.	107.	112.	31.	1263.	603596.
1000.	100.	8852.	1587.	142.	107.	141.	31.	1590.	744212.
1200.	100.	9747.	1587.	171.	107.	169.	31.	1947.	896281.
1400.	100.	10643.	1587.	199.	107.	197.	31.	2349.	1064299.
400.	150.	6389.	1587.	57.	278.	56.	47.	808.	462576.
600.	150.	7284.	1587.	85.	278.	84.	47.	1146.	607540.
800.	150.	8180.	1587.	114.	278.	112.	47.	1524.	767147.
1000.	150.	9076.	1587.	142.	278.	141.	47.	1960.	947715.
1200.	150.	9971.	1587.	171.	278.	169.	47.	2479.	1158665.
1400.	150.	10867.	1587.	199.	278.	197.	47.	3120.	1414419.
400.	200.	6613.	1587.	57.	527.	56.	63.	1057.	650728..
600.	200.	7508.	1587.	85.	527.	84.	63.	1530.	845013.
800.	200.	8404.	1587.	114.	527.	112.	63.	2118.	1080912.
1000.	200.	9300.	1587.	142.	527.	141.	63.	2881.	1381100.
1200.	200.	10195.	1587.	171.	527.	169.	63.	3925.	1783608.
1400.	200.	11091.	1587.	199.	527.	197.	63.	5432.	2355146.
400.	250.	6837.	1587.	57.	856.	56.	79.	1672.	1000947.
600.	250.	7732.	1587.	85.	856.	84.	79.	2595.	1359255.
800.	250.	8628.	1587.	114.	856.	112.	79.	3959.	1878972.
1000.	250.	9523.	1587.	142.	856.	141.	79.	6119.	2688839.
1200.	250.	10419.	1587.	171.	856.	169.	79.	9797.	4052819.
1400.	250.	11315.	1587.	199.	856.	197.	79.	16596.	6555946.
400.	300.	7060.	1587.	57.	1262.	56.	94.	3955.	1988608.
600.	300.	7956.	1587.	85.	1262.	84.	94.	7258.	3215792.
800.	300.	8852.	1587.	114.	1262.	112.	94.	13765.	5612461.
1000.	300.	9747.	1587.	142.	1262.	141.	94.	27986.	10824430.
1200.	300.	10643.	1587.	171.	1262.	169.	94.	63092.	23659953.
1400.	300.	11539.	1587.	199.	1262.	197.	94.	163493.	60327835.

*Annual Cost
**Daily Cost

Figure 4. Annual cost for undivided major-road intersections controlled by stop sign.

MAJOR VOLUME	MINOR VOLUME	ACCIDENT * COSTS	EQUIPMENT* COSTS	FUEL ** MAJOR	FUEL** MINOR	MAJOR** OTHER	MINOR** OTHER	DELAY COST**	ANNUAL COST
400.	50.	5941.	1587.	57.	14.	56.	16.	587.	274082.
600.	50.	6837.	1587.	85.	14.	84.	16.	868.	398055.
800.	50.	7732.	1587.	114.	14.	112.	16.	1173.	530967.
1000.	50.	8628.	1587.	142.	14.	141.	16.	1520.	679070.
1200.	50.	9523.	1587.	171.	14.	169.	16.	1939.	853349.
1400.	50.	10419.	1587.	199.	14.	197.	16.	2484.	1073943.
400.	100.	6165.	1587.	57.	107.	56.	31.	656.	339028.
600.	100.	7060.	1587.	85.	107.	84.	31.	943.	465015.
800.	100.	7956.	1587.	114.	107.	112.	31.	1257.	601356.
1000.	100.	8852.	1587.	142.	107.	141.	31.	1620.	755353.
1200.	100.	9747.	1587.	171.	107.	169.	31.	2067.	939970.
1400.	100.	10643.	1587.	199.	107.	197.	31.	2664.	1179341.
400.	150.	6389.	1587.	57.	278.	56.	47.	727.	433057.
600.	150.	7284.	1587.	85.	278.	84.	47.	1019.	561378.
800.	150.	8180.	1587.	114.	278.	112.	47.	1345.	701703.
1000.	150.	9076.	1587.	142.	278.	141.	47.	1727.	862580.
1200.	150.	9971.	1587.	171.	278.	169.	47.	2207.	1059371.
1400.	150.	10867.	1587.	199.	278.	197.	47.	2865.	1321154.
400.	200.	6613.	1587.	57.	527.	56.	63.	798.	556346.
600.	200.	7508.	1587.	85.	527.	84.	63.	1098.	687374.
800.	200.	8404.	1587.	114.	527.	112.	63.	1437.	832333.
1000.	200.	9300.	1587.	142.	527.	141.	63.	1840.	1001259.
1200.	200.	10195.	1587.	171.	527.	169.	63.	2360.	1212432.
1400.	200.	11091.	1587.	199.	527.	197.	63.	3092.	1501099.
400.	250.	6837.	1587.	57.	856.	56.	79.	872.	708874.
600.	250.	7732.	1587.	85.	856.	84.	79.	1180.	843044.
800.	250.	8628.	1587.	114.	856.	112.	79.	1533.	993399.
1000.	250.	9523.	1587.	142.	856.	141.	79.	1963.	1171765.
1200.	250.	10419.	1587.	171.	856.	169.	79.	2529.	1399996.
1400.	250.	11315.	1587.	199.	856.	197.	79.	3350.	1721092.
400.	300.	7060.	1587.	57.	1262.	56.	94.	947.	890775.
600.	300.	7956.	1587.	85.	1262.	84.	94.	1266.	1028594.
800.	300.	8852.	1587.	114.	1262.	112.	94.	1636.	1185245.
1000.	300.	9747.	1587.	142.	1262.	141.	94.	2096.	1374711.
1200.	300.	10643.	1587.	171.	1262.	169.	94.	2718.	1623259.
1400.	300.	11539.	1587.	199.	1262.	197.	94.	3646.	1983717.

*Annual Cost
**Daily Cost

Figure 5. Annual cost for divided major-road intersections controlled by PR signal.

MAJOR VOLUME	MINOR VOLUME	ACCIDENT * COSTS	EQUIPMENT* COSTS	FUEL ** MAJOR	FUEL** MINOR	MAJOR** OTHER	MINOR** OTHER	DELAY COST**	ANNUAL COST
400.	50.	9072.	5645.	54.	7.	138.	16.	585.	306826.
600.	50.	11882.	5645.	81.	7.	208.	16.	849.	440898.
800.	50.	14692.	5645.	108.	7.	277.	16.	1114.	575827.
1000.	50.	17502.	5645.	135.	7.	346.	16.	1383.	711722.
1200.	50.	20312.	5645.	162.	7.	415.	16.	1654.	848701.
1400.	50.	23122.	5645.	189.	7.	485.	16.	1929.	986898.
400.	100.	9774.	5645.	54.	14.	138.	31.	653.	340582.
600.	100.	12584.	5645.	81.	14.	208.	31.	919.	475317.
800.	100.	15394.	5645.	108.	14.	277.	31.	1186.	611007.
1000.	100.	18204.	5645.	135.	14.	346.	31.	1457.	747772.
1200.	100.	21014.	5645.	162.	14.	415.	31.	1731.	885746.
1400.	100.	23825.	5645.	189.	14.	485.	31.	2009.	1025077.
400.	150.	10477.	5645.	54.	20.	138.	47.	722.	374684.
600.	150.	13287.	5645.	81.	20.	208.	47.	990.	510161.
800.	150.	16097.	5645.	108.	20.	277.	47.	1260.	646702.
1000.	150.	18907.	5645.	135.	20.	346.	47.	1533.	784442.
1200.	150.	21717.	5645.	162.	20.	415.	47.	1810.	923529.
1400.	150.	24527.	5645.	189.	20.	485.	47.	2091.	1064132.
400.	200.	11179.	5645.	54.	27.	138.	63.	792.	409179.
600.	200.	13989.	5645.	81.	27.	208.	63.	1062.	545488.
800.	200.	16799.	5645.	108.	27.	277.	63.	1335.	682983.
1000.	200.	19609.	5645.	135.	27.	346.	63.	1611.	821815.
1200.	200.	22419.	5645.	162.	27.	415.	63.	1892.	962151.
1400.	200.	25230.	5645.	189.	27.	485.	63.	2177.	1104179.
400.	250.	11882.	5645.	54.	34.	138.	79.	864.	444125.
600.	250.	14692.	5645.	81.	34.	208.	79.	1136.	581365.
800.	250.	17502.	5645.	108.	34.	277.	79.	1411.	719930.
1000.	250.	20312.	5645.	135.	34.	346.	79.	1691.	859986.
1200.	250.	23122.	5645.	162.	34.	415.	79.	1976.	1001723.
1400.	250.	25932.	5645.	189.	34.	485.	79.	2265.	1145350.
400.	300.	12584.	5645.	54.	41.	138.	94.	936.	479584.
600.	300.	15394.	5645.	81.	41.	208.	94.	1211.	617870.
800.	300.	18204.	5645.	108.	41.	277.	94.	1490.	757634.
1000.	300.	21014.	5645.	135.	41.	346.	94.	1774.	899064.
1200.	300.	23825.	5645.	162.	41.	415.	94.	2063.	1042373.
1400.	300.	26635.	5645.	189.	41.	485.	94.	2357.	1187797.

*Annual Cost
**Daily Cost

Figure 6. Annual cost for divided-highway intersections controlled by SA signal.

MAJOR VOLUME	MINOR VOLUME	ACCIDENT * COSTS	EQUIPMENT * COSTS	FUEL ** MAJOR	FUEL** MINOR	MAJOR** OTHER	MINOR** OTHER	DELAY COST **	ANNUAL COST
400.	50.	9072.	6730.	1.	0.	138.	16.	575.	282189.
600.	50.	11882.	6730.	2.	0.	208.	16.	850.	411039.
800.	50.	14692.	6730.	3.	0.	277.	16.	1158.	552137.
1000.	50.	17502.	6730.	8.	0.	346.	16.	1538.	720762.
1200.	50.	20312.	6730.	23.	1.	415.	16.	2083.	953447.
1400.	50.	23122.	6730.	198.	7.	485.	16.	3036.	1395489.
400.	100.	9774.	6730.	1.	0.	138.	31.	643.	313645.
600.	100.	12584.	6730.	5.	1.	208.	31.	925.	446207.
800.	100.	15394.	6730.	11.	1.	277.	31.	1248.	594623.
1000.	100.	18204.	6730.	31.	3.	346.	31.	1663.	781976.
1200.	100.	21014.	6730.	184.	15.	415.	31.	2290.	1099522.
1400.	100.	23825.	6730.	387.	28.	485.	31.	3465.	1634998.
400.	150.	10477.	6730.	5.	2.	138.	47.	712.	346993.
600.	150.	13287.	6730.	11.	3.	208.	47.	1002.	484001.
800.	150.	16097.	6730.	34.	6.	277.	47.	1345.	646965.
1000.	150.	18907.	6730.	166.	25.	346.	47.	1804.	897288.
1200.	150.	21717.	6730.	347.	43.	415.	47.	2540.	1266526.
1400.	150.	24527.	6730.	577.	62.	485.	47.	4023.	1926721.
400.	200.	11179.	6730.	10.	5.	138.	63.	782.	382723.
600.	200.	13989.	6730.	33.	11.	208.	63.	1084.	531302.
800.	200.	16799.	6730.	142.	36.	277.	63.	1452.	742376.
1000.	200.	19609.	6730.	300.	60.	346.	63.	1967.	1025265.
1200.	200.	22419.	6730.	508.	85.	415.	63.	2848.	1459410.
1400.	200.	25230.	6730.	765.	109.	485.	63.	4769.	2291712.
400.	250.	11882.	6730.	27.	17.	138.	79.	856.	426047.
600.	250.	14692.	6730.	114.	47.	208.	79.	1171.	612283.
800.	250.	17502.	6730.	250.	78.	277.	79.	1570.	846786.
1000.	250.	20312.	6730.	435.	109.	346.	79.	2159.	1168961.
1200.	250.	23122.	6730.	670.	140.	415.	79.	3236.	1686865.
1400.	250.	25932.	6730.	954.	170.	485.	79.	5797.	2764777.
400.	300.	12584.	6730.	81.	60.	138.	94.	932.	495881.
600.	300.	15394.	6730.	195.	97.	208.	94.	1265.	700779.
800.	300.	18204.	6730.	358.	134.	277.	94.	1703.	961903.
1000.	300.	21014.	6730.	571.	171.	346.	94.	2390.	1331567.
1200.	300.	23825.	6730.	832.	208.	415.	94.	3737.	1960163.
1400.	300.	26635.	6730.	1142.	245.	485.	94.	7261.	3401376.

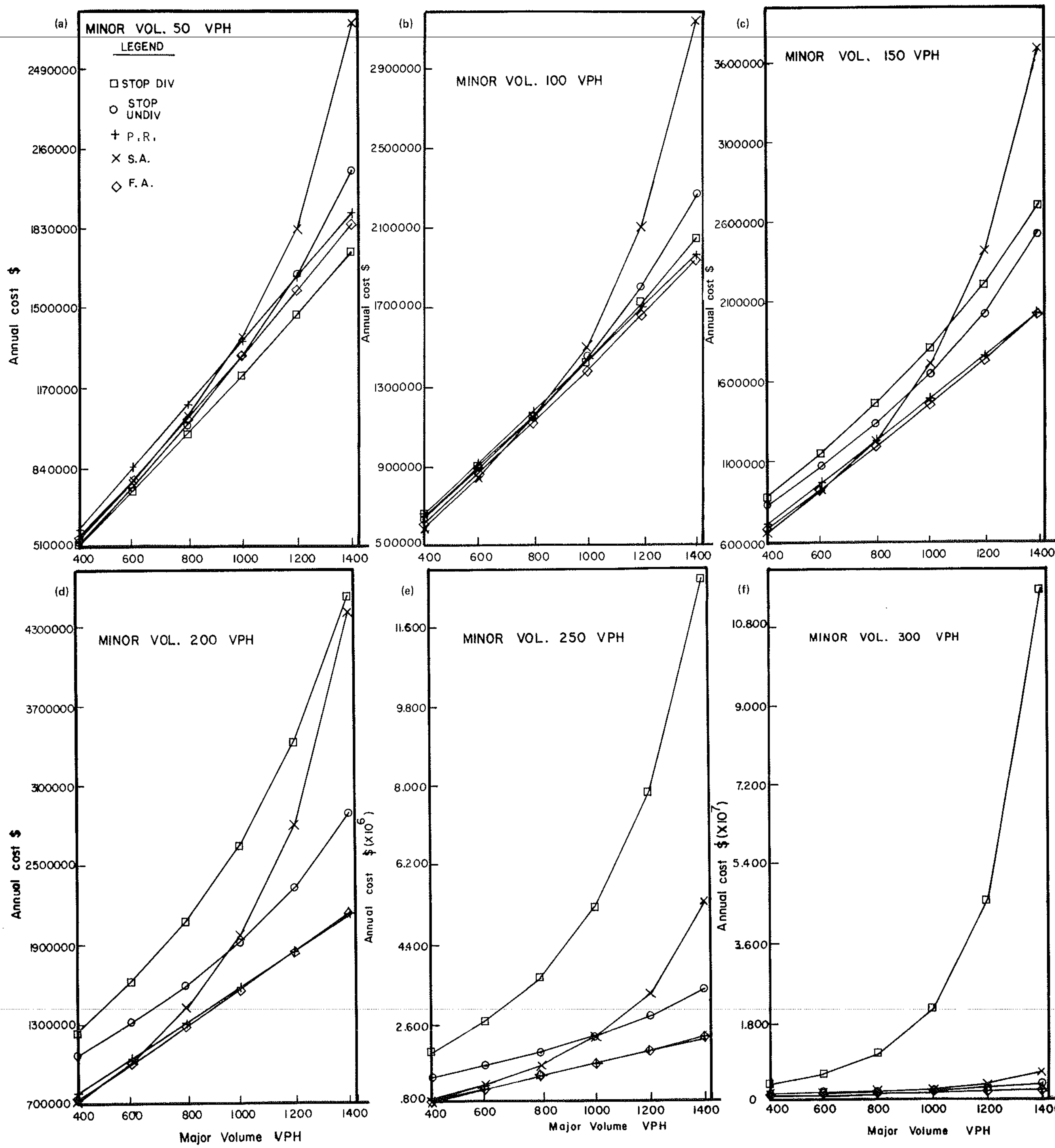
*Annual Cost
**Daily Cost

Figure 7. Annual cost for divided-highway intersections controlled by FA signals.

MAJOR VOLUME	MINOR VOLUME	ACCIDENT* COSTS	EQUIPMENT * COSTS	FUEL ** MAJOR	FUEL** MINOR	MAJOR ** OTHER	MINOR** OTHER	DELAY COST**	ANNUAL COST
400.	50.	9072.	13522.	7.	1.	138.	16.	573.	290991.
600.	50.	11882.	13522.	21.	2.	208.	16.	831.	418679.
800.	50.	14692.	13522.	42.	3.	277.	16.	1092.	549914.
1000.	50.	17502.	13522.	69.	3.	346.	16.	1357.	684938.
1200.	50.	20312.	13522.	104.	4.	415.	16.	1625.	824045.
1400.	50.	23122.	13522.	145.	5.	485.	16.	1900.	967594.
400.	100.	9774.	13522.	14.	3.	138.	31.	640.	324981.
600.	100.	12584.	13522.	31.	5.	208.	31.	900.	454907.
800.	100.	15394.	13522.	55.	7.	277.	31.	1164.	588586.
1000.	100.	18204.	13522.	85.	9.	346.	31.	1431.	726306.
1200.	100.	21014.	13522.	123.	10.	415.	31.	1704.	868421.
1400.	100.	23825.	13522.	168.	12.	485.	31.	1984.	1015363.
400.	150.	10477.	13522.	20.	8.	138.	47.	707.	360101.
600.	150.	13287.	13522.	40.	10.	208.	47.	970.	492296.
800.	150.	16097.	13522.	67.	13.	277.	47.	1237.	628617.
1000.	150.	18907.	13522.	101.	15.	346.	47.	1509.	769284.
1200.	150.	21717.	13522.	142.	18.	415.	47.	1787.	914723.
1400.	150.	24527.	13522.	190.	20.	485.	47.	2073.	1065458.
400.	200.	11179.	13522.	27.	13.	138.	63.	777.	396206.
600.	200.	13989.	13522.	50.	17.	208.	63.	1042.	531162.
800.	200.	16799.	13522.	81.	20.	277.	63.	1313.	670414.
1000.	200.	19609.	13522.	117.	23.	346.	63.	1590.	814101.
1200.	200.	22419.	13522.	161.	27.	415.	63.	1874.	963251.
1400.	200.	25230.	13522.	212.	30.	485.	63.	2167.	1118267.
400.	250.	11882.	13522.	33.	21.	138.	79.	848.	433533.
600.	250.	14692.	13522.	60.	25.	208.	79.	1117.	571308.
800.	250.	17502.	13522.	93.	23.	277.	79.	1392.	713739.
1000.	250.	20312.	13522.	134.	33.	346.	79.	1675.	861332.
1200.	250.	23122.	13522.	181.	38.	415.	79.	1966.	1014713.
1400.	250.	25932.	13522.	235.	42.	485.	79.	2269.	1174273.
400.	300.	12584.	13522.	39.	29.	138.	94.	921.	472232.
600.	300.	15394.	13522.	69.	35.	208.	94.	1195.	613110.
800.	300.	18204.	13522.	106.	40.	277.	94.	1476.	759079.
1000.	300.	21014.	13522.	150.	45.	346.	94.	1765.	910755.
1200.	300.	23825.	13522.	200.	50.	415.	94.	2066.	1068904.
1400.	300.	26635.	13522.	258.	55.	485.	94.	2380.	1234472.

*Annual Cost
**Daily Cost

Figure 8. Annual cost for different levels of minor-road volumes.



stop-controlled intersections, the values were 0.806 and 1.806 cents/vehicle.

Delay Cost

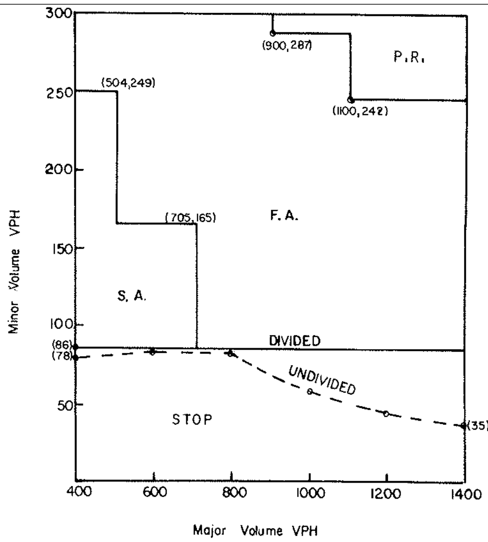
A previous study by Thomas and Thompson (10) provided the magnitude of savings in travel time as a function of motorist income by trip purpose. Knowing the median family income in Indiana, and assuming an average automobile occupancy of 1.5 persons/vehicle and that one-third of the trips on rural highways are for work and the rest for other purposes, the magnitude of delay costs was estimated.

Total Annual Cost

By substituting the individual cost items in the following equation, the total annual cost per combination of traffic volumes on major and minor roads was calculated for each control alternative separately:

$$TAC = AAC + EACMC + \left[\sum_{i=1}^{2} (AFC_i + AOOC_i) \times ADT_i + ADC \times ADT_3 \right] \times 365 \qquad (1)$$

Figure 9. Control alternatives for different major- and minor-road volumes on the basis of minimum total annual cost.



where

TAC = total annual cost ($),
AAC = annual accident cost ($),
EAMAC = equivalent annual construction and maintenance cost ($),
AFC_1 = average fuel cost for major approach ($/vehicle),
AFC_2 = average fuel cost for minor approach ($/vehicle),
$AOOC_1$ = average other operating cost for major approach ($/vehicle),
$AOOC_2$ = average other operating cost for minor approach ($/vehicle),
ADT_1 = average daily traffic for major approach (vehicles/day),
ADT_2 = average daily traffic for minor approach (vehicles/day),
ADC = average delay cost ($/vehicle), and
$ADT_3 = ADT_1 + ADT_2$.

In order to estimate the ADT values, the hourly volumes generated by the simulation model were adjusted by a ratio of peak-hour to average daily traffic. Since peak-hour traffic is not as apparent on rural facilities as it is on urban facilities, a minimum threshold ratio between ADT and peak-hour volumes of 8 percent was used.

The detailed individual cost estimates of the control alternatives are given for each level of major- and minor-road volume combination in Figures 3-7. Furthermore, the total annual cost values are included. These values were then plotted against major-road volumes for different levels of minor-road volumes (50, 100, 150, 200, 250, and 300 vehicles/h), and they are shown in Figure 8. To develop traffic control warrants based solely on traffic demands of major and minor roads, an accepted criterion should be selected. By using the total annual cost as the adopted criterion, a chart (Figure 9) was developed to show boundary lines for the control alternatives under consideration. Similar charts can be developed for other cost criteria.

A closer look at the chart reveals that stop-sign control is warranted for a divided highway when the minor-road traffic volume is less than about 90 vehicles/h for any major-road traffic volume. This value varies from about 80 vehicles/h for a major-road traffic volume of 400 vehicles/h to 35 vehicles/h for a major-road traffic volume of 1400 vehicles/h in the case of an undivided highway. A PR signal is warranted when the minor-road traffic volume is greater than about 240 vehicles/h and the major-road traffic volume is greater than about 1100 vehicles/h.

The warrant for the PR signal rather than the FA control at high traffic volumes on both major and minor roads is probably called for because, as the minor-road volume increases, a queue builds up at the minor-road approach to the intersection, and the fixed cycle length of a PR signal causes less delay than extending the green phase of an FA control to its maximum extension duration.

A control unit equipped with a gap-reduction feature and a variable initial-interval feature (volume-density control) was thought to be a better alternative for reducing average delay per vehicle for this situation until several simulation runs with a volume-density control were tried. The results showed that the average delays per vehicle experienced by using this control were higher than those observed for the PR and FA controls. Since the capital and maintenance costs for the volume-density control are higher than the costs for PR signals, it is doubtful that volume-density control would be a better alternative at high volumes.

CONCLUSIONS

A methodology for selecting the best control alternative at isolated intersections on high-speed rural highways has been presented in this paper. The warrants for a specific traffic control alternative, as indicated in Figure 9, were based on the criterion of minimum total annual cost. The annual cost included (a) annual accident cost, (b) construction and maintenance cost of equipment, (c) fuel cost, (d) nonfuel operating cost, and (e) delay cost.

Similar analysis could be done by considering any of the individual cost items. In addition, the information generated by the model can also be used to evaluate trade-off relationships involving the various cost items with respect to the different control alternatives. Such an evaluation can provide an indication of the relative advantage gained by one control over other alternatives, with respect to, say, safety versus gasoline use.

ACKNOWLEDGMENT

This research was conducted with the financial support of the Joint Highway Research Project of Purdue University and the Indiana State Highway Commission. We are solely responsible for the results and opinions expressed in the article.

REFERENCES

1. Manual on Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, 1971.
2. S. L. Cohen. Application of Network Simulation Models to the Analysis of Urban Intersection Performance. Federal Highway Administration, Rept. FHWA-RD-73-95, Sept. 1973.
3. D. L. Hall. Energy, Air Pollution, Delay, and Safety Evaluation of Non-Signalized Control at Low-Volume Intersections. Highway Extension and Research Project for Indiana Counties, Purdue Univ., West Lafayette, IN, Final Rept., Aug. 1977.
4. F. A. Wagner, Jr. An Evaluation of Fundamental Driver Decisions and Reactions at an Intersection.

HRB, Highway Research Record 118, 1966, pp. 68-84.
5. Automobile Exhaust Emission Modal Analysis Model. Office of Air and Water Programs, U.S. Environmental Protection Agency, EPA-460/3-74-024, Oct. 1974.
6. S. S. Hejal and H. L. Michael. The Estimated Direct Costs (1970) of Traffic Accidents on Indiana Rural State Highways. Purdue Univ., West Lafayette, IN, Joint Highway Research Project No. 20, 1970.
7. P. Abramson. An Accident Evaluation Analysis. TRB, Transportation Research Record 486, 1974, pp. 33-41.
8. H. Wuerdemann. National Indirect Costs of Motor Vehicle Accidents. Center for the Environment and Man, July 1973.
9. R. Winfrey. Economic Analysis for Highways. Intext Educational Publications, New York, 1969.
10. T. C. Thomas and G. I. Thompson. Value of Time Saved by Trip Purpose. HRB, Highway Research Record 369, 1971, pp. 104-115.

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

Use of EC-DC Detector for Signalization of High-Speed Intersections

Peter S. Parsonson, Georgia Institute of Technology, Atlanta
Richard A. Day, Wilbur Smith and Associates, Columbia, South Carolina
James A. Gawlas and George W. Black, Jr., Traffic Engineering Division, Gwinnett County, Georgia

This paper describes a new detector-controller configuration intended to minimize the dilemma-zone problem at signalized intersections on high-speed roads. Included are a complete functional and electrical description of the design, the findings of a field test, and a comparison with two existing designs. The new design uses a basic, actuated, digital controller operated in the nonlocking mode. An approach that has a design speed of 89 km/h (55 mph) has an upstream detection loop located 117 m (384 ft) back from the intersection and a middle loop 77 m (254 ft) back. A loop at the stopline is 8 m (25 ft) in length and is connected to a novel extended-call–delayed-call (EC-DC) detector that is able to change from an EC model to a DC unit at the strategic moment during the green interval. In effect, the change disconnects the stopline loop, leaving the other two loops to control the extension and termination of the green. The controller and detectors are off-the-shelf units that require no internal modification. The only special-logic items are two relays mounted on the back panel. The design does not pose a maintenance problem. A test installation in Georgia significantly reduced conflicts associated with the dilemma zone. A comparison with two existing designs shows that the EC-DC configuration costs somewhat more than the EC design but is superior in three operational categories. It is less expensive than the density design and is superior in four operational aspects.

Drivers face a "dilemma zone" or "zone of indecision" at signalized intersections where approach speeds are 56 km/h (35 mph) or higher. If the yellow comes on while the driver is in this zone, an abrupt stop may produce a rear-end collision. The decision to go through, on the red, may produce a right-angle accident. The traffic engineer can install a vehicle-actuated signal controller and appropriate detection in order to attempt to minimize the untimely display of yellow. This paper describes a new detector-controller design to meet this objective.

The new design was made possible by the following three recent breakthroughs in driver-behavior research and hardware technology:

1. The boundaries of the dilemma zones for various approach speeds are now known with reasonable accuracy.
2. Digital controllers permit the unit extension to be tailored to tenths of a second.
3. Loop detectors are now available off the shelf that have both extended-call (EC) and delayed-call (DC) features as standard equipment.

A number of advanced detector-controller configurations for isolated intersections on high-speed roads have been reported in the literature. Most of these were summarized in a design manual published by the Federal Highway Administration in 1977 (1). Concurrently, Zegeer (2) reported excellent results in Kentucky with a particular configuration known as a green-extension system. In 1978, Parsonson (3) discussed the state of the art and concluded that there appears to be an unmet need for a design for high-speed roads that has the following characteristics: (a) loop-occupancy features; (b) basic, actuated controller with nonlocking detection memory; (c) EC detection; (d) short allowable gap, primarily to prevent frequent "max-out" (which may well show a yellow to a vehicle in the dilemma zone); and (e) dilemma-zone protection over a wide range of speeds. Parsonson then proposed a new detector-controller configuration to meet these objectives and analyzed it on the basis of seven criteria set forth for evaluating any proposed design. In response to a discussion of the paper by Clark (4), Parsonson modified the design in his closure (3, p. 42) and stated that his proposal would soon be field tested in Gwinnett County, Georgia.

The present paper provides a complete functional and electrical description of the modified design, reports the findings of the Gwinnett field test, and compares the new configuration with the most commonly used existing designs.

FUNCTIONAL OPERATION

The design uses a basic, actuated controller operated