Development of an Advisory Speed Signal System For High-Speed Intersections Under Traffic-Actuated Control

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High-speed signalized intersections are hazardous from the standpoint of causing rear-end collisions between vehicles on the same approach. The signal funnel concept developed in Germany is desirable at such locations since it substantially reduces the percent of vehicles stopping. However, the signal funnel has not been incorporated with the semiactuated traffic signal often used at intersections on major thoroughfares in the United States.

The major objectives of this investigation were to design and evaluate a speed signal system capable of functioning effectively with semiactuated control. The study involved a traffic control system for a T-junction utilizing an advisory speed signal on the main approach. The evaluation was accomplished by computer simulation models programmed in GPSS/360. The figures of merit for each model were (a) total number of vehicles stopping on the main approach during 15 signal cycles, (b) percent of vehicles forced to stop against the red signal on the high-speed route, (c) average delay incurred per side road vehicle, and (d) average delay per side road vehicle stopped.

The first simulation model described vehicle activity on a minor approach lane and a high-speed approach lane at a T-junction with a two-phase semiactuated controller. This model was validated by comparing simulation output to field data obtained at an intersection in a 45-mph speed zone. Field data were gathered for side flow ranging from 60 to 250 vph and main flow from 180 to 700 vph per lane. Linear regression equations were established relating each figure of merit to the traffic volume. Comparable data were extracted from the simulation model and regression equations involving the same variables were constructed. The corresponding equations from the field data and from the simulation were then statistically tested for equality of regression coefficients. The simulation model proved satisfactory for predicting the figures of merit for the traffic volumes involved.

The second simulation model was similar to the first, but included a main route speed advisory signal and a more elaborate side route vehicle detection system. Data obtained from the speed signal simulation model were compared to the output from the first model, thus evaluating the proposed signal funnel.

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The traffic-actuated speed signal funnel stopped an average of only 2.0 percent of the main route traffic, while the conventional semiactuated controller stopped 20.9 percent. Furthermore, the speed signal system stopped only 2.8 cars on the high-speed route during 15 typical signal cycles, compared to 25.8 cars stopped in 15 cycles with the semiactuated control. The improvement in main road flow was obtained without causing excessive side road delay.

•A TRAFFIC signal located at an isolated intersection on a high-speed thoroughfare creates a hazardous situation when it interrupts the rapidly moving vehicular flow. The presence of an unexpected signal and the extreme speed differential as traffic halts combine to render vehicles highly susceptible to rear-end collisions in this situation.

Despite the undesirable effects of signalization, regulation is often necessary at high-speed intersections to provide safety for drivers desiring to enter or cross the main stream. Traffic engineers, recognizing the necessity for regulation, have devised controls that reduce the frequency of main flow interruptions. One of the more common controls in use today is the semiactuated signal which retains the main route green phase until a side arrival is detected. Semiactuated control offers the advantage of transferring the green only when required by the side traffic, but does not eliminate the problems resulting from unexpectedly halting the main flow.

THE SIGNAL FUNNEL CONCEPT

The signal funnel system developed in Germany by W. von Stein (10) is a traffic control system that provides access to a route while causing minimum disturbance to the flow. When utilized at high-speed locations, the signal funnel includes advisory speed signals preceding the signalized intersection. The operating principle is illustrated in Figure 1 for a simplified case involving a pretimed traffic signal and one advisory

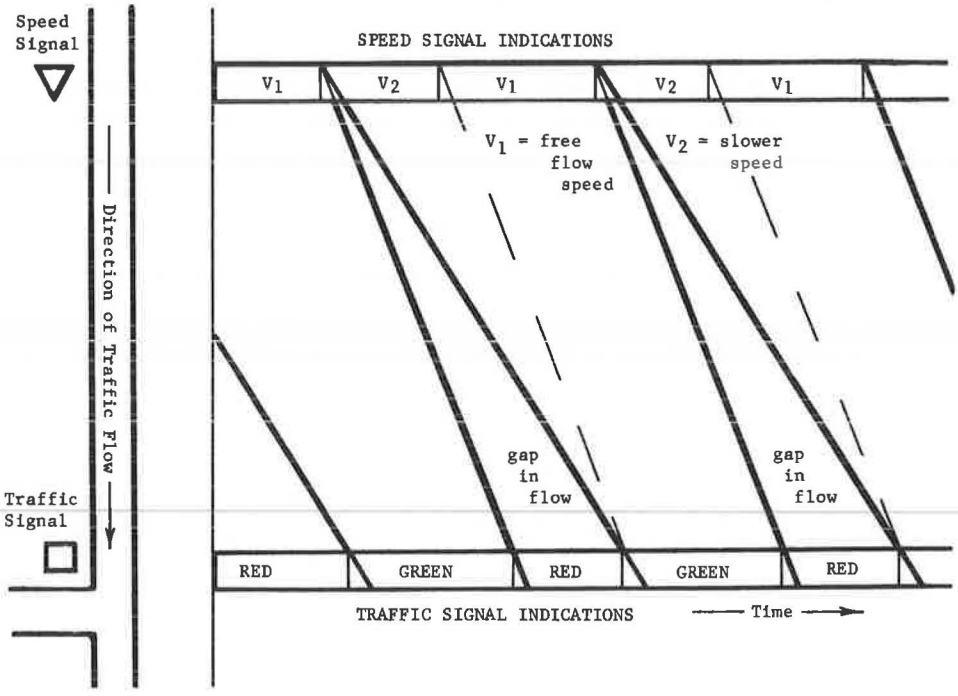

Figure 1. Speed signal operation with pretimed controller.

speed signal. The speed signal displays speeds to approaching traffic, thus regulating vehicle progress to avoid arrival at the intersection during the red phase.

Signal funnel systems have been used with success in Germany since 1954. One of their initial installations permitted 90 to 97 percent of the traffic to pass without stopping during moderate flow, even though the green phase was only 47 percent of the cycle. Up to this time, signal funnels have seen limited use in the United States, the first system being the Traffic Pacer (1, 7) developed at the General Motors Research Laboratory.

The signal funnel concept seems to offer great potential for reducing vehicle stoppages at intersections. Furthermore, one situation where this control would be especially useful is the high-speed location where cross traffic is relatively light compared to the main route volume. If an advance speed signal could be coordinated with a semiactuated controller, smooth and efficient regulation of such an intersection could be achieved. The traffic-actuated controller would cause interruptions only when necessary, and the speed signal would minimize the number of vehicles stopping during the main route red phase.

Schmarsel (8) has indicated the extent of signal funnel application in Germany and relates (9) that it has been combined with traffic-actuated control in few instances. However, no data are available concerning funnel system performance with traffic-actuated signals and the problem of coordinating advance speed signals with traffic-actuated equipment has not been extensively explored. It is, therefore, the purpose of this investigation to design and evaluate a control system with main route advisory speed signals and a traffic-actuated intersection signal.

SCOPE AND METHODOLOGY

The location involved is a high-speed T-junction, where regulation is by semiactuated signals. The analyses concern a single lane on a main approach and a single lane on the minor approach, assuming the results could be generalized to any number of lanes. Since this is a preliminary investigation, the evaluation is based on performance predicted by computer simulation models.

The investigation was conducted in three stages. First, field data were gathered at an intersection with semiactuated control. Next, an initial computer model was programmed to simulate the intersection observed in the field studies. This initial model was validated by comparing its output to the field data. Finally, the traffic-actuated speed signal funnel was developed, simulated by a second computerized model, and evaluated by comparing the output from this model to that from the semiactuated control simulations.

FIELD STUDY

The field study site was a T-intersection formed by a four-lane, two-way highway with a 45-mph speed limit, and a two-lane, two-way street in a 25-mph speed zone. The semiactuated signal at this location was linked to a magnetic detector under the side road pavement 25 feet preceding the stop line. The controller settings granted 45-sec minimum main green and 6-sec amber. The side route settings were 5-sec initial interval, 5-sec vehicle extension, 24-sec maximum side green, and 3-sec amber. The duration of each study was 15 complete signal cycles rather than a predetermined time period, thus avoiding inclusion of incomplete phases. Main route data pertained to one direction of flow, the direction selected to eliminate disturbances caused by left-turning vehicles.

Field data were gathered concerning these figures of merit:

1. The total number main route cars stopped in 15 cycles,
2. The percent main route traffic stopping at the light,
3. The average delay per side road vehicle, and
4. The average delay per side road vehicle stopped.

The high-speed route stoppage characteristics were of primary interest in this study. The side road delay measures were included since an effective system should not cause

TABLE 1

TRAFFIC VOLUME SUMMARY: FIELD DATA

Approach	Flow Range (vph)	Mean (vph)	Std. Dev. (vph)
Side road	59.6 - 249.0	134.67	47.69
Main road			
Outside lane	234.0 - 769.0	448.0	132.93
Inside lane	103.0 - 543.0	313.0	126.47
Average per lane	178.0 - 663.0	381.0	128.94

TABLE 2

MAIN ROUTE STOPPAGE CHARACTERISTICS: FIELD DATA

Lane	Percent Stopped			Number Stopped		
	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.
Outside lane	11.9-39.7	23.3	6.09	6.0-52.0	32.8	14.0
Inside lane	8.9-34.2	20.4	6.41	11.0-69.0	20.8	12.0
Average per lane	10.4-37.1	22.2	5.61	8.5-60.5	26.8	12.8

excessive delay to a particular traffic movement. Data regarding traffic volume were also recorded during the studies.

Results of Field Studies

A total of 72 studies were initiated, of which 15 were discarded due to unusual traffic circumstances. The 57 retained studies represent 1,064 minutes of traffic observation. The volume summary is presented in Table 1. The side road volume, ranging from 59.6 to 249.0 vph, covers light flow through conditions approaching congestion. The average flow per main route lane is reported since subsequent analyses concern one typical approach lane.

It should also be pointed out that the following data analyses are based on mean values of the variables as computed for each study. This was necessary since the figures of merit must be related to the corresponding traffic volume.

Table 2 gives the stoppage characteristics on the high-speed route. A disadvantage of semiactuated control is that an average of 22.2 percent of the main road vehicles were stopped due to side street demands. Furthermore, the total number of vehicles stopping in 15 cycles averaged 26.8 per lane for the field studies.

The figures of merit regarding side road delay are summarized in Table 3. The delay per vehicle stopped averaged 23.4 sec, while the delay per vehicle was 19.0 sec.

Linear Regression Analysis: Field Data

The linear regression equations and statistical measures for the field data are given in Table 4. The statistical measures are as follows:

1. The standard error $S_{y \cdot x}$, which measures the residual variability of the data points around the regression line,
2. The coefficient of multiple determination R^2, indicating the percent of sample sum of squares explained by regression, and
3. The value of the F ratio from an analysis of variance testing the significance of the regression equation.

The main route stoppage characteristics are given by Eqs. 1 and 2, and are shown in Figure 2. Both responses in Figure 2 exhibit a definite increasing trend with respect to traffic volume. The significance of the relationships is indicated by the high F ratio of 301.90 for the number stopped and 37.85 for the percent stopped.

The side road delays plotted in Figure 3 correspond to Eqs. 3 and 4. The average delay per side road vehicle was not significantly related to side volume as indicated by the F ratio of 2.11. The delay per vehicle stopped has a more significant trend, the F ratio being 12.69.

TABLE 3

SIDE ROAD DELAY MEASURES: FIELD DATA

Figure of Merit	Range (sec)	Mean (sec)	Std. Dev. (sec)
Average delay per vehicle	11.4-25.6	19.0	2.76
Average delay per stopped vehicle	14.5-29.4	23.4	3.33

SIMULATION OF SEMIACTUATED CONTROL

The simulation model concerning semiactuated control is programmed in GPSS/

TABLE 4

LINEAR REGRESSION EQUATIONS AND STATISTICS: FIELD DATA

Equation No.	Equation	$s_{y.x}$	R^2	$F_{(df)}$
(1)	$Y_1 = -8.911 + 0.0693\ X_1$	5.06	0.846	$301.90^a_{(1, 55)}$
(2)	$Y_2 = 0.113 + 0.211(10^{-3})\ X_1$	0.0436	0.408	$37.85^a_{(1, 55)}$
(3)	$Y_3 = 11.43 + 0.113\ X_2 - 0.443(10^{-3})\ X_2^2 + 0.427(10^{-6})\ X_2^3$	2.68	0.107	$2.11_{(3, 53)}$
(4)	$Y_4 = 15.60 + 0.045\ X_2 - 0.378(10^{-3})\ X_2^2 - 0.169(10^{-5})\ X_2^3$	2.60	0.418	$12.69^a_{(3, 53)}$

[a]Significant at the 0.1 percent level.

where

Y_1 = number stopped per main road lane in 15 cycles;
Y_2 = percentage of vehicles stopped per main road lane;
Y_3 = average delay (sec) per side road vehicle;
Y_4 = average delay (sec) per side road vehicle stopped;
X_1 = sum of side road and main road flow (vph); and
X_2 = side road flow (vph).

360 (5). The program simulates vehicle activity on a high-speed lane for 1,150 ft preceding the intersection while a minor approach is simulated for 650 ft. Vehicle interarrival times are specified by shifted exponential distributions. The program incorporates signal control settings duplicating those at the field study site. The major assumptions regarding vehicle flow follow:

1. Traffic is composed of passenger cars only,
2. Turning movements from the main route are not permitted,
3. Vehicles do not pass in the vicinity of the intersection,

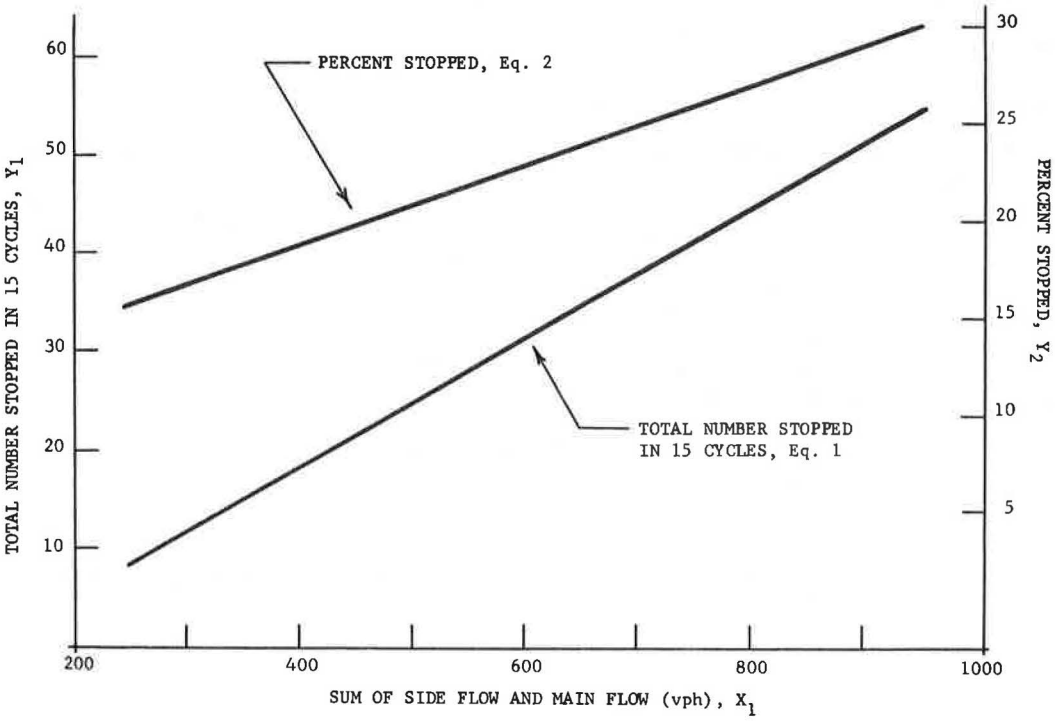

Figure 2. Main route stoppage characteristics, field data.

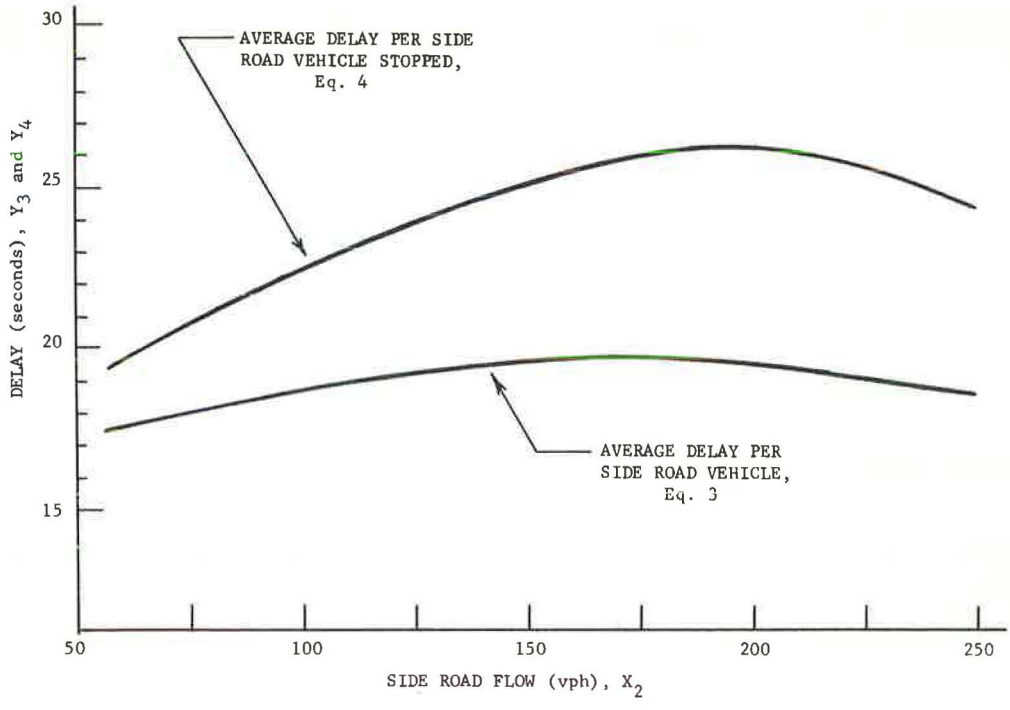

Figure 3. Side road delay measures, field data.

4. Stopping on amber is a simple probabilistic decision, and
5. Vehicles entering the system are assigned an initial velocity equal to their respective speed limit; the vehicle speed is altered as it proceeds, depending on conditions encountered.

Results of the Semiactuated Control Simulation

A total of 132 simulations were processed, each representing 15 cycles of the signal. From these, 57 runs were selected by matching simulated traffic volume to the traffic flows observed in the field studies. The 57 simulated studies represent 1,030 minutes of system observation. Table 5 summarizes simulated flow rates. The mean side flow of the simulation studies, 134.73 vph, is similar to the mean in the field studies, 134.67 vph. Since the road flows were matched first, it was difficult to attain the same agreement for the main road volumes. The mean flow in the field studies was 381.00 vph; the simulation mean is higher at 401.99 vph.

Table 6 summarizes figures of merit pertaining to the main approach. The mean percent main route traffic stopped in the 57 simulation studies was 20.9; the field data indicated 22.2. The total number of vehicles stopping during 15 cycles averaged 25.8 in the simulation and 26.8 in the field. The difference noted in this response is less than 0.1 car per cycle.

TABLE 5

TRAFFIC VOLUME SUMMARY: SIMULATION OF SEMIACTUATED CONTROL

Approach	Flow Range (vph)	Mean (vph)	Std. Dev. (vph)
Side road	63.8-244.0	134.73	47.90
Main road	204.0-684.0	401.99	118.59

TABLE 6

MAIN ROUTE STOPPAGE CHARACTERISTICS: SIMULATION OF SEMIACTUATED CONTROL

Figure of Merit	Range	Mean	Std. Dev.
Percent stopped	8.3-37.5	20.9	5.87
Number stopped	7.0-48.0	25.8	11.4

Table 7 summarizes the simulated minor approach delays. The delay per stopped vehicle averaged 23.1 sec, while the delay per vehicle was 18.2 sec. Both measures from the simulation closely approximate the corresponding means listed in Table 3 for the field data.

TABLE 7

SIDE ROAD DELAY MEASURES: SIMULATION OF SEMIACTUATED CONTROL

Figure of Merit	Range (sec)	Mean (sec)	Std. Dev. (sec)
Average delay per vehicle	12.2-23.0	18.2	2.78
Average delay per stopped vehicle	14.0-28.2	23.1	3.47

Linear Regression Analysis: Semiactuated Control

The regression equations and statistical measures associated with the simulation results are given in Table 8. These equations are plotted in Figures 4 through 6, which also show results from the field study to facilitate comparison.

The figures of merit for main road stoppages are in Figures 4 and 5. In both instances, the simulation results exhibit an increasing trend similar to the field study results, but at a lower level. The discrepancy in either case, however, is less than the standard error associated with the field data equation.

The side road delay figures of merit for both simulation and field study are plotted in Figure 6. Comparisons of these responses and the statistical measures in Tables 8 and 4 indicate excellent conformity.

Statistical Validation of the Simulation Model

The major step in the validation procedure was application of an F test that evaluates the closeness of paired regression lines (3). The linear regression equations as determined from the field data and from the computer simulation were evaluated in pairs by this F test (Table 9). This test indicated that differences between the pairs of regres-

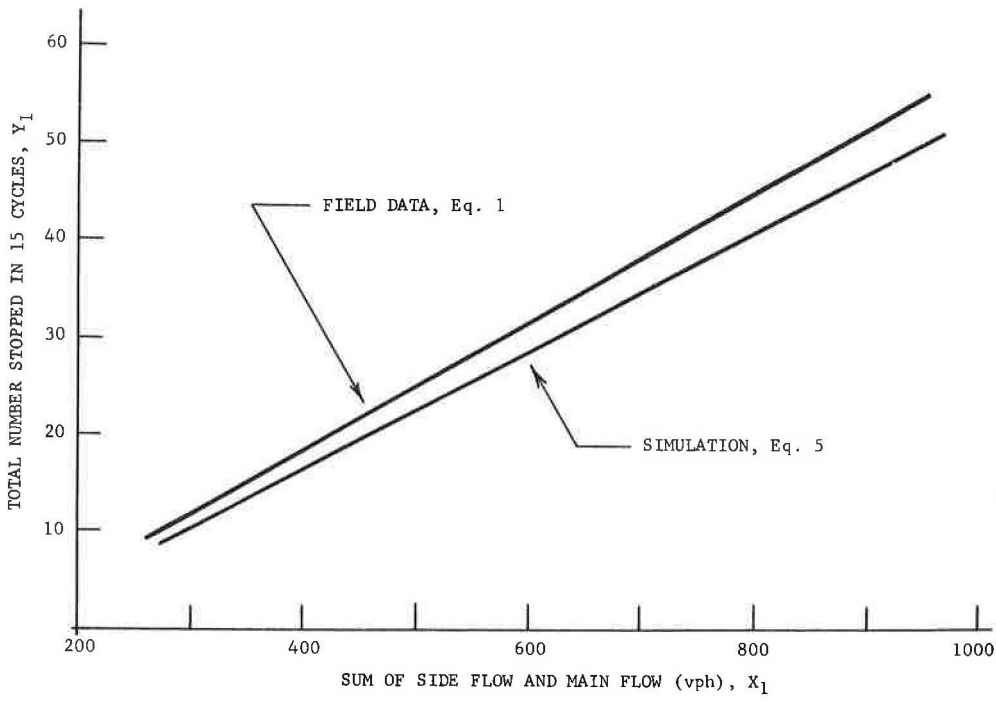

Figure 4. Total number stopped in 15 cycles, semiactuated control.

TABLE 8

LINEAR REGRESSION EQUATIONS AND STATISTICS: SIMULATION OF SEMIACTUATED CONTROL

Equation No.	Equation	$s_{y.x}$	R^2	$F_{(df)}$
(5)	$Y_1 = -9.409 + 0.0657\,X_1$	5.16	0.800	$219.85^a_{(1, 55)}$
(6)	$Y_2 = 0.088 + 0.224(10^{-3})\,X_1$	0.0477	0.353	$29.94^a_{(1, 55)}$
(7)	$Y_3 = 6.90 + 0.214\,X_2 - 0.125(10^{-2})\,X_2^2 + 0.232(10^{-5})\,X_2^3$	2.74	0.075	$1.43^a_{(3, 53)}$
(8)	$Y_4 = 0.77 + 0.405\,X_2 - 0.231(10^{-2})\,X_2^2 + 0.437(10^{-5})\,X_2^3$	3.02	0.286	$7.08^a_{(3, 53)}$

[a]Significant at the 0.1 percent level.

where

Y_1 = number stopped per main road lane in 15 cycles;
Y_2 = percentage of vehicles stopped per main road lane;
Y_3 = average delay (sec) per side road vehicle;
Y_4 = average delay (sec) per side road vehicle stopped;
X_1 = sum of side road and main road flow (vph); and
X_2 = side road flow (vph).

sion equations were not sufficient to warrant rejection of the simulation model as a tool for predicting intersection performance. Thus, the GPSS/360 model was accepted for investigating the figures of merit for the traffic volumes involved.

DEVELOPMENT OF THE TRAFFIC-ACTUATED SPEED SIGNAL SYSTEM

The purpose of a speed signal is to alter progress of certain approaching vehicles, thus creating substantial gaps within the main stream. These gaps then serve as the time intervals for the red phase. Thus, coordination between the speed signal and the traffic controller is imperative so the gaps will coincide with the red phase. Coordi-

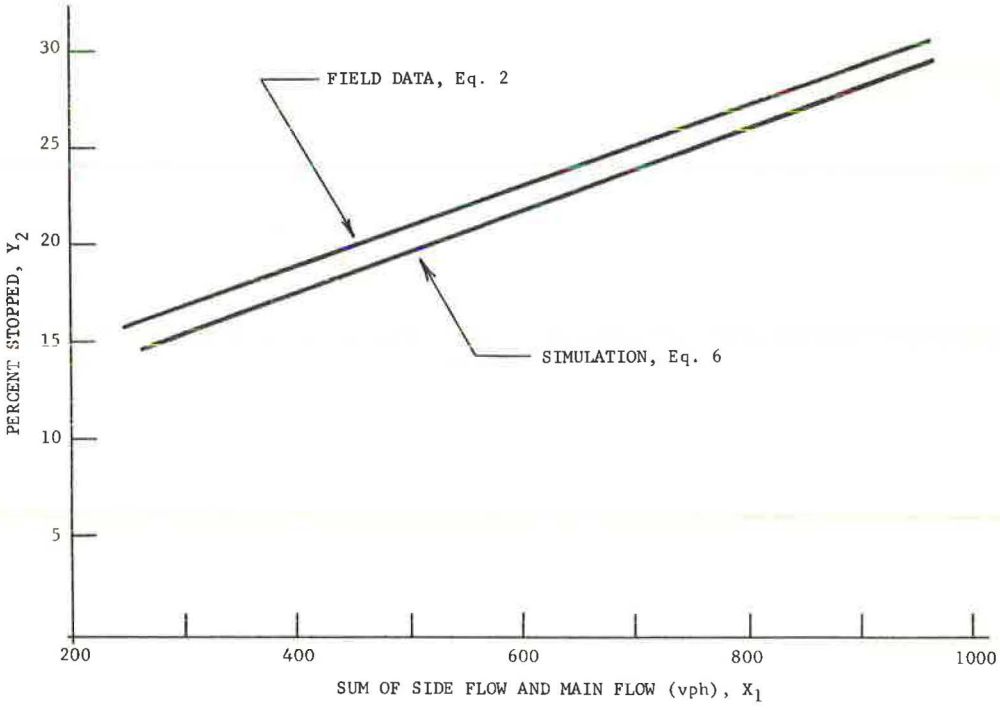

Figure 5. Percent stopped, semiactuated control.

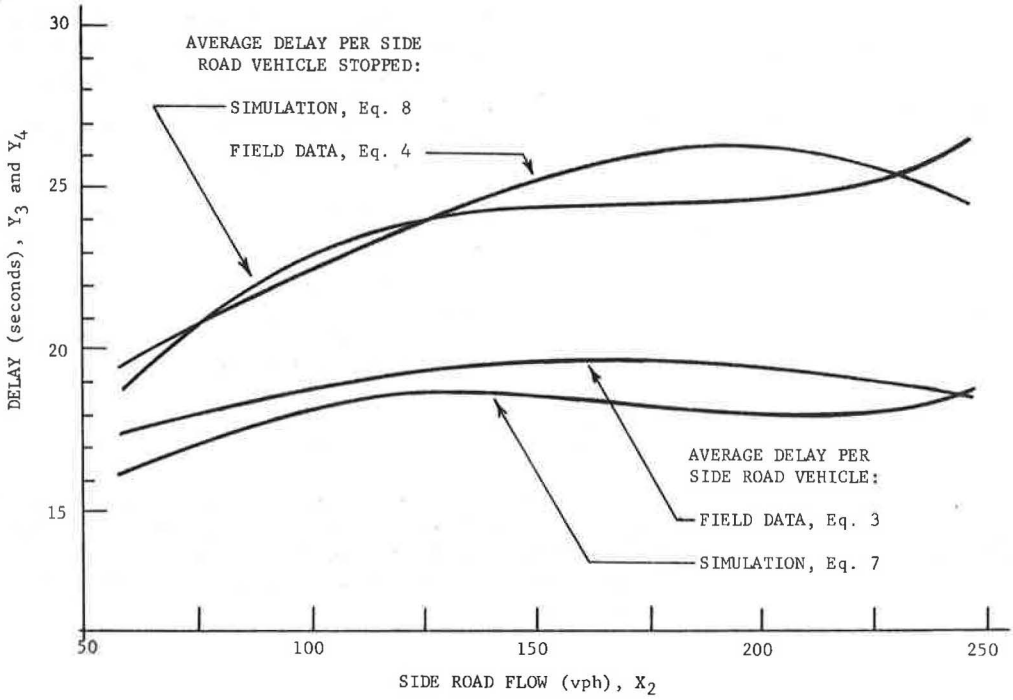

Figure 6. Side road delay measures, semiactuated control.

nating an advance speed signal with a semiactuated traffic controller is difficult since this controller does not function on a completely regular cycle. Figure 7 is a space-time diagram illustrating this problem for a hypothetical traffic-actuated speed signal system. As the traffic signal proceeds through the cycles, times of phase changes do not occur at regular intervals. The start of a main red phase, as shown by Point A, is not known until a side arrival is detected, subject to the minimum main green time restriction. Further, the red termination time noted by Point B is not specified until the last vehicle crosses the side detector or the maximum limit expires.

Speed Signals in Fixed Cycle Systems

Before developing the traffic-actuated speed signal system, it is advisable to consider the principles of speed signal coordination in fixed-cycle signal funnels. This principle is illustrated in Figure 8. The advisory signal in this example alternately shows one of two possible speeds to approaching vehicles. As outlined by Breuning (2), the following expression may be derived based on Figure 8, assuming vehicles adopt speed changes at the speed signal:

$$s = 1.467\ T_r\ V_1\ \left(\frac{V_1}{\Delta V} - 1\right) \tag{9}$$

where

s = funnel length, in ft;
T_r = duration of main red phase, in sec;
V_1 = free flow speed, in mph; and
ΔV = $(V_1 - V_2)$ the speed difference required for creating the gap, assumming V_2 is the slower speed indication.

TABLE 9

TEST FOR EQUALITY OF REGRESSION MODELS

Figure of Merit	Computed F Ratio	Degrees of Freedom	F Table Value (0.01, df)
Number stopped on main road	3.32	(2, 110)	4.81
Percent stopped on main road	2.00	(2, 110)	4.81
Side road delay per vehicle	0.622	(4, 106)	3.50
Side road delay per stopped vehicle	0.837	(4, 106)	3.50

Eq. 9 emphasizes the influence of free-flow speed on the funnel length and shows that for any given free-flow speed the funnel length may be reduced only by increasing the speed differential utilized or by decreasing the gap duration.

Coordinating the Traffic-Actuated Speed Signal

To establish coordination between the advance speed signal and the traffic signal in a traffic-actuated system, the following information must be obtained:

1. Advance notice of the forthcoming side road green, and
2. An estimate regarding the duration of the next side green.

Advance notice of the side green would activate the speed signal and the main route gap could begin to form before the side route traffic reaches the intersection. The estimate regarding the side green duration would be used by the speed signal to create a gap of appropriate size. The speed signal would have this capability if options were available for the lower speed indication to be shown.

Side Route Detection System

The necessary information concerning the time and duration of the next side green could be obtained by installing auxiliary detectors on the side approach (Fig. 9). De-

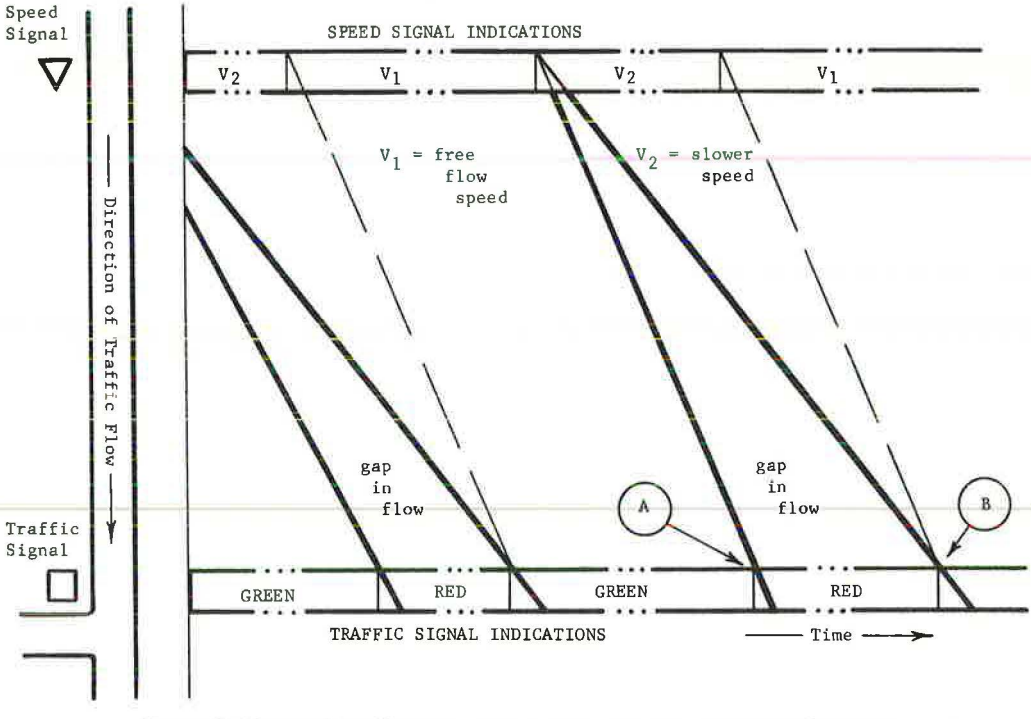

Figure 7. Space-time diagram: speed signal in a traffic-actuated system.

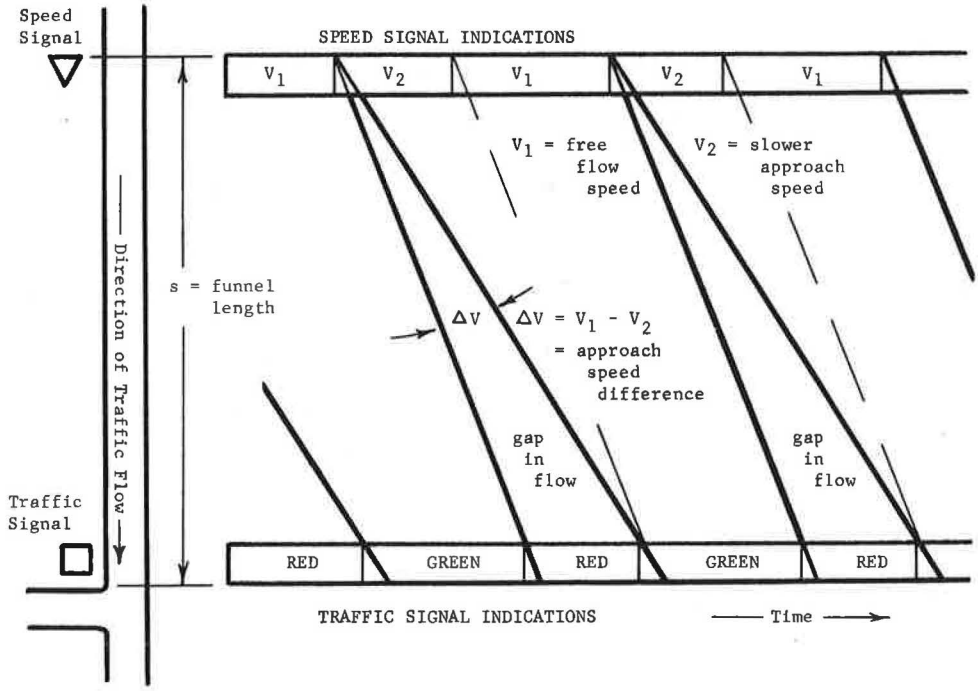

Figure 8. Space-time diagram: speed signal in a fixed-cycle system.

tector 2 provides the advance warning of vehicle arrivals to the main route speed signal. Detector 1, nearest the stop line, has two functions:

1. Places calls in the traffic signal for phase changes and vehicle extensions, and
2. Detects vehicles trapped on the side approach due to overloading the side green phase.

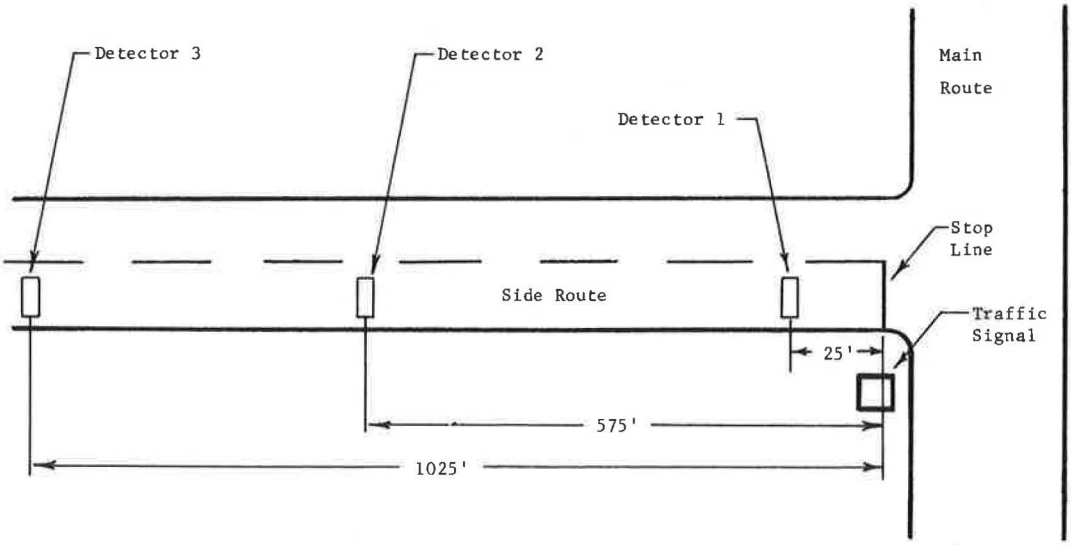

Figure 9. Proposed side road detector arrangement.

The third detector is used in conjunction with detector 1 to indicate the probable length of the next side green phase. Detector 3 maintains a count of vehicles passing in a specified time period and detector 1 reports congested conditions in the vicinity of the intersection stop line.

With adequate information available from the side route, attention is now focused on the main route speed signal system. Unfortunately, there are several important design considerations that prohibit development of the main route components on a general basis. These factors all have significant influence on the design, but each one varies from one location to another, or depends on the desired system complexity.

1. The gaps required for processing the side flow at the site,
2. The intersection controller settings,
3. The free-flow speeds (speed limits) on the approaches,
4. The number of speed signals utilized on the main approach,
5. The number of lower speed options provided each speed signal,
6. Vehicle deceleration distance for various speeds and sites, and,
7. The maximum differential in main road speed indication to be tolerated.

Considering the number of design variables and their complicated interrelationships, it was decided to limit the development to a basic funnel system suitable for the field study site. Therefore, the following design criteria were assumed:

1. The free-flow speed indication would be 45 mph,
2. Only one advance speed signal will be placed on the main approach,
3. The number of options available for lower speed indications on that signal will be limited to two,
4. The speeds shown on the speed signal must all be a multiple of 5 mph for driver convenience, and
5. The maximum differential used must not exceed 20 mph.

It is now possible to evaluate Eq. 9 using the 45-mph main approach speed, giving:

$$s = 66.0\ T_r\ \left(\frac{45}{\Delta V} - 1\right) \tag{10}$$

Eq. 10 indicates numerous system design alternatives still exist for the given approach speed, depending on gap size required and the speed differential selected for the advisory signal.

Next, the intersection controller settings were reviewed to set limits on the gaps to be considered. For the field study location, the minimum main red phase is 13 sec, with a maximum of 30 sec. An additional 3 sec added to these values allowed for the portion of main amber considered an effective red period. Consequently, the gaps required ranged from 16 to 33 sec.

Preliminary computations were then performed using Eq. 10 and the 13-sec minimum gap requirement. It was found that even with the minimum gap the only feasible lower approach speeds were 25 and 30 mph, since excessive funnel length was required when either 35 or 40 mph were utilized.

Having determined the feasible lower speed indications, it became apparent that the length of the maximum gap had to be restricted to avoid the extremely long funnel. Analysis of the field data revealed that a 22-sec main red phase was usually adequate for processing side flows as high as 200 vph. Since side route volumes exceeding 200 vph were seldom observed at the study site, 22 sec was then selected as the maximum gap. The computation performed using the 22-sec gap and the greatest tolerable speed differential (ΔV = 20 mph when 25 mph is shown) in Eq. 10 yields a funnel length of 1,815 ft. An additional 770 ft was added to this length allowing for vehicle deceleration (6) from 45 mph to 25 mph, thus specifying a tentative funnel length of 2,585 ft.

Assuming this distance, the only other feasible speed differential (ΔV = 15 mph when 30 mph is shown) was evaluated to verify the minimum gap adequacy. The result was a 15.1-sec gap. Since this approximated the minimum main route gap requirement, the

tentative length of 2,585 ft was accepted. The speed signal system design parameters were thus established as:

1. Funnel length (s) = 2,585 ft;
2. Speed differential ΔV = 15 mph, yielding a 15.1-sec gap; and
3. Speed differential ΔV = 20 mph, yielding a 22.0-sec gap.

These parameters were included in the speed signal simulation discussed in the following section. Two additional restrictions were also incorporated to establish adequate coordination between the speed signal and the traffic signal:

1. The traffic signal change to main red was delayed until the last vehicle showed a free-flow speed on the main route had sufficient time to clear the intersection, and
2. Speed signal operation was synchronized with the traffic signal so the main road minimum green control setting was recognized.

SIMULATION OF THE TRAFFIC-ACTUATED SPEED SIGNAL SYSTEM

The initial simulation model for semiactuated control was modified to include the speed signal on the high-speed route, a series of three detectors on the minor route, and statements regarding the control and effects of the advisory speed signal. Data were gathered from the speed signal simulation model for the same main and side road flows previously studied.

Results of the Speed Signal Simulation

A total of 132 simulations were run, of which 57 were retained on the basis of matching the vehicular flows to those previously simulated. The studies retained for analysis represent 1,130 minutes of traffic observation. Table 10 sumarizes the flow values from the speed signal simulations. The average side flow of 134.85 vph is closely matched to the 134.73 vph in the semiactuated control simulation. The average main flow in the speed signal analysis, 392.27 vph, is slightly less than the 401.99 vph in the previous simulation model.

The figures of merit regarding main route stoppage characteristics in the speed signal funnel are summarized in Table 11. These measures are extremely important since the ultimate objective of the funnel is reducing the number of main route vehicles stopping. Table 11 indicates the percentage of vehicles stopping is slightly less than 2 percent, considerably below the 20.9 percent in Table 6 for the standard semiactuated signal. Furthermore, the total number stopping during 15 cycles of the intersection signal dropped from an average of 25.8 with semiactuated control to an average of 2.75 for 15 cycles with the speed signal system. Moreover, Table 11 shows the maximum number observed to stop in 15 cycles was only 14 vehicles, or slightly less than one vehicle per signal cycle.

Table 12 summarizes the side road delay measures from the speed signal model. The mean values, 21.2 and 25.9 sec, are both approximately 3 sec greater than the corresponding averages reported in Table 7 for semiactuated control.

LINEAR REGRESSION EVALUATION: SIGNAL FUNNEL VS SEMIACTUATED CONTROL

Equations and statistical measures representing the figures of merit from the speed signal simulation are given in Table 13. These equations are plotted in Figures 10 and

TABLE 10

TRAFFIC VOLUME SUMMARY: SIMULATION OF SPEED SIGNAL FUNNEL

Approach	Flow Range (vph)	Mean (vph)	Std. Dev. (vph)
Side road	60.0-247.0	134.85	47.88
Main road	202.0-709.0	392.27	116.91

TABLE 11

MAIN ROUTE STOPPAGE CHARACTERISTICS: SIMULATION OF SPEED SIGNAL FUNNEL

Figure of Merit	Range	Mean	Std. Dev.
Percent stopped	0.0-7.49	1.99	1.59
Number stopped	0.0-14.0	2.75	2.58

TABLE 12

SIDE ROAD DELAY MEASURES: SIMULATION OF SPEED SIGNAL FUNNEL

Figure of Merit	Range (sec)	Mean (sec)	Std. Dev. (sec)
Average delay per vehicle	16.6-26.0	21.2	2.59
Average delay per stopped vehicle	20.8-29.5	25.9	2.17

13 along with corresponding results from the semiactuated control simulations.

The total number of vehicles stopping in 15 cycles is illustrated in Figure 10 for both types of control. These responses each increase as flow increases, however, the plot for semiactuated control averages 23 units greater than with the speed signal and exhibits a greater slope. The R^2 statistic

TABLE 13

LINEAR REGRESSION EQUATIONS AND STATISTICS: SIMULATION OF SPEED SIGNAL FUNNEL

Equation No.	Equation	$s_{y.x}$	R^2	F(df)
(11)	$Y_1 = -2.453 + 0.987(10^{-2})\,X_1$	2.07	0.363	$31.32^{a}_{(1,\,55)}$
(12)	$Y_2 = 0.186(10^{-2}) + 0.413(10^{-4})\,X_1$	0.0140	0.168	$11.10^{a}_{(1,\,55)}$
(13)	$Y_3 = 23.67 + 0.284(10^{-2})\,X_2 - 0.289(10^{-3})\,X_2^2 + 0.896(10^{-6})\,X_2^3$	2.46	0.149	$3.084^{b}_{(3,\,53)}$
(14)	$Y_4 = 20.21 + 0.111\,X_2 - 0.109(10^{-2})\,X_2^2 + 0.240(10^{-5})\,X_2^3$	2.20	0.027	$0.494_{(3,\,53)}$

[a]Significant at the 0.1 percent level. [b]Significant at the 5 percent level.

where

Y_1 = number stopped per main road lane in 15 cycles;
Y_2 = percentage of vehicles stopped per main road lane;
Y_3 = average delay (sec) per side road vehicle;
Y_4 = average delay (sec) per side road vehicle stopped;
X_1 = sum of side road and main road flow (vph); and
X_2 = side road flow (vph).

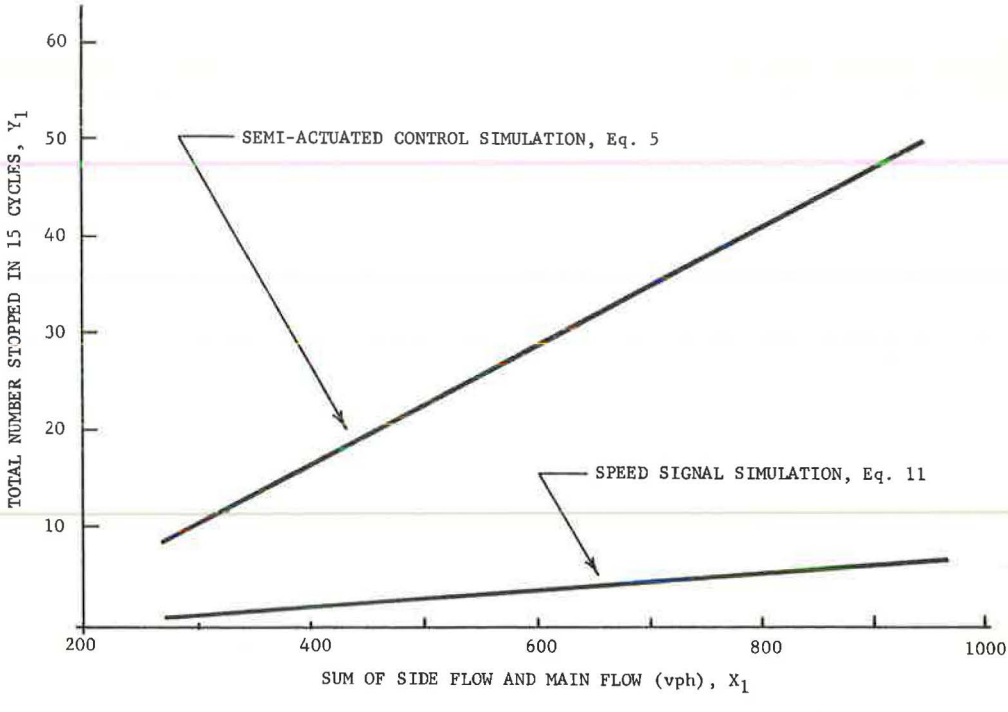

Figure 10. Total number stopped in 15 cycles, speed signal vs semiactuated control.

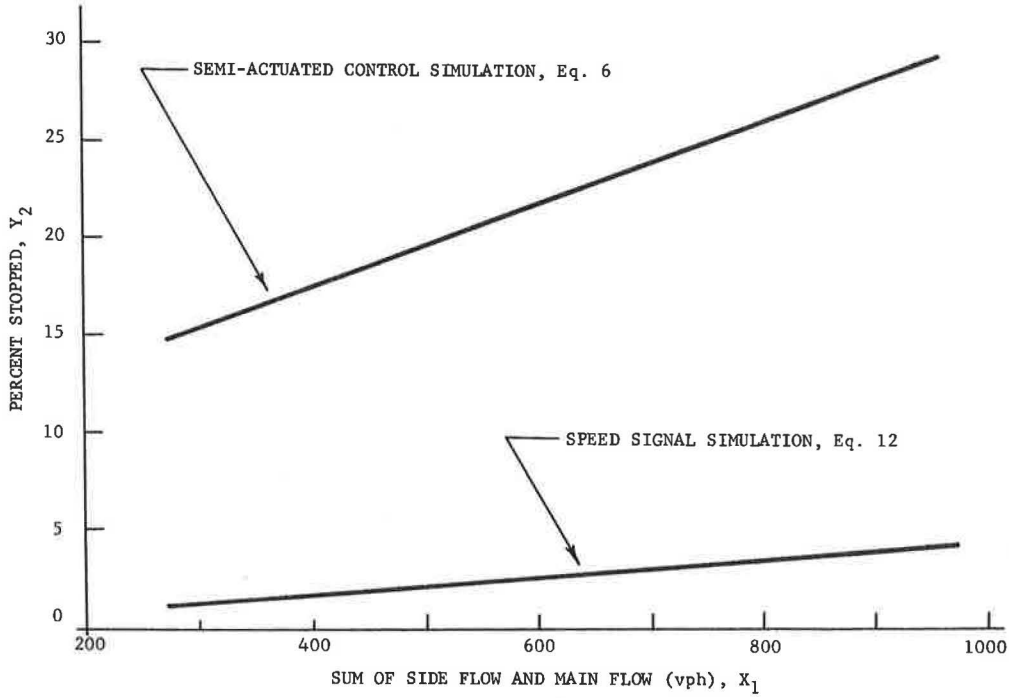

Figure 11. Percent stopped, speed signal vs semiactuated control.

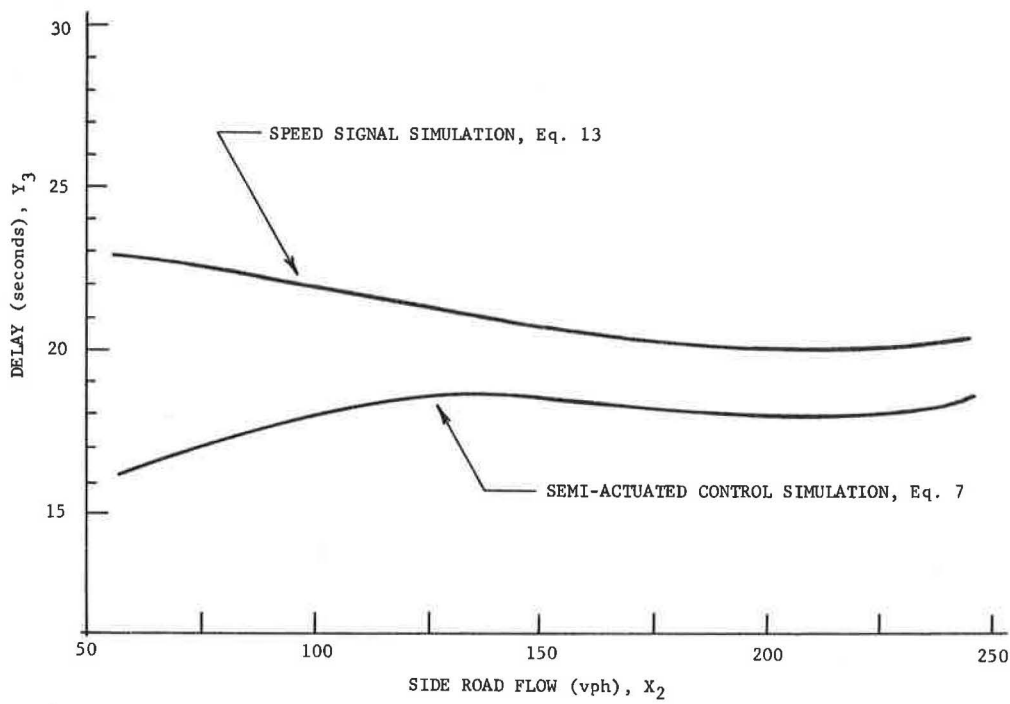

Figure 12. Average delay per side road vehicle, speed signal vs semiactuated control.

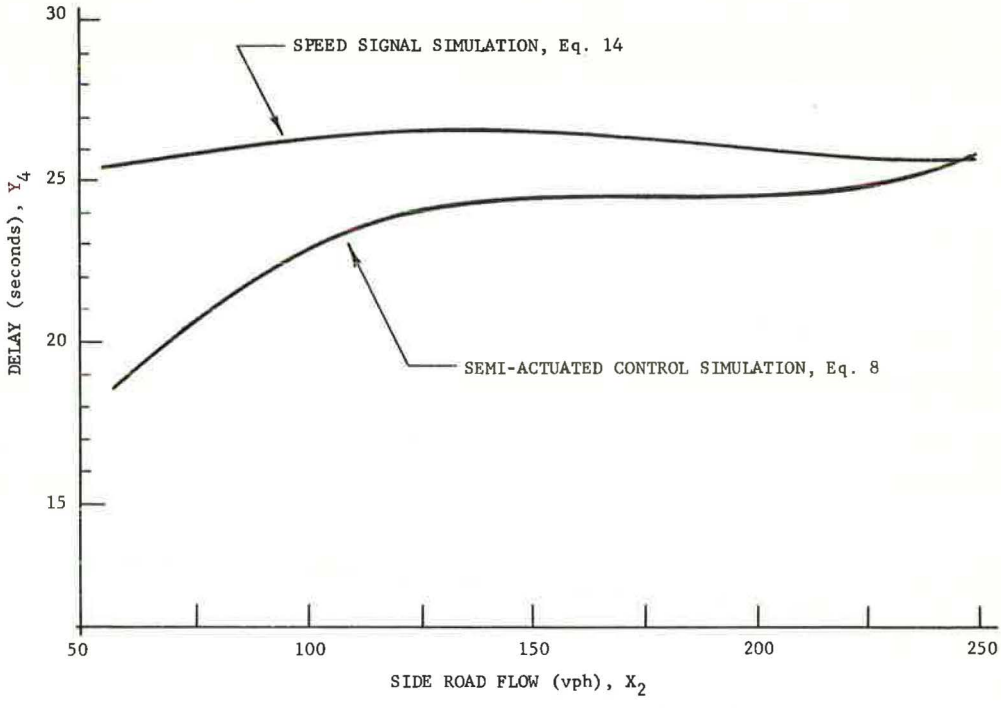

Figure 13. Average delay per side road vehicle stopped, speed signal vs semiactuated control.

with speed signal control is 0.363 which indicates the trend is not as definite as that observed with semiactuated control, where R^2 is 0.800.

Figure 11 concerns the percent vehicles stopped on the main route for the two types of control. Both plots increase with flow; however, the signal funnel averages 19 percentage units less than that indicated for the semiactuated controller. The R^2 value of 0.168 for the speed signal equation indicates a large portion of the variability in this response is random rather than a result of the trend.

The average delay per side road vehicle in Figure 12 shows the speed signal system inflicts higher average delays, especially in the lower flow range. It should be pointed out that above 170 vph the difference between the two curves diminishes to about 2 sec per vehicle.

The delay per side road vehicle stopped is described by Figure 13. This measure also indicates the signal funnel causes longer delays in the lower volumes than does the semiactuated controller. As the side road volume approaches 240 vph, this delay is essentially the same with either type of control.

SUMMARY AND CONCLUSIONS

This investigation has proposed and evaluated a traffic-actuated speed signal funnel for high-speed intersections. The main route speed signal has options available for lower approach speed indications and obtains information regarding side flow from multiple detectors on the side route. Side road volume ranged from 60 to 250 vph, main volume was 180 to 700 vph per lane.

When the advance speed signal was employed, an average of only 2 percent of the main route traffic was forced to stop against the red phase, compared to 21 percent with conventional semiactuated control. Furthermore, the speed advisory system halted only 2.8 vehicles during a typical study of 15 cycles, while the semiactuated controller stopped an average of 25.8 vehicles in that number of cycles. Figures of merit regarding side road delays averaged only 3 sec longer with the speed signal control than with the semiactuated.

The funnel system analyzed in this project is a preliminary design and it is possible that certain modifications would result in further improvement of system effectiveness. For example, several advance speed signals could be placed on the main route, thus providing more control over vehicle approach speed. Certainly, there are other means available for measuring the side route flow conditions.

The author believes the traffic-actuated speed signal concept offers great potential for relieving the access problem on high-speed routes where grade separations cannot be justified due to low side route volume. This control system would limit interruptions to those which were necessary, and would create a minimum disturbance in the flow during these interruptions.

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