Field Measurement of Delay at Signalized Intersections

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For the past five years, studies of delays at signalized intersections have been in progress at the Institute of Transportation and Traffic Engineering, University of California. These studies have dealt with methods for field measurement of intersection delay, and with the effects of different signal timing plans on stopped-time delay during daylight hours at signalized intersections in the San Francisco Bay Area.

Three methods for measuring stopped-time delay were compared: (1) The ITTE delay meter, which accumulates vehicle-seconds of stopped time; (2) a sampling method for estimating vehicle-seconds of stopped time; and (3) use of spaced serial photos to obtain both stopped time and travel time for each vehicle. All three methods were found to be satisfactory for obtaining stopped-time delay at signalized intersections. The spaced serial photo method requires more manpower for reduction of data, but is the only one of the above methods suited for studying travel-time delay at signalized and non-signalized intersections.

A second phase of the study dealt with a comparison of stopped-time delay at three-phase signalized intersections with traffic-actuated vs. fixed-time control. As was expected, the actuated timing was better able to accept short-term fluctuations than fixed-time signals. At intersections with pedestrian movements, the use of pedestrian timers permitted timing plans which substantially reduced vehicular delay, especially in off-peak hours. The use of an overlap sequence in the timing of three-phase signals with heavy left-turn movements from one direction only can materially reduce delay in both peak and off-peak hours.

A third phase of the study dealt with "unnecessary" delay, defined as that portion of stopped-time delay which occurs while no traffic is using the intersecting street. The percent of delay classed as "unnecessary" was substantially lower with actuated as compared with fixed-time control, for tests made in off-peak hours at several intersections.

Stopped-time delay also was compared for semi-actuated and full-actuated traffic signal controls at two urban intersections. Stopped-time delays were substantially lower for full-actuated control, as compared with semi-actuated control, for the signal timings studied.

Stopped-time delay also was studied at two signalized intersections 1,185 feet apart to ascertain the effect on delay of coordinating the timing of two fixed-time signals. With the coordinated signal timing plan, the delay to the main street traffic in both peak and off-peak hours was less than half the delay experienced when using actuate traffic signal control without coordination of the timing of the two signals.

Due to the many variables and to fluctuations in traffic and parking conditions, it is a time-consuming job to isolate, in field studies, the effect on delay of each change

in condition at an intersection. More study is needed of optimum timing of signals, the placement of detectors, and the effects on delay of coordination of timing of traffic-actuated signals. It thus is not possible to draw general conclusions at this time about the effects on delay of signal timing variations, placement of detectors, turning movements, or volume at all levels up to the possible capacity of an intersection.

● STUDIES of vehicular delay at signalized intersections have been carried on at the University of California for the past five years. The purposes of these studies have been (1) to investigate methods for measuring delay, and (2) to compare the delay which resulted when different types of traffic signal controllers were used at the same intersections. Such data should be useful as a guide in selection of the most efficient type of controller for intersections having comparable conditions.

Before discussing the delay studies, however, it should be pointed out that delay is only one of several factors to be considered in evaluating the efficiency or effectiveness of traffic controls at an intersection. Other factors include the following:

1. Motorists' desires—motorists may prefer one type of control even though the average delay per vehicle is greater. For example, they may prefer the certainty of right of way provided by a signal even though delay at some intersections is lower when stop signs are used (*1*).
2. Use of traffic actuated equipment seems to have a psychological advantage since many motorists feel that they have a part in causing the signal to change to green.
3. Comparative accident experience also is a factor in selecting type of intersection control.
4. Other factors include costs of equipment and its maintenance, and comparative costs of vehicle operation.

TYPES OF DELAY

Delays to vehicles in traversing intersections have been subdivided into the following types for purposes of this study.

Travel-Time Delay

This type of delay for an individual vehicle is the difference between the actual time required to traverse some fixed distance at the approach to an intersection, and the travel time which would have been required had the vehicle been able to continue at the average speed of approaching traffic.

Stopped-Time Delay

This is the time an individual vehicle is standing still while waiting in line in the approach to a signalized intersection. Average stopped-time delay is the average of stopped-time delays for all vehicles approaching during the period of time.

"Unnecessary" Stopped-Time Delay

That portion of the stopped-time delay which occurs when there is no vehicle entering or approaching on the opposing legs of the intersection.

Percent Stopped

The ratio of the number of vehicles which come to a stop in approaching an intersection, to the total number entering in the same period of time, expressed as a percentage.

The average travel-time delay appears to be the type of delay which would have the greatest significance in comparing the effectiveness of different traffic control devices. This type of delay is about the only type which can be used to compare delay under signal vs. stop-sign control (*2*).

Stopped-time delay, however, is much easier to measure than travel-time delay. Thus, one part of this study investigated the correlation between stopped-time delay and travel-time delay.

METHODS FOR MEASURING DELAY

Three methods for measuring delay at signalized intersections were investigated. These methods, which are explained more completely in an earlier paper (*3*), are described briefly below:

The ITTE Delay Meter

This is a delay meter which accumulates vehicle-seconds of stopped time. This device consists of electrically operated counters which add vehicle-seconds of stopped time at rates which are directly proportional to the number of vehicles which are standing at any instant. The meter is operated by keeping a rotary switch or handle adjusted to the position corresponding to the number of cars standing and waiting to resume motion (See Figure 1).

The Sampling Method

A visual sampling method for estimating vehicle-seconds of stopped time. At periodic intervals (such as every 15 seconds), the observer determines the number of cars stopped in the approach to the intersection, and records the number of stopped cars corresponding to the exact time of the observation.

The Spaced Serial Photo Method

A method for obtaining travel time and stopped time for each vehicle, utilizing photographs taken at intervals of ½, 1, or 2 seconds apart. Adaptation of spaced serial photos to studies of intersection delay by the ITTE has been described by Van Til (*4*). Figure 2 shows the camera, and Figure 3 shows a typical sequence of two pictures, with the identifying picture number.

These three methods for measuring stopped-time delay were used simultaneously at two intersections in order to permit comparisons of manpower requirements and of accuracy. The data obtained by the camera method also permitted a comparison of travel-time delay with stopped-time delay. Altogether, 21 separate 15-minute periods of data were obtained for this phase of study; detailed results have been reported earlier (*3*) and are only summarized here.

Figure 4 shows the distribution of travel times for all vehicles while traversing a distance from an advance check point to the stop line at one approach to a three-phase signalized intersection in San Francisco during an afternoon hour. Also shown are the distribution of individual travel times for vehicles which stopped, as obtained with the camera, and the travel times for vehicles which did not stop. A total of 735 vehicles were timed by the camera during this hour, with 38 percent of this number being able to proceed through the intersection without stopping.

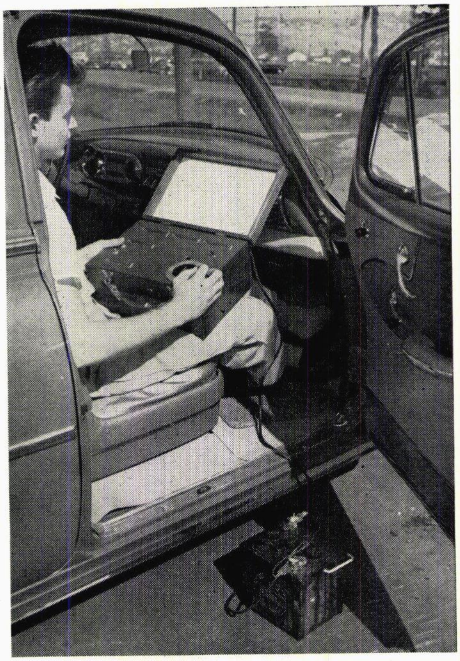


Figure 1. ITTE delay meter in operation.

Travel-time delay is obtained by subtracting from each individual travel time, an average travel time corresponding to a "no delay" condition. The travel time corresponding to the sixty-seventh percentile speed of the non-stopping vehicles was taken as the travel time corresponding to the "no delay" condition. When this value is subtracted from each individual travel time, there result the distributions of travel-time delays and stopped-time delays as shown in Figure 5. Some travel-time delays are shown as negative values, because some vehicles were traveling faster than the speed corresponding to the value picked for the "no delay" condition. The average stopped-time delay for this sample, as shown on this figure, was 14.37 seconds per vehicle. Travel-time delay averaged 18.48 seconds per vehicle.

Table 1 shows a comparison between average travel-time delay and average stopped-time delay for sixteen 15-minute periods of data, as taken at the two approaches studied. Column 6 has percentage figures which show average stopped-time delay as percentages of average travel-time delay. The percentages at the San Jose Avenue approach are above

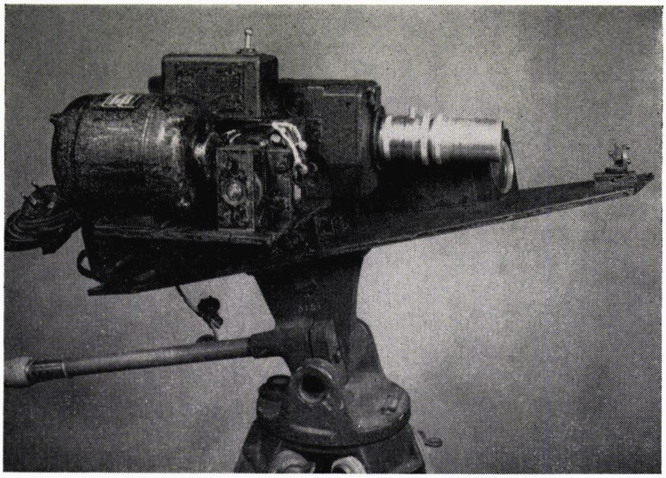


Figure 2. Camera used in delay studies.

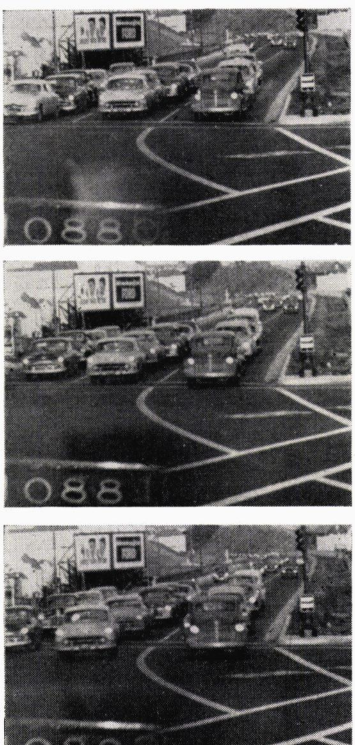


Figure 3. Numbered spaced serial photos taken for delay studies at San Jose Avenue.

70 percent in every case. Average stopped-time delay at the approach on Eastshore Highway (in a suburban area), was about 55 percent of average travel-time delay during non-peak hours. This percentage figure averaged 66 percent during peak-hour conditions.

Results at these two intersections indicate that, for the conditions of approach speeds and signal timing, the measurements of stopped-time delay provide a method for evaluating a substantial portion of the total delay. The portion of the total delay which is evaluated by stopped-time measurements may also be considered to reflect the variable portion which is related to changes in the timing of the signals.

The average stopped-time delay per vehicle, as obtained by each of the three methods, is compared in Tables 2, 3 and 4, for each of the twenty-one 15-minute periods of study. The tables show the percentages by which the results obtained with the delay-meter and the sampling method differed from the results obtained with spaced serial photos.

The delay-meter method yielded average stopped-time delays for individual 15-minute periods which varied from 13.3 percent higher than the camera method to 22.9 percent less. When three or more 15-minute periods were grouped, the results did not deviate more than 9 percent from those obtained with the camera.

The visual sampling method consistently yielded results which, when grouped for similar volumes, were all within 6.4 percent of the values obtained by the camera method at these two intersection approaches.

These data indicate that both the delay-

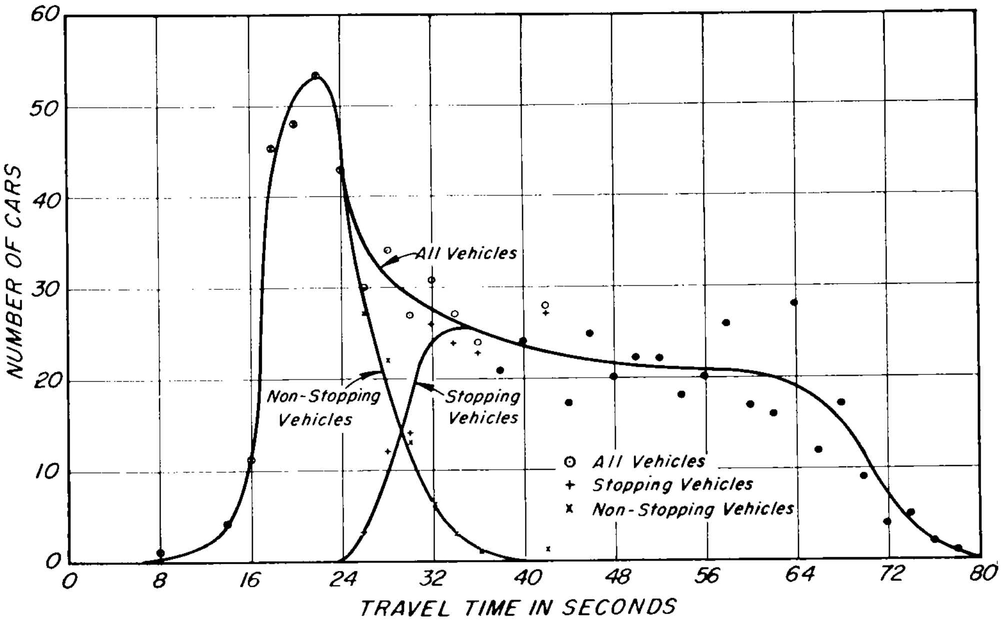


Figure 4. Distribution of vehicle travel times on San Jose Avenue, off-peak hour, November 20, 1953.

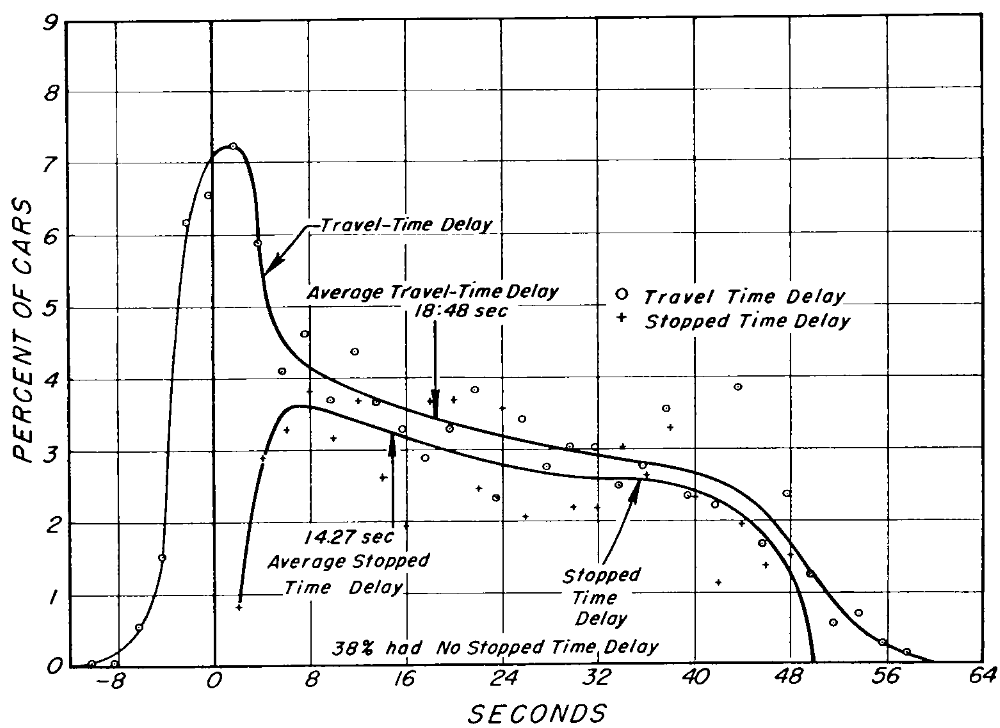


Figure 5. Travel-time delay vs. stopped-time delay, San Jose Avenue, off-peak hours, November 20, 1953.

TABLE 1
STOPPED-TIME DELAY VS TRAVEL-TIME DELAY FROM CAMERA STUDY AT TWO INTERSECTIONS

(1) Time	(2) Volume Vehicles Per Hour	(3) Percent Stopped	(4) Average Travel-Time Delay	(5) Average Stopped Time Delay	(6) Average Stopped Delay as Percent of (4)
Eastshore Highway, Oct. 16, 1953					
p.m.			*seconds*	*seconds*	
2:00–2:15	152	26.3	10.2	5.5	53.9
2:15–2:30	162	22.8	7.8	4.3	55.1
2:45–3:00	173	39.3	11.4	6.4	56.1
4:30–4:45	335	42.4	14.4	9.2	63.9
4:45–5:00	347	39.2	16.2	8.7	53.7
5:00–5:15	340	42.1	17.2	12.2	70.9
5:15–5:30	329	57.1	22.7	17.2	75.8
San Jose Ave., Nov. 20, 1953					
2:15–2:30	172	56.4	17.7	13.8	78.0
2:30–2:45	199	64.3	17.7	13.3	75.1
2:45–3:00	183	61.7	18.5	14.6	78.9
3:00–3:15	181	64.1	20.0	15.9	79.5
3:30–3:45	223	59.6	17.5	14.2	81.1
3:45–4:00	248	64.1	20.1	15.2	75.6
4:15–4:30	297	66.3	21.1	16.7	79.1
4:30–4:45	450	80.9	29.2	22.6	77.4
4:45–5:00	461	59.4	21.5	16.3	75.8

TABLE 2
COMPARISON OF AVERAGE STOPPED-TIME DELAY BY THREE METHODS AT EASTSHORE HIGHWAY, OCT., 16, 1953

Time	Camera Method: Average Stopped-Time Delay	Percent of Differences from Camera Method	
		By delay method	By sampling method
p.m.	*sec per vehicle*	%	%
2:00–2:15	5.5	−12.8	−10.5
2:15–2:30	4.3	+13.3	+0.1
2:45–3:00	6.4	+7.3	−7.5
45-min total	5.4	+2.7	−6.4
4:30–4:45	9.2	+1.8	−11.6
4:45–5:00	8.7	−22.9	−30.1
5:00–5:15	12.2	+0.6	+7.3
5:15–5:30	17.2	−4.4	+3.9
One-hour total	11.8	−5.4	−4.7

meter and the sampling method can be used to give reasonably consistent values of accumulated stopped-time delay under the conditions existing at these high-volume approaches. Frequently, during the peak hour, as many as 50 vehicles were waiting at one time, which required considerable dexterity on the part of the operator of the delay meter.

TABLE 3
COMPARISON OF AVERAGE STOPPED-TIME DELAY BY THREE METHODS AT SAN JOSE AVE., NOV. 20, 1953

Time	Camera Method: Average Stopped-Time Delay	Percent of Differences from Camera Method	
		By delay meter	By sampling method
p.m.	*sec per vehicle*	%	%
2:15–2:30	13.8	−10.2	+4.8
2:30–2:45	13.3	−9.1	+1.1
2:45–3:00	14.6	−7.8	+0.6
3:00–3:15	15.9	−8.2	−6.7
One-hour total	14.4	−8.9	−0.3
3:30–3:45	14.2	−7.5	+3.8
3:45–4:00	15.2	−5.4	−1.8
Half-hour total	14.7	−6.4	+0.7
4:15–4:30	16.7		−3.5
4:30–4:45	22.6		−6.3
Half-hour total	20.2		−5.4
4:45–5:00	16.3		−10.9

TABLE 4
COMPARISON OF AVERAGE STOPPED-TIME DELAY BY DELAY-METER AND CAMERA METHODS

Location and Date	Time	Camera Method: Average Stopped-Time Delay	Delay Meter Difference from Camera Method
	p.m.	*sec per vehicle*	*percent*
Eastshore Highway, 8/6/53	2:30–2:45	6.2	+8.1
	3:45–4:00	5.3	+8.3
	4:15–4:30	9.5	+4.4
45-min total		7.2	+6.2
San Jose Ave., 9/3/53	2:30–2:45	8.0	+5.3
	2:45–3:00	7.8	+5.0
30-min total		7.9	+5.2

The sampling method gave unreliable results at an intersection with two-phase fixed-time signals when the cycle length was a multiple of the sampling frequency, and the length of the red light was relatively short. This pointed out the need for care in selecting the time interval for sampling.

The study also revealed that when the lengths of the cycle did not vary materially, the percent of vehicles stopping may be useful as one measure of delay. However, the vehicle-seconds of stopped time per vehicle provides a more realistic measure for all different types of signalized control, since this measure takes into account the length of time the vehicles must wait.

DELAY AT THREE-PHASE SIGNALIZED INTERSECTIONS

The next phase of the study investigated the effects on stopped-time delay of different types of three-phase traffic signal controllers at three intersections in the San Francisco Bay Area. Delay meters were used to obtain stopped-time delay for two of the approaches to each intersection, with the sampling method used for measuring delay in the third approach (*5*).

Three approaches for each intersection (one for each signal phase) were studied simultaneously. In general, the afternoon peak-hour direction was selected, with studies made for both off-peak and peak-hour traffic volume conditions.

Eastshore and Carlson Study

Figure 6 shows the layout of the intersection of Eastshore Highway and Carlson Boulevard in a suburban area in Richmond, California. The movements studies included north-bound traffic on Eastshore, left-turning traffic entering from the south on Eastshore, and westbound traffic on Carlson Boulevard. The traffic volume turning left from the north approach is very light. The peak-hour volumes at this intersection appear to approach the practical capacity, with about 1200 vehicles per hour northbound on Eastshore, 320 vehicles per hour turning left and 380 vehicles per hour westbound on Carlson Boulevard.

The intersection is normally controlled by a three-phase full-actuated traffic signal controller with a pedestrian timer and an overlap phase sequence. When there is no vehicle actuation for the left-turn lane on the north approach, the northbound traffic on Eastshore is permitted to continue while the left-turn traffic from the south moves. Since the left-turn traffic from the north is very light, this overlapping sequence operates very frequently at this intersection, and thus adds to the available green for northbound traffic.

The delay studies were made for three signal timing plans, as follows:

1. Full-actuated three-phase signal timing with the permissive overlap sequence and with dial settings as established by the authority having jurisdiction.
2. A full-actuated three-phase timing without the overlap sequence, but with substantially the same dial settings as above.
3. A fixed-time three-phase timing, with separate dial settings for peak and off-peak hours.

Table 5 shows a comparison of stopped-time delays for the three approaches under off-peak and peak-hour conditions, for the three types of traffic signal control. The dial settings for the controllers were not necessarily the optimum settings for each type of signal control. The results thus apply only for the timings actually used (*5*).

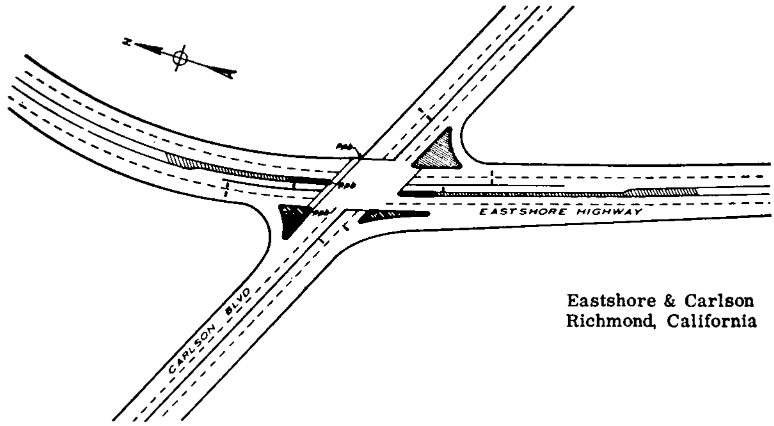
It is readily apparent from the table that the delay to northbound traffic for the actuated controller with the overlap sequence was substantially less than for either of the other two timing plans, under both off-peak and peak-hour conditions. During the off-peak hour the delay per vehicle was 44 percent less than with the fixed-time signal; a decrease of 3.3 seconds per vehicle. A difference as large as 1.8 seconds is possible due to chance only 2 times in a 100 with the size of sample used. The difference for the peak-hour condition was also statistically significant.

The average values for the fixed-time controller and for the actuated timing without the overlap sequence did not differ materially. During the peak-hour condition, however, the individual 15-minute average for the fixed-time signal varied much more than did the values for the actuated signal, because of the inability of the fixed-time signal to adjust itself to a temporary overload on one leg of the three-phase movement. The two highest 15-minute three-leg peak-hour delay values for the fixed time signal averaged 50.5 seconds per vehicle, as compared with 42.1 seconds for the actuated controller with no overlap sequence.

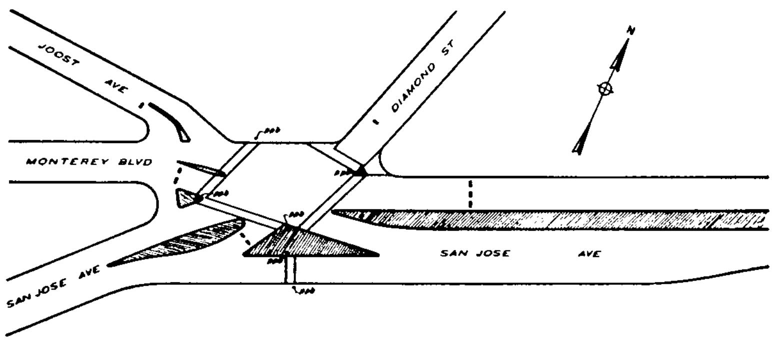
San Jose, Monterey, and Diamond

Measurements of stopped-time delay were also made at the intersection of San Jose Ave., Monterey Boulevard, and Diamond Street in San Francisco. The three major conflicting movements normally were controlled by a three-phase full-actuated traffic signal, with pedestrian push buttons.

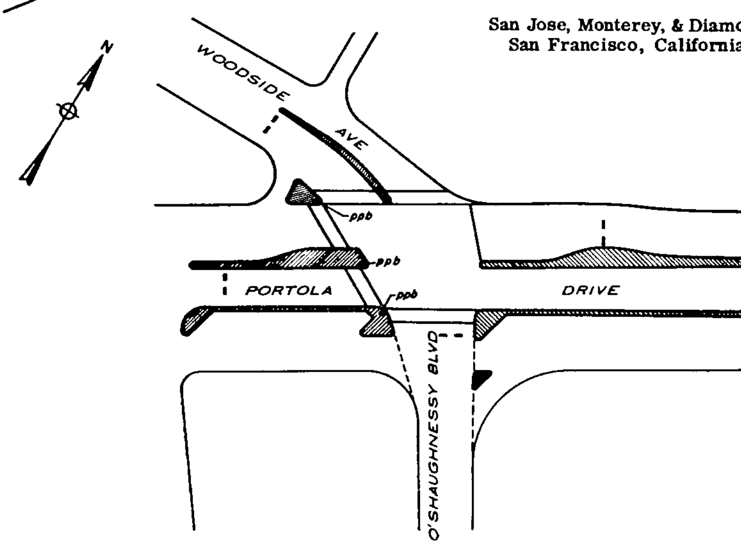
Traffic volumes were heaviest on San Jose Avenue, with the westbound volume increasing in the peak hour from 640 to 2172 vehicles per hour in the three lanes. The volumes on Monterey in the evening peak hour were very little different from in the off-peak hours (220



Eastshore & Carlson
Richmond, California



San Jose, Monterey, & Diamond
San Francisco, California



Portola, Woodside & O'Shaughnessy
San Francisco, California

Figure 6. Layouts of the three-phased signalized intersections.

vs 248); on Diamond the off-peak and peak-hour volumes were 184 and 368 vehicles per hour, respectively.

Table 6 shows average stopped-time delays during afternoon off-peak hours (1:45–3:00 p.m.), under three signal timing plans, as follows:

1. Actuated Control, without pedestrian timers. Minimum initial intervals: San Jose, 15 seconds; Monterey, 18 seconds; Diamond, 16 seconds.
2. Actuated Control, with pedestrian timers. Minimum initial intervals for Monterey and for Diamond were cut to 8 seconds.
3. Fixed-Time Control, with 75 or 80-second cycles, and with green intervals adequate for pedestrians to cross.

The table reveals that the delay was the least when the intersection was controlled by the actuated signal with the pedestrian timer and the low minimum initial intervals. The average delay per total vehicle is significantly less than for the fixed time signal. It should be noted that the average length of cycle is lower (52 seconds), with this timing plan than with either of the other two timings. The delay to vehicles on San Jose Avenue was cut approximately a third (15.0 to 10.3 seconds per vehicle) by using pedestrian timers with low minimum initial intervals, as compared with a timing plan having initial intervals long enough for pedestrians to cross.

For peak-hour conditions, similar results were obtained, although there were only three 15-minute samples without the pedestrian timers. Table 7 shows that the average delays for the actuated controller with pedestrian timers were significantly lower than for the fixed-time controllers. It is interesting to note also that the average delays for each street were greater when the percent of green for that street was lower.

TABLE 5
COMPARISON OF AVERAGE STOPPED-TIME DELAY WITH THREE SIGNAL CONTROLLERS
At Eastshore and Carlson, Richmond, Fall, 1953

Type of Control and Time Period	Volume, 3 Legs, VPH	Avg. Cycle, Secs.	Average Delay per Vehicle—Seconds			
			Total, 3 legs	Eastshore North	Eastshore Left T.	Carlson West
Off-peak (1:00–3:00)						
Actuated						
With overlap	720	63	8.9	4.3	24.6	16.6
No overlap	796	82	13.2	7.6	34.9	21.2
Fixed time	768	84	13.2	7.6	34.1	22.5
Peak (4:30–5:30)						
Actuated						
With overlap	1872	103	21.2	11.5	43.1	36.2
No overlap	1984	138	32.7	25.3	48.6	41.9
Fixed time	1908	110	32.5	22.9	64.9	37.0

TABLE 6
COMPARISON OF AVERAGE STOPPED-TIME DELAY IN OFF-PEAK HOURS AT SAN JOSE, MONTEREY, AND DIAMOND, SAN FRANCISCO
1:45–3:00 p.m. Fall, 1953

Type of Signal Control	Average Delay per Vehicle—Seconds			
	Total, 3 legs	San Jose	Monterey	Diamond
Actuated				
No pedestrian timer	15.1	15.0	14.5	16.6
With pedestrian timer	13.3	10.3	20.3	14.7
Fixed time	15.6	12.8	21.0	19.8
	Average Signal Timing			
	Cycle, sec.	Approx. percent green San Jose	Approx. percent green Monterey	Approx. percent green Diamond
Actuated				
No pedestrian timer	65	35	30	25
With pedestrian timer	52	40	21	22
Fixed time	79	39	25	23

Portola, Woodside, and O'Shaughnessy

The third intersection studied in this series was at Portola, Woodside, and O'Shaughnessy in San Francisco. Tables 8 and 9 present data on signal timing for both off-peak and peak-hour conditions, and the resulting data on stopped-time delay under two signal timing plans. Traffic volumes on the three-lane Portola approach increased from 650 vehicles per hour in the off-peak hour to 1875 vehicles per hour in the peak-hour; for Woodside, the comparative figures were 300 and 472 vehicles per hour; for O'Shaughnessy, 132 and 516 vehicles per hour.

As shown in Table 8, the average stopped-time delay for all traffic entering on the three legs in an off-peak hour was about 30 percent less for the actuated control than for the fixed-time control (10.0 vs 14.5 seconds per vehicle). The delay to the major flow on Portola Avenue was reduced almost 60 percent, with the per-

TABLE 7

COMPARISON OF AVERAGE STOPPED-TIME DELAY IN PEAK HOUR AT SAN JOSE, MONTEREY, AND DIAMOND, SAN FRANCISCO

4:30–5:30 p.m. Fall, 1953

Type of Signal Control	Average Delay Per Vehicle—Seconds			
	Total, 3 legs	San Jose	Monterey	Diamond
Actuated				
No pedestrian timer	26.6	24.3	31.6	37.5
With pedestrian timer	20.7	16.8	44.8	31.3
Fixed time	24.5	20.7	34.8	40.0
	Average Signal Timing			
	Cycle, sec.	Approx. percent green		
		San Jose	Monterey	Diamond
Actuated				
No pedestrian timer	101	50	22	23
With pedestrian timer	90	54	16	22
Fixed time	105	49	20	21

TABLE 8

COMPARISON OF AVERAGE STOPPED-TIME DELAY AT PORTOLA, WOODSIDE, AND O'SHAUGHNESSY IN OFF-PEAK HOURS

2:00–3:00 p.m. Fall, 1953

Type of Signal Control	Average Delay Per Vehicle—Seconds			
	Total, 3 legs	Portola	Woodside	O'Shaughnessy
Actuated	10.0	5.6	14.7	21.5
Fixed time	14.5	12.9	14.6	22.4
	Average Signal Timing			
	Cycle, sec.	Approx. percent green		
		Portola	Woodside	O'Shaughnessy
Actuated	51	48	22	14
Fixed time	63	34	30	21

cent of vehicles being required to stop dropping from 76 percent to 46 percent.

There were fourteen 15-minute samples for the actuated timing, and eight 15-minute samples for fixed-time timing. The variation in results was sufficiently low, so that the differences found are statistically significant, and could not have been due to chance alone.

The data for the peak hour shown in Table 9, reveal no great differences between delay values for fixed-time and actuated controls.

TABLE 9

COMPARISON OF AVERAGE STOPPED-TIME DELAY AT PORTOLA, WOODSIDE, AND O'SHAUGHNESSY, IN PEAK HOUR

4:30–5:30 p.m. Fall, 1953

Type of Signal Control	Average Delay Per Vehicle—Seconds			
	Total, 3 legs	Portola	Woodside	O'Shaughnessy
Actuated	20.2	17.0	26.0	28.0
Fixed time	21.8	15.7	26.2	34.5
	Average Signal Timing			
	Cycle, sec.	Approx. percent green		
		Portola	Woodside	O'Shaughnessy
Actuated	81	47	21	21
Fixed time	74	46	26	18

However, the size of the sample was too small to permit any statistical comparison. It is interesting to note, however, that the average length of cycle was approximately the same for the two timing plans during this peak-hour condition. The lower percentage of green time on O'Shaughnessy with the fixed-time control is probably the cause of the increased delay on this approach.

Alemany Boulevard Study

Stopped-time delay was obtained on Alemany Boulevard at Santa Rosa Avenue and at Ocean Avenue in San Francisco during 1951–1952 in order to compare different types of two-phase traffic signal controllers and timing plans. Santa Rosa Avenue and Ocean Avenue are 1185 feet apart, and normally are controlled with full-actuated volume-density traffic-signal controllers without interconnection. Figure 7 shows the spacings of signals along Alemany, and the time-space diagram for the fixed-time system which was installed for one part of the study. Alemany Boulevard is an 80-foot street which at the time of the study carried about 1500–2200 vehicles per hour in the peak hour in the southbound direction, and about 600 vehicles per hour in the northbound direction. Calculating machines and delay meters were used in accumulating vehicle-seconds of stopped time, as described by Edward M. Hall in an earlier report (*2*).

The dial settings used for timing the traffic-

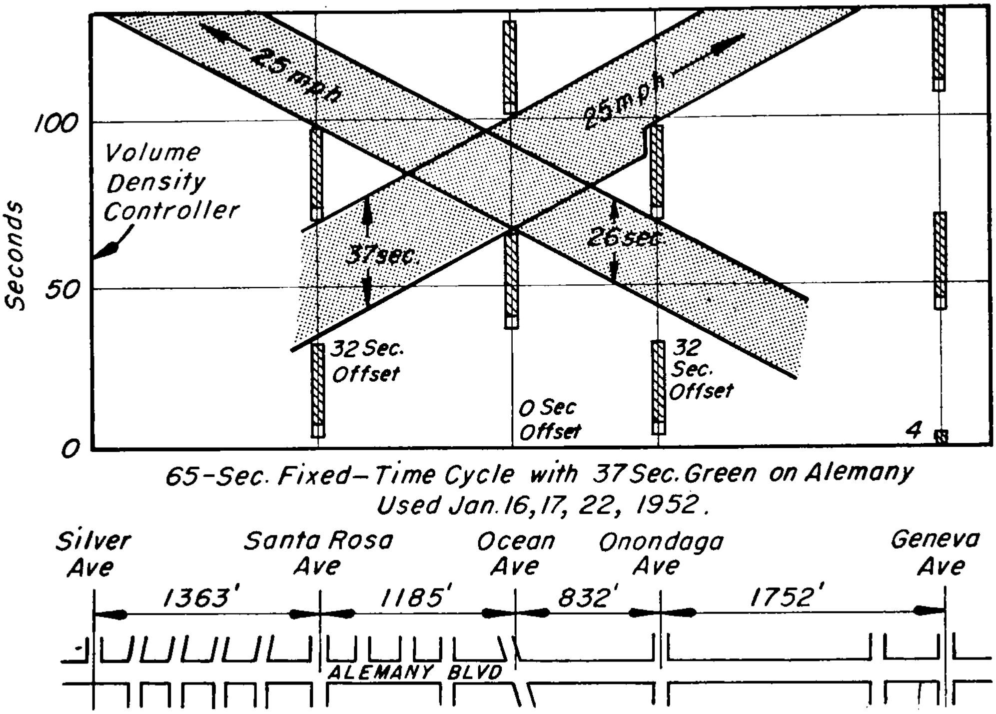


Figure 7. Time-space diagram for Alemany Boulevard.

actuated signals were suggested by officials of the City of San Francisco and/or by the District Office of the California Division of Highways. No claim is made that the settings actually used provided the optimum timing for the conditions. However, the men who timed the signals were experienced in timing traffic-actuated signals. The vehicle detectors on Alemany were located 250 feet from the intersection, and the detectors on the side streets were between 40 and 50 feet from the curb line.

Results of the delay studies made during peak-hour conditions at Santa Rosa Avenue are shown in Table 10. This table shows, for each of six signal timing plans, the stopped-time delay in seconds per vehicle for each of the two studied approaches, the traffic volumes, and the percent of vehicles which stopped.

The lowest delay for the two legs combined was found when using timing plan No. 6, with a volume-density traffic-actuated controller. Only 18.6 percent of the vehicles moving south on Alemany were required to stop. The delay to cross traffic was higher (20.5 seconds per vehicle, with 81.5 percent stopping) than for other signal timing plans. Timing plan No. 4 (full-traffic-actuated controller) showed delay values which compared favorably with the volume-density controller for this location. Delays with the semi-actuated controller and the fixed-time controller were higher. Traffic approaching the fixed-time signal from the approach studied did not have the benefit of coordinated timing of the signals, since this traffic was approaching the first of the three fixed-time signals, as shown by the time-space diagram in Figure 7.

Results of studies made at the Ocean Avenue intersection, for several ranges of volumes, are shown in Tables 11, 12, 13 and 14. The fixed-time controller at this intersection was coordinated with fixed-time controllers at nearby intersections, as shown in Figure 7, thus providing a simple progressive system for Alemany Boulevard.

The results indicate that, for the conditions studied, the fixed-time progressive timing produced delay values for southbound traffic

TABLE 10
STOPPED-TIME DELAY IN PEAK HOUR WITH SIX SIGNAL TIMING PLANS AND NO COORDINATION WITH NEARBY SIGNALS
Alemany and Santa Rosa, San Francisco, 1951–1952
4:30–5:30 p.m.

Controller and Timing Plan	Street	Volume in Veh/Hr	Percent Stopped	Delay in Seconds per Total Veh.
1. *Fixed-time* 65 Sec. cycle with 37 Sec. green on Alemany; 1/22/52	Alemany, S.B.	2192	36.8	6.0
	Santa Rosa, E.B.	125	54.4	10.3
	Both legs	2317	37.7	6.3
2. *Semi-actuated* Phase A: 36 sec. min.; Phase B: 15 + 5; max. 30; 3/21/51	Alemany, S.B.	1580	46.2	7.3
	Santa Rosa, E.B.	166	63.2	10.8
	Both legs	1746	47.8	7.6
3. *Semi-actuated* Phase A: 49 sec. max.; Phase B: 7 + 4, max. 25; 3/28/51	Alemany, S.B.	1501	25.8	4.3
	Santa Rosa, E.B.	207	70.5	17.7
	Both legs	1708	31.3	6.0
4. *Full actuated (804)* Phase A: 25 + 5; max. 75; Phase B: 10 + 5; max. 30; 4/11/51	Alemany, S.B.	1646	26.2	3.1
	Santa Rosa, E.B.	152	75.6	16.9
	Both legs	1798	30.4	4.3
5. *Volume density (1022)* Timing plan A; 3/7/51	Alemany, S.B.	1519	44.2	5.5
	Santa Rosa, E.B.	169	—	13.7
	Both legs	1688	—	6.3
6. *Volume density (1022)* Timing plan B; 4/4/51	Alemany, S.B.	1545	18.6	2.4
	Santa Rosa, E.B.	157	81.5	20.5
	Both legs	1702	24.4	4.1

TABLE 11
STOPPED-TIME DELAY IN PEAK HOUR, COMPARING FIXED-TIME COORDINATED TIMING WITH SEVERAL NON-COORDINATED ACTUATED TIMINGS OF A TWO-PHASE SIGNAL
Alemany and Ocean, San Francisco, 1951–1952
4:30–5:30 p.m.

Controller and Timing Plan	Street and Direction of Movement	Volume in Veh/Hr	Percent Stopped	Delay in Seconds per Total Veh.
1. *Fixed-time*, coordinated for progressive movement on Alemany 65 sec. cycle with 37 sec. green on Alemany; 1/17/52	Alemany, S.B.	2164	8.0	1.1
	Ocean, E.B.	370	67.3	14.8
	Both legs	2534	16.7	3.1
2. *Semi-actuated* Phase A: 40 sec. min.; Phase B: 6 + 4, max. 25; 4/26/51	Alemany, S.B.	1572	39.5	6.9
	Ocean, E.B.	384	64.6	15.0
	Both legs	1956	44.4	8.5
3. *Semi-actuated* Phase A: 60 sec. min.; Phase B: 14 + 5, max. 25; 6/6/51	Alemany, S.B.	1653	32.7	4.8
	Ocean, E.B.	392	68.9	17.7
	Both legs	2045	39.6	7.3
4. *Semi-actuated* Phase A: 50 sec. min.; Phase B: 10 + 5, max. 25; 8/22/51	Alemany, S.B.	1781	39.7	7.6
	Ocean, E.B.	355	87.3	26.4
	Both legs	2136	47.6	10.8
5. *Full actuated (804)* Phase A: 15 + 5; max. 70; Phase B: 10 + 5; max. 45; 5/9/51 and 9/12/51	Alemany, S.B.	1565	24.0	3.7
	Ocean, E.B.	357	59.4	21.6
	Both legs	1922	30.6	7.0
6. *Volume density (1022)* Timing plan C; 5/16/51 (omitting 5:00–5:15)	Alemany, S.B.	1438	22.0	3.2
	Ocean, E.B.	400	66.2	17.9
	Both legs	1838	31.6	6.4
7. *Volume density (1022)* Timing plan D; 6/20/51	Alemany, S.B.	1936	25.9	3.4
	Ocean, E.B.	361	75.6	17.5
	Both legs	2297	33.7	5.6
8. *Volume density (1022)* Timing plan E; 10/10/51	Alemany, S.B.	1670	27.9	3.6
	Ocean, E.B.	342	66.7	17.4
	Both legs	2012	34.5	5.9

TABLE 12
STOPPED-TIME DELAY AT INTERMEDIATE VOLUMES, COMPARING FIXED-TIME COORDINATED TIMING WITH NON-COORDINATED ACTUATED TIMING
Alemany and Ocean, San Francisco, 1951–1952
3:30–4:30 p.m.

Controller and Timing Plan	Street	Volume in Veh/Hr	Percent Stopped	Delay in Seconds per Total Veh.
1. *Fixed-time*, coordinated for S.B. on Alemany 65 Sec. cycle with 37 sec. gr. on Alemany; 1/17/52	Alemany, S.B.	757	10.2	0.8
	Ocean, E.B.	293	63.5	12.7
	Both legs	1050	25.0	4.2
2. *Semi-actuated* See Table 11; 4/26/51	Alemany, S.B.	689	29.0	3.3
	Ocean, E.B.	308	76.5	22.4
	Both legs	997	43.5	9.2
3. *Semi-actuated* See Table 11, 8/22/51	Alemany, S.B.	745	31.1	3.8
	Ocean, E.B.	269	87.7	27.8
	Both legs	1014	46.2	10.2
4. *Full actuated (804)* See Table 11; 9/12/51	Alemany, S.B.	783	26.3	2.6
	Ocean, E.B.	278	73.0	12.6
	Both legs	1061	38.5	5.3
5. *Volume density (1022)* Timing plan C; 5/16/51	Alemany, S.B.	764	33.0	4.2
	Ocean, E.B.	309	69.3	12.3
	Both legs	1073	43.4	6.5
6. *Volume density (1022)* Timing plan D; 6/20/51	Alemany, S.B.	749	27.8	2.6
	Ocean, E.B.	276	66.3	11.2
	Both legs	1025	38.1	4.9
7. *Volume density (1022)* Timing plan E; 10/10/51	Alemany, S.B.	703	27.9	2.9
	Ocean, E.B.	279	68.8	14.8
	Both legs	982	39.5	6.3

TABLE 13
STOPPED-TIME DELAY IN OFF-PEAK HOURS, COMPARING FIXED-TIME COORDINATED TIMING WITH NON-COORDINATED ACTUATED CONTROLLERS
Alemany and Ocean, San Francisco, 1951–1952
9:45 a.m.–3:00 p.m.

Controller and Timing Plan	Street	Volume in Veh/Hr	Percent Stopped	Delay in Seconds per Total Veh.
1. *Fixed-time*, coordinated for progressive movement on Alemany. 65 Sec. cycle with 37 sec. green on Alemany 15 15-min. periods, 1/16/52	Alemany, S.B.	391	14.8	1.1
	Ocean, E.B.	211	63.5	12.8
	Both legs	602	31.8	5.2
2. *Semi-actuated* Phase A: 50 sec. min.; Phase B: 10 + 5, max. 25; 14 15-min. periods, 8/22/51	Alemany, S.B.	523	24.9	2.9
	Ocean, E.B.	209	83.3	25.2
	Both legs	732	41.5	9.1
3. *Full actuated (804)* Phase A: 13 + 5, max. 70; Phase B: 10 + 5, max. 45; 15 15-min. periods, 7/11/51	Alemany, S.B.	492	31.5	3.3
	Ocean, E.B.	183	58.5	8.3
	Both legs	675	38.8	4.6
4. *Volume density (1022)* Timing plan D; 20 15-min. periods, 6/20/51	Alemany, S.B.	498	27.9	2.6
	Ocean, E.B.	215	66.5	8.9
	Both legs	713	39.6	4.5

on Alemany Boulevard which were less than half of those resulting from the other types of signal control, for both peak-hour and off-peak traffic conditions. The volume-density method of providing coordinated control apparently was not nearly as effective in reducing delay as was the fixed-time progressive timing for the conditions existing at the intersections along Alemany Boulevard.

A summary of the stopped-time delay occurring at all four legs of the intersection at Ocean Avenue is shown in Table 14 for both coordinated fixed-time and volume density control. It is readily apparent that the delay

TABLE 14
STOPPED-TIME DELAY FOR FOUR LEGS ON AN INTERSECTION, COMPARING TWO TYPES OF TWO-PHASE SIGNAL TIMING
Alemany and Ocean, San Francisco, 1951–1952

Controller and Timing Plan	Street	Volume in Veh/Hr	Percent Stopped	Delay in Seconds per Total Veh.
Peak hour: 4:30–5:30 p.m.				
1. *Fixed-time*, coordinated for progressive movement on Alemany 1/17/52	Alemany, S.B.	2164	8.0	1.1
	Alemany, N.B.	567	23.8	1.6
	Ocean, E.B.	370	67.3	14.8
	Ocean, W.B.	312	67.9	15.3
	Four legs	3413	22.5	4.0
2. *Volume density*, not coordinated with other signals 10/10/51	Alemany, S.B.	1670	27.9	3.6
	Alemany, N.B.	671	26.4	2.8
	Ocean, E.B.	342	66.7	17.4
	Ocean, W.B.	307	71.0	18.5
	Four legs	2990	36.4	6.5
Intermediate volumes: 3:00–4:30 p.m.				
3. *Fixed-time*, coordinated for progressive movement on Alemany 1/17/52	Alemany, S.B.	684	10.7	0.9
	Alemany, N.B.	567	26.3	1.6
	Ocean, E.B.	297	62.3	13.1
	Ocean, W.B.	179	67.0	14.9
	Four legs	1727	30.5	4.7
4. *Volume density*, not coordinated with other signals 10/10/51	Alemany, S.B.	633	30.0	3.3
	Alemany, N.B.	599	30.1	3.2
	Ocean, E.B.	287	69.7	14.2
	Ocean, W.B.	203	64.5	11.6
	Four legs	1722	40.8	6.0

to traffic on Alemany Boulevard was lower for both directions of movement under the fixed-time, progressive-timing system than when using volume-density traffic-actuated controllers.

Effect of Timing: Although time did not permit measuring delay for all possible dial settings, the results in Tables 10 to 14 have been summarized separately for each setting of the timing dials so as to permit some comparison of the effect of timing plans. For example, the timing of the semi-actuated controller at Alemany and Santa Rosa on March 28, 1951 (Timing Plan 3 of Table 10) differed from that used on March 21, 1951 (Timing Plan 2 of Table 10) by providing a longer Phase-A green, and a lower minimum initial interval for the side street. As would be expected, the delay to vehicles on Alemany Boulevard decreased, while delay to side-street traffic increased. Total stopped-time delay for the two legs combined decreased also.

Considerable time was spent in attempting to adjust the timing of the volume density controllers so as to provide more efficient control. At Ocean Avenue, Timing Plan D (See Tables 11 and 12) appeared to be the most effective of the three volume-density timing plans in minimizing delay. It is possible, of course, that other timing plans might have reduced delay still further, or that delay might have been lower with detectors located at a different distance from the intersection.

Portola and Vicente Study

Studies of stopped-time delay were also made at the intersection of Portola and Vicente in San Francisco in 1954. In this study, the "necessary" delay to vehicles on Portola Drive was recorded separately from "unnecessary" delay. Two fixed-time and two semi-actuated timing plans were investigated, as shown in Table 15.

The results for off-peak traffic-volume conditions indicate that there was no appreciable difference in average stopped-time delay for semi-actuated as compared with fixed-time signals for the timing plans used at this location. However, the percent of the delay which could be classed as "unnecessary" was cut

TABLE 15
STOPPED-TIME DELAY IN OFF-PEAK HOURS FOR FOUR SIGNAL TIMING PLANS
Portola and Vicente Avenue, San Francisco, 1954

Controller and Timing Plan	Street	Volume in Veh/Hr	Percent Stopped	Stopped-Time Delay	
				Total-sec. per veh.	Percent "unnecessary"
1. *Fixed-time, 40 sec. cycle* 21 sec. gr. on Portola; 13 sec. gr. on Vicente; 8 15-min. periods, 7/28/54	Portola, E.B.	428	43.9	3.7	18.5
	Vicente, S.B.	112	60.7	8.2	—
	Both legs	540	47.4	4.7	—
2. *Fixed-time, 55 sec. cycle* 34 sec. gr. on Portola; 15 sec. gr. on Vicente; 6 15-min. periods, 7/28/54	Portola, E.B.	519	29.5	3.0	22.1
	Vicente, S.B.	103	76.4	14.9	—
	Both legs	622	37.3	5.0	—
3. *Semi-actuated* 30 sec. min. on Portola; 10 sec. min. on Vicente and ped. timer; 18 15-min. periods, 7/29/54	Portola, E.B.	468	27.4	2.3	11.3
	Vicente, S.B.	114	71.9	15.6	—
	Both legs	582	36.1	4.9	—
4a. *Semi-actuated* 28 sec. min. on Portola; 12 sec. min. on Vicente and ped. timer; 8 15-min. periods, 9/2/54	Portola, E.B.	456	30.3	2.8	8.7
	Vicente, S.B.	149	65.1	13.8	—
	Both legs	605	38.8	5.5	—
4b. *Semi-actuated* Same timing as plan 4a, above; 8 15-min. periods, 9/15/54	Portola, E.B.	559	31.3	2.9	10.6
	Vicente, S.B.	138	70.3	12.8	—
	Both legs	697	39.0	4.9	—

almost in half when using semi-actuated signal timing. The percent of green time which was classed as "unnecessary" was cut to less than half, as shown in Table 16.

TABLE 16
PERCENT OF SIDE-STREET GREEN CLASSED AS UNNECESSARY
Portola and Vicente, San Francisco, 1954

Controller and Timing	Vicente Green as Percent of Cycle	Percent of Vicente Green, Unnecessary
1. *Fixed-time* (*off-peak*)		
40 sec. cycle	33.5	21.1
55 sec. cycle	27.0	19.9
2. *Semi-actuated* (*off-peak*)		
10 sec. min. on Vicente	21.7	9.7
12 sec. min. on Vicente	25.1	6.2
3. *Semi-actuated* (*peak*)		
12 sec. min. on Vicente	28.2	1.7

STUDIES AT A LOW-VOLUME INTERSECTION

Stopped-time delays were obtained at the intersection of 47th and Cutting in Richmond, California, during the summer of 1954. Table 17 shows a comparison of results for both off-peak and intermediate traffic volumes, for both fixed-time and semi-actuated controllers. Traffic volumes in the off-peak hour are below those normally warranting a fixed-time traffic signal.

Delay was found to be somewhat lower when using the semi-actuated controller, with substantial reductions in "unnecessary" delay in the off-peak hours, as compared with the fixed-time control.

EFFECT ON DELAY OF DEGREE OF SATURATION

The Road Research Laboratory in England has utilized simulators and electronic computors in studying the relation between stopped-time delay and the degree of saturation of the entering volume, for the case of the fixed-time signal (*6*). This laboratory has developed a semi-empirical equation (*7*) for relating delay to the degree of saturation, as follows:

$$d = \frac{.45C(1-g)^2}{1-gx} + \frac{1620x^2}{q(1-x)}$$

where d = Average delay in seconds per vehicle in the approach to the intersection.

C = Cycle length in seconds.

g = The proportion of the cycle which is effectively green for the particular phase.

q = Volume in vehicles per hour, arriving at random.

s = Volume at saturation in vehicles per hour.

x = Degree of saturation, or ratio of actual volume to the maximum volume which can be passed through the intersection, given by $x = q/gs$.

TABLE 17
STOPPED-TIME DELAY AT A LOW VOLUME INTERSECTION
SEMI-ACTUATED VS FIXED-TIME CONTROL
47th and Cutting Blvd., Richmond, California

Controller and Timing Plan	Street	Volume in Veh/Hr	Percent Stopped	Stopped-Time Delay	
				Total sec. per veh.	Percent "unnecessary"
Off-peak hours					
1. *Fixed-time*, not coordinated 50 sec. cycle with 25 sec. gr. on Cutting; 14 15-min. periods, 8/12/54	Cutting, E.B.	161	32.3	3.0	64.1
	47th, N.B.	44	54.5	7.7	35.2
	Both legs	205	37.1	4.0	52.2
2. *Semi-actuated* (*505*) Phase A: 22 sec. min.; Phase B: 9 + 4, 20 sec. max.; no ped. timer; detector 70′ from curb; 5 15-min. periods, 8/17/54	Cutting, E.B.	181	27.6	2.1	35.6
	47th, N.B.	47	72.3	9.0	21.0
	Both legs	228	36.8	3.5	27.9
3. *Semi-actuated* (*505*) Same timing; detector 80′ from curb; 13 15-min. periods, 8/18/54	Cutting, E.B.	143	21.7	1.7	42.9
	47th, N.B.	38	57.9	5.8	26.1
	Both legs	181	29.3	2.5	34.7
Higher-volume hour: 4:00–5:00 p.m.					
4. *Fixed-time*, not coordinated 50 sec. cycle with 25 sec. on Cutting; 8/12/54	Cutting, E.B.	342	27.8	2.8	41.9
	47th, N.B.	152	56.6	6.7	14.2
	Both legs	494	36.6	4.0	27.7
5. *Semi-actuated* (*505*) See Plan 2, above; 8/17/54	Cutting, E.B.	364	28.6	2.3	25.9
	47th, N.B.	146	74.7	10.8	15.6
	Both legs	510	41.8	4.7	19.2
6. *Semi-actuated* (*505*) See Plan 3, above; 8/18/54	Cutting, E.B.	303	40.6	3.3	21.3
	47th, N.B.	162	57.4	7.3	16.2
	Both legs	465	46.5	4.7	18.6

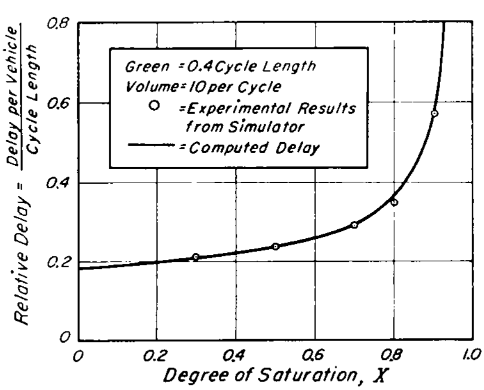


Figure 8. Typical fixed-time delay curve of Road Research Laboratory. (1)

In Figure 8 there is a typical delay curve for one approach to a fixed-time signal, showing the relation between travel-time delay per vehicle (as a percent of cycle length), and the degree of saturation. The points on the curve represent results obtained by utilizing the simulator. The curve itself was derived from the above equation. Note that, as the degree of saturation approaches 1.0 (or 100 percent), the delay increases rapidly.

The traffic volume at which the delay increases sharply depends primarily on the capacity of the approach, expressed in terms of the product of the saturation flow and the effective green. The formula assumes that saturation flow remains constant, whereas actually the saturation flow may vary according to the time of day or changes in traffic conditions. Considerable variations in delay would thus be expected when traffic volumes approach the capacity of an intersection approach.

The above formula has been used to compute the delay at several intersections in the San Francisco area to determine whether computed results are similar to results obtained in field studies. The computed values for off-peak hours generally checked the observed values within 25 percent; the differences for the peak-hour condition sometimes exceeded 25 percent. The observed values are lower than computed values for the case of progressive timing of signals.

The comparison of actual vs. computed de-

TABLE 18
COMPARISON OF COMPUTED VS OBSERVED DELAYS USING ROAD RESEARCH LABORATORY FORMULA (6)
Portola, Woodside, and O'Shaughnessy, San Francisco

Intersection Approach	Volume in VPH		Effective green	Degree of Saturation	Delay in Sec. Per Veh.	
	Actual flow	Saturation flow			Computed	Observed
Off-peak—2:15–3:15 p.m., 8/26/53. 55 sec. cycle						
			percent	*percent*		
Portola, W.B.	611	4700	38	34	11.3	9.3
Woodside	304	3000	29	35	14.7	15.4
O'Shaughnessy	139	3400	21	19	16.6	19.4
			88			
Peak—4:45–5:15 p.m., 8/26/53. 80 sec. cycle						
Portola, W.B.	1670	4700	51	70	14.9	17.8
Woodside	440	3000	22	67	30.9	29.9
O'Shaughnessy	580	3400	21	81	36.7	52.3
			94			
Peak—4:45–5:15 p.m., 9/15/53. 100 sec. cycle						
Portola, W.B.	1982	4700	57	74	16.0	12.7
Woodside	424	3000	22	64	36.3	29.0
O'Shaughnessy	684	3400	18	112	Infinite	223.5
			97			

lay values for one intersection is shown in Table 18. These results for O'Shaughnessy Avenue serve to demonstrate the effect of slight changes in volume and proportion of green on delay for peak-hour conditions. The volume during the peak hour on one day (September 15, 1953) was 20 percent greater than on August 26, 1953, and the effective green decreased from 21 percent of the cycle length to 18 percent. These slight changes increased the degree of saturation from 81 percent to over 100 percent, and delay increased drastically, for both computed and observed values, as shown in the table.

These results demonstrate the critical problem of setting the timing of three-phase, fixed-time signals for near-capacity conditions, and the disastrous effect of variations in arrival rates. It is difficult to time such signals for efficient operation at near-capacity conditions, if there are fluctuations in the proportion of traffic arriving on the intersecting legs during different portions of the peak hours. Such fluctuations can be taken into account automatically by vehicle-actuated signals, since the proportion of effective green allocated to each phase can change in accordance with the change in approach volumes.

CONCLUSIONS AND RECOMMENDATIONS

1. Field measurements of stopped-time delay can be used as a basis for comparing vehicular delay under different types of control at signalized intersections. However, due to the many variables (signal timing, day-to-day fluctuations in traffic, parking, capacity, time of year, etc.), it is difficult to isolate the effects of small changes in timing, without extensive field investigations.
2. Delay meters which accumulate vehicle-seconds of stopped time can give reliable results under conditions in which the number of vehicles accumulated at any time can be estimated with reasonable accuracy by the operator. The sampling method of determining stopped-time delay is simpler than the delay-meter technique and gives equally reliable results under the conditions tested. The time interval between observations must be selected to avoid repetitive sampling in the same parts of the signal cycle.
3. Vehicle-actuated traffic signals are better able to accept short-term fluctuations in traffic volume than fixed-time signals.

The percent of delay which can be classed as "unnecessary" was cut substantially when using actuated signals at locations where signal coordination is not a factor.

4. The following conclusions apply at three-phase signalized locations where interconnection with nearby signals is not a factor.
   a. At intersections with actuated control and some pedestrian movements, the use of pedestrian timers can substantially reduce vehicular delay, especially at off-peak hours.
   b. The use of an overlap sequence in the timing of three-phase signals with heavy left-turn movements from only one direction can materially reduce delay under both off-peak and peak-hour conditions, provided the volume of vehicular traffic from the opposing left-turn movement is sufficiently light to permit one through- and one left-turn movement to overlap a substantial portion of the time.
5. When signalized intersections are spaced so that the signals can be timed for progressive movement, the use of fixed-time coordinated timing can cut delay substantially, as compared with fixed-time or traffic-actuated signals with no coordination in the timing.
6. More study should be given to such problems as:
   a. The use of traffic simulators and computors for studying in the laboratory the effects of small differences in timing of signals and placement of detectors.
   b. The relative delay under different types of coordinated traffic signal systems.

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