Capacities of One-Way and Two-Way Streets with Signals and with Stop Signs

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● BOTH stop signs and signals are used extensively to control traffic at intersections. Generally, stop-sign control is used only on the less important of the two intersecting streets, but in some instances four-way stop-sign control is used. The relative merits of each of the various types of control devices has long been a topic of discussion and

TABLE 1

TRAFFIC VOLUMES AND DELAY PER VEHICLE WITH STOP-SIGN CONTROL ON ALL APPROACHES
While Volume on 13th Street was at a Peak

Location	1-Hour period						10-Minute period					
	For 13th Street		For cross streets		Total for intersection		For 13th Street		For cross streets		Total for intersection	
	Traffic volume	Avg. delay	Traffic volume	Avg delay	Traffic volume	Avg. delay	Traffic volume	Avg. delay	Traffic volume	Avg delay	Traffic volume	Avg. delay
	Vph	Min	Vph	Min.	Vph	Min	Vph	Min.	Vph	Min	Vph	Min.
13th Street two-way (parking one side)												
At Park Road	1,231	0 44	512	0 54	1,743	0.47	1,476	0.31	642	0 39	2,118	0 33
At Columbia Road	1,400	0 41	567	0.27	1,967	0 37	1,602	0 49	480	0.28	2,082	0 44
At Harvard Street	1,389	0.49	492	0 47	1,881	0 48	1,542	0.47	594	0 42	2,136	0.46
13th Street one way (parking prohibited)												
At Park Road	1,502	0 23	691	0 80	2,193	0.41	1,794	0 25	810	1 05	2,604	0 50
At Columbia Road	1,615	0.31	668	0 42	2,283	0 34	2,280	0.43	762	0.52	3,042	0 45
At Harvard Street	1,481	0 38	653	0 60	2,134	0 45	1,890	0.26	696	0 86	2,586	0 42
While Volumes on Two-way Cross Street were at a Peak												
13th Street two-way												
Park Road	1,147	0.35	565	0.54	1,712	0.41	1,476	0 31	642	0.39	2,118	0.33
13th Street one-way												
Park Road	1,502	0 23	691	0 80	2,193	0 41	1,794	0 25	810	1 05	2,604	0.50
While Volumes on One-way Cross Streets were at a Peak												
13th Street two-way												
Columbia Road Westbound	1,400	0 41	567	0.27	1,967	0.37	1,314	0 36	684	0.37	1,998	0 36
Harvard St Eastbound	1,387	0 53	495	0.49	1,882	0.52	1,530	0 41	600	0.36	2,130	0.40
13th Street one-way												
Columbia Road Westbound	1,615	0 31	668	0.42	2,283	0.34	1,968	0.45	822	0.70	2,790	0.52
Harvard St Eastbound	1,481	0.38	653	0.60	2,134	0.45	1,818	0.25	858	0.45	2,676	0.31

it is therefore desirable that factual information be obtained for use as a guide in determining the conditions under which traffic signals, two-way stop signs, and four-way stop signs provide the most efficient operation.

[1] The data were collected in the field by 19 Junior Highway Engineers. A preliminary report was prepared by four of these engineers, Robert D. Bee, Walter W. Bryant, Dwight A. Hodgens, Jr., and Joseph Rekas, as part of the Bureau of Public Roads Training Program. This report is based chiefly on further analysis of the data. The District of Columbia Department of Vehicles and Traffic supplied the signs and adjusted signal timing as directed by John H. Mitton, Assistant Director and Traffic Engineer. The Metropolitan Police provided officers for emergency control as directed by Deputy Chief of Police John J. Agnew.

This report covers a study of traffic at four intersections while the traffic signals were in normal operation and also studies at the same locations while two-way stop signs and four-way stop signs were used in place of the traffic signals.

All four intersections are on 13th Street, N.W., in Washington, D.C., a four-lane street which, during the peak period carries more than 3,200 vehicles per hour. It is operated one-way inbound during the morning peak period and one-way outbound during the evening peak period. During off-peak periods, it operates as a two-way street with parking on one side. The 1.8-mile section of 13th Street between Logan Circle and Spring Road with a peak-hour overall speed of about 18 mph is an unusually efficient arterial street, carrying far heavier traffic than most streets of this width are capable of accommodating under usual conditions. The three types of intersection control were observed under heavy traffic loads at intersections with both one-way and two-way streets.

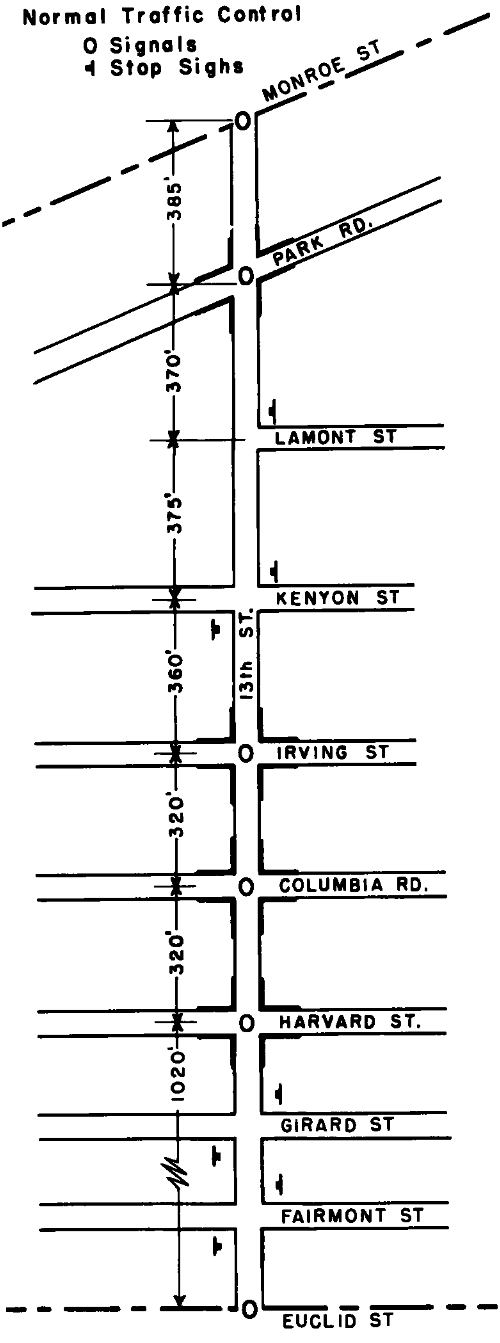

Figure 1. Four intersections studied on Thirteenth Street.

Thirteenth Street is a through north-south street carrying much heavier traffic volumes than the cross streets. The cross streets at which studies were made are: Irving Street and Park Road, which carry two-way traffic; Harvard Street, which is one-way eastbound; and Columbia Road, which is one-way westbound. The general layout is shown in Figure 1. Details of each intersection are shown in Figure 2, while Figures 3 and 4 are photographs of 13th Street when operating two-way and one-way respectively.

All four intersections are normally controlled by an interconnected system of coordinated fixed-time traffic signals. There is a single dial in the time controller at each intersection. Consequently, the 80-second signal cycle and the stop and go intervals for 13th Street and the cross streets remain constant throughout the day. The signals are interconnected with a master controller, however, so that the time offsets between successive signals on 13th Street can be changed. This provides for progressive traffic movement favoring the desired direction of travel at different times of the day.

Three different signal progressions are used. The first, which is used during the morning rush period, provides progressive movement for 13th Street traffic while it is one-way inbound. The second, which is used during nonrush periods, provides reasonably good progression in both directions while 13th Street carries two-way traffic. The third, which is used during the afternoon rush, provides excellent progression while 13th Street is operating one-way outbound.

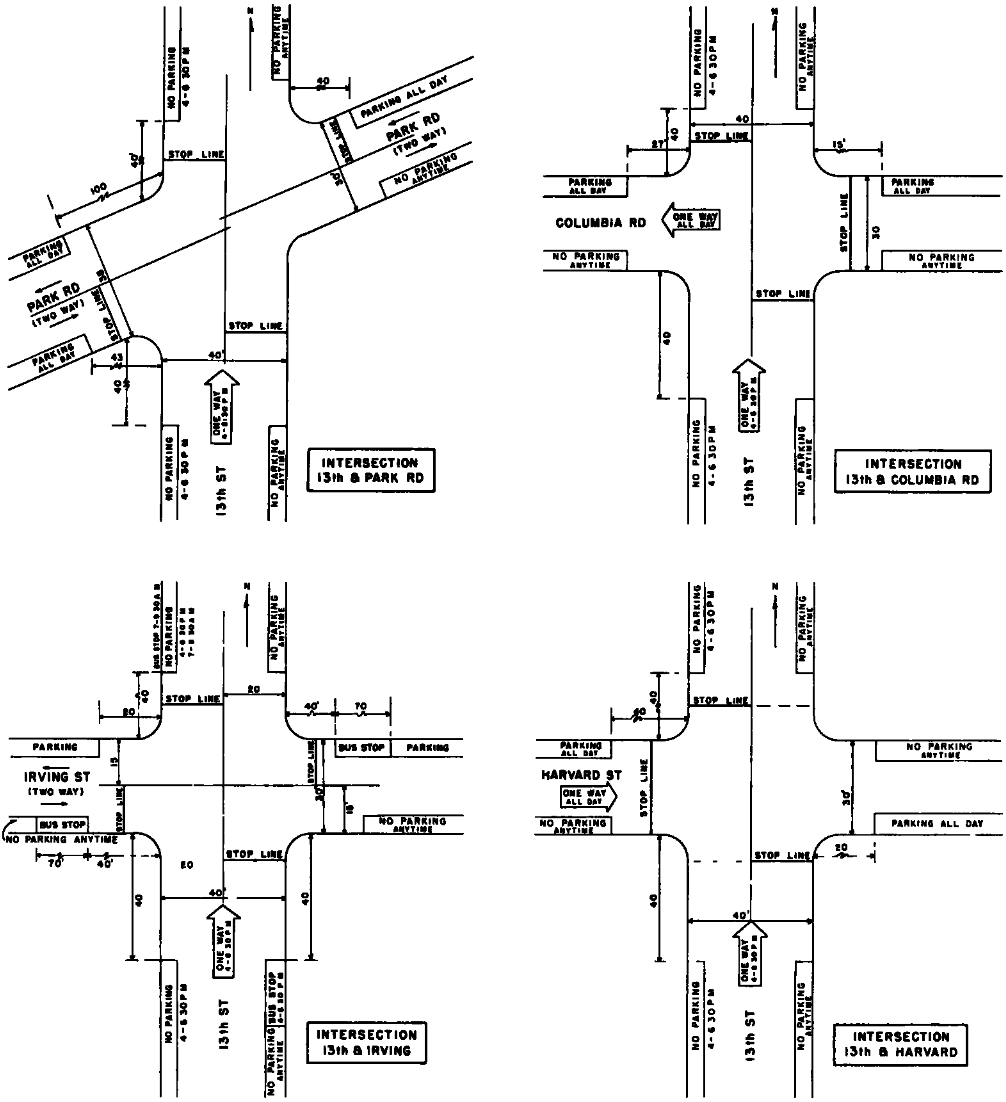

Figure 2. Details of intersections studied.

Accident data for 13th Street are summarized and compared with those for other arterial streets and a nearby freeway in Table 2. The accident rate is 13 percent higher than the average based on a nationwide study of representative arterial city streets. This higher accident rate may be due in part to the very complete reporting of accident data in the District of Columbia. It is not believed to indicate a significantly higher accident potential. It is much higher, however, than the accident rate for the Shirley Freeway, a facility with full control of access which carries comparable traffic volumes.

The principal field studies were conducted on three weekday afternoons in March 1954. Operation with signal control was observed the first day. The green time on the cross streets was reduced in an attempt to provide a continual backlog of vehicles on cross streets so that their possible capacities could be determined. On another day, stop signs were used to control traffic on the cross streets. On a third day, stop-sign control was used on all approaches to the intersections. Additional field studies were conducted in November to measure the delay to traffic with the normal signal timing and to determine the capacity of 13th Street with two-way traffic controlled by signals.

TABLE 2

ACCIDENTS PER HUNDRED MILLION VEHICLE-MILES ON THIRTEENTH STREET COMPARED WITH OTHER FACILITIES

	13th Street[a]	Arterial streets[b]	Shirley Freeway[c]
All reported accidents	1,091	966	192
Fatalities	2	3	3

[a]Logan Circle to Spring Road 1.8 miles, January 1, 1952, through June 30, 1954.
[b]Preliminary figure for urban streets with no access control based on cooperative study by the Bureau of Public Roads and State Highway Departments.
[c]Ridge Road to Shirlington Circle 1.6 miles, Arlington County, Virginia, January 1, 1950, through June 30, 1954.

Manual counts of all through and turning movements, classified by type of vehicle, were made at all entrances to the intersections. These were recorded for every cycle when signals were in operation, and every 2 minutes when signals were off and traffic was being controlled by stop signs. Fully utilized "go" periods (loaded cycles) were noted while observing traffic controlled by signals. To provide data from which vehicular delay might be computed, counts were made of standing vehicles on each intersection approach at regularly spaced intervals. Thirty-second intervals were used when signals were in operation and two-minute intervals were used when stop-sign control was employed.

Field data have been summarized by 10-minute periods. Rates per hour of green signal time have been calculated so that the rates are comparable regardless of signal timing. The rate per hour of green is calculated by dividing the hourly volume as normally determined by the percentage that the green period, not including any amber time, is of the total cycle.

To calculate total delay, the number of stopped vehicles as determined by the periodic count was multiplied by the time interval between counts. This value was then divided by the number of vehicles entering the intersection to determine the delay per vehicle.

SIGNAL CONTROL

Despite the high traffic volumes observed at the four intersections while they were controlled by signals, the traffic demand on some of the approaches was insufficient to utilize fully the green interval during any of the signal cycles. On several of the approaches the green interval was fully utilized during a few cycles only. The green or "go" interval was considered fully utilized when the traffic demand at the observed approach was equal to the possible capacity of that intersection approach with vehicles continuously entering the intersection throughout the green interval. Cycles during which these conditions occurred are called "loaded cycles." A loaded cycle for an intersection approach is independent of the traffic on the other approaches which may or may not be loaded during the same period.

In Table 3 the first four columns show the traffic on 13th Street, the percentage of dual-tired vehicles, and the percentage of right and left turns during the 1-hour period of maximum traffic. The next column shows the number of seconds of green signal time per cycle. The traffic volume per hour of green signal time follows. The highest hourly rate observed during 10 consecutive minutes is shown next, followed by the rate per hour of green time for loaded cycles. All these data were compared for similar intersection approaches, and the possible capacity was determined for each approach. This is tabulated in the last column of the table. Table 4 is similar to Table 3 and lists the data for the cross streets.

The estimated possible capacities shown in the last columns of Tables 3 and 4 were determined on the basis of the 1-hour, 10-minute, and loaded-cycle volumes. Data for similar intersection approaches were considered collectively in arriving at these capacities. The values represent the possible capacities over a 1-hour period even though volumes for shorter time periods were used in their determination. A detailed description of the method of determining these values is necessary for an appreciation of their reliability.

Figure 3. Looking south on Thirteenth Street during off-peak period - near Irving Street with two-way traffic on Thirteenth Street.

TABLE 3

OBSERVED TRAFFIC AND POSSIBLE CAPACITY OF 13th STREET[a] AT FOUR SIGNAL-CONTROLLED INTERSECTIONS

Intersection entrance	Conditions during continuous 1-hour period of maximum traffic					Maximum observed traffic vols. per hour of green or "Go" time			Estimated possible capacity per hour of green
	Volume	Dual tired	Left turns	Right turns	Green time for 80-sec. cycle	During a 1-hour period	During a 10-min. period	During loaded cycles[b]	
	Vph	Per-cent	Per-cent	Per-cent	Seconds	Vehicles	Vehicles	Vehicles	Vehicles
13th Street Carrying Two-way Traffic									
Southbound (parking permitted)									
At Park Rd. (two-way)	482	3.5	0.4	7.0	38	1,015	2,080	1,530(1-1)	1,600
At Irving St. (two-way)	524	2.9	1.9	1.3	-[c]	1,435	1,720	1,605(25-39)	1,600
At Columbia Rd. (one-way WB)	557	3.4	-	6.8	45	990	1,181	None	1,600
At Harvard St. (one-way EB)	555	4.3	5.4	-	29	1,531	1,707	1,610(55-78)	1,600
Northbound (parking prohibited)									
At Park Rd. (two-way)	836	2.7	4.1	6.6	40	1,672	2,124	2,460(3-3)	2,600
At Irving St. (two-way)	748	2.9	4.3	1.3	-[c]	2,100	2,916	2,635(10-25)	3,000
At Columbia Rd. (one-way WB)	671	3.3	6.8	-	45	1,193	1,611	None	3,000
At Harvard St. (one-way EB)	849	2.8	-	4.1	29	2,342	3,321	3,576(5-20)	3,300
13th Street Carrying One-way Traffic									
Northbound (parking prohibited)									
At Park Rd. (two-way)	2,747	0.9	6.4	10.3	40	5,494	7,140	6,857(8-16)	7,000
At Irving St. (two-way)	3,128	1.0	1.8	0.5	52	4,811	5,623	None	7,000
At Columbia Rd. (one-way WB)	3,168	1.0	3.6	-	45	5,633	6,614	None	7,000
At Harvard St. (one-way EB)	2,987	0.8	-	4.7	50	4,779	5,309	5,637(4-16)	7,000

[a]13th Street is 40 ft. wide. Parking is permitted only on the west side used by southbound traffic while 13th Street is operating two-way. All parking is prohibited on 13th Street while one-way.
[b]The number of loaded cycles observed is shown by the first of the two figures in parentheses while the second figure is the total number of consecutive cycles in the period during which the loaded cycles were observed.
[c]24 32-second green periods, 11 28-second green periods, and 10 24-second green periods.

Figure 4. Looking south on Thirteenth Street during evening peak period - near Park Road with one-way traffic on Thirteenth Street.

TABLE 4

OBSERVED TRAFFIC AND POSSIBLE CAPACITY OF FOUR SIGNAL-CONTROLLED STREETS CROSSING 13th STREET[a]

Cross Streets Carrying Two-way Traffic

Intersection entrance	Conditions during continuous 1-hour period of maximum traffic					Maximum observed traffic vols. per hour of green or "Go" time			Estimated possible capacity per hour of green
	Volume	Dual tired	Left turns	Right turns	Green time for 80-sec. cycle	During a 1-hour period	During a 10-min. period	During loaded cycles[b]	
	Vph	Per-cent	Per-cent	Per-cent	Seconds	Vehicles	Vehicles	Vehicles	Vehicles
13th Street two-way									
Park Rd. EB	273	8.0	2.9	9.9	18	1,213	1,502	1,333(24-40)	1,400
Park Rd. WB	294	3.4	25.8	1.7	18	1,307	1,551	1,400(30-45)	1,400
Irving St. EB	203	13.8	13.8	18.7	18	902	1,200	1,120(10-44)	1,200
Irving St. WB	115	15.6	6.1	7.8	18	511	649	800(1-1)	1,200
13th Street one-way									
Park Rd. EB	366	2.7	13.1	-	18	1,627	1,849	1,542(43-52)	1,600
Park Rd. WB	304	3.0	-	4.9	24	1,013	1,249	1,433(6-52)	1,400
Irving St. EB	245	9.8	19.6	-	18	1,089	1,450	1,055(40-92)	1,400
Irving St. WB	179	7.3	-	16.8	18	795	1,000	850(8-39)	1,400
	Cross Streets Carrying One-way Traffic								
13th Street two-way									
Columbia Rd. WB	465	3.9	7.3	9.0	15	2,480	2,917	2,824(13-28)	3,000
Harvard St. EB	447	5.6	20.4	5.1	15	2,384	2,821	3,120(5-7)	3,000
13th Street one-way									
Columbia Rd. WB	668	1.0	-	12.6	-[c]	3,185	3,960	3,553(41-95)	3,600
Harvard St. EB	708	1.8	33.5	-	17	3,332	3,936	3,600(60-89)	3,600

[a]All cross streets are 30 feet wide with parking permitted on one side except that the west leg at Park Road is 38 feet wide with parking permitted on both sides.

[b]The number of loaded cycles observed is shown by the first of the two figures in parentheses while the second figure is the total number of consecutive cycles in the period during which the loaded cycles were observed.

[c]37 15-second green periods and 8 25-second green periods.

First, the 1-hour volume was compared with the maximum 10-minute volume and the volume during loaded cycles at the particular approach. The relation between these values, as well as the frequency of loaded cycles, formed a basis for tentatively estimating possible capacity. For instance, if the 1-hour volume and loaded-cycle volume were well below the maximum 10-minute volume, it was evident that the first two were well below capacity. The presence of only a few loaded cycles during a large number of consecutive cycles would confirm this. In such a case it is possible that even the maximum 10-minute volume was below possible capacity. On the other hand, if the three volumes were about equal and a large and fairly concentrated number of loaded cycles were observed, this was an indication that possible capacity was reached. In such instances a volume somewhat below the maximum 10-minute volume, but not less than the loaded-cycle volume, might have been tentatively selected as the possible capacity.

After the tentative values for all similar intersection approaches were selected by this process, they were compared with each other for consistency and reasonableness. In this comparison differences in turning movements, frequency of commercial vehicles, bus stops, and other factors known to affect traffic operation were considered. If the tentative possible-capacity estimate for any approach appeared inconsistent, a reappraisal was made. In the case of similar approaches where the tentative estimates were close, a single value was selected for the possible capacity of all. If only one of several otherwise similar approaches was observed at or near possible capacity conditions, the value determined for this approach was assigned to the others.

Unusually high values were determined for the possible capacity of 13th Street when it was operating one-way northbound. The highest volumes per hour of green were observed at Park Road where the green time was least. Even here, with only one-half the total cycle green to 13th Street, only eight loaded cycles occurred. With a volume during these cycles of 6,857 vehicles per hour of green and a maximum 10-minute volume of 7,140 vehicles per hour of green, the indicated 7,000 vehicles per hour of green is evidently the approximate possible capacity. Since the turning movements were less at the other approaches, it must be inferred that possible capacities at these approaches are at least equal to the 7, 000 vehicles per hour of green determined at Park Road. In the absence of factual data indicating higher capacity, this value was accepted for all four locations, rather than some higher value.

The results of an analysis of the data in Tables 3 and 4 indicate that within the range of values observed, the percentage of commercial vehicles and the percentage of left and right turning traffic at the intersections had little apparent effect on capacities of the approaches. An exception is the case of Irving Street which carried about twice as high a percentage of dual-tired vehicles as the other cross streets. It had a capacity somewhat lower than the other cross streets.

The rates of traffic flow based on the 10-minute periods of maximum volume were frequently greater than the rates based on the loaded cycles. These 10-minute periods included many cycles that were not fully loaded. It is evident, therefore, that greater volumes are sometimes carried during unloaded cycles than during loaded cycles. A cycle was considered to be loaded at an intersection approach if vehicles were traveling through the intersection during the entire green signal period and the stream was interrupted by the red signal. Frequently, when all drivers were alert, accelerated quickly, and allowed a minimum headway, all vehicles waiting at the intersection and those arriving during the green interval were able to clear the intersection before the green time expired. A cycle of this type would not be classed as a loaded cycle. At other times one or two slow drivers or some other impediment tended to reduce the movement of vehicles through the intersection and, as a result, the cycle was classified as being fully loaded despite the fact that the number of vehicles counted was less than during other cycles which were not so classified.

The possible capacity of 13th Street operating one-way northbound is 7, 000 vehicles per hour of green. This is equivalent to 1, 750 vehicles per hour of green per 10 feet of width or per lane. This extremely high volume is only 2 percent below the maximum 10-minute volume observed on 13th Street at Park Road. At the time there was little delay to traffic, although some vehicles required more than one signal cycle to clear the intersection. Traffic counts obtained by automatic recorders indicate that traffic volumes of 3, 200 vehicles during 1 hour occur frequently. This is equivalent to 6, 400 vehicles per hour of green at Park Road. Thus 13th Street often carries a volume for a 1-hour period which is in excess of the peak volume recorded during this study.

The possible capacity of 3, 600 vehicles per hour of green for each of the one-way streets crossing 13th is also unusually high. This is equivalent to 1, 200 vehicles per hour of green per 10 feet of surface width, curb to curb, with parking on one side. The capacity of each of the two-way streets crossing 13th Street is also unusually high.

These very high capacities certainly exceed those attained on most city streets. At these high capacities the flow of traffic through an intersection is likely to be greatly affected by a slight change in signal timing, especially in the time offset between succeeding signals which is very critical in a progressive system. Minor accidents, stalled vehicles, and severe weather conditions also result in sharp reductions in capacity. Capacity values considerably lower than those found on 13th Street must therefore be used for design when planning one-way street systems and other improvements to city traffic facilities, or it is likely that adequate capacity will not be provided.

By comparing the possible capacities of the approaches, the effect that two-way and one-way operation have on capacity has been determined for both 13th Street and the cross streets. The effect of parking on the capacity of 13th Street while operating as a two-way street was also determined by comparing the capacity in the northbound direction with the capacity in the southbound direction. Southbound vehicles could park on the west side of the street while parking was prohibited on the east side. The effects of these conditions are shown graphically in Figure 5.

Figure 5 shows that under one set of conditions the possible capacity of 13th Street is only 3, 200 vehicles per hour of green signal time, whereas, under another set of conditions, the possible capacity is 7, 000 vehicles per hour of green or 2. 19 times as high as for the first. The improvement in capacity was realized by eliminating parking and changing from two-way to one-way operation on 13th Street. Likewise, the capacity of a cross street in one case is 2, 600 vehicles per hour of green time and in another case 3, 600 vehicles per hour of green. The difference of 1, 000 vehicles per hour or 38 percent is a direct result of changing from two-way to one-way operation on both of the intersecting streets and does not involve a change in the parking condition on the cross street.

One of the most important results of the study, which is illustrated by Figure 5, is that the operating conditions on one street affect not only the capacity of that street but also the capacity of the intersecting street. Under certain conditions, for example, the capacity of 13th Street is higher when the cross street carries one-way traffic than when it carries two-way traffic. The same is true for the capacity of the cross streets in relation to the directional flow on 13th Street.

TABLE 5

INCREASE IN CAPACITIES OF STREETS AT SIGNALIZED INTERSECTIONS BY CHANGING FROM TWO-WAY TO ONE-WAY OPERATION AND BY THE ELIMINATION OF PARKING ON MAJOR STREET[a]

Change in conditions	Increase in possible capacity: On major street	Increase in possible capacity: On minor street
	Percent	Percent
Changing from two-way to one-way operation		
On major street with no parking		
With two-way traffic on minor street	25	12
With one-way traffic on minor street	11	20
On minor street		
With two-way traffic on major street		
Parking both sides of major street	0	15
Parking one side of major street	8	15
No parking on major street	12	15
With one-way traffic on major street		
No parking on major street	0	24
Elimination of parking from major street[b]		
From one side		
At one-way minor streets	48	-
At two-way minor streets	37	-
From both sides		
At one-way minor streets	97	-
At two-way minor streets	75	-

[a]Parking on one side of minor street in all cases
[b]Two-way traffic on major street in all cases

Table 5 shows the effect on intersection capacity of each change that was made on 13th Street and the cross streets with respect to directional operation and parking conditions. In this table 13th Street is referred to as the major street and the cross streets are referred to as minor streets. By using this terminology the results can be more directly compared with the results of studies at other locations and more readily applied to similar situations elsewhere.

It is of particular interest that a change from two-way to one-way operation of traffic on the major street increased the capacity of the minor street as well as the capacity of the major street. The increase for the major street was 25 percent at locations where the minor street was two way and only 11 percent where the minor street was one-way. This same change also increased the capacity of the one-way minor streets 20 percent and the capacity of the two-way minor streets 12 percent. Thus, the minor streets that were benefited most were those at locations where the major street benefited least by a change in its directional operation.

The cross streets with one-way traffic had a greater capacity than those with two-way traffic. The difference was greater (24 percent compared to 15 percent) when the major street was also one-way rather than two-way. This difference in operation did not, however, benefit the capacity of the major street when it carried two-way traffic with parking on both sides or one-way traffic with no parking. One-way operation on the cross streets was of some benefit to the major street when it carried two-way traffic and parking was eliminated from one or both sides.

Eliminating parking on the major street had a far greater effect on its capacity than changing from two-way to one-way operation. Eliminating parking from both sides of the major street nearly doubled its capacity (an increase of 97 percent) at the intersections with one-way minor streets. At intersections with two-way minor streets, the increase was 75 percent. Eliminating parking on one side of the major street had about half the effect of eliminating parking on both sides.

It should also be pointed out that progressive movement, which reduces travel time, is usually more easily attained on a one-way than on a two-way street. This is an additional and very important advantage of one-way operation.

STOP-SIGN CONTROL ON CROSS STREETS

All cross streets were operating at their possible capacities during the rush period on the day that stop signs were used only on the cross streets. Long queues of waiting vehicles developed, and occasionally it was necessary for a police officer to clear the backup on the cross streets. Vehicles on the cross streets were aided somewhat by the signals at intersections on the through street north and south of the study area, which caused gaps

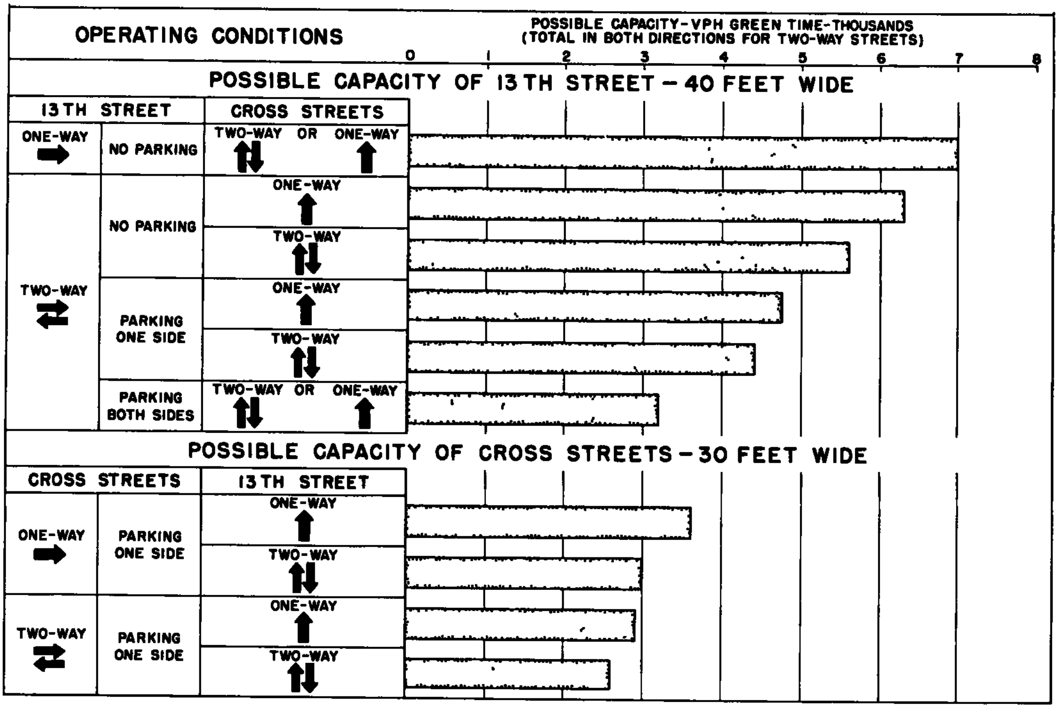

Figure 5. Street capacity with signal control related to directional operation and parking conditions.

in traffic on 13th Street.

Table 6 shows the observed traffic volumes and the delays to traffic on the cross streets at the intersections studied. Volumes and delays are listed for the 1-hour and for the 10-minute periods of heaviest cross-street traffic while 13th Street was one-way and also while 13th Street was two-way.

The same type of information was obtained for all 10-minute periods during the studies, and the average delays to cross-street traffic were compared for various traffic volumes on the cross streets and on 13th Street. As was expected, the delay to cross-street traffic was found to increase with an increase in the total traffic volume on 13th Street as well as with an increase in the total cross-street traffic. A less expected finding was that the delay to cross-street traffic was independent of the directional usage of either 13th Street or the cross street. Consequently, the delay to cross-street traffic when controlled by stop signs can be shown on one graph representing both two-way and one-way operation on both of the intersecting streets. This has been done in Figure 6.

The two lower curves of Figure 6 show the combinations of sustained through-street and stop-street traffic volumes which produced average delays to cross-street traffic of 30 seconds and of 1 minute per vehicle. The total traffic volume on 13th Street is shown on the horizontal axis, and the total traffic volume on the cross street is shown on the vertical axis. For example, a cross flow of about 600 vehicles per hour can be accommodated with an average delay of 1 minute when the total traffic volume on 13th Street is 1,600 vehicles per hour. Combinations of volumes which lasted for only short periods sometimes caused delays much longer or shorter than those indicated by the curves. If the volumes were sustained for 20 or 30 minutes, however, the delays were as indicated by the curves.

The third curve in Figure 6 shows the maximum volumes that the cross streets can accommodate with various volumes on 13th Street. The delay accompanying these volumes was at least 2 minutes and for any given combination of volumes might have been several minutes. Once the traffic volumes on the cross street and on 13th became sufficiently great to cause a delay of 2 minutes, the delay could increase to several minutes within a short period of time with no change in the traffic volumes. This curve therefore also represents the traffic volumes for all delays above 2 minutes. It thus represents the possible capacities of the cross streets when controlled by stop signs and with no control on 13th Street.

Volumes which cause a 30-second delay can be exceeded by as much as 100 percent without increasing the delay to more than 1 minute. Volumes which result in a 1-minute average delay, however, can only be exceeded by about 10 percent without increasing the delay to more than 2 minutes.

The small difference between the volumes shown for the curve representing a 1-minute delay and the curve representing a delay in excess of 2 minutes indicates that at these intersections the critical volumes are those producing a delay of between 1 and 2 minutes per vehicle to cross-street traffic.

The volume combinations indicated by the 30-second delay curve fit the usual definition of practical capacity for the prevailing roadway and traffic conditions since greater delay and restriction to movement would appear unreasonable to most drivers. With the normal setting of the signals, average delays of 30 seconds or more to minor-street traffic were infrequent even at the highest volumes observed. In another study it was found that drivers are unwilling to accept longer delays at stop signs than at signals.[2] It is concluded that the practical capacity of the cross street when controlled by stop signs with no control on the through street is represented by the curve for an average delay of 30 seconds.

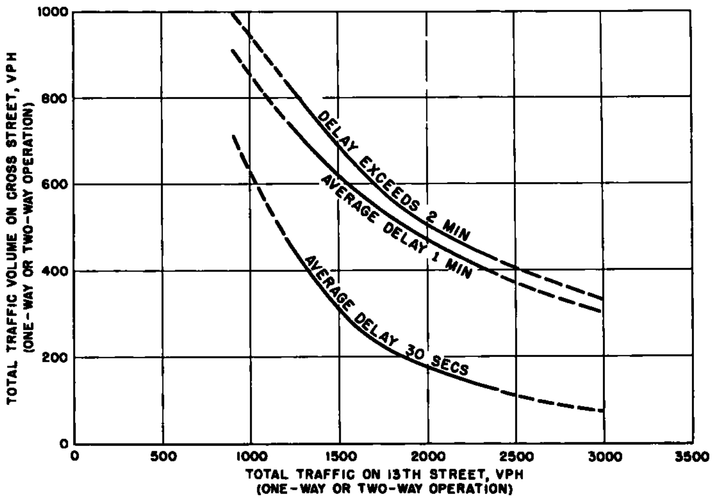

FIGURE 6 - DELAY TO TRAFFIC ON CROSS STREETS WHEN CONTROLLED BY STOP SIGNS (NO CONTROL ON 13TH ST)

Figure 6. Delay to traffic on cross streets when controlled by stop signs (no control on Thirteenth Street).

Figure 7 shows the possible and practical capacities of the cross streets with stop-sign control on these streets and the possible capacities with signal control. The curves for stop-sign control represent both one-way and two-way operation and are based on the delay to cross-street traffic. With stop signs on the cross streets, 13th Street could no doubt carry as much traffic as with signals but not without an unreasonable delay to cross-street traffic.

For the signals, separate curves are shown for one-way and two-way operation, but separate curves are not shown for possible and practical capacities. With the progressive signal control there was no appreciable increase in the delay to traffic as the traffic increased from comparatively low volumes to those at possible capacity. Thus it was not feasible to establish a value for practical capacity with progressive signal control on the basis of delay to traffic. For the purpose of comparing the three different types

[2] "Effects of Reversible Lane Movement, Signalization of Three-Lane Highways," by M. Mansfield Todd. Proceedings HRB 1950.

of control on the basis of a tolerable delay to traffic, the curves for practical capacity with stop-sign control should be compared directly with the possible capacity curves for signal control.

It may be noted that the curves for signal control intersect the x axis and the y axis at values below those given in the last columns of Tables 3 and 4. This is because the amber time in each cycle was not included in the green time when calculating the traffic volumes for the signal-control curves.

From Figure 7 it may be seen that both the possible and the practical capacities of the cross streets are much lower with stop-sign control than with signal control. This is especially true with one-way operation on both streets. Even with volumes as low as 1,000 vehicles per hour on 13th Street and with two-way traffic on both streets, the possible capacity of the cross streets with stop signs is about one-half the capacity with signal control. With one-way traffic and at other volumes on 13th Street, the difference is even greater.

At all traffic volumes there was practically no delay to traffic on the through street when stop signs were used to control traffic on the cross streets. Cross-street traffic, however, experienced some delay even at the lower volumes, and this delay increased rapidly as the volume increased. With signal control both 13th Street traffic and cross-street traffic experienced some delay. This delay at all observed volumes, however, was never greater for the cross streets than the delay with stop signs. The delay with signals was small as a result of the well-coordinated progressive system operating on the cross streets as well as on 13th Street.

While the difference in delay with stop signs and with signals was small at low volumes, it became very large at the higher volumes. For example, when the traffic volume on the through street approached 3,000 vehicles per hour, the delay to traffic on the cross street varied from 1½ to 6 minutes per vehicle with stop signs on the cross street, compared to 20 to 40 seconds per vehicle with signals. At a volume of 1,800 vehicles per hour on the through street and a cross-street volume of about 250 vehicles per hour, the average delay to all traffic on both streets was 10 seconds per vehicle with cross-street traffic controlled by stop signs and also when traffic was controlled by signals. At lower volumes the delays were only slightly less and were about equal

TABLE 6

OBSERVED VOLUMES AND DELAYS FOR TRAFFIC CONTROLLED BY STOP SIGNS AT APPROACHES TO 13th STREET (NO CONTROL ON 13th STREET)

Cross Streets Carrying Two-way Traffic

Cross street	Study time [a]	Average for study			Average during peak 10 minutes		
		Traffic volume			Traffic volume		
		Cross street	13th street	Delay per vehicle on cross street	Cross street	13th street	Delay per vehicle on cross street
Name	Minutes	Vph	Vph	Minutes	Vph	Vph	Minutes
13th Street two-way							
Park Rd. EB	32	272	1,140	0.34	336	1,128	0.43
Park Rd WB	32	248	1,140	0.48	276	1,140	0.61
Irving St. EB	38	207	1,265	0.41	234	1,236	0.15
Irving St WB	38	111	1,265	0.46	114	1,236	0.74
13th Street one-way							
Park Rd EB	60	322	1,658	2.89	366	1,950	3.21
Park Rd. WB	60	228	1,658	0.51	276	1,746	0.74
Irving St EB	60	245	2,172	1.67	318	3,126	1.25
Irving St. WB	60	143	1,927	0.80	168	2,490	0.71
Cross Streets Carrying One-way Traffic							
13th Street two-way							
Columbia Rd. WB	40	491	1,270	0.59	570	1,260	0.63
Harvard St. EB	34	434	1,200	0.63	462	1,152	0.70
13th Street one-way							
Columbia Rd. WB	60	572	1,915	3.81	738	1,866	4.78
Harvard St EB	60	744	1,785	0.92	882	2,070	0.64

[a]Where study was conducted for more than 1 hour, the data for the 1-hour period of maximum flow have been used. The studies of less than a full hour are for the periods immediately ahead of the time when 13th Street was changed to one-way operation.

for both types of control. At volumes above 1,800 vehicles per hour on the through street, the average delay to all traffic was greater with stop-sign control on the cross streets than with signal control.

Traffic on the through street was protected by stop signs on the cross streets, and had it not been impeded at other intersections along the route, the volume of traffic could theoretically have increased to 7,000 vehicles per hour. This type of control is not feasible, however, for such heavy volumes of traffic on the through street because cross traffic is almost completely blocked.

When an intersection at which traffic on one of the streets is controlled by stop signs is adjacent to an intersection at which traffic on the through street is controlled by signals, the capacity of the cross street is somewhat greater than it would be if there were no traffic signals in the immediate vicinity. The signal at the neighboring intersection creates gaps in the stream of traffic on the through street into which vehicles waiting at the stop sign may enter. Traffic volumes greater than those indicated by the curves in Figure 7 could probably be discharged from cross streets controlled by stop signs at such locations.

The traffic volumes observed in this study are evidently too great to be handled satisfactorily at intersections controlled by stop signs on the cross street. Even with moderately heavy volumes on the cross streets, this traffic was delayed as much or more by stop signs than by signals. At the higher volumes the delay with stop signs definitely became intolerable to cross-street traffic, although through traffic was completely unrestricted.

STOP-SIGN CONTROL ON ALL APPROACHES

When stop signs were used on all approaches to the three intersections studied with this type of control, they were installed on the near side as well as the far side of the intersections, and advance warning signs were erected. On the one-way streets, signs were mounted on the left as well as the right-hand side of the street. Even under these conditions, however, it was necessary to discontinue the studies when the traffic volume reached the practical capacity of the intersections. The study had to be terminated after 13th Street had been operating one-way for little more than an hour and before the height of the afternoon rush was reached. The frequency with which a police officer was required to regulate the various movements immediately before the study was terminated made it apparent that the practical capacities of the intersections for this type of control were reached.

Table 1 shows traffic volumes for the heaviest hour and for the heaviest 10-minute period of the study with stop-signs on all intersection approaches. For each intersection, the volumes are shown separately for 13th Street and for the intersecting or cross street, and the combined total for the two is shown in the column, "Total for intersection." The average delay per vehicle during the period when the particular volume occurred is shown in Table 1. The peak volume on 13th Street did not always occur during the same time period as that for the cross street, and for this reason each intersection is listed twice in the table. The volumes for the cross streets as shown in the upper one-half of the table are those observed during the period when 13th Street was carrying its peak load. In the lower portion of the table the volumes shown for 13th Street are those observed when the cross streets were at a peak.

The highest 10-minute volume was observed at the intersection of 13th Street and Columbia Road, with 13th Street operating as a one-way street northbound and Columbia Road one-way westbound. The rate of flow on 13th Street during this period was 2,280 vehicles per hour, while the rate on Columbia Road during the same period was 762 vehicles per hour. The total volume for the intersection, 3,042 vehicles per hour, is equivalent to an average of 507 vehicles per lane per hour for all lanes entering the intersection. The accompanying delay averaged 31 seconds per vehicle to traffic on the cross street and 26 seconds per vehicle to traffic on the through street. This is very close to the delay of 30 seconds which was used as the criterion for practical capacity with stop-sign control on the cross streets. It seems reasonable to assume that most drivers would consider a delay greater than this intolerable at an all-way stop intersection just as they do at a cross street with stop signs.

During the 10-minute periods of maximum traffic flow listed in Table 1, it is noteworthy that the average volume per lane, including all approaches, was usually between 400 and 500 vehicles per hour. Most of the average delays to cross-street traffic observed during these same periods vary between 21 and 52 seconds. This indicates that the traffic load was between the practical and possible capacities of the intersections. It seems reasonable to assume that somewhat higher volumes might be carried with no increase in delay after a period of familiarization for the drivers. The practical capacity of these intersections with stop-sign control on all approaches and under the other existing conditions is therefore somewhere near 500 vehicles per hour for each lane used by traffic entering the intersection. This capacity is based on a reasonable traffic delay but does not take into consideration pedestrian delays or accident hazards which would probably tend to reduce the 500 figure to a somewhat lower value. The few pe-

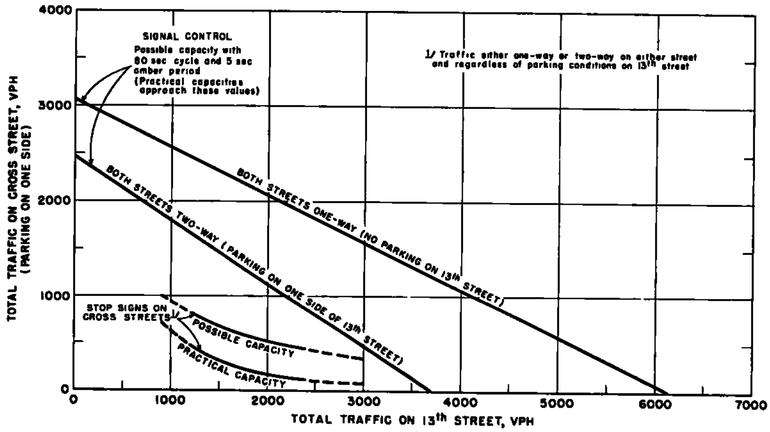

Figure 7. Capacities for two types of intersection control.

destrians at the intersections studied experienced long delays in crossing the streets even at moderate volumes.

Practical capacity for all-way stop control is compared with the capacities determined for the other types of control in Figure 8. This shows that under the traffic conditions prevailing at these intersections the capacity with all-way stop control is greater than with cross-street stop-sign control and less than with signal control. As previously stated, the capacities with stop signs on the cross streets are limited to those that permit a reasonable movement of the cross-street traffic.

At intersections where both streets are two-way, the practical capacity with four-way stop signs approaches the capacity with signals. The capacity with signals is, however, much greater than with stop signs on all approaches when both streets are one-way.

The delay to traffic was compared for the three types of control. At the traffic volumes observed, the delay to all traffic was found to be more with stop signs on all approaches than with signal control. Also, when the volume on the through street was below 1,800 vehicles per hour, stop signs on all approaches resulted in a greater average delay to all traffic than did stop signs on the cross streets. When the volume on the through street was greater than 1,800 vehicles per hour, the average delay to all traffic was less with stop signs on all approaches than with stop signs on the cross streets.

An analysis of the delays shown in Tables 6 and 1 indicates that the delay to cross-street traffic is far less when stop signs are used on all approaches than when used on the cross street only. An examination of other data obtained for lower traffic volumes shows this also to be the case for the lower volumes. The cross-street volumes in one direction during this study were never below 100 vehicles per hour. For cross-street volumes lower than this figure the relationship between delay and type of stop-sign control might be quite different from that found in this study.

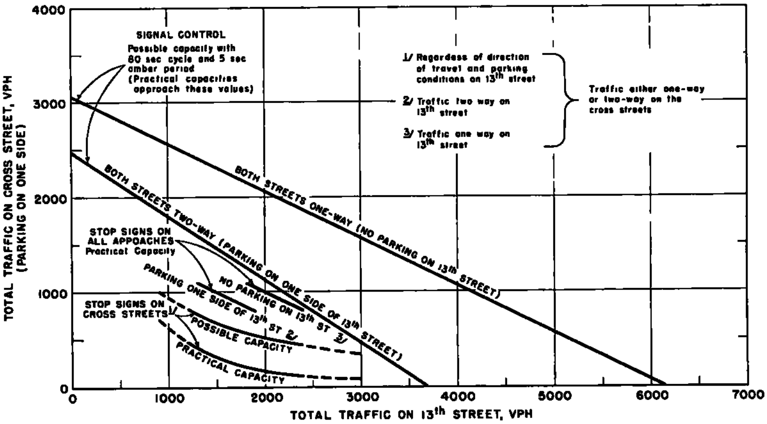

FIGURE 8 - CAPACITIES FOR THREE TYPES OF INTERSECTION CONTROL

Figure 8. Capacities for three types of intersection control.

SUMMARY OF FINDINGS

A definite value for either practical or possible capacity was determined for each of the three types of intersection control included in this study. The effect of one-way and two-way operation on the capacities of both through and cross streets and the effect of parking on the through street were also determined. These determinations have been based on the magnitude of the delays to traffic as well as on the traffic volumes which were observed. The studies were conducted at intersections where the through street was 40 feet wide and the cross streets 30 feet wide with parking on one side. The intersections were in a densely developed residential area with comparatively few pedestrians. Traffic on the through street was exceedingly heavy during the rush periods, and traffic on each of the four important cross streets was seldom less than 250 vehicles per hour during the day. The following are the more important findings for the prevailing roadway and traffic conditions:

Progressive Signal Control

1. The capacity of 13th Street with one-way operation and all parking prohibited was found to be 1,750 vehicles per hour of green per 10 feet of street width.
2. The capacity of 13th Street when operating two-way with parking on one side is 37 percent greater at two-way cross streets and 48 percent greater at one-way cross streets than with parking on both sides. With no parking on either side, the through-street capacity is 75 percent greater at two-way cross streets and 97 percent greater at one-way cross streets than when parking is permitted on both sides.
3. Changing from two-way to one-way operation on the through street, with no parking, increased the capacity of the through street 25 percent at intersections with two-way cross streets and 11 percent at intersections with one-way cross streets.
4. The capacity of the through street was increased 119 percent by the elimination of parking from both sides and the use of one-way rather than two-way operation.
5. Changing from two-way to one-way operation and eliminating parking on the through street increased the capacity of the two-way cross streets 11 percent and the one-way cross streets 20 percent.
6. The capacity of the one-way cross streets was 15 percent greater than the capacity of the two-way cross streets while there was two-way operation on 13th Street. The corresponding figure while 13th Street was operating as a one-way street was 24 percent.
7. Traffic delays with progressive signal control increased comparatively little with an increase in the traffic volume until the volumes approached very closely the possible capacities of the streets. This was true for delays to both through and cross-street traffic.

Stop-Sign Control on Cross Streets

8. The capacities of the cross streets with stop-sign control only on these streets were affected principally by the traffic volume on the through street. Whether the cross streets or the through street were operated as one-way or two-way streets made no apparent difference on the capacity of the cross street. The possible capacity of one-way and two-way cross streets decreased from 800 vehicles per hour to 400 vehicles per hour when the volume on the through street increased from 1,300 to 2,500 vehicles per hour. The decrease in capacity of the cross streets was not, however, directly proportional to the increase in volume on the through street.

9. Delay to traffic on the through street was practically nil, regardless of the traffic volume on the cross streets.

10. The delay to traffic on the cross streets was the principal criterion for a determination of possible and practical capacities with stop signs on the cross streets. The possible capacity is the volume which if exceeded even a slight amount will result in extremely long delays. For a given volume of traffic on the through street, the delay to traffic on the cross street when operating at possible capacity is more than double the delay when operating at practical capacity. Also, the practical capacity of a cross street is less than half of its possible capacity.

11. Changing either the through street or the cross street from two-way to one-way operation had no apparent effect on the delay to traffic on the cross street or the capacity of the cross street.

All-way Stop-sign Control

12. The practical capacity of the intersections with all-way stop-sign control was found to approach 500 vehicles per lane per hour including the lanes used by traffic on both streets. The validity of this finding under other conditions with a high traffic volume per lane on one of the streets and a low volume per lane on the other street was not determined.

13. With similar traffic volumes per lane on both streets, the delay per vehicle on the through street was approximately the same as the delay per vehicle on the cross street.

CONCLUSIONS

The following conclusions appear to be justified for the conditions under which these studies were conducted:

1. With properly coordinated progressive signal control, the practical capacity of the one-way street closely approaches its possible capacity. The delays to traffic when volumes are near possible capacity are not excessive under these conditions and only slightly greater than the delays at much lower volumes.

2. Intersection capacities are greater with progressive signal control than with either type of stop-sign control. When the through street is one-way, the intersection capacities with progressive signal control are substantially greater than with either type of stop-sign control. The average delay to all traffic is less with progressive signal control than with either type of stop-sign control, except possibly with stop-sign control at cross streets carrying exceedingly low volumes while the through street is carrying a high volume.

3. Possible and practical capacities for cross-street stop-sign control are much lower than with progressive signal control or all-way stop-sign control. Somewhat higher volumes than those found during this study might be practical with stop-sign control on the cross street when the intersection is located between signal-controlled intersections on the through street.

4. The capacity of an intersection at which all traffic is controlled by stop signs approaches that of an intersection with progressive signal control when both streets carry two-way traffic. When one or both of the streets carry traffic in only one direction, the capacity with all-way stop signs is considerably lower than that possible with progressive signal control.

5. The capacity of an intersection will vary greatly with the control and regulation of traffic. Additional studies are necessary to determine the most effective type of control for the many conditions that exist other than those included in this study.

In the application of the above conclusions, it must be remembered that they apply only to conditions similar to those found on 13th Street. The very high values for capacity with signal control cannot be used when estimating capacities because for most streets the results would be erroneously high. The very efficient operation of the progressive signal system should be reemphasized since it expedites the movement of exceedingly high volumes of traffic to a degree seldom equaled on streets of this type. It may be significant that most of the drivers on 13th Street during the peak period use this street daily and are therefore practiced in maintaining optimum speed and spacing.

These facts are important considerations when comparing the results of this study with those of other studies[3] which do not show the same advantages for signal control as compared with stop-sign control. There is close agreement, however, in the results of this study and those of other studies in the traffic volumes accommodated by the two types of stop-sign control. The fact that 13th Street can accommodate such high traffic volumes smoothly and at a reasonable speed for urban conditions is a tribute to the traffic engineers who operate the progressive signal system.

Discussion

HERBERT S. LEVINSON, Wilbur Smith and Associates, New Haven, Connecticut—French clearly indicates that the way to move traffic is to develop efficient usage of curb lanes through "all rolling" regulations, coupled with one-way movements and progressive signal timing.

Peak traffic movements on 13th Street in Washington approximate 700 vehicles per lane per hour. This is in accord with loadings observed on key radials in other cities.

French states that progressive timing develops practical capacities almost as high as saturation flow values. In this regard it is significant to note that the 80 percent relationship between the two capacity criteria can be demonstrated, assuming random arrivals. Platoon movements, with gaps between successive platoons, have, if at all, a very limited and particularistic randomness. Practical capacity in a progressive signal system is closely related to the capacity in vehicles per hour of the "through bands." This "band capacity" is generally high on a progressively timed one-way street.

French's analysis of vehicular operations at stop sign controlled intersections should also indicate the effects of the location of cross intersections as related to the time-space pattern of the through street. For example, midway between two signals that operate essentially simultaneously, gaps are generally well defined, even with heavy loadings. On the other hand, midway between two signals, ½ cycle offset from each other, there will be very few breaks in traffic, even under moderate volumes.

ALEXANDER FRENCH, Closure—It is true, as Levinson points out in his comments, that the high traffic volumes observed during this study are not unique. Since sufficient capacity to carry such volumes is not easily obtained on most city streets, many locations where high volumes are carried must be studied to determine the principal factors which influence the traffic-carrying capacities of streets. The Department of Traffic and Operations of the Highway Research Board is now engaged in just such a study. The Highway Capacity Committee of this department is cooperating with traffic engineers in cities throughout the nation to obtain traffic data for a large number of high-volume intersections. A result of this study will be a more complete understanding of the traffic-

[3] "A Capacity Relationship Between Four-Way Stop Intersection Control and Fixed-Time Traffic Signal," by James Madison Hunnicutt, Jr. Thesis, Bureau of Highway Traffic, Yale University, 1954.

"A Comparison of Delay to Vehicles Crossing Urban Intersections, Four-Way-Stop versus Semi-Traffic-Actuated Signal Control," by Edward M. Hall. Student Research Report No. 4, The Institute of Transportation and Traffic Engineering, University of California, January 1952.

carrying capacity of intersections. Until more information is available, the high capacities, such as those found in this study, will not easily be duplicated. There is, therefore, as yet no assurance that such high capacities can be designed into a city street.

A comparison of delays to cross-street traffic shown in Table 5 of the report supports Levinson's belief that signals at intersections on the through street will affect the operation of intermediate cross-street approaches that are controlled by stop signs. With 13th Street operating one way, for example, the delay to cross traffic at Columbia Road is considerably greater than at Harvard Street. Since Harvard Street is closer to Euclid Street, where the signal was operating, it appears that the bunched platoon gradually spread out as it progressed up 13th Street, blocking the cross streets farther from the signal for a longer period than those near the signal. The significance of the relationship between vehicle spacing on the through street and the operation of the cross streets when controlled by stop signs could not be determined since so many other factors evidently had some effect. Data from studies at a large number of different locations must be analyzed to determine the significance of the many variables which influence the operating efficiency of street intersections. It is for this reason that the work now being carried on by the Highway Capacity Committee is of special value.