A Study of Four-Way Stop Intersection Capacities

JACQUES HEBERT, Graduate Student, Northwestern University, Evanston, Ill.

This study was an endeavor to determine capacities of four-way stop-controlled intersections under various traffic and operating conditions.

Three right-angle intersections in the Chicago Metropolitan Area were observed and analyzed. The average headway of departure was obtained, and the effects on capacity of left- and right-turning vehicles, the number of lanes on the cross-street, and the split in volumes between the intersecting streets, were determined. The effect of commercial vehicles was tentatively investigated, but the small size of the sample precluded any specific conclusions. Only daytime driving characteristics were observed.

Due to the amount and complexity of the data to be obtained, all intersections but one were filmed for a period of 80 min each. The movie camera technique had the advantage of requiring the least amount of field observations, and presenting a permanent record of the complex interrelationship of the data to be analyzed.

Some of the interesting findings of this study are as follows:

1. Variations in the split of volume between the two intersecting streets of a four-way stop intersection produce a significantly different headway of departure for two different intersections.
2. Left-turning vehicles have no effect on the capacity, the average headway of departure for left-turning and through vehicles not being significantly different under various traffic conditions.
3. For each 1 percent of right-turning vehicles, the capacity is increased by 0.2 percent.
4. Under pressurized and ideal traffic conditions through passenger cars per lane may be expected to be discharged across a two-lane cross-street at an average of one every 7.65 sec if the split is 50/50, and one every 7.15 sec if it is 60/40. These rates are averages for the whole intersection.
5. If the split becomes 100/0 (i.e., all on-coming vehicles are on two opposite approaches only) and for the same conditions as in item 4, one might expect a discharge rate of one vehicle every 4.05 sec from each of the two approaches.
6. For the conditions of item 4 and a 50/50 split, the capacity per lane averages one vehicle every 8.08 sec if the street to be crossed has four moving lanes.
7. Seventy percent of vehicles are found to be moving two abreast if there are two lanes on a loaded approach.

•OF ALL the problems of interest to the traffic engineer, the urban intersection at grade is undoubtedly the most important. If one considers that approximately one-half of all urban accidents and more than three-quarters of all urban delays are caused by or related to urban intersections, the range and far-reaching consequences of the problem are more fully understood.

To provide efficiency and safety of movement through these intersections, vehicles and pedestrians are regulated by various types of traffic control devices. In many cases the actual warrants used for the application of these devices need much refinement and development and are often subjects of controversy. The application of the four-way stop type of control is presently very controversial, and a definite solution

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has yet to be attained. Contradictory statements such as the following have become common language: "... the four-way stop as a solution should be used more frequently" (4); and "... there can be no logical warrant for a four-way stop except as a safety measure or as a device to satisfy pressure groups that demand action at an intersection warranting no action." (12)

Little factual study had been made in the past to crystallize the use warrants for the four-way stop intersection control. McEachern (13) reported: "While most cities do use warrants for the establishment of four-way stop intersections, the warrants are not specific; and the single most widely used warrant is the high-accident frequency at two-way stop intersections." The four-way stop, as usually employed, finds applications at urban intersections as a safety measure, or as an intermediate treatment between the two-way stop and the signal control.

In the "Manual on Uniform Traffic Control Devices" (3) the warrants for four-way stops require a total vehicular volume of 500 vph for any 8 hr of an average day, with at least 200 vehicles and pedestrians entering from the minor street. No mention is made of maximum permissible volumes. However, the Institute of Traffic Engineers suggests a maximum volume of 1,000 vph (average for 6 hr), with at least 250 vph from the side street.

These requirements are useful as a guide, but are not based on such fundamental characteristics of vehicular flow as arrival rates, departure headways, and effects of opposing and intersecting flows. A rational analysis is needed of the various relationships between these fundamental traffic features at four-way stop intersections. This, together with the subsequent derivation of capacities, is dealt with herein. It is hoped that the findings of this study will contribute to the understanding of this complex urban traffic problem.

PURPOSE AND SCOPE

The purpose of this study was to determine the basic and practical capacities of four-way stop intersections, under various geometric and traffic conditions. Capacities were derived from the average departure headway of vehicles as they enter the intersection area.

The Highway Capacity Manual (1) defines basic capacity as the "maximum number of passenger cars that can pass a given point on a lane or roadway during one hour under the most nearly ideal roadway and traffic conditions which can possibly be attained." To satisfy this definition, the headways of departure were obtained and recorded separately for passenger cars, commercial vehicles, left- and right-turning vehicles, and through vehicles. Possible capacity, which is the capacity under the prevailing roadway and traffic conditions, was derived from the basic capacity by applying certain reducing factors. The investigation and determination of these factors is included hereinafter.

Practical capacity is defined as "the maximum number of vehicles that can pass a given point on a roadway or in a designated lane during one hour without the traffic density being so great as to cause unreasonable delay, hazard, or restriction to the driver's freedom to maneuver under the prevailing roadway and traffic conditions." (1) This level of capacity is equal to the possible capacity multiplied by a factor which is given in the Manual as 0.80.

Another approach to the determination of the practical capacity of an intersection could be based on a delay criterion. Assuming random distribution of the vehicles on the approach, it is possible, using the observed average headway of departure, to determine the vehicular volume that will cause a certain percentage of the drivers to be delayed by a given preferred amount of time. Any volume that causes a greater percentage of the drivers to be delayed by the same amount of time, or causes the same percentage of drivers to be delayed by a larger amount of time, will be above practical capacity. Figure 10 is a set of curves derived for various time periods and percentages of drivers.

Variables Studied

The following variables were investigated as to their effect on the capacity of four-way stop intersections:

1. Two splits in volume (51.5/48.5 and 64.0/36.0) for one-lane approaches, during pressurized conditions, with a continuous backlog of waiting vehicles.
2. Four-lane and two-lane two-way cross-streets for similar traffic conditions.
3. Variations in left and right turns, and percentage of commercial vehicles. Unfortunately, truck travel at the intersections studied was almost negligible, and the data obtained regarding their effect on headways were insufficient.
4. Waiting vehicles on the cross-street, vs no vehicles on the cross-street, vs vehicles from cross-street entering the intersection in turns with the approach vehicles under study. These analyses are further detailed hereafter.

Limitations of the Study

The study was made at three outlying intersections in the Chicago metropolitan area, and is therefore representative of Chicago drivers only. This had the advantage of eliminating the variations resulting from dissimilar driving behavior inherent to different groups of drivers. No attempt was made to relate the results with those of other parts of the country, and nighttime driving characteristics were not investigated. All control signs bore the "4-way" supplementary message (Fig. 1), because it was believed that this signing policy insured higher capacities (2).

PROCEDURE

In consideration of the limited manpower and time available for field observations, it seemed logical to use the movie-camera technique of study. This method, besides being economical in manpower, provided a permanent record of the behavior of each traffic stream and the relationships between the streams, and allowed for leisurely extraction of the data, with possible re-running of the films whenever desired. The locations were intentionally selected to provide a suitable vantage point for filming. Figure 2 shows the camera installed for filming at a high point at the intersection of Winnetka and Hibbard Streets in Winnetka. It was at a height of approximately 15 ft, and 120 ft from the intersection.

The camera was operated by a small 100-rpm synchronous motor using 120-v ac power provided by an ordinary 12-v dc battery, through a dc-ac converter. Filming was performed at the rate of 100 frames per minute; one complete 100-ft film lasted approximately 40 min.

Two right-angle intersections were filmed for 80 min each. A third intersection was filmed for 40 min. The camera was so located as to offer a view of the whole intersection and a certain length of each leg. The headways of departure for vehicles in each lane of each approach were recorded separately for each item of study. Extraction of data, although simple, was found to be very time consuming.

Figure 1. 4-Way supplementary message on stop signs.

LOCATIONS STUDIED

Intersection A: Willow and Hibbard (Fig. 3)

The first intersection studied was Willow and Hibbard in Winnetka, a community in the outlying north suburbs of Chicago. This location was selected because of its high volume, nearly equal split, high percentage of turns and little small pedestrian and roadside interference. During the period of study (p.m. peak hour), the traffic conditions were as follows:

Date: Tuesday, April 3, 1962
Time: 4:00 to 4:45 p.m.
Total intersection volume: 1,209 vph
Split: 51.5/48.5
C.V.: 6.5%
Total intersection left turns: 23.9%
Total intersection right turns: 22.9%
Basic number of lanes: 2 on each street

Figure 2. High camera location.

Because of the sparse development of the immediate surroundings, the intersection was ideally free of pedestrians, parking, and driveway interference. In fact, not a single pedestrian was encountered during the whole study period. The effects of nearby intersection controls were minimized because of their distance (more than 2,000 ft). All sight distances were adequate.

Intersection B: Winnetka and Hibbard (Fig. 4)

Immediately south of Intersection A, in the same community, is the intersection of Winnetka and Hibbard Streets. Although it does not offer a very high volume of traffic, which is a desirable feature for the purpose of the study, the main advantage of this intersection is its different split in traffic volume. The traffic conditions during the study period were as follows:

Date: Friday, April 13, 1962

Time: 4:00 to 5:30 p.m.
Total intersection volume: 742 vph
Split: 64.0/36.0
C.V.: 3.3%
Total intersection left turns: 16.6%
Total intersection right turns: 18.8%
Basic number of lanes: 2 on each street

This location also has a high vehicle turning movement, and almost no interference from pedestrians, parking, or driveways. In contrast to Intersection A, the sight distances were adequate in three quadrants only, and very limited in the fourth. Basically, the two intersecting streets have one moving lane in each direction.

Intersection C: Cumberland and Devon (Fig. 5)

The third intersection is quite different from the previous ones. It was selected so as to provide data on headways of vehicles on a two-lane highway when crossing a street with four moving lanes. Basically, the two intersecting streets were designed for four moving lanes each, but parking reduced to two the number of moving lanes on Devon. West of the intersection, Devon Street has a 35-ft median; east of the intersection the median width is reduced to 14 ft. Cumberland Street has a 4-ft median south of the intersection only. Because the intersection is located in a well-developed

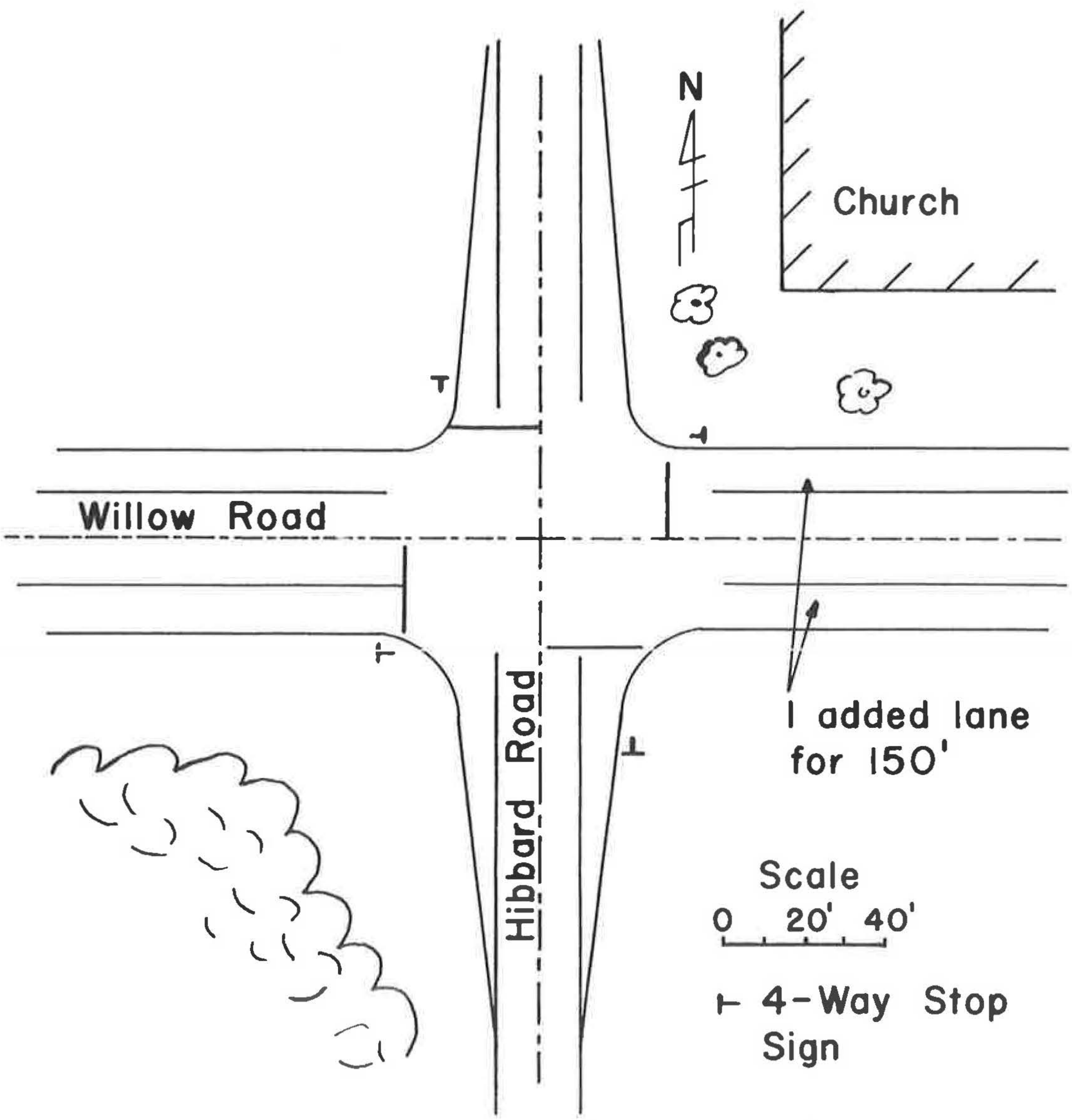

Figure 3. Intersection A (Willow and Hibbard).

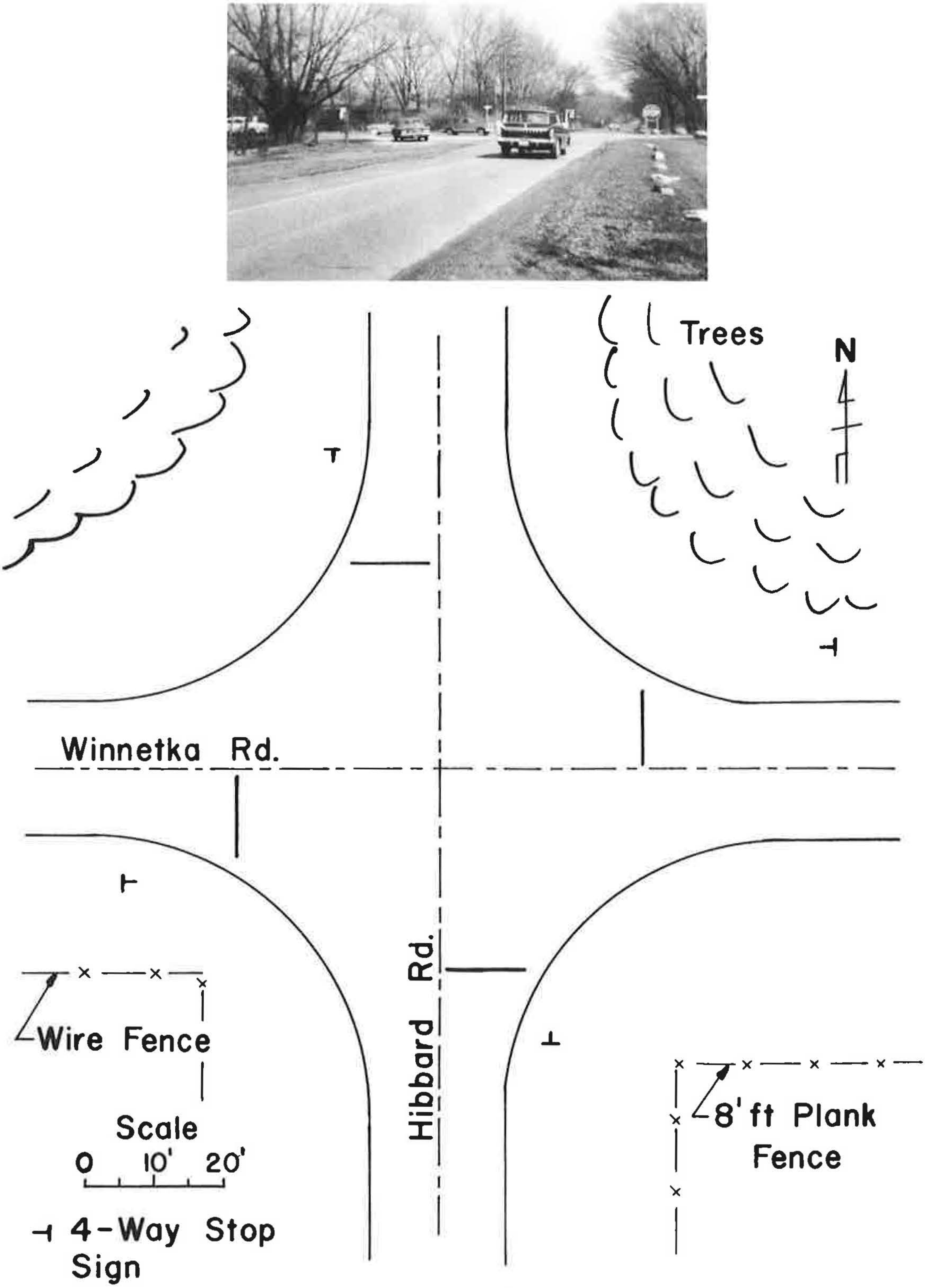

Figure 4. Intersection B (Winnetka and Hibbard).

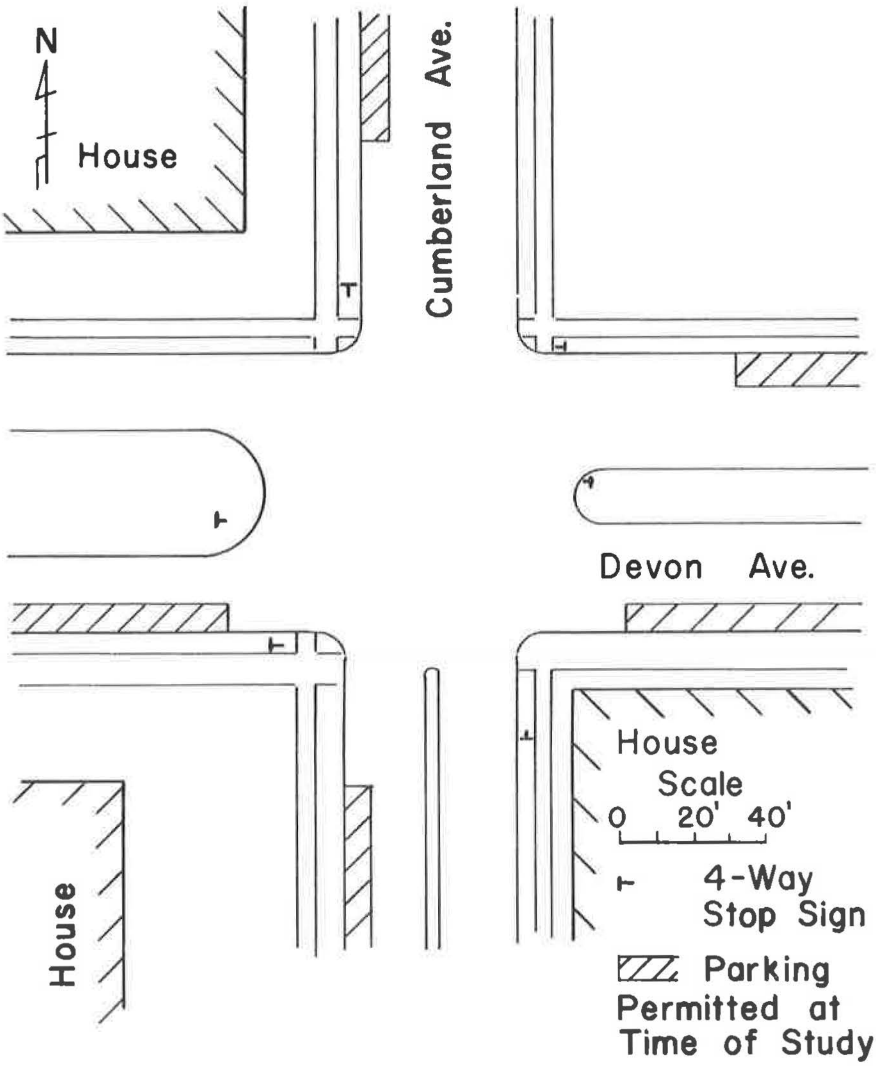

Figure 5. Intersection C (Cumberland and Devon).

community (Park Ridge), a certain amount of interference was encountered, including some pedestrian movement and parking. At the time of the study, parking was as shown in Figure 5. The eastbound traffic on Devon was studied as it crossed four-lane Cumberland Street. During the p.m. peak hour of filming, the following conditions were encountered:

Date: Friday, April 20, 1962

Time: 3:45 to 5:15 p.m.	C.V.: 4.3%
Total intersection volume: 1,800 vph	Number of lanes: as shown in Figure 3
Split: 51.2/48.8	

STATISTICAL ANALYSIS

Calculation of Minimum Sample Size

The size of a sample of data needed to give a mean within some desired range of accuracy is dependent on the desired confidence level and the standard deviation of the population. If no data are available, the standard deviation of the population may be assumed. However, if data have already been taken, an estimate of the standard deviation of the population may be obtained from that of the sample, and it becomes possible to determine whether the size of the available data is sufficiently large. Inasmuch as the data of this study were obtained from films, it was not feasible to measure time closer than one frame (0.60 sec). Using a 95 percent confidence limit, a standard deviation of 3.7, 3.0 and 2.0 frames (all sample standard deviations are smaller than 3.7 frames), and a limit of error of 1.0 frame, the size of sample needed is

$$E = 1.96 \frac{S}{\sqrt{n - 1}} \tag{1}$$

from which $n = \frac{3.84 \times (3.7^2, 3.0^2, 2.0^2)}{E} + 1 = 53.5, 35.6, 15.4.$

Interpreting this result, any sample of data of size 54, 36, or 16 or more, would have a mean value within 1.0 frame from the true population mean in 95 cases out of 100, depending on the consistency of the sample, as expressed in the standard deviation. These sample sizes are strict minimums, and more readings should be obtained where feasible.

Tests on Data

To calculate the basic capacity of four-way stop intersections, it is necessary to register the headway of departure of the vehicles on any approach during loaded conditions. If both streets are loaded, the vehicles usually proceed through the intersection in turns, each one moving to the first position as the cross-street vehicle accelerates. However, it often happens that one approach is clogged with waiting vehicles while there are none or few on the cross-street. Obviously, one would expect the headways to be much smaller on one street if there are no vehicles coming from the cross-street. Besides being recorded separately for passenger cars, commercial vehicles, through, left-turning, and right-turning vehicles, headways were also obtained separately for the three following cases:

1. L headways: When both streets are loaded vehicles proceed through in turns, with one vehicle accelerating from a cross-street approach within the headway recorded.
2. N headways: The approach under study is loaded, with no vehicles approaching on the cross-street (50 ft or less) or waiting at the stop line.
3. I headways: The approach under study is loaded, with interference from vehicles on the cross-street (within 50 ft of the stop line). This type of headway is there-

TABLE 1

NUMBER OF HEADWAYS OBSERVED

Type of Headway	Passenger Cars			
	Left	Through	Right	Total
(a) Intersection A				
L	50	100	23	173
N	15	47	15	77
I	18	34	19	71
Total	83	181	57	321
(b) Intersection B				
L	21	75	17	113
N	7	87	10	104
I	14	70	23	107
Total	42	232	50	324
(c) Intersection C				
L	—	210	—	210
N	—	—	—	—
I	—	—	—	—
Total	—	210	—	210

fore the time taken by two successive vehicles on a loaded approach to proceed through the intersection, without any vehicle from the cross-street moving in between them, but only causing interference and hesitation. The 50-ft distance was selected as being representative of a critical lag of 3 to 4 sec, as found at four-way stops. A detailed analysis of acceptance and rejection of gaps at four-way stops was made by Cooper (2).

A total of 321 passenger car headways was recorded for Intersection A, 324 for Intesection B, and 210 for the lane studied at Intersection C. Table 1 gives the number of headways for each of the several items studied.

The size of the commercial vehicle sample was negligible. It is to be noted that the sample obtained from left- and right-turning vehicles is rather limited. In many instances, the data are very consistent, with a small standard deviation. In other cases, the data were combined for both Intersections A and B, and tested jointly.

Using a 95 percent confidence level, two types of tests were performed on various groups of data: (a) The normal distribution test (two-sided); and (b) The student's "t" distribution test (two-sided). The tests give the statistical significance of the difference

TABLE 2

STATISTICAL DIFFERENCE OF MEANS OF HEADWAYS[1]

Description	Normal Test	"t" Test
(a) Intersection A		
Through N vs through L	Sig.	Sig.
Through N vs through I	Sig.	Sig.
Through L vs through I	Sig.	Sig.
Through L vs left-turning L	Non-sig.	Non-sig.
(b) Intersection B		
Through I vs through N	Non-sig.	Non-sig.
Through L vs through N	Sig.	Sig.
Through L vs through I	Sig.	Sig.
Through L maj. app. vs through L min. app.	Non-sig.	Non-sig.
(c) Combined Intersections A and B		
Through L vs rt-turn L	Sig.	Sig.
Through L vs lt-turn L	Non-sig.	Non-sig.
(d) Intersection A vs Intersection B		
Through N	Non-sig.	Non-sig.
Through I	Non-sig.	Non-sig.
Through L	Sig.	Sig.
Left-turn L	Non-sig.	Non-sig.
(d) Intersection C vs Intersection A and B		
Through L Int. C vs through L Int. A	Sig.	Sig.
Through L Int. C vs through L Int. B	Sig.	Sig.

[1] Passenger cars only.

of the means of two sets of data. The "t" test is preferable to the normal test for small samples, because it does not require the population values. The results (Table 2) indicate that left turns have no effect on the headway of departure, whereas right turns do. Except for the L headways of through passenger cars, computed on a total intersection basis, the split evidently has no effect. It must be agreed that this significant difference may also be influenced by location, sight distance, geometric configuration, etc., of the intersection. It so happens that Intersection B, which has relatively restricted sight distances when compared to Intersection A, gave shorter headways for through passenger cars. The three different types of headways (L, N, I) produced significant differences except in one case (see Table 2b). One of the important results obtained was the significantly longer headways needed to cross a four-lane vs a two-lane cross-street (Table 2e).

These analyses form a necessary basis from which one can estimate the effects of the various factors affecting the traffic behavior at intersections. These factors are considered quantitatively hereafter, and their influence on capacities is derived.

PRESENTATION AND DISCUSSION OF RESULTS

Table 3 gives the headways of departure of passenger cars for the conditions shown, as well as the standard deviation of each sample group. Figure 6 compares L-type mean headways for Intersections A and B; Figure 7 compares through mean headways for these intersections.

Factors Affecting Headway

Split. —Table 2d shows that the L type of headway of departure for through passenger cars is significantly different for Intersection A, with a split of 51.5/48.5, and Intersection B, with a split of 64.0/36.0 (Fig. 8). Because this type of headway (defined on loaded conditions at all times) is of interest in the calculation of basic capacity, the foregoing difference must be taken into account. Whether the difference is totally or partially due to the split, or to a certain unknown factor, cannot presently be determined and additonal research is needed.

If the split is assumed to be the most influential factor, it is possible to derive an equation of the headway as a function of the split. Inasmuch as only two different splits are available for study, the equation is the straight line:

$$H = 10.15 - 5S \qquad (2)$$

in which H is the average headway of departure for through passenger vehicles, for loaded condition; and S is the ratio of volume on major street to volume of total intersection. As S (split) increases, H (headway) decreases, and a larger volume of vehicles can be handled on the major approach. Although the capacity of the high-volume street increases, however, the minor-volume approach capacity decreases substantially, in order to satisfy the S (split) requirements. This obviously affects the capacity of the total intersection, for both basic and possible capacities.

Left Turns. —Under loaded conditions, left-turning passenger vehicles did not, as might have been expected, take a significantly longer time than through vehicles to proceed through the intersection (see Table 2c). This is undoubtedly due to the fact that many left turns are made simul-

TABLE 3

HEADWAYS OF PASSENGER CARS ENTERING A FOUR-WAY STOP INTERSECTION[1]

Intersection	Movement	Type of Headway	Mean (sec.)	Std. Dev. (sec.)
A	Through[1]	N	3.81	1.61
	Through[1]	I	4.73	1.86
	Through[1]	L	7.58	2.09
	Left[1]	L	7.40	2.22
	Right[1]	L	5.40	2.05
B	Through[2]	L	6.90	1.60
	Through[3]	L	7.04	1.18
	Through	N	4.18	1.36
	Through	I	4.28	1.62
	Through	L	6.96	1.51
	Left	L	7.57	2.12
	Right	L	6.38	2.06
A and B	Through	L	7.32	1.89
	Left	L	7.45	2.19
C	Through	L	8.08	1.03

[1] Averages for all four approaches.
[2] High-volume street.
[3] Low-volume street.

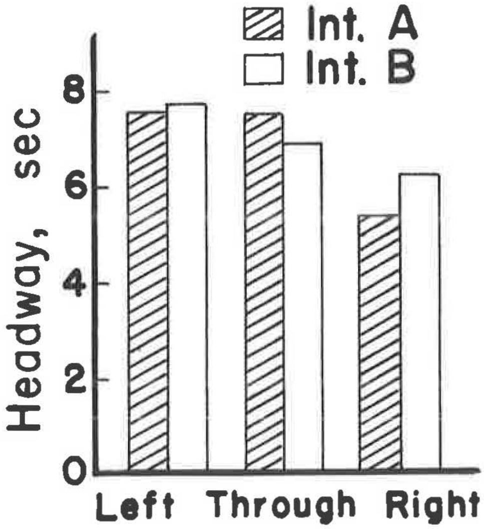

Figure 6. Comparative L-type mean headways, Intersections A and B.

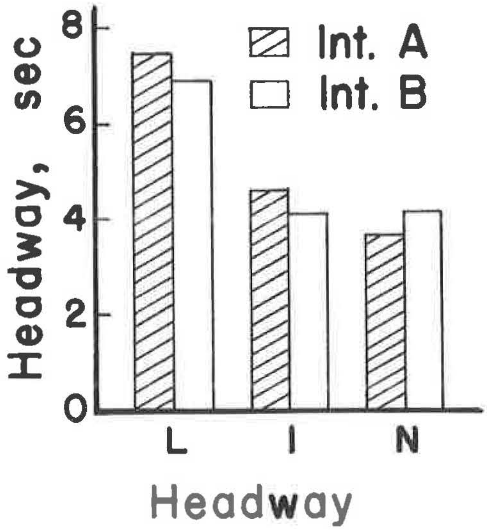

Figure 7. Comparative through mean headways, Intersections A and B.

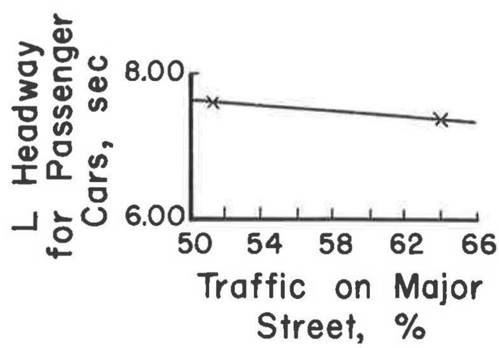

Figure 8. Variation of headway with split, Intersections A and B.

taneously with right turns from the cross-street. These movements are not in conflict, and a high percentage of them were observed to be made simultaneously. It must be concluded that left turns have a negligible effect on the average headway, and, therefore, on the capacity of the four-way stop intersection with appreciable right-turning volumes.

Right Turns.—It was observed that right-turning vehicles have significantly lower headways and, consequently, contribute to an increase in the capacity. This is not in accord with the Highway Capacity Manual (1), which states that, for traffic signal controls, capacity is decreased 0.5 percent for each 1 percent that right turns are of the total approach volume. This difference is easily understood if one examines the peculiar operation of the right turn at the four-way stop. A right-turning vehicle is not in conflict with either the right- or left-turning vehicle movements from the cross-street, and, furthermore, does not interfere with the through vehicles coming from the right-hand approach. During most of the time, right turns were performed simultaneously with other movements within the intersection area. The result is a smaller average headway. The fact also must not be overlooked that pedestrians, who mostly interfere with right turns, were totally absent from the intersections studied.

The mean headways for right turns and through vehicles, under loaded conditions, are, respectively, 5.82 and 7.32 sec, or a difference of 7.32 - 5.82/7.32 = 20.5 percent. In other words, for each 1 percent that right turns are of the through movement, the capacity is increased by 0.2 percent. Further research is required to verify the validity of this finding.

Commercial Vehicles.—As previously mentioned, data on commercial vehicles were negligible and no specific conclusions can be made as to their effect at four-way stops. However, it appears reasonable to assume their effect to be analogous to that observed at traffic signals. As reported in the Manual (1) capacity is reduced by 1 percent for each 1 percent that commercial vehicles are of the total traffic.

Pedestrians, Parking, Type of Urban Area. —The effects of pedestrians, parking, and type of urban area were not evaluated in this study.

Capacities

Basic Capacity. —As defined, the basic capacity is the maximum number of passenger vehicles that can be handled in one hour, under the most ideal conditions. This requires the intersection to be fully loaded, with queues of waiting vehicles on its approaches.

Two-Lane Street vs Two-Lane Street. —Referring to the specific operations of four-way stops, maximum volumes are handled when vehicles on opposite approaches accelerate simultaneously, alternating with the cross-street vehicles. Obviously, this is highly idealistic, and observed vehicle performance at four-way stops differs from it to a certain extent. The ideal performance is shown in Figure 9, with the two vehicles numbered 1 accelerating simultaneously across the intersectional area while the two vehicles numbered 3 move forward to the first position. Successively, vehicles 2, and then vehicles 3, 4, 5, etc., pass through the intersection. This procedure results in an equal volume of traffic being handled on both streets, and a split of 50/50. Under such conditions, the average headway on any approach can be calculated from Eq. 2; with $S = 0.50$, $H = 7.65$ sec. The basic capacity of the total intersection then becomes 3, 600 sec/hr/7. 65 sec/veh × 4 approaches = 1, 885, or approximately 1.900 passenger cars per hour.

It is interesting to note that if vehicles would be entering the intersection from two opposite approaches only, with a clear cross-street at all times for one hour (split = 100/0), headways drop to 4.05 sec and the capacity for the whole intersection becomes 1, 780, or approximately 1, 800 passenger cars per hour.

This is 100 P. C./hr less than for the 50/50 split, as previously computed. This points out that the maximum number of passenger cars handled by two-way stops at the entrance to an arterial street is 900 per one-lane approach per hour. In order to do so, there must be no traffic on the arterial, and a continuous reservoir of vehicles at the stop sign. Any other actual conditions decrease the capacity.

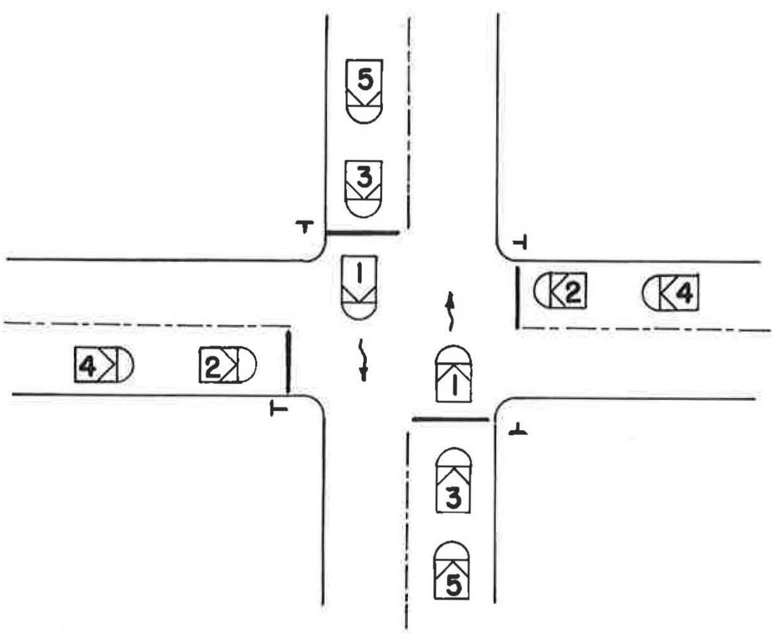

Figure 9. Ideal vehicle performance at 4-way stops.

It was observed that a certain number of vehicles at four-way stops do not always comply with the normal in-turn movement procedure for loaded conditions. Some bold drivers have a tendency to follow the vehicle immediately ahead of them through the intersection, thus proceeding across from the second position instead of the first. This behavior obviously causes a longer headway for the cross-street vehicles, because these must allow time for two vehicles to accelerate through instead of one. However, a shorter gap—which balances the one before—is produced by the bold driver, and the total capacity of the intersection is unaffected.

The previously computed basic capacity of 1,900 P.C./hr applies for a 50/50 split, which normally results when the two intersecting streets are loaded. The capacity for a different split can be calculated from (Table 4).

$$\text{Tot. int. basic cap.} = \text{vol. on loaded street} + \text{vol. on other street}$$

$$= \left(\frac{3,600}{10.15 - 5S}\right) \times 2 + \left(\frac{3,600}{10.15 - 5S}\right) \times 2 \times \left(\frac{1 - S}{S}\right)$$

$$= \frac{7,200}{(10.15 - 5S)S} \tag{3}$$

Four-Lane Street vs Four-Lane Street.—As already pointed out in Table 2e, it took significantly longer for vehicles to cross the four-lane cross-street at Intersection C than the two-lane cross-streets of Intersections A or B. This is reflected in a longer headway of departure (8.08 sec). Assuming, on a two-lane approach basis, the ideal traffic behavior depicted in Figure 9 (i.e., simultaneous movement of vehicles entering from opposite approaches), the maximum capacity of this type of four-way stop intersection (split = 50/50) is 3,600/8.08 x 8 moving lanes = 3,570 P.C./hr, or approximately 3,600 P.C/hr.

Two-Lane Street vs Four-Lane Street.—Applying the foregoing assumptions, the maximum volume that can be handled by the intersection of a two-lane street with a four-lane street is (3,600/8.08 x 2) + (3,600/7.65 x 4) = 2,790, or approximately 2,800 P.C/hr.

The foregoing volumes are extremely high, and could only be attained under the most ideal conditions of roadway and traffic. The delays experienced by the waiting vehicles would be intolerably great. Under the best of prevailing conditions, and taking into account the effect of inept drivers and a variety of other factors, these theoretical capacities are impossible for most, if not all, four-way stop intersections.

Possible Capacity.—

Two-Lane Street vs Two-Lane Street.—The possible capacity of a four-way stop is equal to its basic capacity, adjusted for the specific conditions of the intersection. It is suggested that for two-lane vs two-lane streets the basic capacity values of Table 4 be used.

Adjustment factors for use with these basic capacities are then as follows:

1. Left turns: No adjustment.
2. Right turns: Increase capacity by 0.2 percent for each 1 percent that right turns are of the total traffic.
3. Interference factor: Because the values derived were from observations in outlying areas where no interference was encountered, it is suggested that a reduction factor be used for intersections in intermediate and downtown areas. More research is needed to determine the value of this factor. For the present, a value of 0.9 is suggested.

TABLE 4

BASIC CAPACITY[1] OF INTERSECTIONS FOR VARIOUS TRAFFIC SPLITS

Split	Basic Capacity (vph)
50/50	1,900
55/45	1,800
60/40	1,700
65/35	1,600
70/30	1,550

[1] Passenger cars per hour.

4. Commercial vehicles: Reduce capacity by 1 percent for each 1 percent that commercial values are of total traffic.

Four-Lane Street vs Four-Lane Street. —An analysis of Intersection C revealed that 702. percent of the time two vehicles waiting abreast on a two-lane approach moved simultaneously across the intersection. Of 336 cases observed, 236 pairs of vehicles accelerated at the same time. This obviously had an effect on the capacity. Taking the conservative value of $^2/_3$ for simultaneous movements, the possible capacity of the total intersection is $(3,600/8.08 \times 8 \times {^2/_3}) + (3,600/8.08 \times 4 \times {^1/_3}) =$ 2,970 P.C./hr, or approximately 3,000 P.C./hr. The adjustment factors are the same as for the previous case.

Two-Lane Street vs Four-Lane Street. —If one considers that two-thirds of the time two vehicles abreast on the four-lane street move simultaneously, and one-third of the time only one does, the possible capacity for this type intersection is $(3,600/8.08 \times 2) + (3,600/7.65 \times 4 \times {^2/_3}) + (3,600/7.65 \times 2 \times {^1/_3}) = 2,460$, or approximately 2,500 P.C./hr. The adjustment factors are the same as for the previous case.

Example of Application. —Intersection is two-lane vs two-lane; right turns = 10 percent; left turns = 10 percent; commercial vehicles = 5 percent; interference factor = 0.9; split = 60/40.

Required: To find possible capacity if present split is maintained. Using Table 10, possible capacity = $1,700 \times 0.9 \times 0.95 \times 1.02 = 1,700 \times 0.873 = 1,500$ vph.

Required: To find ultimate possible capacity (split = 50/50). Possible capacity = $1,900 \times 0.873 = 1,660$ vph.

Practical Capacity. —The Highway Capacity Manual (1) definition of practical capacity is based on the fact that most drivers are able to clear the intesection without waiting for more than one complete cycle. If the normal length of a cycle is assumed to be, say, 50 sec, it becomes possible to apply this definition to four-way stop intersections. Quoting the Manual: "With the normal short-time variation in flow, practical intersection capacities have been found to be approximately 80 percent of the possible capacities." Applying this factor, combined with the interference factor, practical capacities (before adjustments) are as follows:

Two-Lane Street vs Two-Lane Street. —Table 5 gives the practical capacities, in passenger cars per hour, for two-lane vs two-lane streets. The adjustment factors, except for interference factor, are the same as for possible capacity.

Four-Lane Street vs Four-Lane Street. —Practical capacity = $3,000 \times 0.9 \times 0.8 = 2,160$, or approximately 2,200 P.C./hr. The adjustment factors are the same as for the previous case.

Two-Lane Street vs Four-Lane Street. —Practical capacity = $2,500 \times 0.72 =$ 1,800 P.C./hr. The adjustment factors are the same as for the previous two cases.

POISSON DISTRIBUTION APPLIED TO DELAYS AND PRACTICAL CAPACITY

Because most driving inconveniences result from unnecessary waiting at intersections, delay is undoubtedly the best-suited single criterion on which to judge capacity. The Manual (1) definition of practical capacity is based on delay: 50 percent of vehicles or less waiting for a cycle length, or approximately 50 to 60 sec. If the rate of discharge of one lane through a four-way stop intersection is known, it is possible, assuming random arrival of vehicles and a Poisson distribution, to compute the volume of traffic

TABLE 5

PRACTICAL PASSENGER CAR CAPACITIES ON TWO-LANE vs TWO-LANE STREETS

Split	Practical Capacity (vph)
50/50	1,370
55/45	1,300
60/40	1,230
65/35	1,150
70/30	1,100

that will cause a certain percentage of drivers to wait for a certain selected time. Figure 10 shows approach volume as a function of percent of cleared periods, for 20-, 30-, 40-, and 50-sec periods. These periods are somewhat comparable to cycles; likewise, a period fails whenever more vehicles arrive at the intersection than can be discharged through. The average rate of vehicle discharge is taken as 6.00 sec, based on the assumption that 50 percent of the time, for practical capacity conditions, vehicles would enter the intersection alternately with the vehicles of the cross-street (L headway = 7.65 sec), and 50 percent of the time they would do so under no interference from the cross-street (N headway = 4.05 sec). Taking the average for the foregoing, H = (7.65 + 4.05)/2 = 5.85 sec, or a conservative value of 6.00 sec.

If, for instance, a 20-sec period is considered, whenever four or more vehicles arrive during that time, there is a failure, because on the average four vehicles require 24 sec to proceed through the intersection. For periods of 30, 40, and 50 sec, 5, 7, or 9 or more vehicles arriving during the respective periods produce a failure. From Poisson distribution, the probability of x vehicles arriving during time t is

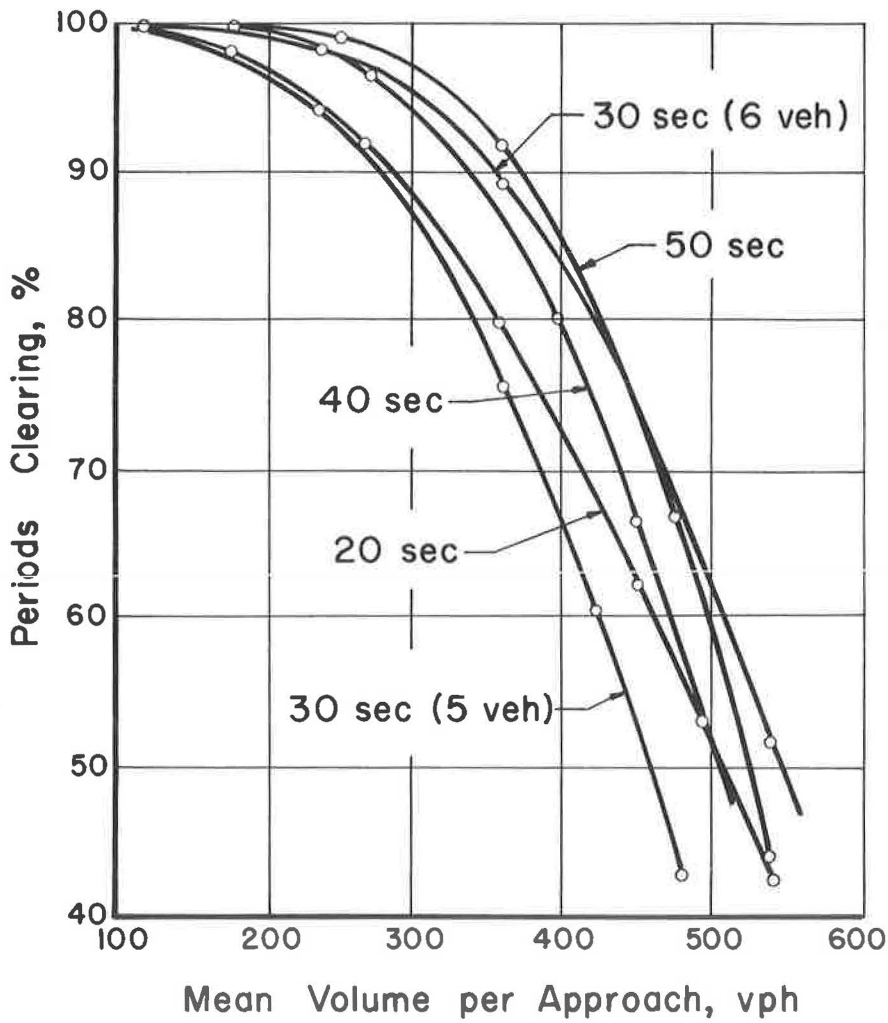

Figure 10. Relationship of approach volume to clearing period.

$$P(x) = \frac{e^{-m} m^x}{x!} \qquad (4)$$

in which

x = number of vehicles arriving during t sec;
m = mean number of vehicles arriving during t sec (=Vt/3, 600); and
V = vehicles per hour on the approach.

Inasmuch as $\sum^{\infty} P(x) = 1$, the probability of x or more vehicles arriving during time t is

$$P(x \text{ or more}) = 1 - P(\text{less than } x) = 1 - \sum_{0}^{x} \frac{e^{-m} m^x}{x!} \qquad (5)$$

For instance, if four or more vehicles fail a 20-sec period and a volume of 360 vph is assumed, m = 2 (or an average of 2 veh per 20-sec period) and P (4 or more) = 0.143 or 14.3 percent of failures. If the volume is 180 veh/hour, P (4 or more) = 0.018 or 1.8 percent of failures. It must be noted that a period failure affects the chances of the following period. Two periods (20 sec each) in a row will fail, for instance, if four vehicles arrive during the first and three during the second, or five during the first and two during the second or six during the first and one during the second. Summing up all these probabilities gives the probability of failure for any assumed volume.

The knee on each of the curves of Figure 10 is somewhere between 90 and 95 percent of cleared periods. A higher percentage of cleared periods requires an extremely low and unpractical volume on the approach, whereas a lower precentage increases delays very fast for a negligible additional volume on that approach. It is suggested, therefore, that practical capacity be of such a magnitude that 90 to 95 percent of the periods succeed in clearing.

It is debatable whether the period should be 20, 30, 40, or 50 sec. Obviously, the period length should be that which the majority of drivers is ready to accept as the maximum waiting time. Comparing the traffic behavior of a four-way stop (in which a driver moves forward toward the intersection in a step-by-step procedure, before "fighting" his way through) with the quiet and "almost relaxing" waiting in front of a red light, the maximum accepted waiting time is definitely much shorter than a cycle length, probably in the vicinity of 25 to 30 sec. Table 6 gives the volumes on one approach for four periods and three clearing percentages.

TABLE 6

VOLUME ON A ONE-LANE APPROACH

Periods Clearing (%)	Volume (vph)			
	20-Sec Period	30-Sec Period	40-Sec Period	50-Sec Period
90	285	6:355 319 5:282	335	372
92.5	262	6:333 296 5:258	314	353
95	233	6:312 270 5:228	288	330

An average of all Table 6 values gives a volume of 305 P.C./hr per lane of approach. Taking 300 P.C./hr as the practical capacity of a one-lane approach, it is found that 90 percent of the periods clear if their length is 24 sec, 92.5 percent do if their length is 33 sec, and 95 percent for a length of 41 sec. According to this criterion, the practical capacity of two-lane vs two-lane four-way stop intersections would be 300 × 4 = 1,200 P.C./hr, before adjustments.

CONCLUSIONS AND RECOMMENDATIONS

Because the results of this study are based on relatively limited data, it is possible that certain unknown location factors may have biased the samples. Therefore, additional data should be taken on the issue of four-way stop intersection behavior. Many characteristics of traffic, including commercial vehicles, parking, pedestrians, type of urban area, etc., were not covered. Their effects on the capacity of the type of intersection control studied are still to be determined. The observed intersections were located in the Chicago area only, and data from other parts of the country are needed. Some unexpected results, like the effect of left- and right-turning vehicles and split, demand further research. Additional studies should ascertain the effect of location and split on the capacity by analyzing a number of different intersections having the same split. Covariance, as a tool of statistical analysis, should be considered.

Table 7, which summarizes the most important results of this study, is suggested as a trial capacity chart for four-way stop intersections. It may be useful as an upper-limit volume warrant.

TABLE 7

CAPACITY CHART FOR FOUR-WAY STOP INTERSECTIONS WITH 50/50 SPLIT

Capacity Type	Capacity[1] (vph)		
	2-Lane × 2-Lane	2-Lane × 4-Lane	4-Lane × 4-Lane
Basic	1,900	2,800	3,600
Possible	1,900	2,500	3,000
Practical	1,200	1,800	2,200

[1] Before adjustments.

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Appendix

DISTRIBUTION OF PASSENGER CAR OBSERVATIONS

Headway Cell Length (sec)	Through Car Headways (no.)							L-Type Headways (no.)			
	Intersection A			Intersection B			Inters. C	Inters. A		Inters. B	
	L Type	N Type	I Type	L Type	N Type	I Type	L Type	Left Turns	Right Turns	Left Turns	Right Turns
0.0 - 0.9	-	0	0	-	0	0	-	-	-	-	-
0.9 - 1.5	-	1	0	-	1	0	-	-	-	-	-
1.5 - 2.1	-	5	1	-	3	2	-	-	-	-	-
2.1 - 2.7	-	9	4	-	8	11	-	0	0	0	0
2.7 - 3.3	-	6	3	0	8	10	-	0	2	0	3
3.3 - 3.9	0	6	4	2	18	8	0	0	4	0	0
3.9 - 4.5	4	3	4	2	15	8	0	4	4	1	0
4.5 - 5.1	3	7	6	3	13	11	8	3	3	3	3
5.1 - 5.7	8	5	3	7	11	8	2	6	1	1	4
5.7 - 6.3	9	2	3	12	7	4	4	7	3	5	1
6.3 - 6.9	18	1	2	10	0	5	10	3	2	3	2
6.9 - 7.5	15	1	2	12	1	1	17	3	1	3	1
7.5 - 8.1	10	0	0	12	2	0	67	7	1	0	2
8.1 - 8.7	10	1	0	7	0	0	53	3	0	1	0
8.7 - 9.3	11	0	1	4	-	2	32	5	0	0	0
9.3 - 9.9	3	-	1	2	-	0	17	2	0	1	0
9.9 - 10.5	1	-	0	1	-	-	0	2	1	0	0
10.5 - 11.1	1	-	-	0	-	-	-	2	1	2	0
11.1 - 11.7	1	-	-	1	-	-	-	0	-	1	1
11.7 - 12.3	1	-	-	0	-	-	-	2	-	0	0
12.3 - 12.9	4	-	-	-	-	-	-	1	-	-	-
12.9 - 13.5	0	-	-	-	-	-	-	0	-	-	-
13.5 - 14.1	0	-	-	-	-	-	-	-	-	-	-
14.1 - 14.7	0	-	-	-	-	-	-	-	-	-	-
14.7 - 15.3	2	-	-	-	-	-	-	-	-	-	-
15.3 - 15.9	0	-	-	-	-	-	-	-	-	-	-