Left-Turn Characteristics at Signalized Intersections on Four-Lane Arterial Streets

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The purpose of this research was to determine left-turn characteristics that would be suitable for defining a left-turn component of a signalized intersection computer simulation model.

The primary characteristic studied was the left-turn gap acceptance distribution and its variation with types of left turns (non-stop or turn from waiting position) and types of gaps in the opposing traffic stream. Studies were conducted at 6 intersections in 4 large Texas cities using multiple-event recorder and 16-mm time-lapse filming techniques to develop data. Over 1000 left-turning vehicles were observed for gap acceptance and other left-turn characteristics.

Gap acceptance distributions were developed on rectangular coordinates, probability-logarithmic coordinates and as regression lines on probit-log time coordinates. Chi-square tests show that there are differences in gap acceptance distributions for moving vs stopped position turns and between distributions for different types of gaps. Comparisons with more recent data from California were very favorable while other research for different left-turn situations was shown to be quite different.

•THE research reported in this paper was the first phase of a project which developed a digital computer model for the simulation of traffic operating through a signalized intersection (12).

In preparing to formulate a model it was found that the literature adequately defined most intersection characteristics but was practically devoid of data relating to left-turn characteristics. Therefore, it was necessary to conduct enough studies to enable these characteristics to be defined and used in the simulation model. This research was necessarily limited to isolated signalized intersections on 4-lane arterial streets, since funding and time would not permit a larger scope of study. Intersection approaches studied included both those with and without separate left-turn lanes, but none of the signals were equipped with separate left-turning phases.

The principal characteristics were the acceptable gap distributions applicable to drivers of vehicles turning left from the inside lane of one approach across the two opposing lanes of traffic. Other left-turn characteristics evaluated include:

1. The percentage of drivers that "jump-the-gun" at the beginning of a green phase;
2. The location within the intersection area that left-turn drivers position their vehicles while evaluating gaps in the opposing traffic stream;
3. The frequency of left turns made after the end of the green phase; and
4. The change in accepted gap requirements with delay.

PREVIOUS RESEARCH

When a driver prepares to make a left turn at a signalized intersection, he will generally encounter an opposing traffic stream which may consist of one, two, or three

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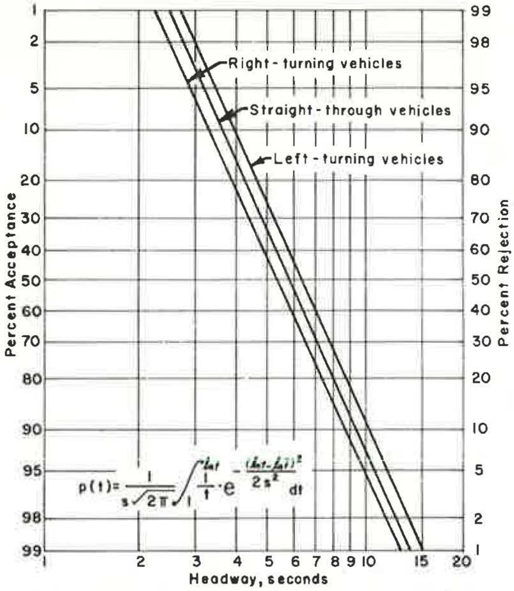


Figure 1. Gap acceptance distributions for vehicles passing a stop sign (2).

lanes of traffic depending on the location. The left-turning driver has to evaluate the gap sizes in this opposing stream and select an opening which he considers large enough for him to cross through the stream safely into the cross street. The gap is known as the acceptable gap for this particular maneuver.

Very little earlier research in determining acceptable gap distributions was directly applicable to the type of maneuver described. Raff (1) and Bissell (2) have provided data for vehicles leaving a cross street under stop sign control, but they do not apply to a 4-lane street left turn under signal control. Bissell's distributions are shown in Figure 1 and were used in Kell's simulation work (3). (Note the typical log-normal form for these distributions.)

More recent studies by Solberg and Oppenlander (4) provided gap and lag-acceptance data for minor street vehicles crossing or entering main street traffic streams from a stopped position. In addition, they utilized the technique of probit analysis which permitted a statistical evaluation of differences in gap-acceptance times. In general, they concluded that there was general agreement among the three methods investigated.

Research reported by Wagner (5) deals with the same type of gap and lag acceptances at a single intersection, but he investigated the effects of certain factors on driver decisions. These factors included vehicle type, pressure of traffic demand, direction of movements through the intersection, sequence of gap formation, and conditions on the opposing side-street approach.

A number of student theses at the Yale Bureau of Traffic have dealt with left turns but only three have dealt specifically with gap-acceptance characteristics. These were limited studies dealing with 2-lane, two-way traffic streams, each conducted for a single intersection in the city of New Haven. Kaiser (6) found for a sample of 158 drivers of left-turning vehicles at an unsignalized intersection that the smallest gap accepted was 3.75 sec and the largest gap rejected was 4.75 sec. Clark (7), at another unsignalized intersection, found a critical gap size (size where there are an equal number of rejected gap sizes larger than this size and accepted gap sizes smaller than this size) of 3.2 sec as compared with 4.2 sec in Kaiser's study; the difference is probably attributable to the geometric differences and location of the two intersections. Noblitt (8) found gap acceptances for left-turning truck combinations to be 1.4 to 1.8 times as large as the required gap for cars, and 1.2 to 1.5 times as large as the required gap for single-unit trucks.

Based on 500 field observations on 2-lane two-way streets, Kell (9) found the left-turn gap-acceptance distribution given in Table 1. Again, he pointed out the log-normal nature of these data.

The most recent field studies evaluating left-turn gap and lag acceptances were conducted by the Traffic Research

TABLE 1

GAP ACCEPTANCES BY LEFT-TURN VEHICLES ON TWO-LANE, TWO-WAY STREETS[a]

Gap Size (sec)	Cumulative % Accepting	Gap Size (sec)	Cumulative % Accepting
1.0	0	4.5-5.0	94.7
1.0-1.5	1.4	5.0-5.5	96.4
1.5-2.0	10.2	5.5-6.0	97.9
2.0-2.5	18.3	6.0-6.5	98.2
2.5-3.0	31.3	6.5-7.0	98.5
3.0-3.5	50.0	7.0-7.5	99.3
3.5-4.0	64.6	7.5-8.0	99.4
4.0-4.5	85.3	8.0+	100.0

[a]After Kell (9).

TABLE 2

SUMMARY OF STUDY SITE CHARACTERISTICS

CHARACTERISTIC	INTERSECTION NUMBER 1	2	3	4	5	6
CITY	AUSTIN	FT. WORTH	HOUSTON	HOUSTON	HOUSTON	WACO
STREET NAMES (STREET STUDIED LISTED FIRST)	24th. ST. AT LAMAR	UNIVERSITY AV. AT E-W FREEWAY FRONTAGE RD.	SHEPHERD ST. AT W. GRAY	WASHINGTON ST. AT SAWYER	FRANKLIN ST. AT CAROLINE	18th. ST. AT WACO DRIVE
INTERSECTION TYPE	4—WAY	TEE	4-WAY	TEE	TEE	4-WAY
SIGNALIZATION	FULL-ACTUATED	UNSIGNALIZED	FIXED-TIME 62 & 75 SEC. CYCLE LENGTHS (50-50 SPLIT)	FIXED-TIME 70 SEC. CYCLE (75-25 SPLIT)	UNSIGNALIZED	FIXED-TIME 62 SEC. CYCLE (40-60 SPLIT)
ON STUDY APPROACH (1/2 OF FULL STREET WIDTH)						
NO. OF LANES & APPROACH STUDIED	2-BOTH	3-NORTHBOUND	2-SOUTHBOUND	2-EASTBOUND	2-WESTBOUND	2-BOTH
CHANNELIZATION	NONE	MEDIAN OPENING	NONE	NONE	PAINTED-LEFT-TURN SLOT	LEFT-TURN SLOTS OUTLINED BY 6" RAISED BUTTONS
PARKING	NONE	NONE	NONE	YES-PROHIBITED 1-WAY AT PEAK	NONE	NONE
MAXIMUM 1-WAY VOLUME, VPH	700	1250	1050	2000	1170	800
% LEFT TURNS	5-12	10-30	5-20	5-10	15-40	10-25
STUDY TYPE	MOTION PICTURES ON GREEN PHASE	20-PEN RECORDER & LIMITED TIME-LAPSE PICTURE	1-SEC. TIME-LAPSE PICTURES	1-SEC. TIME-LAPSE PICTURES	1-SEC. TIME-LAPSE PICTURES	20-PEN RECORDER & 1-SEC. TIME-LAPSE PICTURES
HOURS STUDIED	7-8 AM, 5-6 PM	8 AM - 4:30 PM	2:30-5:15 PM	3-6 PM	7-9 AM	11 AM - 6 PM

Corporation (10). They were interested in validating probability tables used in left-turn decision components of signalized intersection simulation models. Three intersections in the Berkeley-Oakland area of California were studied with left-turn gap and lag-acceptance distributions being developed for streets that were 40 to 46 ft wide.

INTERSECTION FIELD STUDIES

Variables

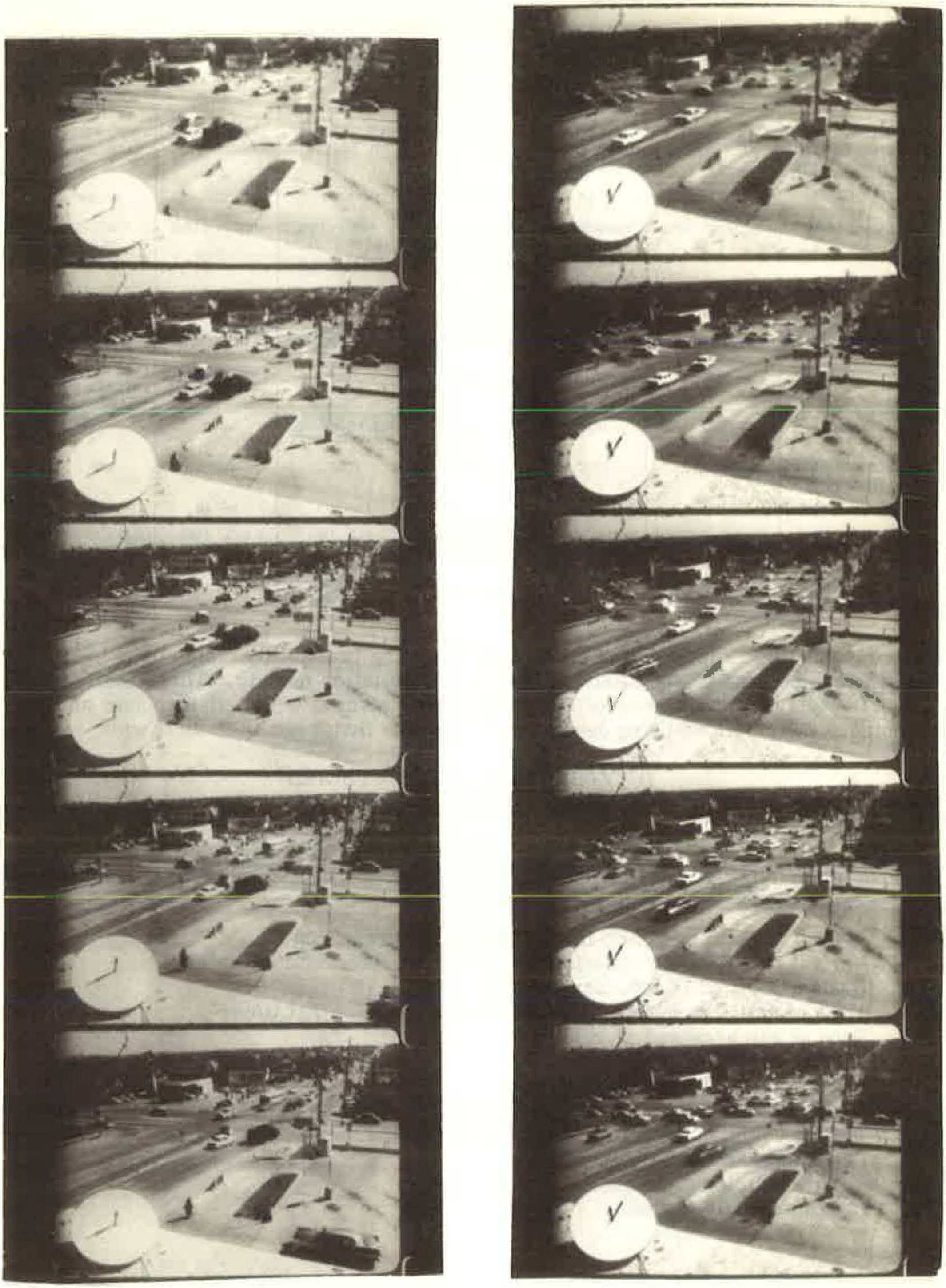
To evaluate gap acceptance of left-turning drivers and to provide other data for the purpose of verifying simulation output, it was decided that the following variables had to be measured in any field studies conducted:

1. Arrival time of each left-turn vehicle at intersection;
2. Arrival time of each opposing vehicle in the intersection center;
3. Waiting position of left-turn vehicle;
4. Time of actual turn maneuver and signal phase at that time;
5. Type of gap accepted or rejected;
6. Vehicle type;
7. Sex and approximate age of driver;
8. Arrival and depature time of each vehicle from intersection approach "system";
9. Traffic volumes operating in both directions;
10. Percentage of turns in each lane;
11. Signal cycle length and phasing split; and
12. Length of study period.

Site Selection

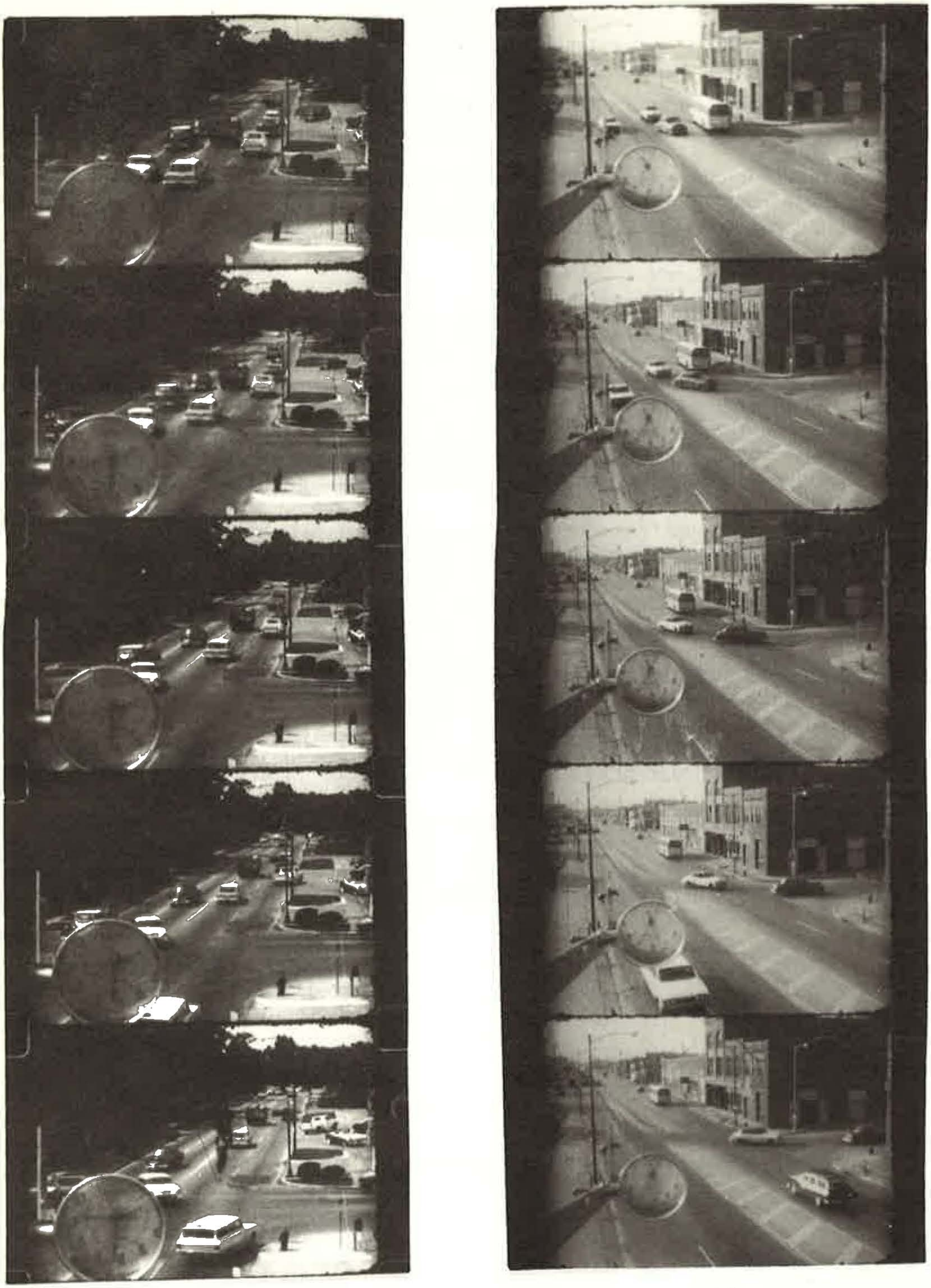
It is difficult to locate many intersections with all the desirable characteristics that one would prefer for study purposes. All of the intersections finally selected were not ideal but did provide a good range of traffic volume and percentage of turns.

On the basis of preliminary investigations, six intersections were selected for detail studies. They were located in the following cities: Austin, 1; Ft. Worth, 1; Houston, 3; and Waco, 1. Specific characteristics of each study site are summarized in Table 2.



(a) (b)

Figure 2. Typical time-lapse film strips, 18th at Waco Drive: (a) "jumping-the-gun" and (b) clearing on the red phase.



(a) (b)

Figure 3. Typical time-lapse film strips, Houston: (a) turning on amber, yielding to opposing right turn and (b) gap acceptance.

Although principally interested in 4-way signalized intersections, two of the locations studied were unsignalized T-intersections with relatively high volumes (Table 2). This was permitted for the following reasons:

1. Gap acceptance for left turns from a stopped position at an unsignalized intersection should be the same as those operating on the green phase of a signalized intersection; and
2. A relatively high percentage of left turns at this type of intersection are made without stopping and therefore gap sizes required for this different maneuver could be evaluated and applied to the comparable maneuver at a signalized intersection.

Study Methods Considered

Accepted methods for obtaining the required data include the use of a multiple-event recorder connected to road tube actuated air switches and hand switches, 16-mm motion-picture photography, 16-mm time-lapse photography, or combinations of these methods. Each of these techniques was used for at least two hours of study at one location. The details of each study method can be obtained elswhere (12).

On the basis of these studies, it was decided that the most satisfactory and economical procedure, from both field study and data analysis time standpoints, was the time-lapse photography technique. This procedure was used for all three Houston studies (Table 2).

A 16-mm camera and tripod were set up on either a nearby roof-top or a platform truck within 250 ft of the intersection. The single frame button on the camera was actuated at 1-sec intervals through a special electrical timer-solenoid circuit.

This technique required only one-tenth as much film as the motion picture technique and still provided gap measurements to an accuracy of ±0.5 sec. A filming technique is more desirable than the 20-pen recorder method, since a complete picture of the intersection system is available at any instant and complete analysis of a situation can be obtained by running and rerunning the film through a projector. Typical film strips obtained by this method are shown in Figures 2 and 3.

Data on left-turn operation obtained from time-lapse films were transferred to punch cards and a Fortran program was written for an IBM 709 digital computer to analyze these data.

There were four types of gaps considered in this analysis of 4-lane street studies (Fig. 4). There are two types of lane gaps, i.e., gaps formed by two successive inside-lane vehicles or two successive outside-lane vehicles. In addition there are two types of offset gaps, i.e., gaps formed by a vehicle in one lane trailed by a vehicle in the adjacent lane.

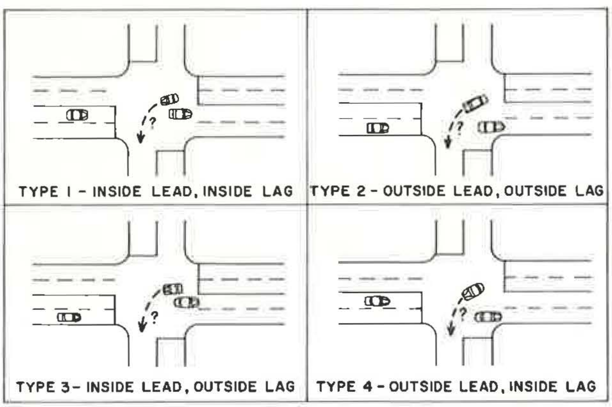


Figure 4. Opposing traffic stream gap types confronting left-turn vehicles.

Other studies (4, 5, 6, 10) have distinguished between "gaps" and "lags" in developing acceptance distributions. The difference in these two terms is shown by Figure 3b. The first left-turn vehicle accepts a gap formed by the bus and the trailing station wagon. The second left-turn vehicle accepts a lag or the time elapsed between its arrival at the center of the intersection and the arrival of the station wagon at the same location (in its own lane). In this research, there was generally no distinction between lags and gaps except for turns made without stopping. The drivers of these vehicles accept lags rather than gaps.

RESULTS

The principal objective of the field studies was to determine the distributions of acceptable gaps for left-turning vehicles on 4-lane arterial streets. This included variations for moving and stopped vehicles and different types of opposing gaps.

Other characteristics of left turns were also noted such as the waiting or starting position in the intersection area, the percentage of left-turning vehicles that jump-the-gun at the start of the green phase, the frequency of left turns clearing the intersection after the end of the green phase, the percentage of left-turn drivers accepting gaps smaller than the largest gap previously rejected, and the variation of gap acceptance with driver characteristics.

Turn Types and Starting Positions

Aside from left turns that jump-the-gun, most left turns at a signalized intersection under moderate to heavy traffic conditions are made from a stopped or waiting position in the intersection proper.

Other left turns may be made while the vehicles are slowly moving (or creeping) into the intersection proper; still others are made by vehicles that never slow much below maximum permissible turn speed. Under relatively heavy traffic conditions, these vehicles follow on the "heels" of other left-turn vehicles; under relatively light traffic conditions, the majority of the turns are likely to be nonstopping turns.

Analysis of data for 174 turns at the most typical intersection studied, West Gray at Shepherd in Houston, showed 126, or 72.4 percent, were made from a stopped position. Of these 126 turns, 75, or 59.6 percent, were waiting in a position near the center of the intersection; 41, or 32.5 percent, were waiting in a position about half-way into the intersection from the stop line; and the remaining 10 (9 of which jumped-the-gun) were made from the stop line.

At the unsignalized intersection of Franklin and Caroline Streets in Houston, data for 690 left turns showed 447, or 64.9 percent, were moving-type turns.

Left-Turn Gap Acceptance

There are four possible gap types to be found in the opposing traffic stream (Fig. 4). In each of the three principal studies, gap acceptance distributions were determined for each gap type. For each particular gap size (nearest 0.5 sec), the percent of gaps accepted is defined by the number of these gaps accepted divided by the total number of these gaps accepted and rejected. Turns that jumped-the-gun, forced their turn, or completed their turn after all opposing traffic had stopped were not considered to have accepted a normal gap.

Turns From a Stopped Position—The largest sample of turns from a stopped position came from the intersection of Franklin and Caroline Streets in Houston. A total of 232 accepted gaps were distributed as to type as follows: 51, Type 1; 66, Type 2; 55, Type 3; and 60, Type 4. These 232 turns also rejected a total of 809 gaps. The resulting cumulative distribution of acceptable gaps by type is shown in Figure 5, where there is considerable scatter of data points.

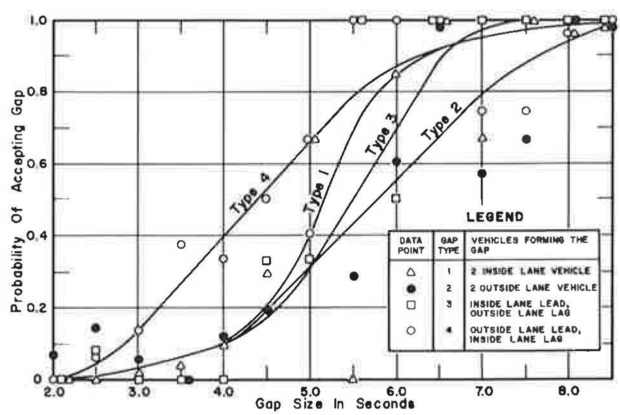


Figure 5. Probability of left-turn vehicle accepting gap from stopped position at unsignalized, channelized T-intersection; Franklin at Caroline, Houston.

When unsatisfactory turns (forced, unopposed, etc.) were eliminated from the 126 vehicle sample at the West Gray and

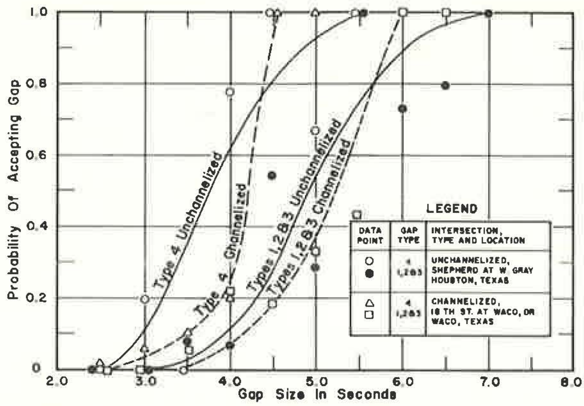


Figure 6. Probability of left-turn vehicle accepting gap from stopped position at signalized 4-way intersections.

Shepherd location, there were only 75 turns left. Accepted gaps distributed as to type included: 14, Type 1; 21, Type 2; 11, Type 3; and 30, Type 4. These sample sizes were too small to provide satisfactory cumulative curves, but there did appear to be a distinct difference between Type 4 gaps and the other 3 combined (Fig. 6).

At the Waco location, only those turns that could be verified by time-lapse films in the same manner as in the other two studies were used for further comparison. With a high percentage of turns being made without opposition or jumping-the-gun, only 35 of 232 turns could be analyzed, providing data on 16 Type 4 acceptable gaps as compared with 19 gaps of Types 1, 2, and 3. The cumulative distributions are also shown in Figure 6.

Turns From a Moving Position—The gap accepted by a moving left-turn vehicle is not defined by two opposing vehicles but by the difference in arrival times (at the intersection center) of the turning vehicle and the nearest opposing vehicle. (Some authors designate such a gap as a lag.) Therefore, there were only two types of gaps to be evaluated; one with the nearest opposing vehicle in the outside lane (Type 2) and the other with the nearest opposing vehicle in the inside lane (Type 1).

The 447 moving left-turns filmed at Franklin and Caroline Streets in Houston were classified as either creeping or moving at normal turn speed as they began their turn. An analysis of gap acceptance distributions for both conditions showed no significant difference between the two for both Type 1 and Type 2 gaps. The data were then separated into two groups by type providing 185 Type 1 and 262 Type 2 gaps.

Since a moving turn does not reject a gap, it was necessary to check the first gap rejected by each of the 243 left turns that stopped at this location before making the turn. Analysis provided 129 Type 1 and 114 Type 2 gaps that were rejected. The cumulative gap acceptance distributions provided the two curves shown in Figure 7. As would be expected for a given gap size, a lower percentage of drivers will accept the gap if it is formed by an opposing vehicle in the the outside lane, as compared with one in the inside lane; it takes longer to clear the outside lane than the inside lane when making the left turn.

Left Turns That Jump-the-Gun—It was observed that many drivers whose left-turn vehicle is at the head of the inside lane or left-turn channelization queue when the signal changes to a green indication will jump-the-gun, i.e., make the turn before the opposing traffic enters the intersection. In some states this maneuver is outlawed; in others it is encouraged—but it definitely does occur at the intersections studied in Texas cities.

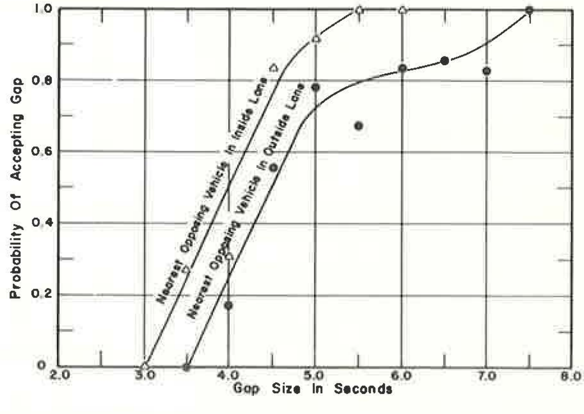


Figure 7. Probability of left-turn vehicle accepting gap without stopping at unsignalized, channelized T-intersection; Franklin at Caroline, Houston.

To determine the probability of its occurrence, the number of signal cycles at which a left turn was

TABLE 3

PROBABILITY OF LEFT-TURN DRIVER'S JUMPING-THE-GUN

Intersection Location	Approach Type	No. of Signal Cycles			Probability of Occurrence
		Total	With L. T. at Queue Head	With LT's Jumping-the-Gun	
Houston	Nonchannelized	130	35	6	0.171
Austin 1	Nonchannelized	65	12	2	0.167
Austin 2	Nonchannelized	65	8	0	0.000
Total	Nonchannelized	260	55	8	0.145
Waco 1	Channelized	127	79	8	0.101
Waco 2	Channelized	127	86	16	0.186
Total	Channelized	254	165	24	0.145

observed at the head of the inside lane or channelized queue was divided into the number of cycles when such a vehicle jumped-the-gun. The results for 5 signalized approaches are given in Table 3. The same percentage occurred for the total observations of each type of intersection.

Change of Required Acceptable Gap—As hypothesized, there were a number of drivers of left-turn vehicles who accepted a gap that was smaller than the largest one previously rejected. In general the difference was only about 0.5 to 1.0 sec. The frequency of such a change in gap requirements and consequent probability of occurrence is given in Table 4. Although there was an attempt to relate this occurrence with vehicle waiting time and opposing traffic stream density, no relationship was apparent.

Turns Made on Yellow and Red Phases—Many left turns were completed after the signal phase had changed to yellow or even red. Observation of 260 cycles of operation on 3 nonchannelized approaches in Houston and Austin found 58 left-turn vehicles still waiting to turn when the green phase ended. All 58 of these turns were then completed, 40 percent of them on the red phase.

At these and other locations, more than one vehicle turned after the end of the green phase. As many as four turned on one occasion at the Waco location, the last one almost colliding with cross street vehicles that had started legally (Fig. 2b).

ANALYSIS OF GAP DISTRIBUTIONS

The distribution curves in Figures 5, 6, and 7 were fitted by eye to the highly scattered data after attempts to fit various mathematical distributions were unsuccessful. However, this type of data usually takes a log-normal form and can be represented by straight lines on probability X log paper as in Figure 1. The other statistical treatment of this type of data involves the use of probit analysis as described by Finney (11). This technique is used successfully in biological assay work where it is necessary to analyze the relationship between insecticide concentrations (or dosages) and its effectiveness in percent of insects killed at each concentration. The typical cumulative distribution of percent killed vs insecticide concentration takes the form of the nonlinear normal

TABLE 4

PROBABILITY OF LEFT-TURN DRIVER'S REDUCING ACCEPTABLE GAP

Study Location and Approach Type	No. of Left Turns		Probability of Occurrence
	Total	Accepting Gap Smaller Than Largest Rejected	
Houston, nonchannelized	119	14	0.117
Waco, channelized	241	22	0.091
Grand total	360	36	0.100

TABLE 5

PROBIT ANALYSIS REGRESSION EQUATIONS

Location and Turn Type	Gap Types	Regression Equation	df	χ^2
Franklin at Caroline, Houston—turns from stopped position (channelized)	1	Y = -1.265 + 8.937X	4	0.604
	2	Y = 1.795 + 4.749X	4	2.687
	3	Y = 0.469 + 7.609X	1	1.299
	4	Y = 0.455 + 6.985X	4	0.604
	All	Y = 1.007 + 5.931X	5	12.752[a]
W. Gray at Shepherd, Houston—turns from stopped position (unchannelized)	1-3	Y = -4.044 + 13.342X	3	0.867
	4	Y = -0.747 + 11.018X	2	1.208
	All	Y = -2.142 + 11.094X	4	0.803
18th St. at Waco Dr., Waco—turns from stopped position (channelized)	1-3	Y = -5.241 + 15.368X	2	1.690
	4	Y = -2.310 + 14.075X	2	8.500[a]
	All	Y = -3.840 + 13.662X	2	2.157
Franklin at Caroline, Houston—turns without stopping (channelized)	1	Y = -8.027 + 21.874X	3	0.142
	2	Y = -1.979 + 10.807X	4	2.240
	All	Y = -2.638 + 11.795X	4	1.245

[a]Significant at 5 percent level.

sigmoid curve. By utilizing the probit transformation, the relationship is expressed in linear form.

Solberg and Oppenlander (4) applied this technique to lag and gap acceptances at stop-controlled intersections. They showed that the probit of the gap acceptance percentage, Y, was related to the logarithm of the time gap, X, by the straight-line equation

$$Y = a + bX$$

They also determined the parameters of the tolerance distribution, its mean and variance, as well as the median gap and lag acceptances. The probit transformation is given by the linear equation

$$Y = 5 + \frac{1}{\sigma}(X - \mu)$$

where Y is the probit of acceptance percentages and X is the log of the time gap. The median is estimated from values of X when Y = 5 (when percent acceptance = 50 percent), which is the median effect dosage in the biological assay work.

Probit Analyses

The probit transformation was applied to the gap acceptance data and produced the linear regression equations in Table 5 and Figures 8 through 12. Table 5 includes the results of testing the goodness-of-fit of these equations to the experimental data. The data were grouped in 1-sec intervals (1.26-2.25, 2.26-3.25, etc.) to eliminate some of the inconsistencies. This shows that most of the experimental data can be represented adequately by the straight-line probit relationships.

To ascertain if there were differences between types of gaps and similar data at different locations further evaluations were made using the χ^2 test.

TABLE 6

CHI SQUARE TEST
OF GAP DISTRIBUTION DIFFERENCES

Intersection	Gap Types Compared	df	χ^2
Franklin at Caroline, stopped turns, channelized	Type 1 vs Type 4	5	14.09[a]
	Type 2 vs Type 4	4	5.81
	Type 3 vs Type 4	2	0.47
	Type 1 vs Type 2	3	3.36
Franklin at Caroline, moving turns	Type 1 vs Type 2	2	6.59[a]
	All moving vs all stopped	5	11.28[a]
W. Gray at Shepherd, unchannelized	Types 1-3 vs Type 4	1	28.40[b]
	All vs all stopped turns at Franklin-Caroline	5	3.94
18th St. at Waco Dr., channelized	All vs all stopped turns at Franklin-Caroline	5	11.24[a]

[a]Significant at 5 percent level.
[b]Significant at 1 percent level.

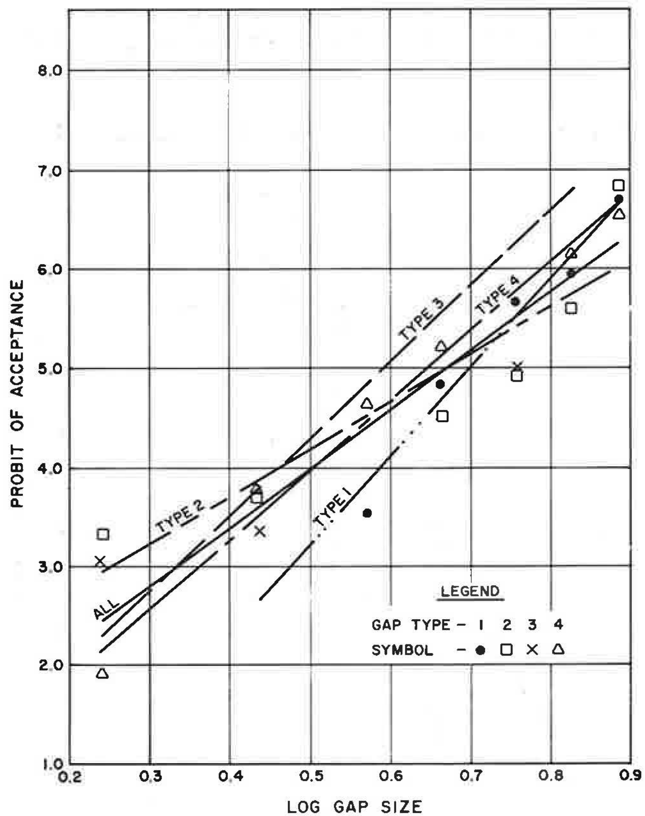


Figure 8. Probit regression lines by gap types, Franklin at Caroline, turns from stopped position (Houston).

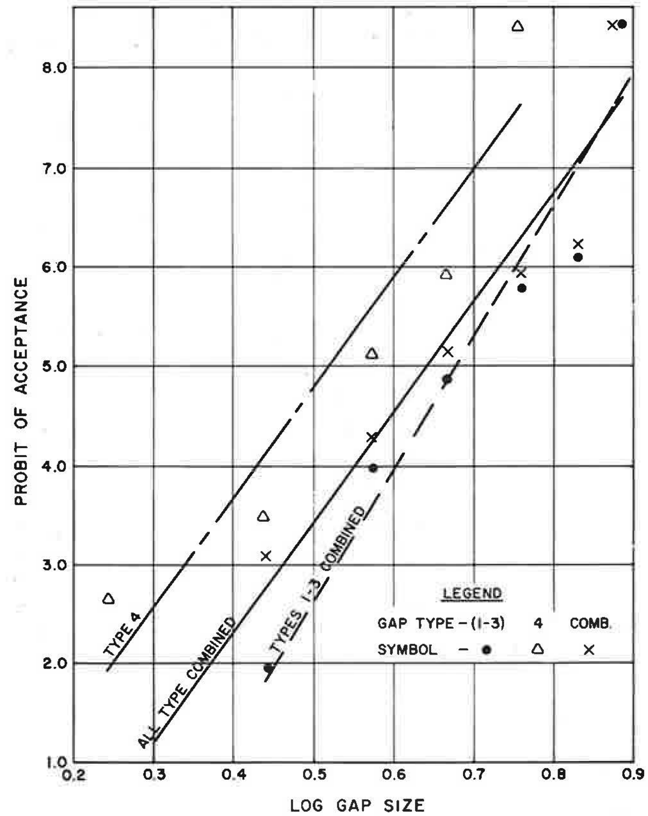


Figure 9. Probit regression lines by gap types, W. Gray at Shepherd, unchannelized (Houston).

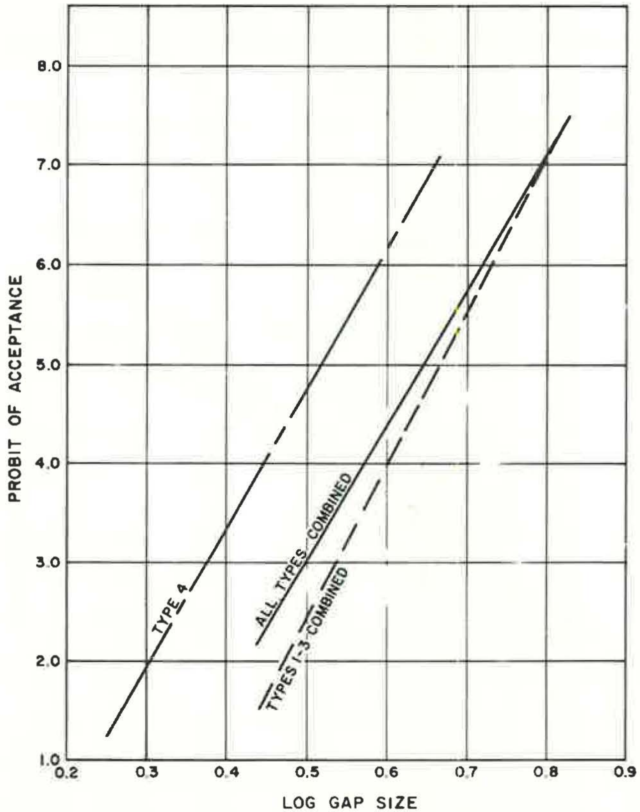


Figure 10. Probit regression lines by gap types, 18th St. at Waco Drive, channelized (Waco).

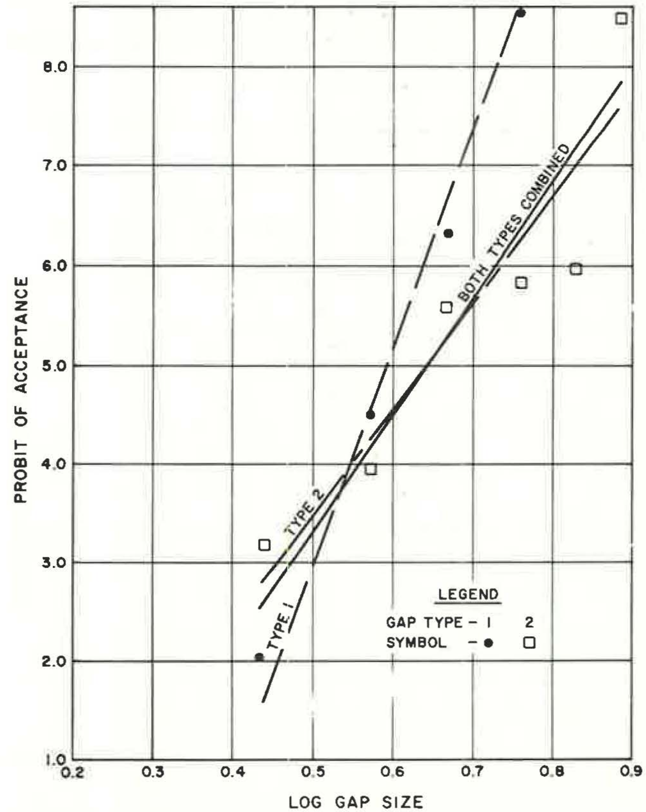


Figure 11. Probit regression lines by gap types, Franklin at Caroline, moving turns (Houston).

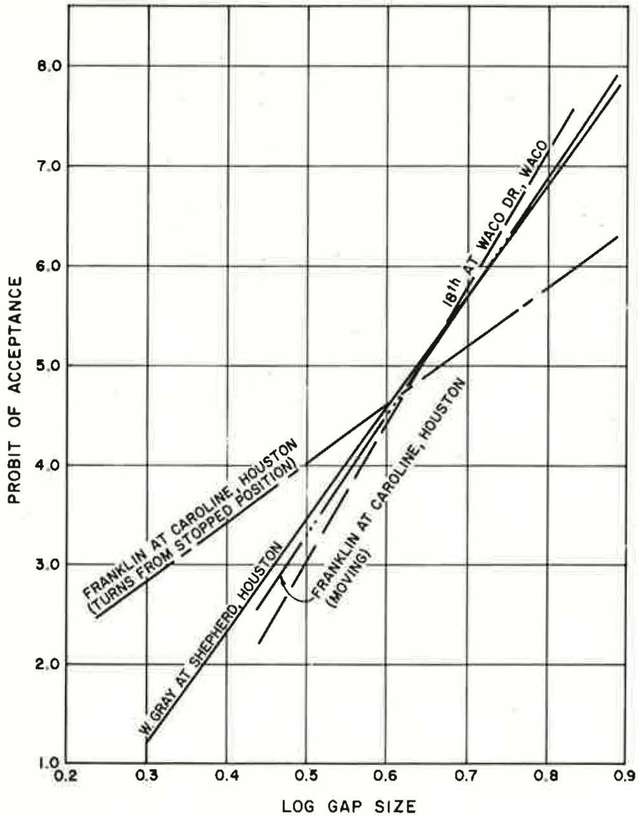


Figure 12. Probit regression lines, all gap types combined.

Observed data for one group were tested against the regression line of the group being used as the expected or theoretical data. The results are given in Table 6. There is a significant difference between Type 1 and Type 4 gap acceptance distributions at the Franklin and Caroline intersection in Houston and between acceptance of Types 1, 2, and 3 gaps as a group vs Type 4 gap acceptance at the Waco intersection.

For moving turns there is also a significant difference between the gap (lag) acceptance distributions for Types 1 and 2 gaps (lags). Furthermore there is a significant difference between the gap acceptance distribution for turns made without stopping as compared with the distribution for turns made from a stopped position.

When all gap types are combined into one distribution, the somewhat limited data of the Waco intersection produce a distribution that is different from that obtained at the Houston intersection. (Both intersections are channelized but the Houston one is unsignalized.)

Comparisons With Other Research

It is interesting how the distributions developed in this study compare with those of other researchers. Figure 13 compares two distributions with combined (all gap types) data from this study with the combined left-turn gap acceptance data from the validation study of Traffic Research Corporation (10) and the left-turn gap acceptance from a cross street developed by Bissell (2) and Solberg and Oppenlander (4).

The gap acceptance distributions obtained from the intersection of Franklin and Caroline compare quite favorably with those obtained by Traffic Research Corporation. For

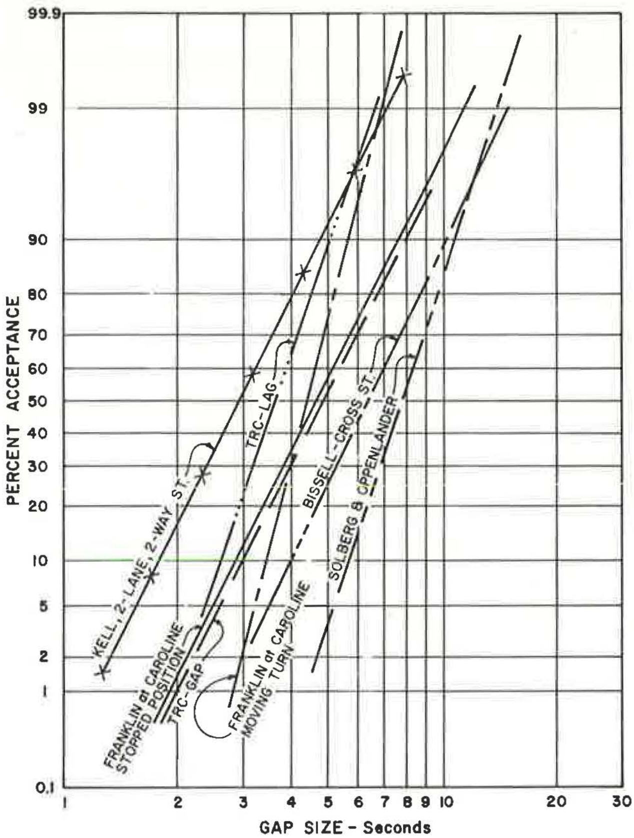


Figure 13. Gap acceptance comparison.

turns from a stopped position, the distribution is almost identical with that obtained for the combined California data. The moving-turn gap distribution is similar to the TRC acceptable lag distribution but has a steeper slope.

As would be expected, there is a definite difference between distributions obtained for left turns from cross streets under stop sign control and the left turns across opposing traffic streams as reported in this paper. Another comparison with Kell's data (9) shows that left turns across a single-lane opposing stream require smaller gaps than turns across a two-lane stream (Fig. 13).

CONCLUSIONS

On the basis of the research reported in this paper the following conclusions seem to be in order. Although these are based on a limited number of studies, it is felt that the results are representative of similar types of signalized intersections.

1. A time-lapse 16-mm filming technique that utilizes 1-sec intervals was found to be the most satisfactory and economical method for studying gap-acceptance characteristics of left turns at a signalized intersection.

2. More than one gap-acceptance distribution or one critical value is necessary to cover the existing range of left-turn types on a 4-lane street: (a) moving-turn gap or lag-acceptance distributions are significantly different from distributions for turns made from a stopped position; (b) shorter gaps are required for most moving turns, if the next opposing vehicle is in the inside lane as compared with one in the outside lane; and (c) for turns made from a stopped position, there is evidence that Type 4 gaps will more likely be accepted than any of the other three gap types of the same size.

3. There was no appreciable difference between gap acceptance requirements for left turns and other turn characteristics on a channelized approach as compared with those on an unchannelized approach. In general, it is very rare that a gap smaller than 2 sec will be accepted or that one larger than 8 sec will be rejected.

4. With the exception of turns that jump-the-gun or turn without stopping almost every left turn is made from a waiting position within the intersection area ahead of the stop line. There are likely to be twice as many turns made from a position (front of vehicle) at the center of the intersection than from a position about half-way between the stop line and the intersection center.

5. There are a significant number of drivers who will jump-the-gun in turning left at the beginning of a green phase, and this feature should be incorporated in any left-turn model. The probability of this occurring appears to be about 0.15 for all left-turn vehicles at the head of a queue when the signal first displays the green phase.

6. Although 10 percent of left-turning drivers accepted gaps smaller than the largest gap rejected, this research did not establish any significant relationships with driver delay or opposing traffic stream characteristics to explain this phenomenon. The difference in gap sizes being generally less than 1 sec makes this result of little value to a simulation model.

7. A large number of left turns will be completed after all opposing traffic has passed and many will turn even after the green phase has ended. This fact makes it difficult to collect gap acceptance data under light to moderate traffic conditions.

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