An Evaluation of Fundamental Driver Decisions And Reactions at an Intersection

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There has been broad interest and increasing emphasis in the development and utilization of mathematical theories and computer simulation models of traffic flow phenomena. The development and effective application of these new techniques is unalterably dependent on a fuller understanding of the fundamental parameters of vehicle and driver behavior. In this connection, there is no substitute for the measurement and analysis of real traffic behavior under actual operating conditions.

This paper reports the field measurement and analysis of fundamental driver decision and reaction parameters at a stop-signed intersection. The following research objectives were pursued:

1. A detailed examination to determine and verify the characteristics of lag and gap acceptance of drivers waiting at a stop sign.
2. Evaluation of the influence of the following traffic factors on driver decisions: (a) vehicle type, (b) pressure of traffic demand, (c) direction of movements through the intersection, (d) sequence of gap formation, and (e) conditions on the opposing side street approach.
3. Determination of the characteristics of starting delay time in accepting lags and gaps, and evaluation of the influence of certain traffic factors on these distributions.

The results strongly supported earlier findings which indicated the relationship between lag or gap size and percent acceptance is log-normal. Of the traffic factors studied, those which significantly influenced driver decisions were (a) pressure of traffic demand, (b) direction of traffic movement during periods of heavy demand, and (c) sequence of gap formation during periods of heavy demand.

Definitions of starting delay time in accepting lags and gaps were set forth. Analysis of field observations of this parameter indicated that factors which had important influence on driver decisions, namely, pressure of traffic demand and sequence of gap formation, had similar and significant effects on starting delay times.

•IN RECENT years there has been broad interest and increasing emphasis in the engineering and scientific communities in the development and utilization of mathematical theories and computer simulation models of traffic flow phenomena. As in other

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more mature fields of endeavor, progress on this front has been slow, difficult, and often indirect. In the beginning, this work was principally academic, but the practical value of these new tools is steadily winning a place of importance in the profession. The time lag between development by the theoretician and implementation by the practitioner, however, has been characteristically long.

Although the many theories and models are diverse in purpose and approach, all of them are inherently dependent on the availability, in one form or another, of fundamental parameters of vehicle and driver behavior. The models are only as good as the input data which they use. In this connection, there is simply no substitute for the measurement and analysis of real traffic behavior under actual operating conditions. It is ironic that, in the face of greater need, some have recognized a subordination of interest in the tedious work of comprehensive field observations of the fundamentals of behavior. Fundamental parameters must be pursued more microscopically to take into account the complexity of interactions existing in the real traffic situation. This would serve to broaden the base for theoretical accomplishments and lead to more realistic models which can be more effectively applied by the profession.

The problem of dealing with the conflict of vehicles traveling on roadways intersecting at grade has always been a primary concern of traffic engineers. Intersections at grade remain critical elements of the highway system in that they are principal sources of accidents and delays; furthermore, their capacities restrain the entire system's ability to process traffic. The most common method of controlling this conflict is the stop sign. Traffic operation and driver performance associated with stop sign control of intersections has been the subject of extensive empirical and theoretical study. Beginning with the classic work of Greenshields (1), which included both observation and sample applications of probability theory, many have carried the work forward, including Raff (2), Herman and Weiss (3), Bissell (4), and a host of others (5-11). Yet our understanding of this universal problem remains significantly incomplete.

This paper reports a limited but intensive field study and evaluation of fundamental driver decisions and reactions at a stop-signed intersection. The emphasis was not so much on the absolute values of the statistics compiled, since these were peculiar to the particular intersection studied, but rather on uncovering the degree of influence of certain traffic factors on the fundamental driver decisions and reactions.

OBJECTIVES AND TERMINOLOGY

Research Objectives

At an intersection controlled by a stop sign, where delays are for the most part encountered by vehicles on the yielding street, the overall efficiency of performance is highly dependent on the decisions and reactions of the waiting driver attempting to cross or enter the mainstream. In an effort to increase the understanding of traffic behavior, the following research objectives were pursued:

1. Perform a detailed examination of an intersection controlled by a stop sign to determine and verify the characteristics of lag and gap acceptance distributions of the waiting vehicles.
2. Evaluate the influence of the following traffic factors on the lag and gap acceptance distributions: (a) vehicle type, (b) pressure of traffic demand, (c) direction of movement through the intersection, (d) sequence of gap formation, and (e) conditions on the opposite stop-signed approach.
3. Determine the characteristics of the distributions of starting delay times in accepting lags and gaps, and evaluate the influence of certain traffic factors on these distributions.

Terminology

Definition of the following terms is necessary for an understanding of the procedures and results of this research.

A gap is considered as the elapsed time between arrival of successive main street vehicles at a specified reference point in the intersection area.

A lag is that portion of a current gap remaining when a side street vehicle arrives; in other words, the elapsed time between arrival of a side street vehicle and arrival of the next main street vehicle.

A lag or gap is either accepted or not accepted (rejected) by the side street vehicle. A lag is accepted if the side street vehicle crosses or enters the main street before the arrival of the first main street vehicle. A gap is accepted if the side street vehicle crosses or enters between two main street vehicles comprising a gap.

Starting delay time in accepting gaps is the elapsed time between arrival of the first main street car comprising the accepted gap and the complete entry into the intersection of the side street car.

Starting delay time in accepting lags is the elapsed time between arrival of a side street car and its complete entry into the intersection.

A side street car is assumed to have completed entry into the intersection when its rear bumper has crossed the line which is an extension of the near side edges of the traveled portion of the main street.

Arrival of a side street vehicle on an unoccupied stop-signed approach is considered the point in time when the vehicle either stops or reaches its lowest speed.

When more than one vehicle is waiting in queue at a stop sign, the arrival of the second or succeeding side street vehicles is defined as coinciding with the complete

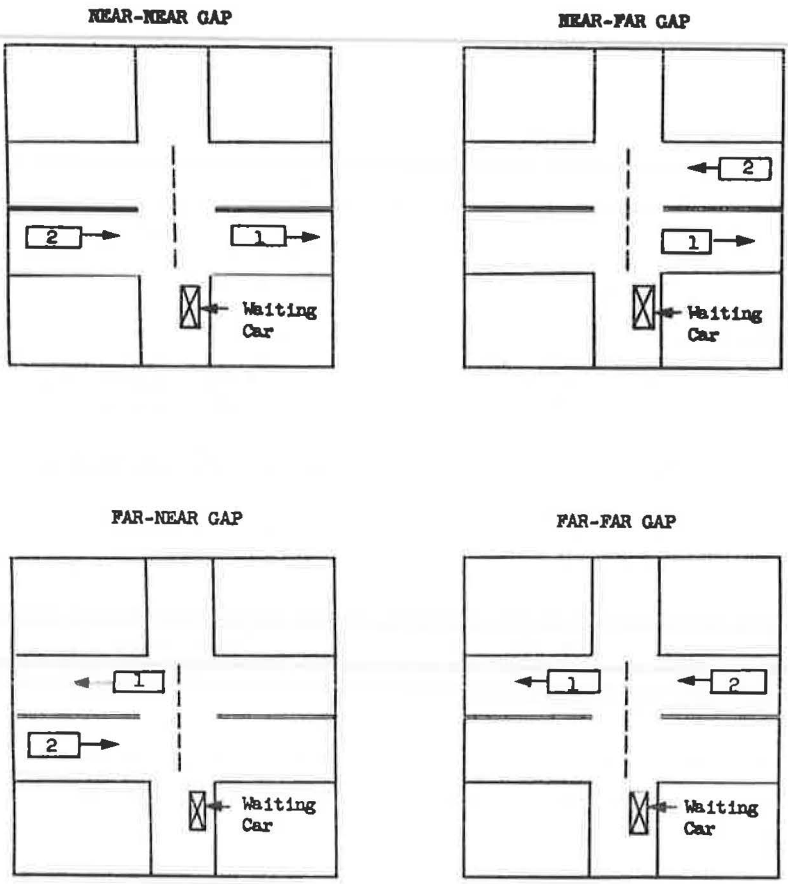

Figure 1. Sequence of main street gaps.

entry into the intersection of the first waiting car. This definition provides a beginning reference point for the measurement of the lag presented to the succeeding vehicle.

Near-side main street vehicles are those passing closer to the waiting side street car; in other words, those which approach from the waiting driver's left. Far-side main street vehicles are those approaching from the waiting driver's right.

The formation of gaps in main street traffic, therefore, is characterized by one of the following sequences: near-near, near-far, far-near, or far-far (Fig. 1).

STUDY PROCEDURE

Field data were collected at the intersection of a four-lane, undivided, intermediate-speed state highway with a two-lane, low-speed city street controlled by stop signs (Fig. 2). Traffic flow levels and fluctuations on the main highway during the day were such that observed gaps covered the full range, from those so small as to be unacceptable to all waiting drivers, to those large enough to be acceptable to all. In selecting the study site, special characteristics were avoided such as substantial horizontal or vertical curvature near the intersection, oblique crossing, severe sight distance restrictions, and one-way operation.

Two observers operated a specially devised survey device consisting of 10 push-button microswitches electrically connected to a multiple-pen event recorder. The observers manually actuated the switches to denote: (a) arrival of main street vehicles, by direction; (b) arrival of side street vehicles, by direction and vehicle type; and (c) complete entry into the intersection of side street vehicles, by direction and turning maneuver. This technique enabled gap and lag size and acceptability data, and starting delay data, to be extracted from the chart records. A total of 472 min of sample data were gathered during daylight hours on week days in fair, dry weather. The

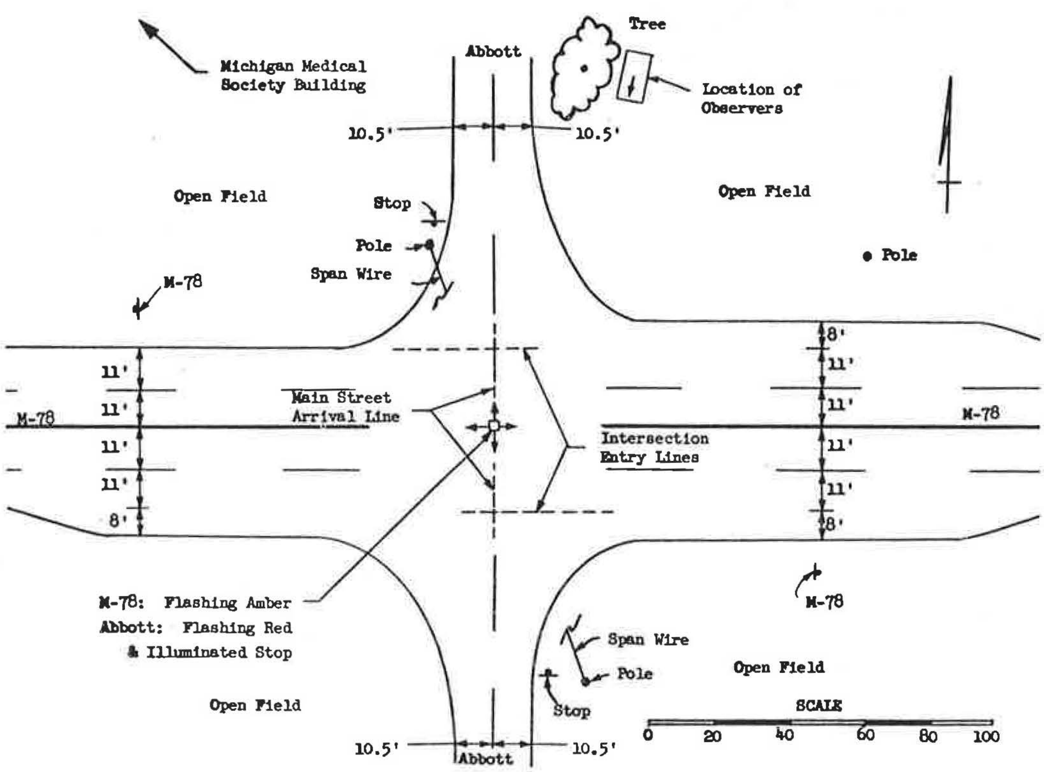

Figure 2. Condition diagram of the intersection in East Lansing, Michigan.

decisions and reactions of 1,203 separate side street vehicles, giving rise to a total of 5,179 separate lag or gap acceptance decisions, were extracted from the records.

Furthermore, the study procedure was designed to permit an effective evaluation of the influence of certain traffic factors on the lag and gap acceptance distributions. Data were stratified in the manner shown in Figure 3. Such stratification is often undertaken to safeguard against overlooking or misinterpreting the significance of a given factor caused by submerging the effects in a larger population affected by other important variables. For each category of data, the characteristics of the acceptance distributions were determined and pertinent comparisons were made.

Gap and lag size data were separated into 1-sec class intervals, and for each interval the observed percent acceptance was computed. The form and parameters of the lag and gap acceptance distributions were then determined using a graphical curve fitting technique, and a specialized application of standard statistical difference tests was used to test the significance of the influence of various traffic factors on the distributions.

RESULTS

Decisions of Side Street Drivers

Form of the Acceptance Distribution.—In developing the statistical analysis methodology for this study, approaches used in earlier work of Robinson (12) and Bissell (4) were reviewed. A modified version of the earlier techniques was used to determine the form of the acceptance distribution. Rather than plotting sample percentages alone, confidence interval estimates surrounding the sample percentages were computed and plotted vs the logarithmic transform of gap or lag size. A straight line could be drawn which passed through a great majority of the confidence bands plotted on logarithmic-probability paper. This held up well for all levels of data stratification. Thus, the results gave rather strong verification of earlier findings that the relationship between lag or gap size and percent acceptance has a log-normal form.

Figure 4 shows the composite lag and gap acceptance distribution resulting from combining all driver decision data into one sample. The curve is presented in its untransformed state; that is, on a rectilinear graph. The absolute value of the median

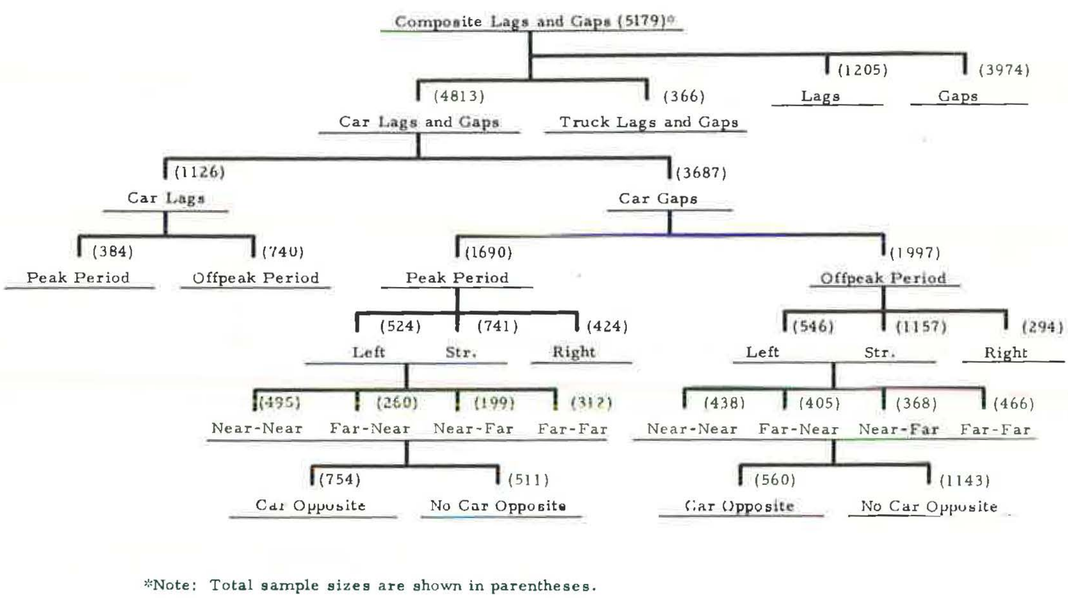

Figure 3. Stratification of lag and gap acceptance data.

acceptable size was 7.4 sec. Gaps or lags smaller than 4.3 sec were accepted by fewer than 10 percent of the side street drivers, and openings larger than 12.5 sec were accepted by more than 90 percent. One can use the graph to estimate the percent of vehicles accepting a given lag or gap size.

Comparison of Gaps and Lags. —The results of separating the composite data into lag acceptance and gap acceptance categories are indicated in Figure 5. To test whether the two distributions differed significantly, statistical tests were performed on the hypotheses that (a) the means were equal and (b) the standard deviations were equal. These tests were performed at the 0.05 level of significance, which means that there is only a 5 percent chance of incorrectly concluding the distributions differ, if in fact they are equal.

In this case, both hypotheses were rejected, and it was concluded that the two samples were not members of a common distribution. The gap acceptance curve had a lower central tendency, and the lag acceptance curve was more disperse. Therefore, the acceptance of gaps and the acceptance of lags should be treated separately. A rejection of either hypothesis would have caused the same conclusion. Except for very small sizes, a gap of a given size was more readily accepted than a lag of the same size. For example, a gap of 8 sec was acceptable to 60 percent of the waiting drivers, but a lag of the same size was acceptable to only 50 percent.

Influence of Traffic Factors on Driver Decisions. —Vehicle Type. The lag and gap acceptance distributions for the two classifications of side street vehicles, cars and trucks, are shown in Figure 6. From a logical viewpoint, considering the limited acceleration capability of trucks, there was reason to expect that differences would be found. In the graph the two curves are narrowly separated. However, the statistical tests led to the conclusion that this sample data gave no evidence that truck behavior and car behavior were significantly different.

If the truck-car comparison had been made separately for lags and gaps, or for offpeak and peak periods, differences might have been found. Unfortunately, the small size of the truck sample prohibited such further stratification. Until contrary evidence is found, the decision characteristics of truck and car drivers need not be handled separately.

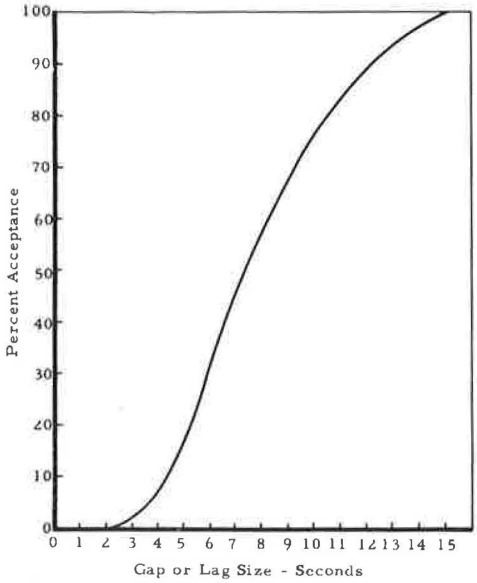

Figure 4. Composite lag and gap acceptance distribution.

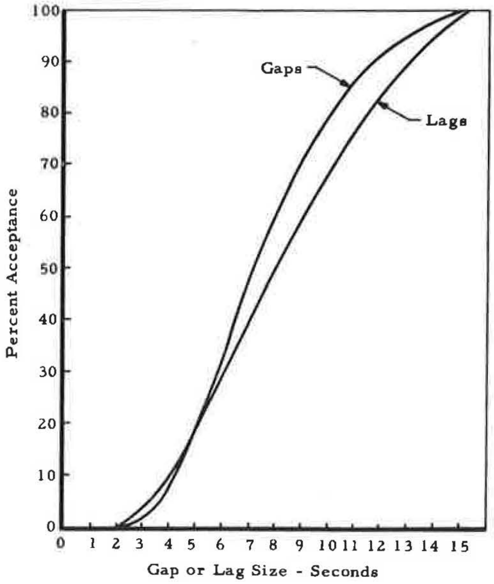

Figure 5. Comparison of lag and gap acceptance distributions.

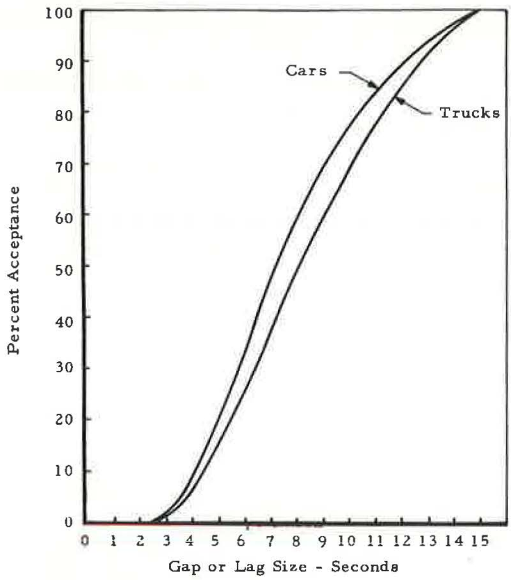

Figure 6. Effect of vehicle type on lag and gap acceptance distribution.

Pressure of Traffic Demand. Figure 7 shows the influence of pressure of traffic demand on lag and gap acceptance. Here the differences were indeed significant. The evidence indicates drivers accept smaller lags and gaps during peak periods. In other words, a greater percentage of drivers tend to accept a lag or gap of a given size during peak periods than will accept an opening of the same size during offpeak periods. For example, a lag of 6 sec was acceptable to nearly 50 percent of the peak-period drivers, but to just over 20 percent of the offpeak-period drivers.

The influence of traffic demand was more striking in the case of lag acceptance, where there was more than a 2-sec difference between the median acceptable lag during peak and offpeak periods. In the case of gap acceptance, the separation of the peak and offpeak curves was narrower but nevertheless significant.

In evaluating the influence of subsequent traffic factors, the separation of peak and offpeak data was retained.

Direction of Movement. The comparison of gap acceptance distributions for side street cars waiting to proceed straight, turn left, or turn right into the intersection is shown in Figure 8. The effect of direction of traffic movement was found to be limited during peak periods and insignificant during offpeak periods.

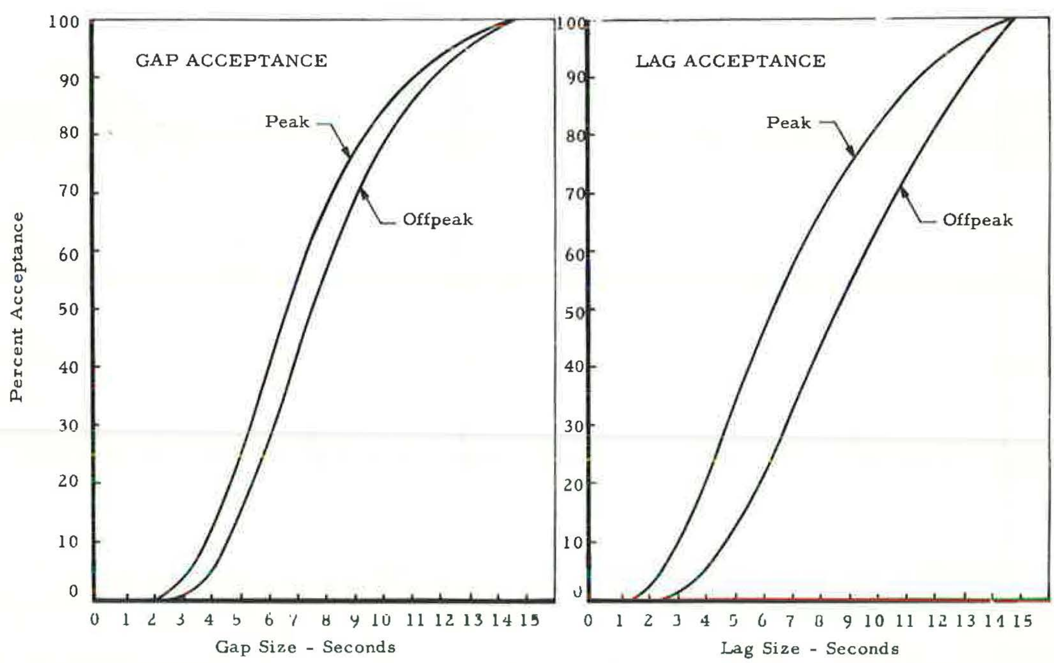

Figure 7. Effect of pressure of traffic demand on lag and gap acceptance distributions.

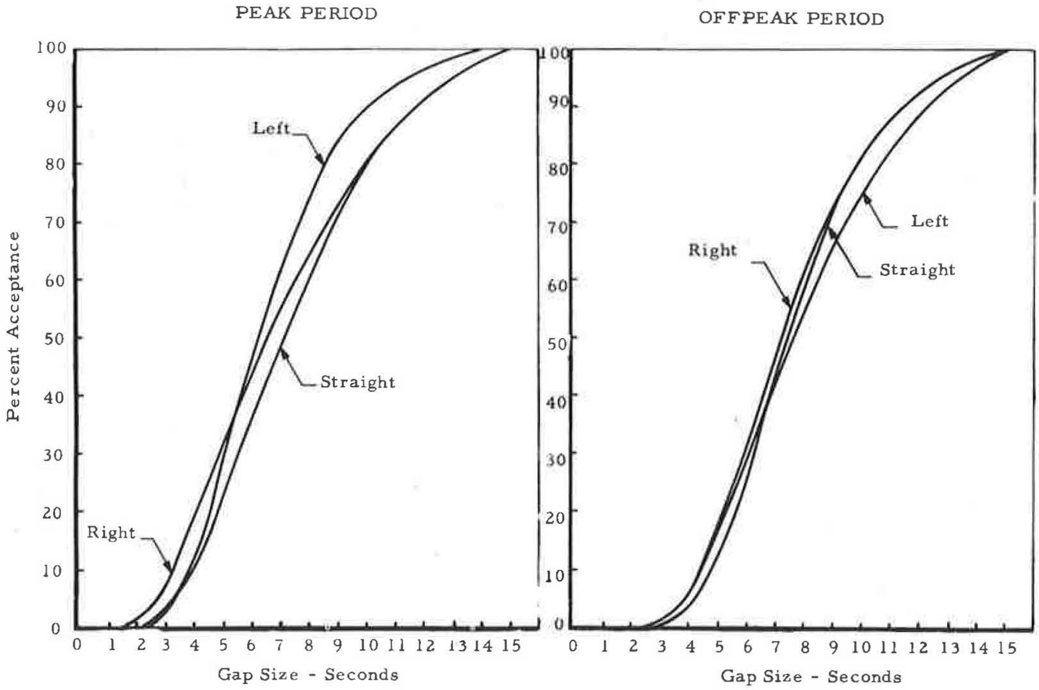

Figure 8. Effect of direction of side street vehicle movement on gap acceptance distribution.

For peak-period data, the most widely separated means were statistically tested, and no significant difference was found. However, in analyzing dispersion, the distribution for right-turners was found to be more disperse than the distribution for left-turners. This difference was attributed to the right-turning driver's willingness to accept a greater percentage of gaps in the low range of the distribution. No statistical differences, either in central value or in dispersion, were evident in the comparison of turning and straight-through drivers. It was concluded that in considering peak-period behavior it is only necessary to segregate right-turners from the others.

For offpeak-period data, the effects of direction of movement appeared even smaller. In fact, there was no evidence to indicate that the left, straight, and right gap acceptance samples did not come from a common distribution. Consequently, there is no need to make this distinction during the periods of reduced traffic demand.

Main Street Vehicle Sequence. Another factor investigated was the sequence of main street vehicles comprising the gaps presented to waiting drivers. Only the left-turning and straight-through side street cars were included in this analysis, since for right-turn decisions only those gaps in the near-side main street traffic are relevant.

Figure 9 shows that the sequence of gap formation had a strikingly significant influence on driver decisions during the peak period. The two most widely separated distributions (for near-far and far-near gaps) were more than 2 sec apart at the 50-percent acceptance level. This difference was found to be highly significant statistically. A much greater percentage of drivers accepted a given far-near gap than accepted a near-far gap of equal size. For example, a far-near gap of 6 sec was acceptable to nearly 60 percent of the waiting drivers, whereas a near-far gap of the same size was acceptable to less than 30 percent.

Still considering the peak-period data, the two inner distributions, characterizing the acceptance of near-near gaps and far-far gaps, were compared, and no significant difference was indicated. Thus, in the consideration of peak-period gap acceptance, near-far and far-near gaps should be segregated, but near-near and far-far gaps may be grouped.

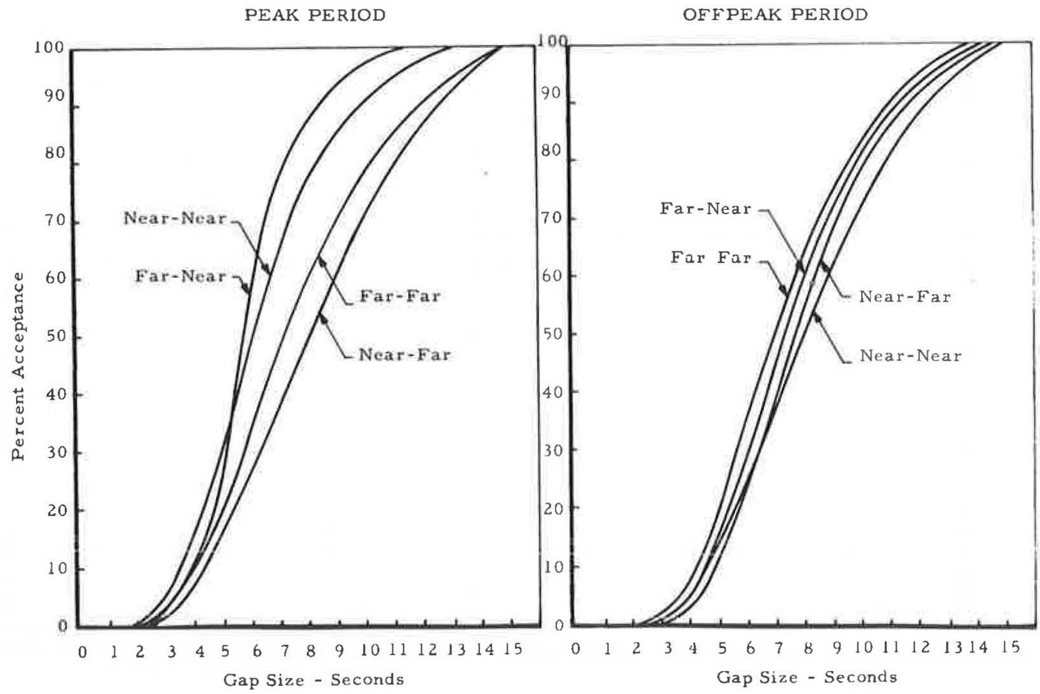

Figure 9. Effect of sequence of main street gaps on gap acceptance distribution.

A similar analysis of the effect of main street vehicle sequence was made for off-peak traffic. In Figure 9, the four offpeak distributions are in much closer proximity. The most widely separated pair of values for mean and standard deviation was selected for testing, and no significant differences were found. Therefore, during periods of reduced traffic demand, gap acceptance data need not be segregated on the basis of sequence of gap formation.

Conditions on the Opposing Side Street Approach. The final traffic factor considered was the presence or absence of one or more vehicles waiting on the opposite side street approach. It was assumed that this factor is irrelevant to drivers turning right into the main stream; hence, only left and straight vehicles were included in the analysis. The results (Fig. 10) show the gap acceptance curves, under the conditions of (a) no car opposite and (b) one or more cars opposite, to be in very close proximity. By statistical inference, there was no evidence to indicate that the decisions of waiting drivers were significantly affected by conditions on the opposing approach.

Reactions of Side Street Drivers

Starting Delay Time Distributions. —Starting delay time in accepting gaps and lags at a stop-signed intersection can be considered analogous to starting delay time of the first vehicle in queue at a traffic signal. It is an important parameter in both theoretical study and simulation of traffic behavior at intersections, particularly at any time when more than one vehicle is waiting in line at the stop sign. Both the central tendency and dispersion of starting delay times are of interest. It was rather surprising to find no past reports of such measurements.

Starting Delay Time in Accepting Gaps. Starting delay time in accepting a gap was previously defined as the elapsed time between arrival of the first main street car comprising the accepted gap and the complete entry into the intersection of the side street car. A total sample of 703 such starting delay times were extracted from the multiple-pen chart records. Data were segregated into 0.5-sec class intervals, and

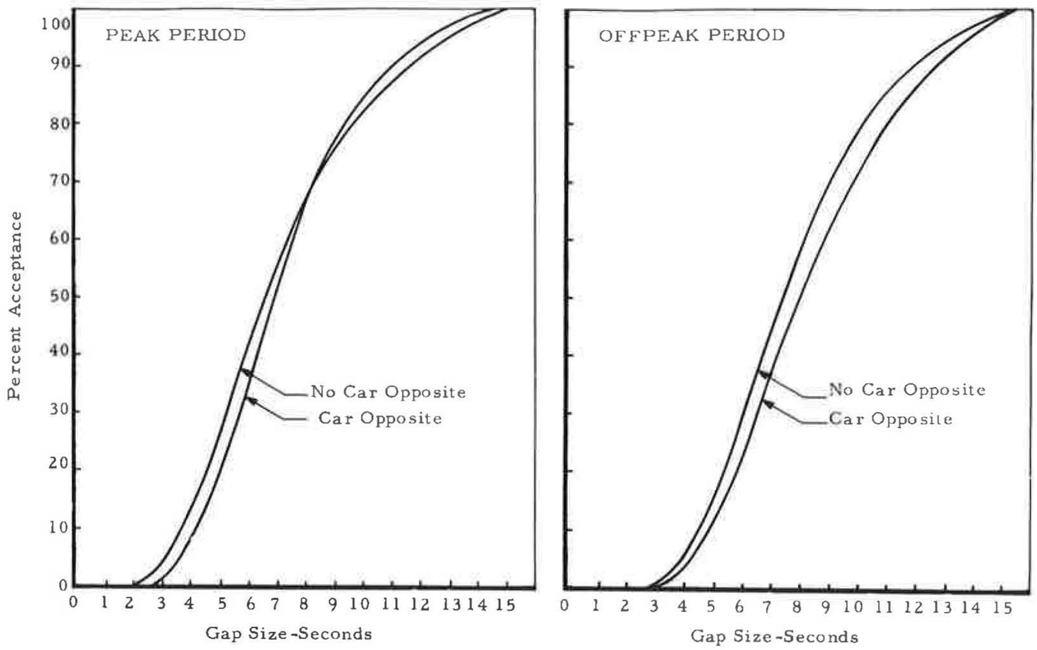

Figure 10. Effect of conditions on the opposite side street approach on gap acceptance distribution.

the resulting frequency distribution is shown in Figure 11. The composite sample presented included data from both peak and offpeak traffic periods. The distribution appears approximately normal except for a long tail to the right. Observed values ranged from virtually 0 to more than 9 sec. The median was 2.8 sec, and there were more observations in the 2.5- to 3-sec class than in any other. The 15 percentile and 85 percentile of the sample were 1.8 and 4.4 sec, respectively.

Starting Delay Time in Accepting Lags. Starting delay time in accepting lags was defined as the elapsed time between the arrival of a side street car and its complete

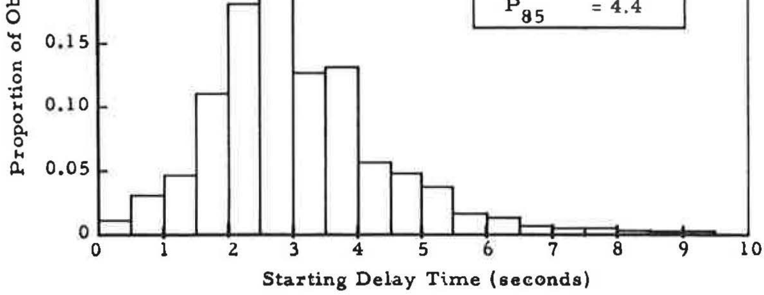

Figure 11. Distribution of starting delay times in accepting gaps.

entry into the intersection. In the special case where more than one vehicle is waiting on the side street approach, the arrival of the second, or succeeding, vehicle was defined as coinciding with the complete entry into the intersection of the first vehicle in queue.

Frequency distributions of starting delay time for first vehicles in queue and for succeeding vehicles are shown in Figure 12. One immediately notes that the two distributions are different. Because the distribution for succeeding vehicles was skewed and the other approximately normal, the standard difference tests were not performed. However, it is obvious by inspection that starting delay time for succeeding vehicles was smaller and less disperse than for the first vehicle in queue.

The statistical properties of starting delay of succeeding vehicles in accepting lags did not differ markedly from the previously presented properties of starting delay in accepting gaps. Conversely, starting delay for first vehicle in queue lag acceptances was significantly higher and more disperse than starting delay for gap acceptances.

Influence of Traffic Factors on Starting Delay Times. —Pressure of Traffic Demand. The sample of starting delay times in accepting gaps was segregated on the basis of period of the day to reflect different intensities of traffic pressure (Fig. 13).

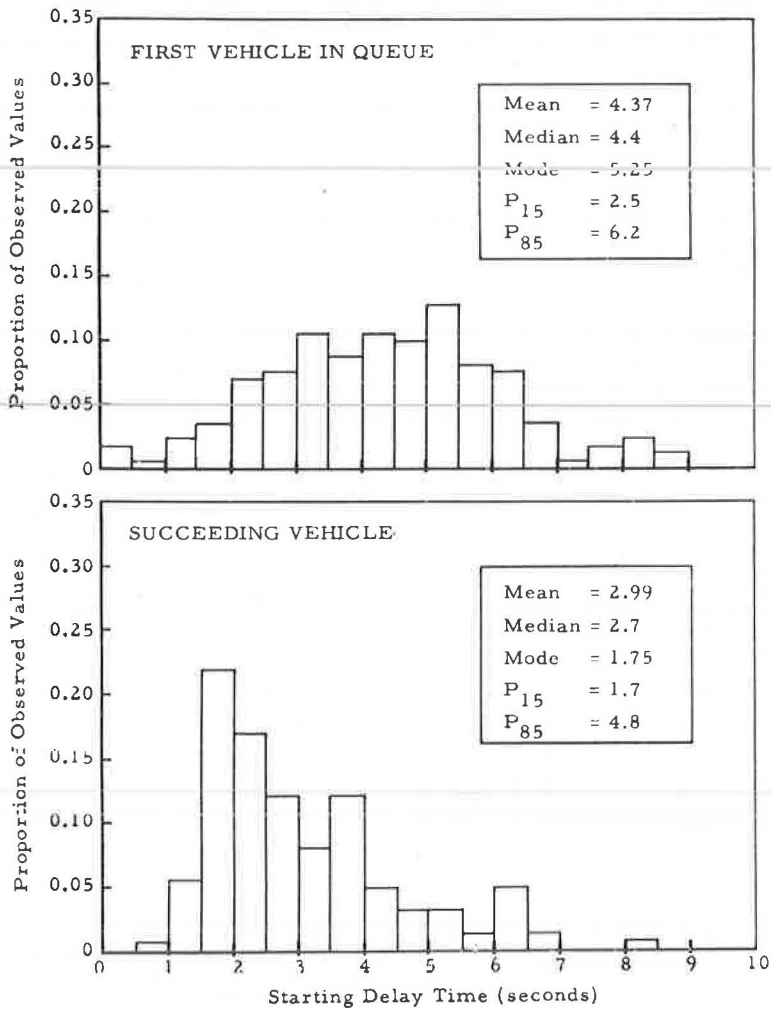

Figure 12. Distribution of starting delay times in accepting lags.

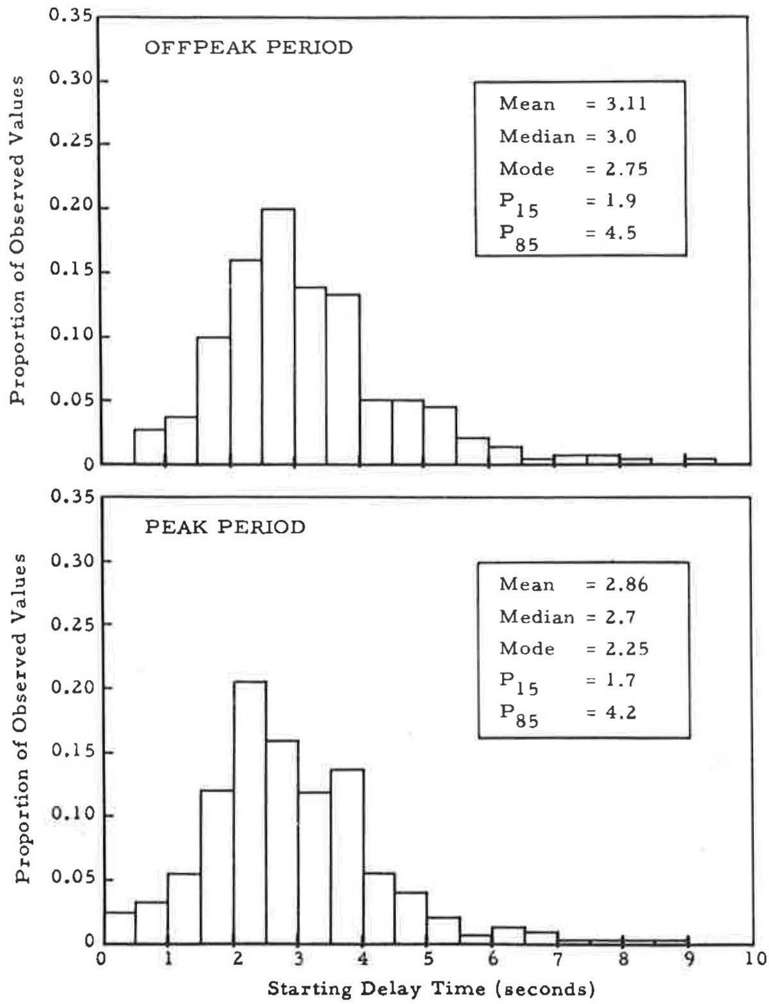

Figure 13. Effect of pressure of traffic demand on starting delay time in accepting gaps.

Since both distributions appeared normal, standard tests were performed which indicated that mean starting delay time during peak periods (2.86 sec) was significantly smaller than during off-peak periods (3.11 sec).

The influence of traffic demand was much more striking in the case of starting delay time in accepting lags. Here only succeeding vehicles were considered, since during the peak period the occurrence of a vehicle arriving first in queue on an empty stop-signed approach, and accepting the lag, was practically nonexistent at the study site. Figure 14 shows that the mean starting delay time in accepting lags during the peak period was nearly 0.7 sec lower than during the offpeak period. The peak period mode was a full 1 sec lower than the offpeak mode. These differences were highly significant. On the other hand, little difference was noted in the dispersion of these two distributions.

Main Street Vehicle Sequence. From a logical viewpoint, it was expected that starting delay time in accepting gaps might be affected to some degree by the sequence of gap formation. In particular, if the first car comprising the gap was on the far side, the side street vehicle might commence motion earlier and complete its entrance more quickly than if the first car of the gap was on the near side. Figure 15 indicates that

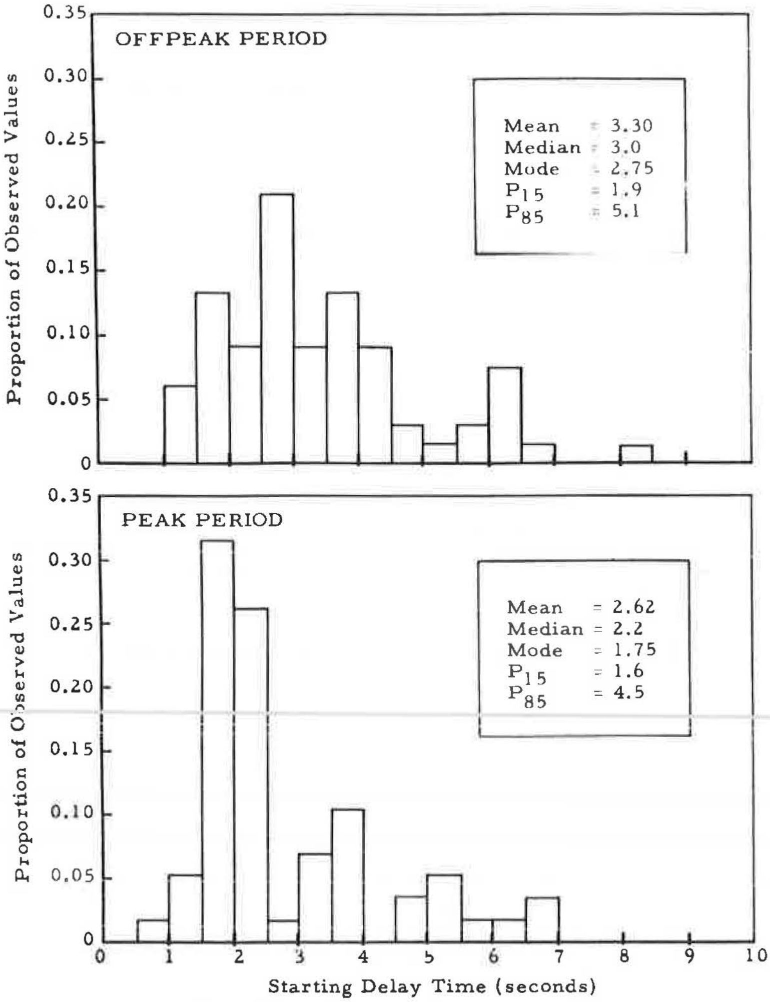

Figure 14. Effect of pressure of traffic demand on starting delay time in accepting lags (succeeding vehicles).

such reasoning was indeed valid. During both peak and offpeak periods, starting delay times were smaller when the first car of the gap was on the far side. The effects were largest during the peak period when there was nearly 1 sec difference between the means being compared. The differences were less marked but nonetheless significant during the offpeak period.

INTERPRETATION OF RESULTS

Generally speaking, the results of this research tended to verify rather than contradict that which a professional traffic engineer might deduce on the basis of logical consideration of the factors involved.

For example, the differences in gap and lag acceptance were not surprising. One might expect that a driver who has just arrived at a stop sign needs some time to orient his senses to the decision-making process. Furthermore, when such a driver is nearing the stop sign, he is often not in as advantageous a position for the critical observation of main street traffic as if he had been waiting near the intersection entry line for some period of time. These factors help to explain why a gap of a given size was more readily acceptable than a lag of the same size.

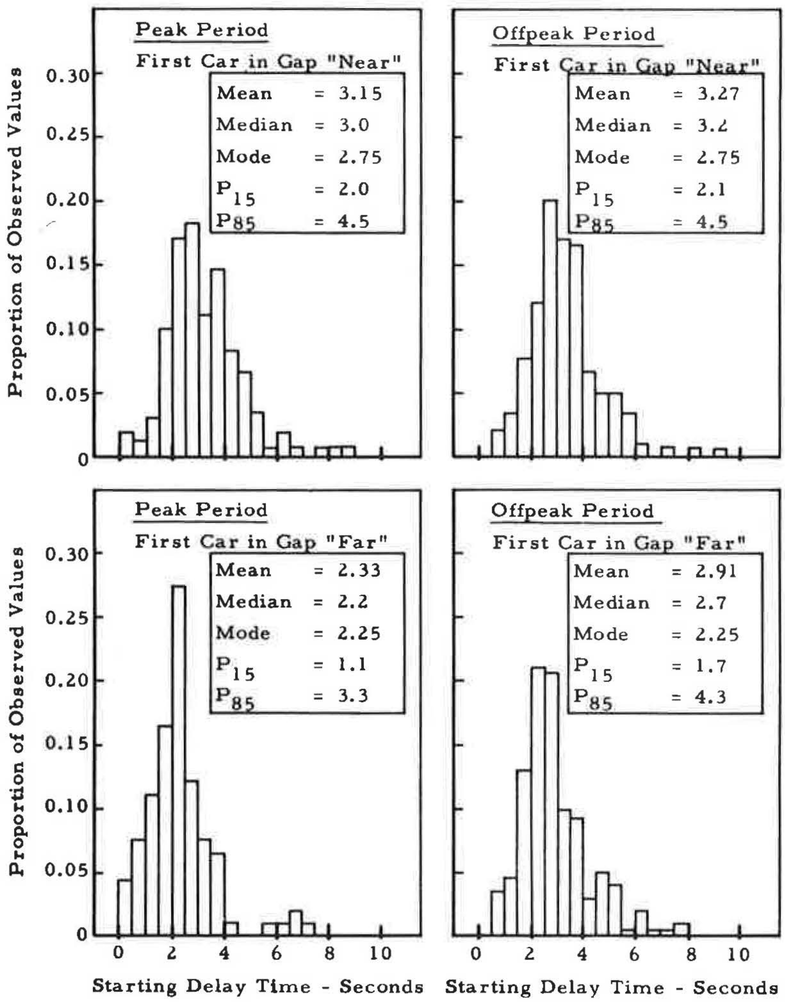

Figure 15. Effect of sequence of accepted main street gap on starting delay time in accepting gaps.

The factor which had the most striking effect on the lag and gap acceptance distributions was the pressure of traffic demand. A given lag or gap is more readily accepted during peak periods than during periods of reduced traffic demand. Several factors might be important in explaining these differences. During the peak period, many drivers are traveling between work and home. Before they reach the position of queue leader, they most likely have spent a substantial period of time in the queue. Furthermore, when they do reach the front of the line, it is likely that one or more vehicles are waiting behind. All of these factors might be expected to contribute some degree of impatience. Of possibly equal importance is the higher traffic volume, or in other words, smaller average gaps, on the main street during the peak period. The driver who rejects a marginal lag or gap may have to wait a substantial time for another opportunity that good or better.

There is also a logical basis for explaining the results relating to the sequence of main street vehicles. At least three factors are believed to be important: (a) if the first car of the gap is on the near side, it blocks the waiting driver's vision of far-side main street vehicles; (b) if the first car in the gap is on the near side, the waiting driver cannot normally begin his entry into the intersection until the near-side car has passed; (c) if the second car of the gap is on the far side, the crossing driver must travel a longer distance to clear the area of conflict. In considering a far-near gap, the favorable conditions of all three of these factors are met, whereas in the case of a near-far gap all of the unfavorable conditions are working. Near-near and far-far gaps have a mixture of favorable and unfavorable conditions.

Differences in gap acceptance due to main street vehicle sequence were evident only during the peak period. It is theorized that during offpeak periods drivers feel no special compulsion to attempt to attain the maximum performance. But during peak periods, when some degree of compulsion is working, reasonable lower boundaries on gap size corresponding to maximized performance are lower for far-near gaps, and higher for near-far gaps, than for the other types.

The study of starting delay times yielded results which can be closely correlated with the driver-decision data. The traffic factors which had important effects on driver decisions also influenced starting delay times, and in the same direction. For example, the average starting delay time in accepting gaps was lower during periods of heavy traffic demand. It is impossible to state with assurance that lower starting delays enable shorter gaps to be accepted, or, alternatively, that the decisions to accept shorter gaps cause the lower starting delays. Rather, it is probably more accurate to say that both behavior characteristics are affected similarly by common factors, such as impatience, degree of motivation, and the reduced size of main street gaps presented to waiting drivers.

Regarding another important factor, main street vehicle sequence, which similarly affects starting delay and gap acceptance, there is some reason to note a causal relationship. It is believed that a partial explanation for far-near gaps being more readily acceptable is that the position of the first car in the gap enables the side street car to start into the intersection sooner.

Comparison with Related Research

The results of this study are compared with those Bissell, Greenshields, Raff, and Herman and Weiss in Figure 16. Both Greenshields and Raff estimated central values for lag acceptance; their results are plotted on the 50-percent line. Bissell's distribution of lag and gap acceptance is shown.

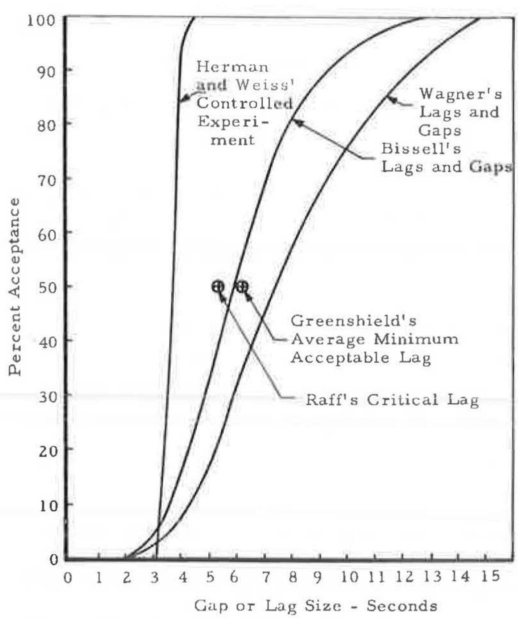

Figure 16. Comparison with related findings.

The acceptance distributions determined in this study had significantly higher central tendency than those found in any of the other studies. The variance of Bissell's lag and gap acceptance distribution, however, did not differ significantly from the present findings.

It is believed that an explanation of the differences is related to differences in the nature of the intersections studied. In particular, the main street of this study was much wider and carried higher-speed traffic than the main streets studied by the others.

Of special interest is a comparison of the studies of actual traffic intersections and the controlled experimentation done by Herman and Weiss (12). These data differ markedly from the rest. No lag smaller than 3.2 sec was accepted and none larger than 4.2 sec was rejected. The point where their line crosses 50 percent corresponds to only 3- to 10-percent acceptance in the distributions of Bissell and this study. Herman and Weiss state that "these experiments were rather artificial in that the drivers were highly motivated and quickly adapt to the situation." However, their results are especially interesting and useful in that they represent maximized performance characteristics.

Future Research

Although this study was intensive, it was limited due to time and resources to only one intersection. It would seem important, therefore, to make similar studies of driver decisions and reactions, and the effects of variable traffic factors on them, at other intersections.

Certain specific items which could not be adequately handled in this study might be of interest. For example, the effects of direction of movement, gap sequence, and conditions on the opposite approach on lag acceptance could not be studied here due to inadequate sampling. Another inadequacy was the inability to make a really detailed study of the effects of conditions on the opposing approach, particularly as related to the direction of movement of the car in question and the car opposite. Although the effects of different types of vehicles on the side street were studied, no consideration was given to vehicle type on the main street.

Concluding Remarks

In the final analysis, these efforts are wasted unless the findings can be applied. Theoretical treatment and simulation both require the application of driver-decision and reaction parameters. In using either of these approaches, broad ranges of traffic variables such as turning percentages, truck percentages, directional splits, and traffic volumes must be studied. Realistic models must take into account significant changes in driver decisions and reactions associated with these variables. The key to more effective use of the new techniques is a renewed and vigorous attempt to understand more fully and document the fundamentals of traffic behavior.

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