Warrants for Left-Turn Signal Phasing

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Warrants for the installation of left-turn phasing in Kentucky were developed. A review of the literature was conducted, along with a survey of the policies of other states. Field data on delays and conflicts were taken before and after installation of exclusive left-turn signalization. Left-turn delay studies were conducted at intersections that had varying volume conditions. Analysis of the effect on accidents of adding a left-turn phase was made. The relationship between left-turn accidents and conflicts was investigated. Other types of analyses concerning gap acceptance, capacity, and benefit-cost ratios were also performed. It was found that exclusive left-turn phasing significantly reduced left-turn accidents and conflicts. This reduction was offset in part by an increase in rear-end accidents. Left-turn delay was reduced only during periods of heavy traffic flow. Total delay for an intersection increased after installation of left-turn phasing. Warrants were developed dealing with accident experience, delay, volumes, and traffic conflicts.

A vehicle attempting to turn left across opposing traffic is a common problem. Separate left-turn lanes minimize the problem but may not be the final solution. At signalized intersections, left-turn phasing can be used as an additional aid. However, warrants have not been established for the addition of separate left-turn lanes or signal phasing. In this study, warrants or guides were developed for installing left-turn phasing at signalized intersections that have separate left-turn lanes. Before-and-after data were taken at locations where left-turn phasing had been added. Studies at locations that had varied traffic conditions were made to determine the relationship between various volumes and left-turn delays. The relationship between left-turn accidents and conflicts was investigated. Comparisons of signalized intersections with and without left-turn signals were also made.

SURVEY OF OTHER STATES

Other state highway agencies were requested to describe their procedure used to determine the need for left-turn phasing. Of the 45 states responding, only 6 cited numerical warrants for left-turn phasing. In one state, warrants were proposed. The various numerical warrants used when considering left-turn phasing were as follows (some states had more than one warrant):

1. Product of the left-turn highest-hour volume and the opposing traffic ≥50 000;
2. Five or more left-turn accidents within a 12-month period (two states);
3. Cross product of left turns and conflicting through peak-hour volumes >100 000 (two states, one listing this for traffic-actuated signals only);
4. Delay to left-turning vehicle in excess of two cycles;
5. One left-turning vehicle delayed one cycle or more in 1 h;
6. At a pretimed signal, left-turn volume of more than two vehicles per approach per cycle during a peak hour;
7. Average speed of through traffic exceeds 72 km/h (45 mph) and the left-turn volume is 50 or more on an approach during a peak hour;
8. Left-turning volume exceeds 100 vehicles during the peak hour;
9. More than 90 vehicles/h making a left turn; and
10. For four-lane highways with left-turn refuges, a relationship between left-turn volume, opposing-traffic volume, and posted speed.

Nearly all of the responses listed guidelines that have been used. Following is a list of the general guidelines (areas that should be considered) that were mentioned, some of which were listed by several states: accident experience, capacity analysis, delay, volume counts (peak-hour left-turn and opposing through volumes), turning movements, speed, geometrics, signal progression (consistency with and effect on adjacent signals), queue lengths, right-of-way available, number of opposing lanes to cross, gaps, consequences imposed on other traffic movements, type of facility, sight distance, and percentage of trucks and buses. Several states listed more detailed guidelines involving specific left-turn volumes, etc.

Following is a summary of guidelines used when considering a separate left-turn signal phase: left-turn volume > 500 (two-lane roadway), wherever a left-turn lane is installed on divided highways; 100-150 left-turning vehicles during the peak hour (small cities); 150-200 left-turning vehicles during the peak hour (large cities); at new installations, where left-turn phases already exist at other intersections on the same roadway; average cycle volume exceeds two vehicles turning left from the left-turn bay, and the sum of the number of left-turning vehicles per hour and the opposing-traffic volume per hour exceeds 600 vehicles; high percentage of left-turning vehicles (20 percent or greater); not provided at intersections with left-turn volume < 80 vehicles/h for at least 8 h/day; the number of left-turning vehicles is about 2 per cycle; 120 left-turning vehicles in the design hour; turning volume in excess of 100 vehicles/h, and more than one cycle of the signal needed to clear a vehicle stopped on the red; left-turn volumes of 90-120 in peak hours; and more than 100 turns/h.

RESULTS

Accident Warrant

Before-and-After Accident Studies

Accident data before and after installation of separate left-turn phasing were collected for 24 intersections. The length of the before and after periods was usually one year, but it varied in some cases depending on the available data. There was an 85 percent reduction in left-turn accidents, defined as those occurring when one vehicle turned left into the path of an opposing vehicle. This reduction in left-turn accidents was offset in part by a 33 percent increase in rear-end accidents. There was a reduction of 15 percent in total accidents.

Accident severity was reduced only slightly after installation of the left-turn phasing. Rear-end accidents (which were increased) are less severe than left-turn (angle) accidents (which were decreased). Injury accidents decreased from 13 to 11 percent after left-turn phasing was installed.

Comparison of Accident Rates at Intersections With and Without Left-Turn Phasing

Accident rates at intersections in Lexington, Kentucky, with and without left-turn phasing were compared. Rate were calculated by using 1972 accident data, and the volume data were taken for 1971 through 1973. Volume counts were available for a 12-h period (7:00 a.m. to 7:00 p.m.) at each intersection. The assumption was made that 80 percent of the total daily volume occurred in this 12-h period, so the volumes were multiplied by 1.25 to obtain the 24-h volume. The total rate of the intersection-type accidents was computed in terms of accidents per million vehicles entering the intersection. The left-turn accident rate was calculated, for each approach that had a separate left-turn lane, in terms of left-turn accidents per million vehicles turning left from the approach. Intersections without left-turn phasing (44 intersections) had average annual daily traffic (AADT) of approximately 20 000, compared with slightly more than 32 000 for intersections that had left-turn phasing (16 intersections). The higher AADT affects the accident rate. Calculating rates for only the high-volume intersections (AADT > 25 000) eliminated this variable. There were 13 intersections that had separate phasing and 10 intersections without separate phasing that met this criterion.

The left-turn accident rate was drastically lower for the approaches that had left-turn phasing (0.77 left-turn accidents/million vehicles entering the intersection for all intersections, 0.86 for high-volume intersections) than for approaches without left-turn phasing (2.74 for all intersections and 3.76 for high-volume intersections). The lower rate agreed with the findings of the before-and-after accident studies. The data again showed that left-turn phasing did not reduce the total intersection accident rate. The total accident rate was almost identical at locations with (1.66 for all intersections and 1.63 for high-volume intersections) and without (1.63 for all intersections and 1.69 for high-volume intersections) left-turn phases.

Critical Left-Turn Accident Number

By using the Lexington data base, the average number of left-turn accidents for the approaches with no left-turn phasing was calculated. By using this average number of accidents, the critical number of accidents was also determined. For 1968 through 1972, the average number of left-turn accidents per approach was 0.93 (for 96 approaches with a left-turn lane but no separate phase). For a street that had a left-turn lane in each direction, both approaches were included. The formula for critical accident rate (1) can be converted to calculate the critical number of accidents by substituting accidents divided by volume for the rate. Multiplying both sides of the equation by volume resulted in the following formula for critical number of accidents:

$$N_c = N_a + K\sqrt{N_a} + 0.5 \qquad (1)$$

where

- N_c = critical number of accidents,
- N_a = average number of accidents, and
- K = constant related to level of statistical significance selected (for P = 0.95, K = 1.645; for P = 0.995, K = 2.576).

For P = 0.995, the critical number of left-turn accidents per year per approach was found to be four. Using the high probability increases the likelihood of selecting for improvement only intersections that have a significant left-turn problem. Therefore, four left-turn accidents in one year on an approach would make that approach critical. The number of accidents in a two-year period necessary to make an approach critical was also determined. There was an approximate average of two left-turn accidents on an approach during a two-year period. By using this average of two accidents, the number of left-turn accidents necessary in a two-year period to make an approach critical was found to be six.

The same procedure was used to determine the critical number of accidents for both approaches when a street has left-turn lanes in both directions. For 1968 through 1972, the average number of left-turn accidents for both approaches on a street was 2.1 (for 36 streets with left-turn lanes for both directions at an intersection but no separate phase). This resulted in a critical number of 6 for a one-year period for both approaches. For a two-year period, an average of 4 accidents resulted in a critical number of 10 for both approaches.

Delay Warrant

Before-and-After Delay and Conflict Studies

To determine the change in vehicular delay, studies were conducted before and after installation of left-turn phasing at three intersections that had two-phase, semi-actuated signalization. Left-turn delay was defined as the time from when the vehicle arrived in the queue or at the stop bar until it cleared the intersection. The arrival and departure times of each left-turning vehicle were noted; delay could then be calculated. If the vehicle did not have to stop, a zero delay was noted. The number of left turns was counted. Opposing volumes and left-turn conflicts were also counted during the study period, usually 30 min of each hour.

Because of high volumes involved when determining total intersection delays, the stop-type delay, the time in which the vehicle is actually stopped, was used because it was the easiest and most practical delay to measure (2, 3). The estimating procedure consisted of counting the number of vehicles stopped in each intersection approach at periodic intervals. The interval used was 15 s for two of the intersections and 20 s for the other. The volume on each approach was also counted. The total delay was the product of the total vehicles stopped at periodic intervals and the length of the interval. The delay per vehicle was obtained by dividing the total delay by the volume for that approach. Data were taken for 30 min out of the hour in most cases and were taken during an average of 9 h/day at the three intersections. The delay was calculated for each approach and then combined with left-turn delay to determine total intersection delay. The results of the studies are given in Table 1.

As expected, total delay increased after installation of the exclusive left-turn phasing. Two of the locations were T-intersections at which left-turn phasing was installed on only one approach. The T-intersections had an average increase in delay of less than 1 s, compared with about 5 s at the other intersection. The reason for the difference was clear when the delay for each approach was examined. The T-intersections had one approach on the main street that had a substantial reduction in delay because it was allowed to proceed while

Table 1. Summary of delay and conflict studies.

Item	Dixie Highway and Deering Road, Louisville (T-intersection) Before	After	Change (%)	US-41A and Skyline Drive, Hopkinsville (T-intersection) Before	After	Change (%)	Dixie Highway and Pages Lane, Louisville Before	After	Change (%)
Delay (s/vehicle)									
Total intersection									
All hours	6.8	6.8	0	4.7	5.4	+15	9.4	15.2	+62
Peak hours	11.3	11.2	-1	6.8	6.2	-9	11.7	21.6	+85
Nonpeak hours	6.5	6.8	+5	3.9	5.0	+28	8.9	13.7	+54
Side street	8.4	10.6	+26	20.0	18.2	-9	17.9	24.0	+34
Opposing approach traffic	2.0	4.5	+125	4.7	6.4	+36	6.9	11.9	+72
Unopposed approach traffic	4.0	1.0	-75	2.4	1.7	-29			
Left turn									
All hours	22.1	32.7	+48	15.5	20.5	+32	39.0	38.3	-2
Peak hours	48.8	36.8	-25	30.0	27.8	-7	52.8	44.2	-16
Nonpeak hours	23.9	34.0	+42	11.2	19.2	+71	37.2	36.8	-1
Left-turn conflicts	50	12	-76	42	13	-69	53	3	-94
Total volume (vehicles)	9057	8372	-8	8606	7208	-16	10 531	5036	-52
Left-turn volume (vehicles)	481	492	+2	653	650	0	364	397	+9

the left turns were made, thus increasing its green time. This was the unopposed approach. This reduction in delay compensated for the increase in delay for the approach that was opposing the left turns. Another study had found a 3.5-s increase in delay when left-turn phasing was added on one street (2); increased delay of 8.6-12.5 s/vehicle was observed when additional phasing was installed on all approaches.

Total left-turn delay was not decreased by the addition of left-turn phasing. Delay actually increased at two of the locations and remained the same at the other. Left-turn delay was reduced at all three locations during the peak hour. The data clearly showed that exclusive left-turn phasing will only reduce left-turn delay during periods of heavy traffic flow. The total left-turn delay was reduced at the one location because it had several high-volume hours, while there were only a few hours of heavy volume at the other locations.

Left-turn conflicts were classified into three categories (4). The first type of conflict (basic left-turn conflict) occurred when a left-turning vehicle crossed directly in front of or blocked the lane of an opposing through vehicle. This conflict was counted when the through vehicle braked or weaved. This was the most common type of left-turn conflict. A second type of conflict is a continuation of the first type. If a second through vehicle following the first one also had to brake, this conflict was counted. There were very few of these conflicts. The third conflict consisted of turning left on red. This conflict was counted when the vehicle entered the intersection after the signal turned red. Vehicles that entered the intersection legally and completed their movement after the signal changed were not counted.

Left-turn conflicts were reduced drastically after installation of left-turn phasing. The only conflicts in the after period involved vehicles running the red light. The after-period data were not taken immediately after installation in order to allow drivers to become accustomed to the left-turn phase, but there were still some red-light violations. This large reduction in conflicts corresponded to the accident reduction found at locations where left-turn phasing was added.

There was a slight increase in left-turn volumes after installation of the separate phasing. This could be expected, because drivers would take advantage of the safer movement allowed by the left-turn phase. The total volume happened to be lower during the after studies. The delays during the after period might have been slightly higher if the volumes had been equal to the before-period conditions.

Benefit-Cost Analysis

The benefits and costs of installing left-turn phasing were compared to determine the economic consequences. The benefit considered was the reduction in accident costs. As was discussed above, left-turn accidents were reduced by 85 percent after installation of left-turn phasing, but rear-end accidents increased, partly offsetting the benefits of the reduction. For the 24 intersections where accident data were collected, the average reduction in the number of left-turn accidents was 4.1, compared to a reduction of 3.0 in total accidents. This factor (3.0/4.1) was applied to the 85 percent reduction in left-turn accidents to account for the increase in other accidents. Accident savings resulting from a left-turn phase were then determined by using an average cost of $7112/accident. This cost was calculated by using National Safety Council accident costs and considering the distribution of fatalities, injuries, and property-damage-type accidents in Kentucky. The operating cost considered was that due to the increase in intersection delay.

Benefits and costs were calculated on an annual basis. The cost of installation, when computed as an annual cost, becomes insignificant compared to the delay costs. Therefore, installation costs were not included. Annual delay costs of adding left-turn phasing on one approach (T-intersections) as well as both approaches on a street were tabulated as a function of intersection volume (AADT). An added delay of 1 or 5 s/vehicle was used when phasing was added on one approach or two approaches, respectively. These numbers were obtained from the delay studies. A delay cost of $4.87/vehicle-h was used. This number was derived from a 1970 report that listed values for delay of $3.50/vehicle-h for passenger automobiles and $4.47/vehicle-h for commercial vehicles (5). By using the consumer price index to convert to 1975 costs and assuming 5 percent of the total volume to be commercial vehicles, a delay cost of $4.87/vehicle-h was derived.

The benefit-cost ratio would vary greatly according to AADT and the number of left-turn accidents. As an example, an AADT of 30 000 was used because it was close to the average volume for the Lexington intersections that had left-turn phases. This would result in an annual delay cost of $14 800 and $74 100 for adding phasing to one and two approaches, respectively. The critical number of left-turn accidents in one year was used to determine accident savings. For a T-intersection, the critical number of four yields an annual savings of $17 700. The benefit-cost ratio would be 1.20. For two approaches, the critical number is six, which gives an accident savings of $26 500. Using the delay cost of $74 100 yields a benefit-cost ratio of 0.36.

As a general rule, the savings attributable to accident reduction should offset the increased cost due to delay when street geometry makes left-turn phasing necessary on only one approach that has a critical number of accidents. This situation would be approximated if both approaches must be signalized but left-turn volume on one approach is very low. Since the left-turn phasing would be actuated, this would approximate the T-intersection situation if the left-turn phasing for one approach was used only during a very small percentage of the cycles. However, when a street has relatively high left-turn volumes on both intersection approaches, the cost of increased delay will be much higher than the savings from accident reduction.

Left-Turn Delay

Excessive delay in left turns is one of the major reasons for installing separate left-turn signals. A good delay criterion should include both delay and volume. Multiplying the average delay per vehicle (seconds) by the corresponding left-turn volume yields the number of vehicle-hours of delay. This unit of delay was used in this study. Also, further safeguards were built into the delay warrant. Minimum delay per vehicle and minimum volumes were specified so that neither very low volumes with excessive delays nor very high volumes with minimal delays would meet the warrant. The delay during peak-hour conditions was specified, since these are the conditions that create excessive delays.

Cycle time and the number of vehicles that might turn left during amber periods were considered when determining a minimum left-turn volume. The maximum cycle that normally would be used is 120 s. This would give 30 periods of amber/h for use by left-turning vehicles. Assuming that a minimum average of 1.6 vehicles could turn left during each amber phase, 48 vehicles/h could turn left during amber under peak opposing-flow conditions. Therefore, a minimum left-turn volume of 50 vehicles in the peak hour was specified.

A minimum value necessary for the average left-turn delay was also determined. Since installing a separate left-turn phase would increase total delay at the intersection, the supposition was made that a minimum delay was necessary to left-turning vehicles independent of the left-turn volume. To determine this level of delay, a past survey of engineers was used (6). This survey asked the engineers for their opinion of what constituted maximum tolerable delay for a vehicle controlled by a traffic signal. A mean value of 73 s was found. The criterion used was that 90 percent of all left-turning vehicles be delayed less than this maximum of 73 s.

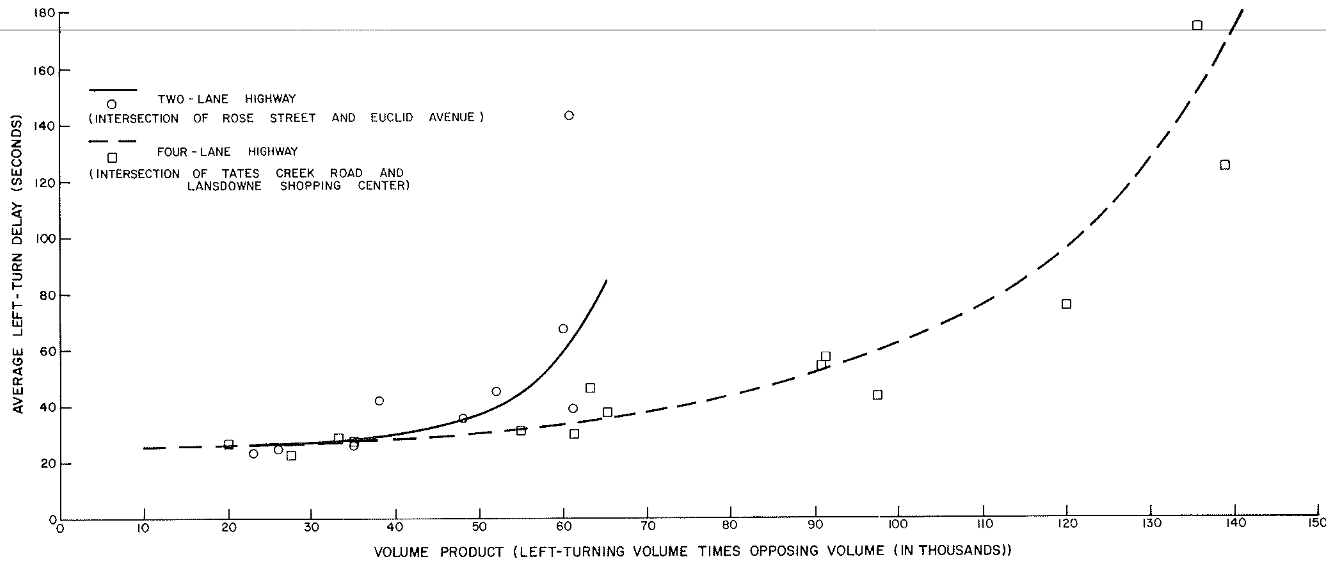
Assuming that the distribution of delays was approximately normal, it was then possible to find the mean of the delay distribution whose 90th percentile value was approximately 73 s/vehicle. From field data, it was found that the ratio of the mean to the standard deviation increased as the mean increased. For average delays approximating 73 s, this ratio was about 1.5. By using this ratio, a value of 35 s for the mean delay was determined. This value of 35 s was used as the minimum average delay necessary, since this constituted the lower bound of excessive delay.

When considering what would constitute excessive delay, the delay to left-turning vehicles turning only on the amber phase was calculated. This would approximate peak-flow conditions when the only gap available to turn left occurs at the end of the amber phase. The maximum delay possible if none of the vehicles had to wait more than one cycle length was determined. The maximum delay possible would occur when the left-turning vehicle arrived at the start of the red phase and departed during the amber phase. This delay would be approximately equal to one cycle. The number of vehicles that could turn left in 1 h during the amber phases was dependent on the cycle length. Since peak-hour conditions were specified, the assumption was made that side-street traffic would be heavy enough to make an actuated signal behave as a fixed-time signal with a constant cycle length. If the cycle length were 60 s, there would be 60 amber phases available to left-turning vehicles. Thirty amber phases would be available during the peak hour at a signal with a 120-s cycle length. If an average of 1.6 vehicles turned left during each phase of amber, 96 vehicles/h could turn left if the cycle length were 60 s. This volume would decrease to 48/h for a cycle length of 120 s. For a maximum delay of one cycle, the total delay for the peak hour was determined to be 1.6 vehicle-h for both cycle lengths. Field experience has shown that during peak conditions the number of vehicles turning left during each phase of amber can become close to 2 if the left-turn volume is heavy. If an average of 2 vehicles turn left during each amber phase, the total left-turn delay becomes 2.0 vehicle-h during the peak hour. Delays in excess of these values could be considered excessive. These delays would apply to the critical approach.

Delay data collected at several intersections were compared with these values to check their validity. As stated earlier, studies were done before installation of left-turn phases at three intersections. During peak-hour conditions before installation, left-turn delays of 2.45, 1.27, and 1.64 vehicle-h were found at those three locations. The location that had a delay of 1.27 vehicle-h also had an average left-turn delay during the peak hour of only 30 s. Six intersections in Lexington that had high left-turn delays were selected for detailed delay studies. Delays were measured on both streets at one of the intersections. Left-turn delays were measured for several hours during the day. The peak-hour delay was ≥ 2.0 vehicle-h (varying from 1.76 to 5.96) in all but one case. Only two of the critical approaches had peak-hour delays > 2.5 vehicle-h. All of these approaches met the criteria of minimum left-turn delay and volume. The field data show that peak-hour, left-turn delay in excess of 2.0 vehicle-h can occur regularly at locations that have a left-turn problem.

A review of the literature (7) disclosed two peak-hour delay warrants for the installation of traffic signals that had been developed in terms of vehicle hours of delay. One warrant requires that the average side-street vehicle delay in seconds multiplied by side-street volume per hour be equal to or exceed 8000. This is equivalent to 2.2 vehicle-h of delay. Another peak-hour delay warrant for a single, critical left-turn approach was 2.0 vehicle-h of delay. A minimum volume of 100 on the approach during the peak hour was also required. Assuming the delays for side-street vehicles can be applied to left-turning vehicles, a delay of 2.0 vehicle-h

Figure 1. Relationship between volume product and left-turn delay.



during the peak hour could be considered a valid warrant.

Volume Warrant

Relationship Between Left-Turn Delay and Traffic Volumes

Data collected at several intersections have shown that average left-turn delay varied substantially between intersections for any given volume-related product. For example, for a product of left-turn and opposing 1-h volumes of approximately 100 000, the average left-turn delay found at approaches at seven intersections on four-lane streets varied from a low of 15 s to a high of 100 s. Three of the approaches had average left-turn delays of less than 30 s, while three had average delays of 60 s or more. This clearly shows that, even if the calculated product was above the specified warrant value, a left-turn phase should not be added to an existing signal unless a delay study also showed an excessive delay.

Better relationships of delay versus the volume product were found when data from individual intersections were plotted. An important deficiency was found in some currently used volume-product warrants; all but one of these warrants did not define the number of opposing lanes. Data showed that a much higher volume product would be necessary to warrant a left-turn phase on a four-lane street than on a two-lane street. The product was directly proportional to the number of opposing lanes.

Plots of data collected at two intersections are shown in Figure 1. In both cases, the left-turn delay increased sharply after the product of the left-turning and opposing volumes reached a certain level. The increase in delay occurred at a much higher volume product on the four-lane street than on the two-lane street. Plots such as these were prepared for several intersections. The increase in delay did not occur at any specific volume product, and the increase was not as dramatic in some cases. The increase in delay did not occur at all if the volume product remained low. For four-lane streets, plots showing this increase in left-turn delay were drawn for the approaches of seven intersections. The 1-h volume product at which the increase occurred was estimated in each case. It varied from a low of 60 000 to a high of 145 000 and averaged 103 000. For two-lane streets, plots were drawn for approaches of three streets at two intersections. The critical volume product varied from 30 000 to 70 000 and averaged 50 000.

Comparison of Locations With and Without Left-Turn Phases

Plots of peak-hour opposing volume versus peak-hour left-turn volume were made for intersections on both four-lane and two-lane highways with data from Lexington (Figure 2). A point was plotted for each approach at a signalized intersection that had a separate left-turn lane. The only exception was that only the critical approach was plotted for streets that had left-turn phasing if it was obvious that only one approach had a problem. The policy is to install left-turn phasing in both directions although it may only be warranted for one approach.

The objective was to construct a line that separated intersection approaches with and without left-turn phases. An attempt was made to construct a line in which the product of the peak-hour left-turn and opposing volumes was a constant. If such a line could be drawn, this product could be thought of as a warrant based on past practices. Such a line was drawn for both four-lane and two-lane highways. There were only a very few exceptions to the division of the approaches into groups with and without left-turn phasing. The lines represented a product of peak-hour left-turn and opposing volumes of 90 000 for four-lane highways and 60 000 for two-lane highways.

Gap Acceptance

Gap acceptance has been proposed as a criterion for left-turn phasing (8). Although it will not be used as a warrant in this study, it can be used to corroborate other data. Some very rough calculations were made that seemed to agree with field observations.

Data were taken to determine the critical gap for vehicles turning left across opposing traffic. The critical gap was defined as the length of gap at which the number accepted was equal to the number rejected. The gap was measured as the interval in time between

Figure 2. Comparison of volumes at intersections with and without left-turn phasing.

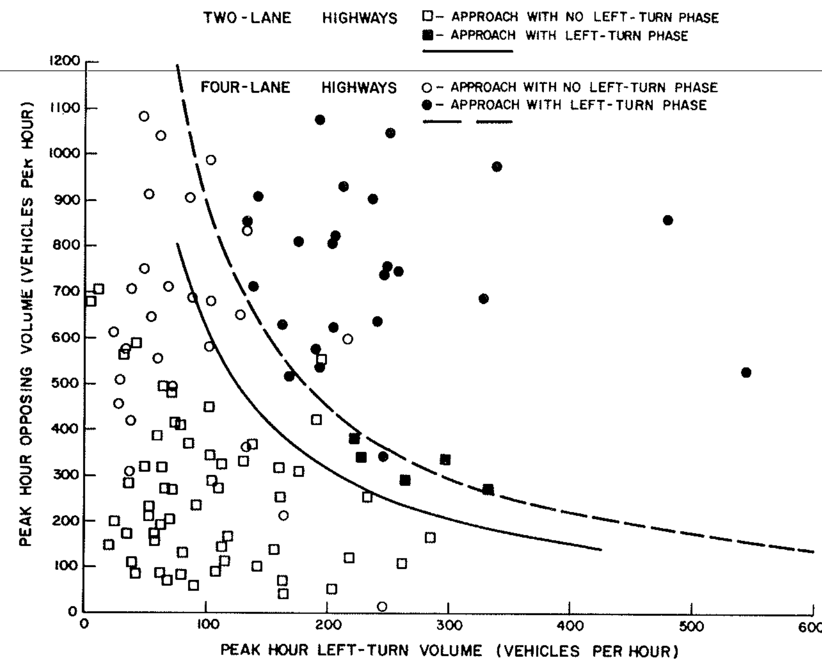
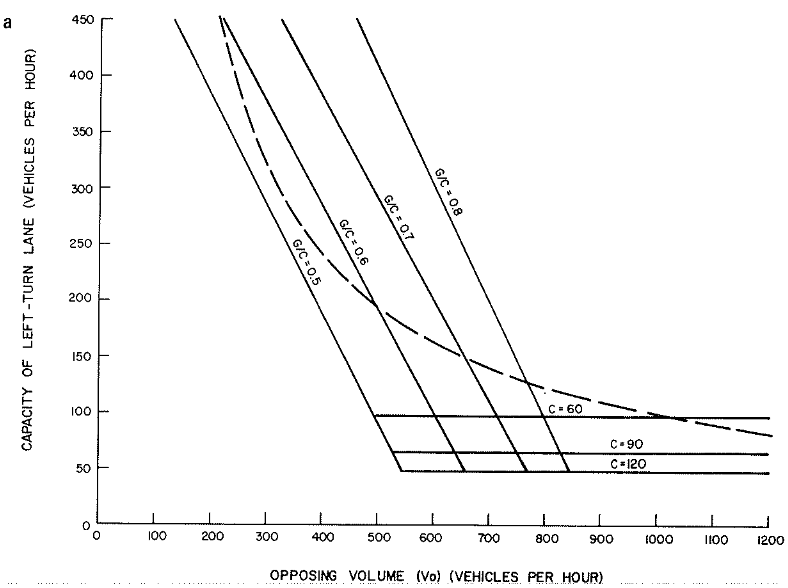


Figure 3. Capacity of a left-turn lane on the basis of a capacity nomograph.



vehicles opposing the left turn. It was measured from the rear of one vehicle to the front of the following vehicle. Observations were made of 500 vehicles attempting to turn left at a signalized intersection. A critical gap of 4.2 s was found.

By using several assumptions, an estimate of the volume of left-turning and opposing traffic necessary to warrant a left-turn phase can be made. The volume at which there are no gaps greater than the critical gap (4.2 s) would be approximately the point at which all left turns must be made during the amber. If the assumption is made that 60 percent of the cycle is green time for the main street, there would be 2160 s of green and amber time per hour on the main street. Making the rough assumption that the vehicles would be equally spaced resulted in volumes of 514 vehicles/h on two-lane highways and 1028 vehicles/h on four-lane highways as the point at which left-turning vehicles could turn only on the amber. It is recognized that vehicles will not be equally spaced under stable flow conditions. This assumption, however, should yield conservative results, since opposing volumes above these volumes will contain gaps greater than the critical gap because of variations in vehicle spacings. However, the results generally agree with field observations that, under average conditions, for opposing volumes of about 500 vehicles/h on two-lane highways and 1000 vehicles/h on four-lane highways, most left turns must be made during the amber period. For a cycle of 60 s, 60 amber periods would be available per hour. Assuming 1.6 vehicles can turn left during each amber period, the capacity of the left-turn lane was 96. Therefore, the critical product of left-turning and opposing volumes was approximately 100 000 for four-lane highways and 50 000 for two-lane highways.

Of course, this critical product would vary as the cycle length or green-time-to-cycle-length ratio for the main street changed. For example, data were taken at one intersection on a four-lane highway that had a cycle of 60 s and a green-time-to-cycle-length ratio of about 0.75 for the main street. For peak-hour opposing volumes of slightly more than 1000/h, most left-turning vehicles did not have to turn during the amber. This was the result of more green time for the main street. By using the same assumptions as before, except that 75 percent of the cycle is assumed to be devoted to the main street, a volume of 1286 vehicles/h was the point at which left-turning vehicles could turn only on the amber. This would yield a critical product of 125 000.

Relationship Between Left-Turn Accidents and Traffic Volumes

By using the same Lexington data base, plots were drawn of the highest number of left-turn accidents in one year for an approach versus the product of peak-hour left-turn volume and opposing volume, as well as just the left-turn volume. The highest accident year was used so that a comparison could be made with the critical accident number. The plots showed that the relationship was very poor in nearly all cases. Plots were drawn for both two- and four-lane highways. With one exception, the maximum coefficient of determination (r^2) was 0.2. The one exception was the plot of accidents versus the product of peak-hour left-turn and opposing volumes for four-lane streets; the r^2 value for this plot was 0.5. Four accidents on an approach in one year had previously been found to be the critical number. This corresponded to a volume product of approximately 80 000. A plot of left-turn accidents versus left-turn volume resulted in an r^2 value of only 0.19. A value of four accidents related to a left-turn volume of 120. The inability to fit a curve to the points makes it hard to draw any valid conclusions from the plots. However, the higher r^2 value for the plot that used the product of left-turning and opposing volumes indicates that this product was a better estimator of left-turn accidents than was left-turn volume.

Capacity Analysis

A capacity analysis is used in several states as a guideline when considering the installation of left-turn phases. The nomograph developed by Leisch was used to develop a warrant curve based on intersection capacity (9). By assuming 5 percent trucks and buses, curves were drawn representing green-time-to-cycle-length ratios of 0.5 to 0.8 and cycles of 60 to 120 s (Figure 3). This figure clearly shows how the left-turn capacity is increased as the green-time-to-cycle-length ratio is increased and the cycle length is decreased. Points above the curves represent intersections where the left-turn volume was above the left-turn capacity that would warrant a left-turn phase. The dashed line in Figure 3 depicts a product of 95 000 for the left-turning and opposing volumes, assuming 5 percent trucks and buses; a green-time-to-cycle-length ratio of 0.6; and a cycle length of 60 s. A deficiency of this procedure is that the number of opposing lanes is not specified.

Selection of Volume-Related Warrants

The preceding sections have dealt with various methods of selecting a critical product of left-turning and opposing vehicle volumes. Although some methods were based on assumptions and collected data and some were based entirely on field data, there was a close agreement of the results. A volume warrant based on all sources of input was developed. The warrant required that the addition of separate left-turn phasing should be considered when the product of left-turning and opposing volumes during peak-hour conditions exceeds 100 000 on a four-lane street or 50 000 on a two-lane street. A limitation is that the left-turn volume must be at least 50. This is based on the same reasoning as that for the minimum volume requirement in the delay warrant. It is important to note that, even if the calculated product exceeds the warrant, a left-turn phase should not be added to an existing signal unless a study shows excessive left-turn delay.

Traffic-Conflicts Warrant

A major reason for installing left-turn phasing is to provide improved safety. An obvious indicator used to warrant a left-turn phase because of a safety problem has been the number of left-turn accidents. A weakness of that indicator is that a substantial number of accidents must occur before any improvement is made. The traffic-conflicts technique has been developed in an attempt to objectively measure the accident potential of a highway location without having to wait for an accident history to evolve.

An attempt was made to find a relationship between left-turn accidents and conflicts. The types of left-turn conflicts counted have been described earlier in this report. The Lexington data base was the source of the accident data. This provided a five-year accident history for the intersection approaches. Comparisons were made for individual approaches that had separate left-turn lanes. The approach also had to be at a signalized intersection. Since conflicts indicate accident potential, the highest numbers of accidents in a one-year and in a two-year period were used in the comparisons. Left-turn accidents were compared with the total number of conflicts (all three types) and with the basic left-turn conflicts (left-turn vehicle crossed directly in front of or blocked the lane of an opposing through vehicle). Conflict counts were taken during peak flow conditions for 1 h. Volume counts were used in selecting times for data collection. Both left-turn and opposing volumes were considered. Peak hours were chosen, because conflicts are highest during these hours; left-turn accidents also reach a maximum during peak-volume hours, and it appeared reasonable that conflict counts should be conducted when accident problems are most acute. It is important to note that conflict data were taken during

Figure 4. Left-turn accidents versus total left-turn conflicts.

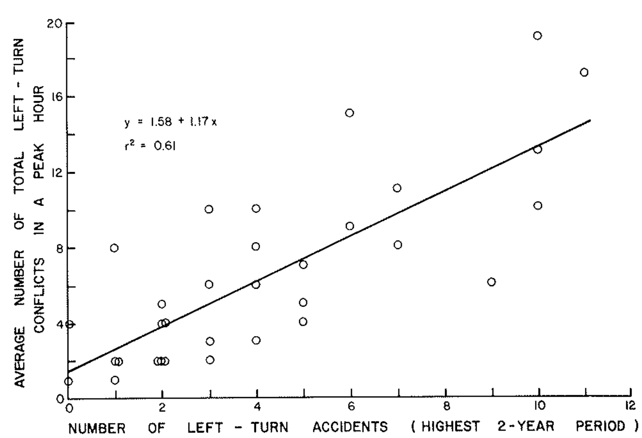
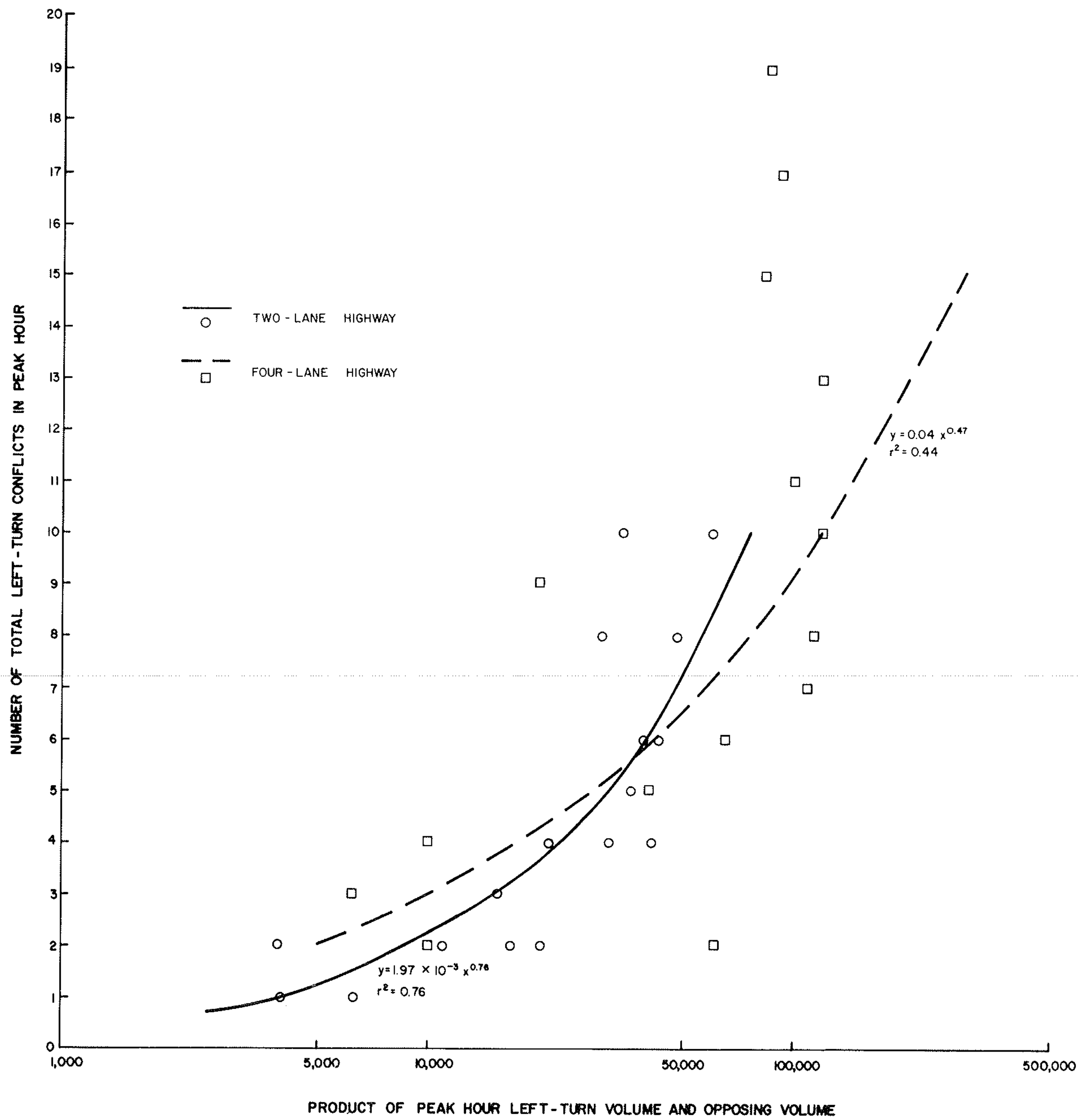


Table 2. Relationship between left-turn accidents and left-turn conflicts.

Variable	Linear Regression Equation[a]	R^2	Critical No. of Conflicts	Range[b]
Number of total conflicts versus				
Highest one-year period of accidents	Y = 1.26 + 1.87X	0.50	8.7	5.4
Highest two-year period of accidents	Y = 1.58 + 1.17X	0.61	8.6	4.8
Number of basic conflicts versus				
Highest one-year period of accidents	Y = 1.42 + 1.13X	0.39	5.9	4.1
Highest two-year period of accidents	Y = 1.70 + 0.69X	0.45	5.8	3.9

[a] Y = number of conflicts; X = number of accidents.
[b] Probability level = 95 percent.

Figure 5. Total left-turn conflicts in peak hour versus product of peak-hour left-turn volume and opposing volume.



several peak hours at each of 32 approaches, so that a reliable average number of conflicts per hour could be obtained.

Plots were drawn of left-turn accidents versus left-turn conflicts; see Figure 4 for an example. By using linear regression and the method of least squares, equations of the best-fit lines were determined. The coefficients of determination (r^2) ranged between 0.39 and 0.61. For both conflict categories, the best relationship was found when the two-year accident maximum was considered. Also, better relationships were found between accidents and total conflicts than basic left-turn conflicts; however, data showed the number of basic conflicts to be more consistent from one period of observation to the next. The critical number of left-turn accidents for one approach was previously found to be four for a one-year period and six for a two-year period. By using the linear regression equations, the number of conflicts corresponding to the critical number of accidents was predicted. The equations for one- and two-year accident data gave similar results. The equations predicted that about nine total conflicts or six basic conflicts corresponded to the critical number of accidents. Since the r^2 values were low, the range (confidence interval) within which conflicts could be predicted was determined. A probability level of 95 percent was used. A range of about ±5 was found for total conflicts, and a range of about ±4 was found for basic conflicts. The various findings are summarized in Table 2.

Simply using the predicted number of conflicts related to the critical accident number as a warrant for left-turn signalization would not be very reliable; this is so because of the uncertainty of the prediction equation, as evidenced by the large range in values possible. A warrant that considered the confidence interval would be much more reliable. The upper bound of values in the confidence interval was used as the conflict warrant. Given that number of conflicts, there would be a 95 percent certainty that the potential exists for the critical number of accidents to occur. Therefore, a warrant for left-turn signalization was developed that listed 14 total conflicts or 10 basic conflicts as its criterion.

A recent report included a critical evaluation of the state of the art of the traffic-conflicts technique and listed the results of work done in this area (10). In terms of accidents per conflict, there were 20 left-turn accidents/100 000 left-turn conflicts in one study (11) and 15 left-turn accidents/100 000 left-turn conflicts in the other study (12). If those results are averaged (17.5 accidents/100 000 conflicts) and if 4 left-turn accidents on an approach in a year is considered to be critical, the critical number of left-turn conflicts would be 22 857 in one year. Assuming the conflicts to be equally distributed throughout the year yielded an average of 62.6 conflicts/day. Volume data for Lexington showed that 14 percent of the daily left-turn volume occurred during the peak hour. Applying this factor to conflicts yielded 7.0 conflicts in the peak hour. This agreed with the previous finding: 6 basic left-turn conflicts in a peak hour would give an accident potential of 4 left-turn accidents in one year. Those two studies gave r^2 values of 0.38 and 0.11. The values for r^2 from 0.39 to 0.61 found for the linear regression lines of accidents and conflicts in this study compared favorably.

Conflicts are inherently related to volume. Plots were drawn to determine the relationship between left-turn conflicts and volumes for data collected in this study. Peak-hour conflicts were plotted against the product of left-turn volume and opposing volume. Volumes were counted while the conflict data were collected. Separate plots were drawn for four-lane and two-lane highways. Both total and basic conflicts were used, and it was found that the use of total conflicts gave better results (Figure 5). Several linear regression lines were tried, and the power curve yielded the best-fit line. The r^2 values for these figures indicate that a better relationship exists between left-turn conflicts and volume than between left-turn accidents and volume. A total of nine left-turn conflicts in the peak hour was previously found to correspond to the critical accident number. This number of conflicts related to volume products of 65 000 and 100 000 for two-lane and four-lane highways, respectively. These agree closely with the other findings for critical products.

RECOMMENDATIONS

It is recommended that the following warrants be used as guidelines when considering the addition of separate left-turn phasing. The warrants apply to intersection approaches that have a separate left-turn lane.

1. Accident experience—Install left-turn phasing if the critical number of left-turn accidents has occurred. For one approach, 4 left-turn accidents in one year or 6 in two years are critical. For both approaches, 6 left-turn accidents in one year or 10 in two years are critical.
2. Delay—Install left-turn phasing if a left-turn delay of 2.0 vehicle-h or more occurs in a peak hour on a critical approach. Also, there must be a minimum left-turn volume of 50 during the peak hour, and the average delay per left-turning vehicle must be at least 35 s.
3. Volumes—Consider left-turn phasing when the product of left-turning and opposing volumes during peak hours exceeds 100 000 on a four-lane street or 50 000 on a two-lane street. Also, the left-turn volume must be at least 50 during the peak-hour period. Volumes meeting these levels indicate that further study of the intersection is required.
4. Traffic conflicts—Consider left-turn phasing when a consistent average of 14 or more total left-turn conflicts or 10 or more basic left-turn conflicts occurs in a peak hour.

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Guidelines for Traffic Control at Isolated Intersections on High-Speed Rural Highways

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This paper involves the development of guidelines for traffic control warrants at isolated intersections on high-speed rural highways by using both field studies and traffic simulation. Gap-acceptance and delay studies were performed at stop-sign-controlled rural intersections in Indiana, and the resulting data were used to validate and modify the UTCS-1 program (known now as NETSIM). Two-way stop signs, pretimed signals, semiactuated signals, and fully actuated signals were evaluated over a range of traffic volumes on both major and minor approaches. Annual economic cost was used as a basis to develop criteria for selecting the most appropriate control type. The resulting warrants are expressed in chart form.

The control of vehicular traffic at highway intersections has been one of the most studied areas in traffic engineering. Intersections critically affect the efficiency, capacity, and safety of a highway system. Not enough information is available on traffic control alternatives at isolated intersections on high-speed rural highways, in particular at the intersection of a multilane high-speed major highway and a two-lane minor road located in suburban or rural areas.

The Manual on Uniform Traffic Control Devices (MUTCD) (1) provides general guidelines for stop-sign and signal warrants at intersections; however, these guidelines do not distinguish between pretimed (PR) signals and vehicle-actuated (VA) control. Section 4C-3 of the MUTCD states:

> When the 85 percentile speed of the major street traffic exceeds 64 km/h (40 mph), or when the intersection lies within the built-up area of an isolated community having a population of less than 10 000, the maximum vehicular volume warrant is 70 percent of the requirement above (in recognition of differences in the nature and operational characteristics of traffic in urban and rural environments and smaller municipalities).

According to that statement, the minimum vehicular volume warrant for traffic-signal installation for a four-lane major street intersecting with a two-lane minor street is 420 and 105 vehicles/h (total traffic per approach), for the major and minor streets, respectively. For the warrant for the interruption of continuous traffic, the vehicular volumes are 630 and 53 vehicles/h. Section 4C-11 of the MUTCD reviews principal factors that may lead to selecting traffic-actuated control. However, there is a need for a detailed examination of warrants for traffic controls at multilane high-speed intersections.

DEVELOPMENT OF THE ANALYSIS TOOL

In this study, the UTCS-1S simulation model (the smaller version of the UTCS-1 model) was modified and used for the purpose of evaluating alternative traffic control devices. The single-intersection version of the UTCS had been successfully validated by Cohen (2) by using field data collected from two intersections that differed widely in geometry and location.

Hall (3) modified the UTCS-1S computer program to provide the vehicle fuel-economy and air-pollution measurements; careful study of the velocity patterns created by automobiles traversing the intersection made it possible to estimate fuel consumption and air pollution resulting from the use of various traffic controls.

Two-Way Stop-Sign-Controlled Intersection

For undivided major highways, the gap-acceptance distributions developed by Wagner (4) were used to modify the UTCS-1S model. These distributions represent the gap-acceptance behaviors of drivers stopped at the stop sign of a two-lane street intersecting with a four-lane undivided highway.

For the case of divided highways, the gap-acceptance distributions were developed from field observations made in the present study. Six rural intersections in Indiana were selected for this purpose, and they fulfilled