

## WARRANTS FOR LEFT-TURN SIGNAL PHASING

by

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### ABSTRACT

Warrants for the installation of left-turn phasing were developed. A review of literature was conducted along with a survey of the policies of other states. Field data of delays and conflicts were taken before and after installation of exclusive left-turn signalization. Left-turn delay studies were conducted at intersections with 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 the following four general areas:

1. accident experience,
2. delay,
3. volumes, and
4. traffic conflicts.

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LEFT-TURN SIGNAL PHASING**

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## INTRODUCTION

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 which have separate left-turn lanes. Before-and-after data were taken at locations where left-turn phasing had been added. Studies at locations with 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

A letter was sent to other state highway agencies requesting their procedure used to determine the need for left-turn phasing. Of the 45 states responding, only six 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 equals 50,000 or greater;
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 greater than 100,000 (two states, one listing this for traffic-actuated signals only);
4. delay to left-turn vehicle in excess of two cycles;
5. one left-turning vehicle delayed one cycle or more in a period of 1 hour;
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 20 m/s (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. over 90 cars in an hour 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 which have been used. Following is a

list of the general guidelines (areas which should be considered) that were mentioned; some 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 ADT above 500 (two-lane roadway), wherever a left-turn lane is installed on divided highways; 100 to 150 left-turning vehicles during the peak hour (small cities); 150 to 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 of less than 80 vehicles per hour for at least 8 hours of the day; the number of left-turning vehicles is about two per cycle; 120 left-turning vehicles in the design hour; turning volume is in excess of 100 vehicles per hour and more than one cycle of the signal is necessary to clear a vehicle stopped on the red; left-turn volumes of 90-120 in peak hours; and more than 100 turns per hour.

## 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 1 year, but it varied in some cases depending on the available data. There was an 85-percent reduction in left-turn accidents defined as 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. Rates were calculated using 1972 accident data, and the volume data were taken in the time period of 1971 through 1973. Volume counts were available for a 12-hour period (7 a.m. to 7 p.m.) at each intersection. The assumption was made that 80 percent of the total daily volume occurred in this 12-hour period, so the volumes were multiplied by 1.25 to obtain the 24-hour volume. The total rate of 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 which had a separate left-turn lane. It was calculated in terms of left-turn accidents per million vehicles turning left from the approach. Intersections without left-turn phasing (44 intersections) had an average AADT of approximately 20,000 compared to slightly over 32,000 for intersections with left-turn phasing (16 intersections). The higher AADT affects the accident rate. Calculating rates for only the high-volume intersections (AADT greater than 25,000) eliminated this variable. There were 13 intersections with separate phasing and 10 intersections without separate phasing which met this criteria (AADT greater than 25,000).

The left-turn accident rate was drastically lower for the approaches having left-turn phasing (0.77 left-turn accidents per million vehicles entering the intersection for all intersections, 0.86 for high-volume intersections) compared to 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** -- Using the Lexington data base, the average number of left-turn accidents for the approaches with no left-turn phasing was calculated. Using this average number of accidents, the critical number of accidents was also determined. For the years 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). A street with a left-turn lane in both directions had both approaches included separately. 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:

$$N_c = N_a + K \sqrt{N_a} + 0.5$$

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 only selecting intersections for improvement which do 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 2-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 2-year period. Using this average of two accidents, the number of left-turn accidents necessary in a 2-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 the years 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 six for a 1-year period for both approaches. For a 2-year period, an average of four accidents resulted in a critical number of ten 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 which 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 time of each left-turning vehicle was noted; delay could then be calculated. If the vehicle did not have to stop, a zero delay was noted. The number of left turns were counted. Opposing volumes and left-turn conflicts were also counted during the study period, usually 30 minutes 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 seconds for two of the intersections and 20 seconds 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 minutes out of the hour in most cases and were taken during an average of 9 hours of the 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 where left-turn phasing was installed on only one approach. The T-intersections had an average increase in delay of under 1 second compared to about 5 seconds 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 which had a substantial reduction in delay because it was allowed to proceed while 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 which was opposing the left turns. Another study had found a 3.5-second increase in delay when left-turn phasing was added on one street (2); increased delay of 8.6 to 12.5 seconds per 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 compared to 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 which entered the intersection legally and completed their movement after the signal changed were not counted.

Left-turn conflicts reduced drastically after installation of left-turn phasing. The only conflicts in the after period were vehicles running the red light. The after-period data were not taken immediately after installation to allow drivers to become accustomed to the left-turn phase, but there was still a number of 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, partially 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 using an average cost of \$7,112 per accident. This cost was calculated 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 seconds per 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 per vehicle-hour was used. This number was derived from a 1970 report which listed values for delay of \$3.50 per vehicle-hour for passenger cars and \$4.47 per vehicle-hour for commercial vehicles (5). Using the Consumer Price Index to convert to 1975 costs and assuming five percent of the total volume to be commercial vehicles, a delay cost of \$4.87 per vehicle-hour 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 having 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 1 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 which 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 criteria 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 which create excessive delays.

Cycle time and the number of vehicles which might turn left during amber periods were considered when determining a minimum left-turn volume. The maximum cycle which normally would be used is 120 seconds. This would give 30 periods of amber per hour for use by left-turning vehicles. Assuming that a minimum average of 1.6 vehicles could turn left during each amber phase means that 48 vehicles per hour 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 seconds was found. A criterion was used that 90 percent of all left-turn vehicles be delayed less than this maximum level of 73 seconds.

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 seconds per 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 seconds, this ratio was about 1.5. Using this ratio, a value of 35 seconds for the mean delay was determined. This value of 35 seconds 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 which could turn left in 1 hour 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 seconds, 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-second cycle length. If an average of 1.6 vehicles turned left during each phase of amber, 96 vehicles per hour could turn left if the cycle length were 60 seconds. This volume would decrease to 48 per hour for a cycle length of 120 seconds. For a maximum delay of one cycle, the total delay for the peak hour was determined to be 1.6 vehicle-hours 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 two if the left-turn volume is heavy. If an average of two vehicles turn left during each amber phase, the total left-turn delay becomes 2.0 vehicle-hours 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 to 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-hours were found at those three locations. The location with a delay of 1.27 vehicle-hours also had an average left-turn delay during the peak hour of only 30 seconds. Six intersections in Lexington with high left-turn delays were selected for detailed delay studies. Delays were taken on both streets at one of the intersections.

Left-turn delays were taken for several hours during the day. The peak-hour delay was equal to or greater than 2.0 vehicle-hours (varying from 1.76 to 5.96) in all but one case. Only two of the critical approaches had peak-hour delays in excess of 2.5 vehicle-hours. All of these approaches met the criterion of minimum left-turn delay and volume. The field data show that peak-hour, left-turn delay in excess of 2.0 vehicle-hours can occur regularly at locations with a left-turn problem.

A review of literature (7) disclosed two peak-hour delay warrants for the installation of traffic signals which had been developed in terms of vehicle-hours of delay. One warrant requires the average, side-street, vehicle delay in seconds multiplied by side-street volume per hour to equal or exceed 8,000. This is equivalent to 2.2 vehicle-hours delay. Another peak-hour delay warrant for a single, critical left-turn approach was 2.0 vehicle-hours 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-turn vehicles, a delay of 2.0 vehicle-hours 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-hour 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 seconds to a high of 100 seconds. Three of the approaches had average left-turn delays of less than 30 seconds while three had average delays of 60 seconds 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 presently 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 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-hour 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, averaging 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 which had a separate left-turn lane. The only exception was that only the critical approach was plotted for streets with 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 which 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 which 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 vehicles opposing the left turn. It was measured from the rear of one vehicle to the front of the following vehicle. A total of 500 observations were made when vehicles were attempting to turn left at a signalized intersection. A critical gap of 4.2 seconds was found.

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 seconds) 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 2,160 seconds 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 per hour on two-lane highways and 1,028 vehicles per hour 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 per hour on two-lane highways and 1,000 vehicles per hour on four-lane highways, most left-turns must be made during the amber period. For a cycle of 60 seconds, 60 amber periods would be available per hour. Assuming 1.6 vehicles can turn left 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 line changed. For example, data were taken at one intersection on a four-lane highway which had a cycle of 60 seconds and a green-time-to-cycle-length ratio of about 0.75 for the main line. For peak-hour opposing volumes slightly over 1,000 per hour, most left-turning vehicles did not have to turn during the amber. This was the result of more green time for the main line. Using the same assumptions as before, except substituting the assumption that 75 percent of the cycle is devoted to the main street, resulted in a volume of 1,286 vehicles per hour as 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** -- Using the same Lexington data base, plots were drawn of the highest number of left-turn accidents in 1 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 a comparison could be made to 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 1 year was previously 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 a  $r^2$  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 using 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). Assuming five 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 seconds (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 which 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 five percent trucks and buses, a green-time-to-cycle-length ratio of 0.6, and a cycle length of 60 seconds. 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 of 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 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 5-year accident history for the intersection approaches. Comparisons were made for individual approaches which had separate left-turn lanes. The approach also had to be at a signalized intersection. Since conflicts indicate accident potential, the highest number of accidents in a 1-year and a 2-year period were used in the comparisons. Left-turn accidents were compared to the total number of conflicts (all three types) and to 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 a 1-hour period. 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 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). 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 2-year accident maximum was considered. Also, better relationships were found between accidents and total conflicts than with 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 1-year period and six for a 2-year period. Using the linear regression equations, the number of conflicts corresponding to the critical number of accidents was predicted. The equations for 1- and 2-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 plus or minus five was found for total conflicts, and range of about plus or minus four 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 because of the uncertainty of the prediction equation as evidenced by the large range in values possible. A warrant which 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 which 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 conflict technique and listed the results of work done in this area (10): in terms of accidents per conflict, there were 20 left-turn accidents per 100,000 left-turn conflicts in one study (11) and 15 left-turn accidents per 100,000 left-turn conflicts in the other study (12). If those results are averaged (17.5 accidents per 100,000 conflicts) and if four 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 1 year. Assuming the conflicts to be equally

distributed throughout the year yielded an average of 62.6 conflicts per 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: six basic left-turn conflicts in a peak hour would give an accident potential of four left-turn accidents in 1 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. Nine left-turn total 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 having a separate left-turn lane.

1. **Accident Experience** -- Install left-turn phasing if the critical number of left-turn accidents have occurred. For one approach, four left-turn accidents in 1 year or six in 2 years are critical. For both approaches, six left-turn accidents in 1 year or ten in 2 years are critical.
2. **Delay** -- Install left-turn phasing if a left-turn delay of 2.0 vehicle-hours 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 seconds.

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 occur in a peak hour.

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TABLE 1. SUMMARY OF DELAY AND CONFLICT STUDIES

| DELAY<br>(SECONDS PER VEHICLE) <sup>a</sup> | DIXIE HIGHWAY AND<br>DEERING ROAD<br>LOUISVILLE<br>(T INTERSECTION) |       |                   | US 41A AND<br>SKYLINE DRIVE<br>HOPKINSVILLE<br>(T INTERSECTION) |       |                   | DIXIE HIGHWAY AND<br>PAGES LANE<br>LOUISVILLE |       |                   |
|---|---|-------|-------------------|---|-------|-------------------|---|-------|-------------------|
|   | BEFORE  | AFTER | PERCENT<br>CHANGE | BEFORE  | AFTER | PERCENT<br>CHANGE | BEFORE  | AFTER | PERCENT<br>CHANGE |
| TOTAL INTERSECTION DELAY                    |   |       |                   |   |       |                   |   |       |                   |
| 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               |
| NON-PEAK HOURS                              | 6.5   | 6.8   | +5                | 3.9   | 5.0   | +28               | 8.9   | 13.7  | +54               |
| SIDE STREET DELAY                           | 8.4   | 10.6  | +26               | 20.0  | 18.2  | -9                | 17.9  | 24.0  | +34               |
| OPPOSING APPROACH TRAFFIC<br>DELAY          | 2.0   | 4.5   | +125              | 4.7   | 6.4   | +36               | 6.9   | 11.9  | +72               |
| UNOPPOSED APPROACH<br>TRAFFIC DELAY         | 4.0   | 1.0   | -75               | 2.4   | 1.7   | -29               |   |       |                   |
| LEFT-TURN DELAY                             |   |       |                   |   |       |                   |   |       |                   |
| 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               |
| NON-PEAK HOURS                              | 23.9  | 34.0  | +42               | 11.2  | 19.2  | +71               | 37.2  | 36.8  | -1                |
| LEFT-TURN CONFLICTS<br>(NUMBER)             | 50  | 12    | -76               | 42  | 13    | -69               | 53  | 3     | -94               |
| TOTAL VOLUME (VEHICLES)                     | 9057  | 8372  | -8                | 8606  | 7208  | -16               | 10531   | 5036  | -52               |
| LEFT-TURN VOLUME<br>(VEHICLES)              | 481   | 492   | +2                | 653   | 650   | 0                 | 364   | 397   | +9                |

<sup>a</sup> EXCEPT AS NOTED

TABLE 2. RELATIONSHIP BETWEEN LEFT-TURN ACCIDENTS AND LEFT-TURN CONFLICTS

| VARIABLES   | LINEAR REGRESSION EQUATION <sup>a</sup> | R <sup>2b</sup> | CRITICAL NUMBER OF CONFLICTS | RANGE <sup>c</sup> |
|---|---|-----------------|------------------------------|--------------------|
| NUMBER OF TOTAL CONFLICTS VERSUS HIGHEST 1-YEAR PERIOD OF ACCIDENTS | $Y = 1.26 + 1.87X$                      | 0.50            | 8.7                          | ±5.4               |
| NUMBER OF TOTAL CONFLICTS VERSUS HIGHEST 2-YEAR PERIOD OF ACCIDENTS | $Y = 1.58 + 1.17X$                      | 0.61            | 8.6                          | ±4.8               |
| NUMBER OF BASIC CONFLICTS VERSUS HIGHEST 1-YEAR PERIOD OF ACCIDENTS | $Y = 1.42 + 1.13X$                      | 0.39            | 5.9                          | ±4.1               |
| NUMBER OF BASIC CONFLICTS VERSUS HIGHEST 2-YEAR PERIOD OF ACCIDENTS | $Y = 1.70 + 0.69X$                      | 0.45            | 5.8                          | ±3.9               |

<sup>a</sup>Y REFERS TO NUMBER OF CONFLICTS; X REFERS TO NUMBERS OF ACCIDENTS  
<sup>b</sup>R<sup>2</sup> IS THE COEFFICIENT OF DETERMINATION  
<sup>c</sup>PROBABILITY LEVEL OF 95 PERCENT

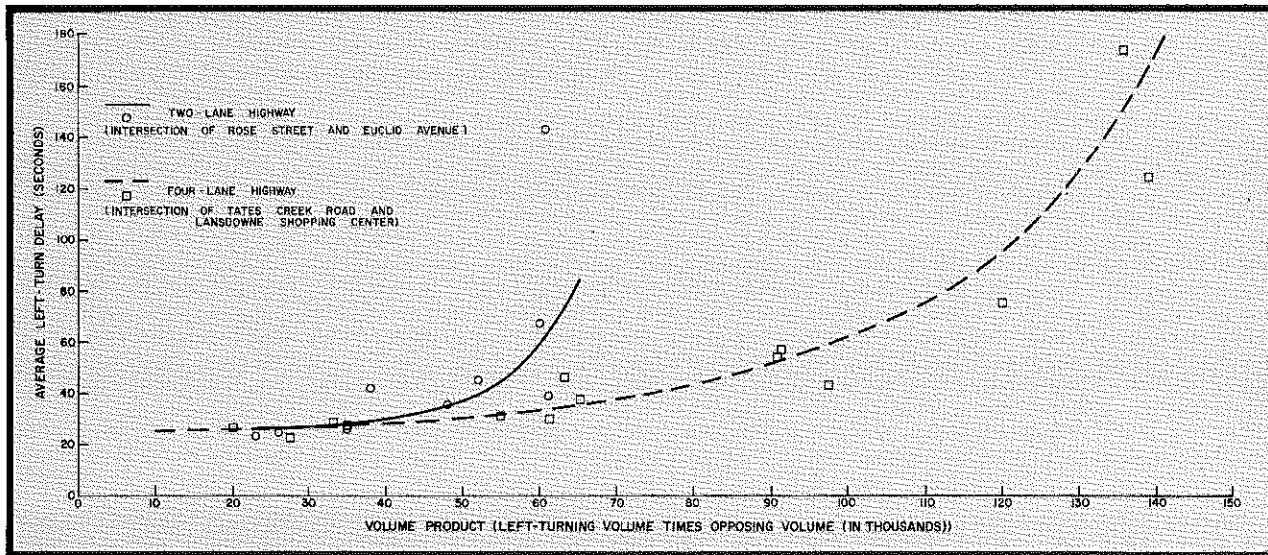


Figure 1. Relationship between Volume Product and Left-Turn Delay.

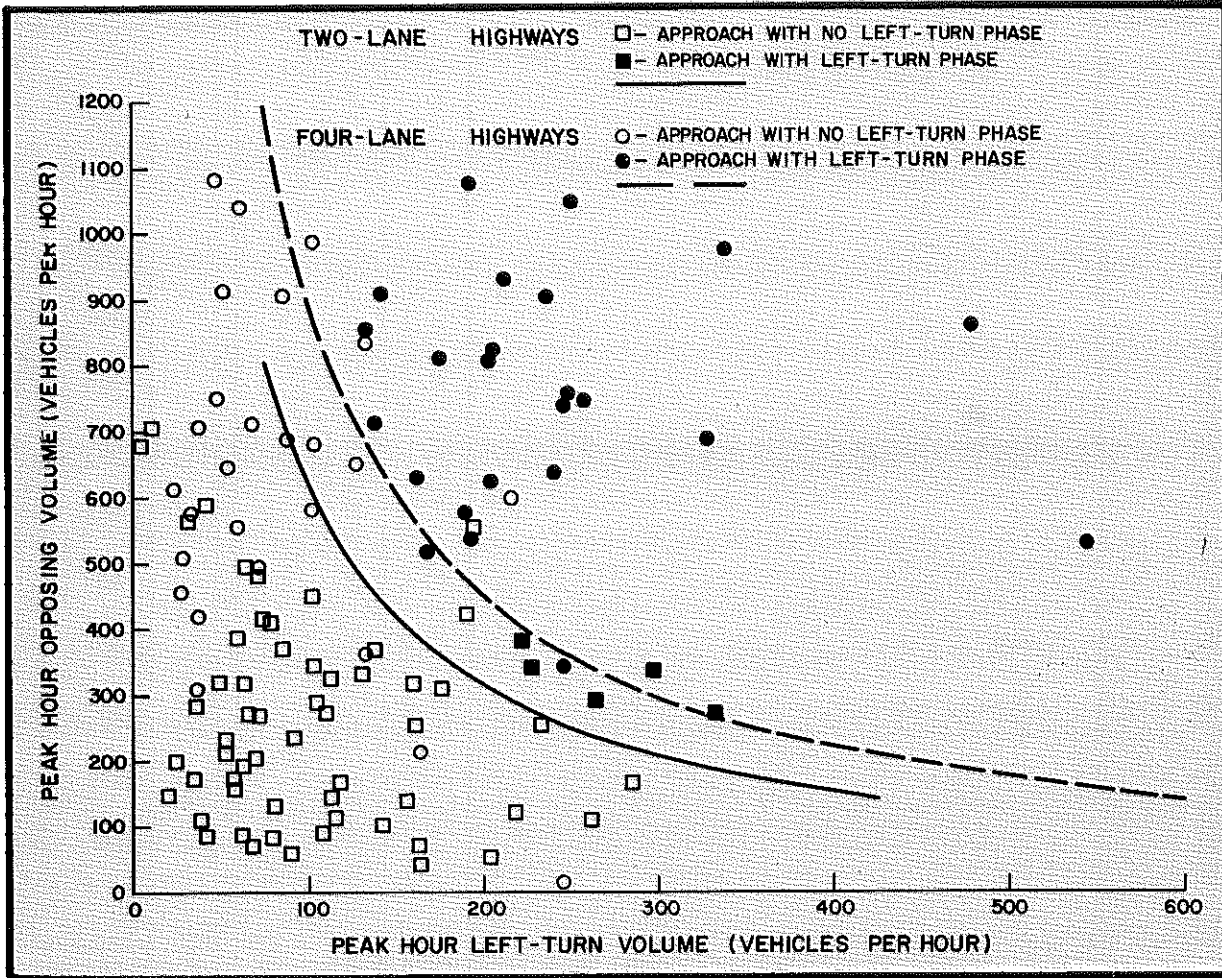


Figure 2. Comparison of Volumes at Intersections with and without Left-Turn Phasing.

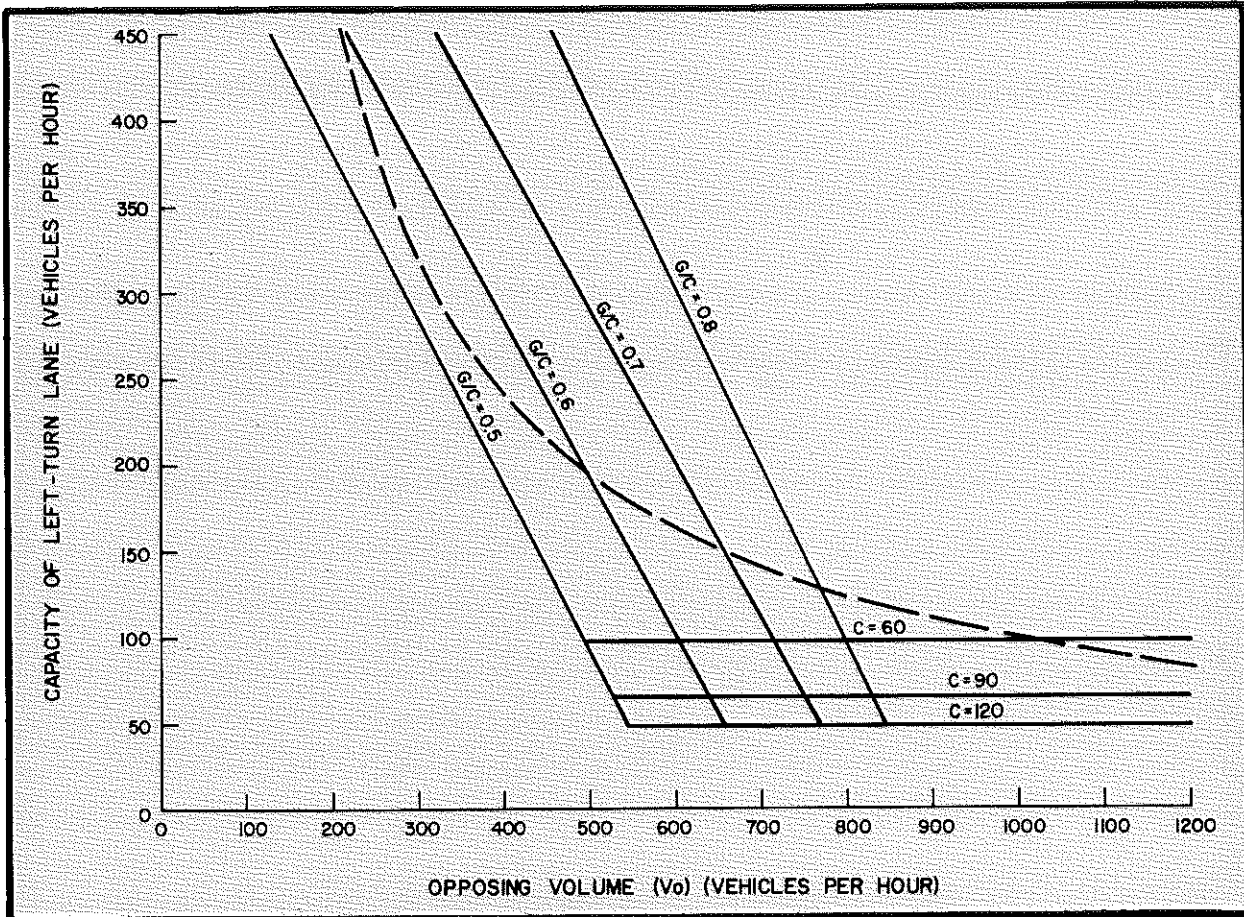


Figure 3. Capacity of a Left-Turn Lane Based on Capacity Nomograph (Trucks = 5 percent).

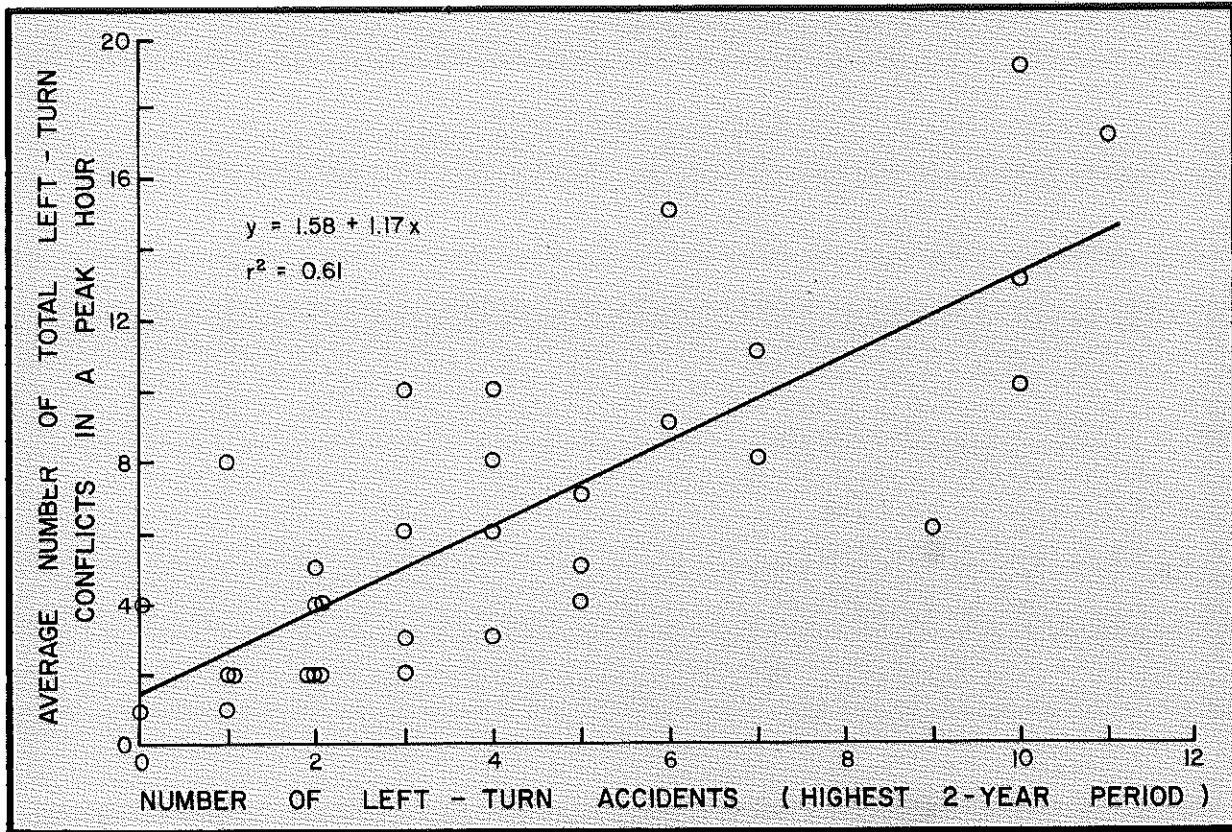


Figure 4. Left-Turn Accidents (Highest 2-Year Period) versus Total Left-Turn Conflicts (Peak-Hour).



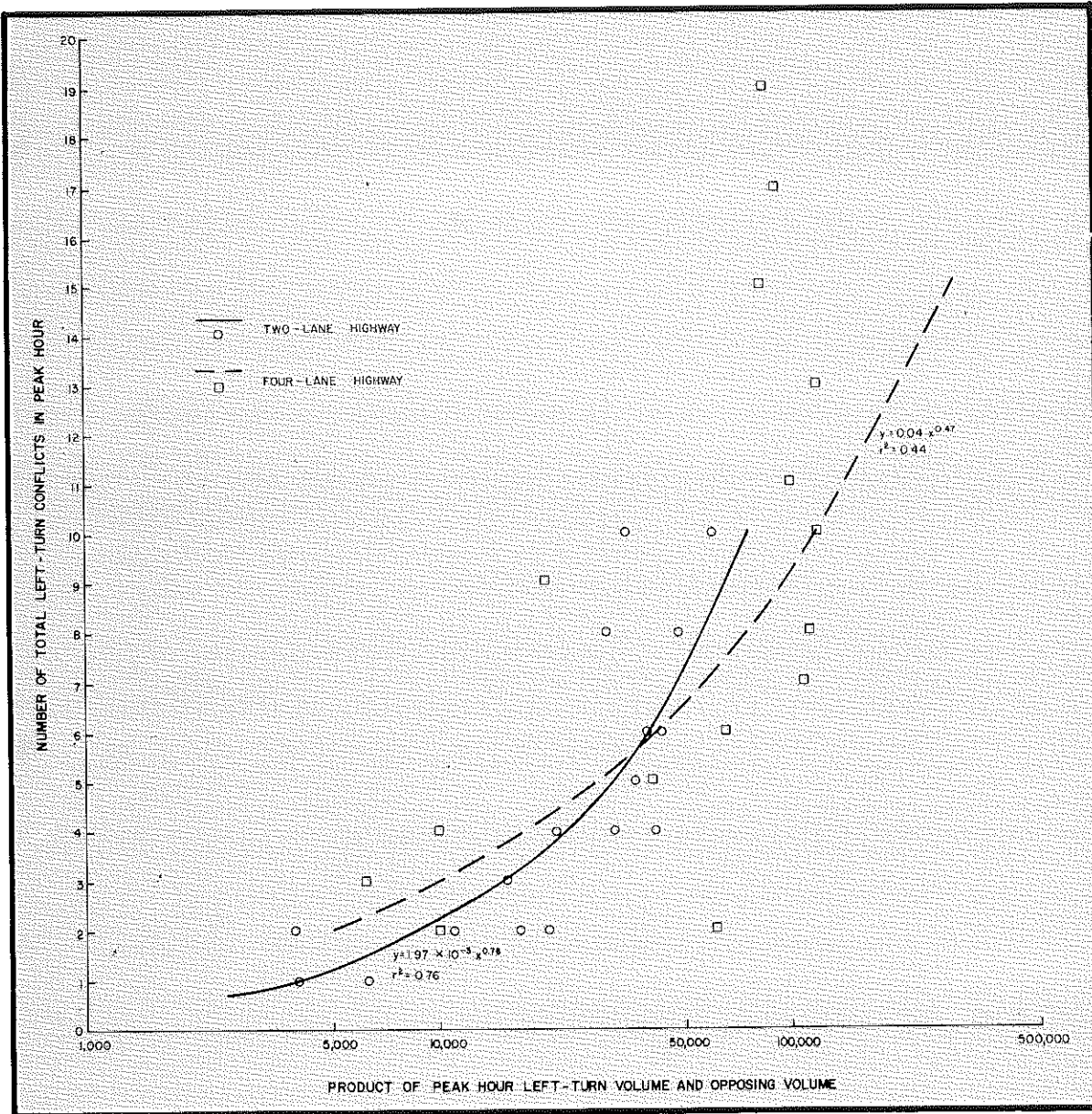


Figure 5. Number of Total Left-Turn Conflicts in Peak Hour versus Product of Peak-Hour Left-Turn Volume and Opposing Volume.