DEVELOPMENT OF WARRANTS FOR LEFT-TURN PHASING

KYP-75-70, HPR-PL-1(12), Part III-B

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 analysis concerning gap acceptance, computer simulation, capacity, and benefit-cost ratios were also performed.

It was found that exclusive left-turn phasing significantly reduced left-turn accidents and conflicts. Left-turn delay was only reduced during periods of heavy traffic flow. Warrants were developed dealing with the following four general areas:

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

**Key Words**

- Left-Turn Delay
- Traffic Conflict
- Volumes
- Left-Turn Accident
- Left-Turn Phase
- Computer Simulation
- Gap Acceptance
- Capacity Analysis
- Benefit-Cost Analysis
August 23, 1976

MEMO TO: G. F. Kemper
State Highway Engineer
Chairman, Research Committee

SUBJECT: Research Report No. 456; "Development of Warrants for Left-Turn Phasing;"
KYP-75-70; HPR-PL-1(12), Part III-B

Traffic engineers speak of warrants in referring to and to mean criteria of eligibility, design standards, or specifications for signalization at intersections. The report submitted herewith completes part of a larger study requested by the Division of Traffic. It provides an in-depth analysis of exclusive left-turn phasing of traffic lights where left-turn lanes exist and includes recommendations toward implementation. Another part of the study will address requirements and eligibility for left-turn lanes.

During the course of the study, questions arose concerning the feasibility or desirability of left-turn-on-red. A survey of state practices, experiences, and opinions was made and reported previously (No. 446; May 11, 1976).

Respectfully submitted,

Jas. H. Havens
Director of Research

JHH:gd
Enclosure
cc's: Research Committee
**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. This study was part of a project in which the left-turn problem at intersections is being investigated. 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 has 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. Using the data, warrants for the addition of left-turn phasing were recommended.

**REVIEW OF LITERATURE**

As will be shown from the results of the survey, few states use warrants in determining the need for separate left-turn phasing. However, there have been several studies dealing with various aspects of left-turn phasing. In one study, typical warrants for left-turn phasing were evaluated (1). The warrants listed were:

1. when the product of left-turn demand and conflicting opposing demand exceeds a certain value,
2. when vehicles desiring to turn left are excessively delayed, and
3. when an excessive number of correctible accidents occur.

The committee conducting that study concluded that left-turn phasing should be considered only as a solution to a problem and only after less restrictive measures have been considered and rejected on the basis of an engineering study. They questioned whether a separate left-turn phase should ever be considered unless a separate left-turn lane could be provided. Concerning warrants for separate phasing, it was concluded that warrants should not be used as more than an indication that left-turn phasing should be considered. Delay accompanying left-turns was found to increase as the product of left turns and opposing traffic increased, but the variance was so great that use of the mean value was found to be misleading. Therefore, it was recommended that the product of left-turns and opposing volume should not be used to indicate need for left-turn phasing. A method of measuring left-turn delays was developed; it involved the proportion of signal cycles in which left-turn demand was observed to exceed left-turn capacity. It was recommended that delay be determined by field observations, as opposed to projection, whenever possible.

In another study, gap acceptance was utilized to determine the need for left-turn phasing (2). Given a critical length of gap and peak hour volume counts, the need for a left-turn phase could be determined. Average critical gap would have to be determined for the area. Unless left-turn phasing was provided, left-turn capacity reduced sharply; and delays and the proportion of vehicles delayed increased significantly when opposing traffic reached 1,000 vehicles per hour.

A capacity analysis was used by many of the states. A procedure developed by Leisch was commonly used (3). This method was also the basis for the procedure taught by the Traffic Institute at Northwestern University (4) and is used by some states. In using this method, the design capacity of the left-turn lane (the larger of values obtained from two charts) is determined for the situation where separate left-turn lanes are provided but where no separate signal indication is provided. One chart uses only the cycle length and the assumption that 1.6 vehicles will turn left on the amber at the end of each cycle to determine the design capacity. This chart would govern under conditions with heavy opposing volumes when most left-turns would have to be made during the amber signal. The other chart gives the higher design capacity where the opposing through volume is relatively light. This chart uses the opposing volume, ratio of green time to cycle length, and the percentage of trucks and buses to determine the design capacity. If the actual left-turn volume is above design capacity, a separate left-turn phase may be needed.

The Highway Capacity Manual also outlines a procedure for determining the capacity of separate turning lanes having no separate signal control (5). In this procedure, the service volume of a left-turn lane (of adequate length) is given (in passenger cars) as the difference between 1,200 vehicles and the total opposing traffic volume in terms of passenger cars per hour of green, but not less than two vehicles per signal cycle. This procedure was the basis of the Leisch nomographs with the exception that minimum vehicles per signal cycle was lowered to 1.6.

In another study, a simulation program was used to develop probability curves for a signalized intersection operating with separate left-turn lanes, but without a separate turning phase on the signal (6). The curves gave the percent of vehicles in the separate...
left-turn lane that were delayed more than one signal cycle. A criteria of design that considers some critical delay level for vehicles in the left-turn lane would have to be selected.

It was theorized in one study (7) that if the average number of left turns made during the yellow and red was greater than two per signal cycle during the peak half hour, chances were good that there was excessive left-turn delay. The yellow light cannot properly provide for more than two left turns per cycle. If such conditions persist for a short period, such as one-half hour or in some cases as little as 15 minutes, the need for an exclusive left-turn phase should be studied.

The Manual on Uniform Traffic Control Devices (8) gives warrants for the installation of traffic signals but not for separate left-turn phasing. The "accident experience" warrant deals with installing traffic signals, but it might be interpreted to relate to the addition of left-turn phasing. The occurrence of five or more correctable accidents during a 12-month period is required under this warrant. The left-turning problem could also be related to the "interruption of continuous traffic" warrant. This warrant applies to operating conditions where volume on a major street is so heavy that traffic on a minor intersecting street suffers excessive delay or hazard in entering or crossing the major street. Volume warrants are given for the major and minor streets. This warrant relates to the left-turn problem in that the left-turning traffic could be thought of as the minor street traffic attempting to cross the opposing traffic, which could be termed the major street traffic. This warrant is satisfied when, for each of any 8 hours of an average day, the major and minor street volumes reach certain levels. For the left-turn situation, the required left-turn volume would be 75 vehicles per hour. The required opposing volume would be 900 vehicles per hour for a four-lane highway or 750 vehicles per hour for a two-lane highway.

Some new traffic signal warrants issued from another study (9), Delay was used as the primary measure of effectiveness for defining criteria to serve as a basis for warrant specification. Operating delay, the difference in travel time between unimpeded travel and travel restricted by a control device, was adopted. New warrants were developed only for the installation of signals and did not consider left-turn phasing. A survey was conducted to determine what could be considered the maximum tolerable delay at signals which would apply to left-turning vehicles. The responses resulted in a mean of 73 seconds, a mode of 60 seconds, and a median of 67.5 seconds. The recommended accident warrant called for a two-step procedure involving installation of intersection control beacons before signals and then signals if accidents are not reduced. The

required accident record was ten correctable accidents in a 24-month period. The proposed warrants concerning traffic volumes involved graphs which were in terms of fourth-highest hour volumes and second-highest (peak) hour volumes. The warrants were satisfied when the traffic volumes were to the right of the appropriate volume or peaking warrant curve.

Another type of delay warrant was developed in an earlier study (10). This delay-type warrant for the installation of a traffic signal was given in terms of hours of delay on the side street during the peak traffic hour of a typical weekday or five peak hours of a Saturday or Sunday. This warrant also required a minimum volume of vehicles on the side street and varied with the number of approaches. If only one approach was involved, a minimum volume of 100 and a value of 2.0 vehicle-hours of delay was listed as the warrant. Use of the total vehicle-hours of delay was shown to be preferable over a warrant which considered only the average delay per vehicle because one vehicle per hour which had a delay greater than the stipulated value would meet the latter type of warrant. The minimum side-street volume was used as another safeguard to prevent signal installations at locations having very low volumes.

The effect of left-turn phasing on intersection delay has been investigated (11). It was found that delay was substantially increased by the installation of left-turn phasing. Left-turn delay was not substantially reduced. An economic analysis indicated that left-turn phasing would not seem to be justified if strictly based upon an accident-reduction-type benefit-cost ratio. This is because the increase in delay cost was greater than the reduced accident cost. It was noted, however, that most drivers appear willing to accept an additional three- to five-second delay at an intersection for the safety and convenience of a left-turn phase.

Delay has been used in many studies as a method of determining levels of service at individual intersections. After studying several available methods of measuring level of service for individual intersections, a special Highway Research Board advisory subcommittee concluded that delay was potentially the best general measure and stopped delay was the most practical measure (12). Stopped delay is the actual time a vehicle is stopped at an intersection as opposed to aggregate delay where a vehicle is considered to be delayed from the time its speed was affected by the intersection condition until it cleared the intersection. The measurement of delay has been accomplished by several methods. In one report, it was suggested that a time-lapse 16-mm filming technique utilizing 1-second intervals was the most satisfactory and economical method for studying left-turn characteristics (13).
Stopped delay was determined from the film by counting the number of frames in which each vehicle was stopped during every cycle. A more direct method which has been used involves counting the number of vehicles stopped in the intersection approach at periodic intervals (usually 15 seconds) (11). Computer simulation is another method which can be used to estimate delay. One such model which has been developed for network simulation is the Urban Traffic Control System (UTCS-1) (14). Given an input, which includes the network geometry, operation, and turning movements, the model will output various information including delay data. This program is being used in the development of design warrants for left-turning vehicles at signalized intersections (15).

Typical warrants for left-turn phasing usually include one based on left-turn accident experience. A more beneficial warrant would involve identifying intersections with high left-turn accident potential. A method of accomplishing this could consist of counting left-turn conflicts. A traffic conflict is a potential accident (collision) situation. Traffic conflicts for various impending accident situations have been developed (16). These include conflicts involving left-turning vehicles.

Once the decision is made to install left-turn phasing, there are several methods of signalizing left-turn movements. Left-turn phasing can be divided into three categories (17). One type is a leading left-turn arrow in which the left turn is permitted during the display of the green arrow as well as during the common green-ball phase. During the green-arrow phase, the affected left-turn movement is unopposed. During the common green-ball phase, the left-turn movements must yield to opposing through traffic. A second method involves a lagging left-turn arrow where the left-arrow phase lags rather than leads the opposing green-ball phase. The third method is an exclusive left-turn phase. This phasing differs from the leading or lagging phasing in that left turns are permitted during the arrow phase only and are held during the other signal phases.

The use of leading or lagging left-turn phasing has the advantage of reducing delay at the intersection, but it may also increase the accident potential. Studies have been done to determine which type of signal indication sequences were superior in conveying the message that the driver had a protected left turn, that the protected left turn was about to terminate, and that the driver did not have a protected left turn. One report recommended an arrangement in which the signal face consisted of circular red, yellow, and green lenses together with yellow and green left-turn lenses placed below the above-mentioned lenses (18). Another recommended that a flashing amber indication be used for left-turning vehicles during the permissive phase when the opposing traffic has a green indication (19).

SURVEY OF OTHER STATES

A letter was sent to other state highway departments 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, the 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 45 mph (20 m/s) 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 highway with left-turn refuges, a graph was drawn with the variables of left-turn volume, opposing-traffic volume, and posted speed (entering the graph with the appropriate values indicated the need for a left-turn phase).

The response from one state said that left-turn phasing was warranted (1) if total delay of left-turn vehicles would be reduced and(or) (2) if the total intersection accident rate would be reduced.

A capacity analysis was used by many states both as a warrant and a guideline. The capacity analysis which was mentioned most often involved the use of capacity charts developed by Leisch (3). This technique involved comparing the capacity of a left-turn lane operating without a separate left-turn phase with the actual left-turn volume. The Highway Capacity Manual was the basis of this procedure.
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:

1. accident experience,
2. capacity analysis,
3. delay,
4. volume counts,
5. turning movement,
6. speed,
7. geometrics,
8. signal progression,
9. queue lengths,
10. right of way available,
11. number of opposing lanes to cross,
12. gaps,
13. consequences imposed on other traffic movements,
14. effect on adjacent intersections,
15. type of facility,
16. sight distance,
17. percentage of trucks and buses,
18. consistency of phasing signals with adjacent intersections,
19. opposing through volume, and
20. peak-hour, left-turn volume versus opposing through volume.

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:

1. left-turn ADT above 500 (two-lane roadway),
2. wherever a left-turn lane is installed on divided highways,
3. 100 to 150 left-turning vehicles during the peak hour (small cities),
4. 150 to 200 left-turning vehicles during the peak hour (large cities),
5. at new installations, where left-turn phases already exist at other intersections on the same roadway,
6. 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,
7. high percentage of left-turning vehicles (20 percent or greater),
8. not provided at intersections with left-turn volume of less than 80 vehicles per hour for at least 8 hours of the day,
9. the number of left-turning vehicles is about two per cycle,
10. 120 left-turning vehicles in the design hour,
11. 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,
12. left-turn volumes of 90-120 in peak hours, and
13. more than 100 turns per hour.

PROCEDURE

LEFT-TURN DELAY STUDIES

Data were taken at several intersections to obtain the relationship between left-turn delays and traffic volumes. 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. A stopwatch was started at the beginning of the study period and allowed to run continuously until the end of the period. Usually, thirty minutes of the hour was taken. The arrival and departure time of each vehicle was noted; delay could be calculated. If the vehicle did not have to stop, a zero delay was noted. The number of left turns were automatically counted in the delays. Opposing volumes and left-turn conflicts were also counted during the study period. A description of the types of conflicts recorded is given later.

TOTAL INTERSECTION DELAY STUDIES

Delay studies were taken before and after installation of left-turn phasing at three signalized intersections. The left-turn delay was obtained by the same procedure. This procedure could not be used for all vehicles in the intersection because of the high volume. Therefore, a method of estimating the stop-type delay was used (11). 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 (12). 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 was taken during an average of 9 hours of the day at the three intersections. This procedure has been shown to give accurate results. The delay was
calculated for each approach and then combined with left-turn delay to determine total intersection delay. Time-lapse filming was used as an aid in analysis of delays during the peak hour at one of the locations.

ACCIDENT DATA
Before-and-after accident data were collected at locations where left-turn phasing had been added. The length of the before and after periods was usually 1 year, but it varied in some cases depending on the available data.

Another type of accident data used consisted of several years of accident analysis of intersections in Lexington. This analysis, including collision diagrams, was available for the years of 1968 through 1972. The accident data were used in several ways. Comparisons between left-turn accidents and conflicts as well as volumes were made. Also, accident rates at locations with and without left-turn phasing were calculated. This was done using volume counts at the intersections. The volume counts were taken for a 12-hour period (7 a.m. to 7 p.m.). The assumption was made that 80 percent of the volume occurred in this 12-hour period, so the volumes were multiplied by 1.25 to obtain the 24-hour volume. Using this as a data base, the critical number of accidents was calculated (to be explained later).

CONFLICT DATA
Left-turn conflicts were classified into three categories (16). 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 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. As a general rule, a maximum of two vehicles could enter the intersection legally and complete their turns after the signal changed.

GAP-ACCEPTANCE DATA
The data were taken to determine the critical gap for vehicles turning left and across opposing traffic. The critical gap was defined as the length of gap (t) 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. There were no data for lags included. A lag is the time from when the left-turning movement can first be made until the first opposing vehicle arrives (20).

COMPUTER SIMULATION
A limited amount of work was done using computer simulation. The simulation program was the UTCS-1 Network Simulation Model developed for the Federal Highway Administration. An intersection with certain geometric characteristics was input into the model, and then various volumes with varying left-turning and through volumes were simulated. Delays were then compared with the associated volumes.

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 (3). The percentage of trucks and buses, green-time-to-cycle-length ratio, and cycle length were assumed, and the capacity of the left-turn lane without a separate left-turn phase was calculated as a function of the opposing volume. Left-turn volumes above the capacity warrant a separate phase. The warrant curve was drawn by plotting a line representing the left-turn capacity as a function of the opposing volume.

BENEFIT-COST ANALYSIS
The benefit of a separate left-turn phase is the reduction in accident cost. The cost is increased by the delay at the intersection. The benefits and costs were compared to determine the economics of installing separate left-turn phases.
RESULTS

ACCIDENT WARRANT

Before-and-After Accident Studies -- Accident data before and after installation of separate left-turn phasing were collected for 24 intersections. These data are summarized in Table 1 and given in detail, by intersection, in the APPENDIX. The left-turn phasing effectively reduced left-turn accidents at the respective approaches. There was an 85-percent reduction in this type of accident, 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. It has been shown that rear-end accidents (which were increased) are less severe than left-turn (angle) accidents (which were decreased). Investigation of the locations in Lexington showed that the percentage of injury accidents reduced from 13 to 11 percent after left-turn phasing were installed.

Comparison of Accident Rates at Intersections With and Without Left-Turn Phasing -- In addition to noting the change in the number of accidents at intersections where left-turn phasing was added, the accident rates at intersections with and without left-turn phasing were compared. The Lexington data were used. Rates were calculated using 1972 accident data, and the volume data were taken in the time period of 1971 through 1973. 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. Accident rates were calculated for all intersections as well as for only the high-volume intersections (AADT greater than 25,000). This was done because the 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 eliminated this variable. There were 13 intersections with separate phasing and 10 intersections without separate phasing which met this criteria. The results are given in Table 2.

The left-turn accident rate was drastically lower for the approaches having left-turn phasing. 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 and without 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).

### Table 1. Summary of Accident Data Before and After Installation of Separate Left-Turn Phasing (For 24 Intersections)

<table>
<thead>
<tr>
<th>NUMBER OF ACCIDENTS</th>
<th>BEFORE INSTALLATION</th>
<th>AFTER INSTALLATION</th>
<th>PERCENT CHANGE AFTER INSTALLATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Accidents</td>
<td>480</td>
<td>409</td>
<td>-15</td>
</tr>
<tr>
<td>Left-Turn Accidents</td>
<td>116</td>
<td>17</td>
<td>-85</td>
</tr>
<tr>
<td>Rear-End Accidents</td>
<td>182</td>
<td>242</td>
<td>+33</td>
</tr>
</tbody>
</table>
A street with a left-turn lane in both directions had both approaches included separately. An average of one accident per year per approach was used in the calculations. The average critical accident rate for an intersection is given by the following formula (21):

\[
A_c = A_a + K \sqrt{A_a/V} + 1/2V
\]

where 
- \(A_c\) = critical accident rate,
- \(A_a\) = average accident rate,
- \(K\) = constant related to level of statistical significance selected (for \(P = 0.95, K = 1.645\); for \(P = 0.995, K = 2.576\)), and
- \(V\) = annual entering volume.

This formula can be converted to calculate the critical number of accidents by substituting accidents divided by volume for the rate. This would give

\[
N_c/V = N_a/V + K\sqrt{(N_a/V)/V} + 1/2V
\]

where 
- \(N_c\) = critical number of accidents
- \(N_a\) = average number of accidents.

Multiplying both sides of the equation by \(V\) resulted in the following formula for critical number of accidents,

\[
N_c = N_a + K \sqrt{N_a} + 0.5.
\]

For \(P = 0.995\), the critical number of left-turn accidents per year per approach was found to be four, based on the average of one. 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). An average of two accidents per year for both approaches was used in the calculations. 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 a 2-year period for both approaches.

The critical number of left-turn accidents for one or two approaches is summarized in Table 3. The critical number of accidents was used as the warrant for the installation of a separate left-turn phase.
TABLE 3. NUMBER OF LEFT-TURN ACCIDENTS NECESSARY TO BE CRITICAL*  

<table>
<thead>
<tr>
<th></th>
<th>1-YEAR'S DATA</th>
<th>2-YEARS' DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Approachb</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Both Approachesc</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

*P = 0.995  

bOne approach with a left-turn lane but no separate phase.  
cStreets with left-turn lanes for both directions at an intersection but no separate phase.

DELAY WARRANT  

Before-and-After Delay and Conflict Studies – The preceding has shown the benefits obtained from left-turn phasing through the reduction in accidents. 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. Delays were collected as described in the procedure. Conflict data were collected to compare with the accident data at locations where left-turn phasing was added. The results of the studies are given in Table 4.

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 added on only one approach. The increase in total delay was much less at these two intersections than at the intersection where left-turn phasing was installed on both approaches. 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 (11). It also found an increased delay of from 8.6 to 12.5 seconds per vehicle 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. One state uses the warrant that left-turn phasing is justified if total delay of left-turn vehicles is reduced. Since left-turn phasing reduces delay only during peak periods and may increase total left-turn delay, this warrant would only be met at very busy locations.

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.
### TABLE 4. SUMMARY OF DELAY AND CONFLICT STUDIES BEFORE AND AFTER INSTALLATION OF LEFT-TURN PHASING

<table>
<thead>
<tr>
<th></th>
<th>DIXIE HIGHWAY AND DEERING ROAD (LOUISVILLE) (&quot;T&quot; INTERSECTION)</th>
<th>US 41A AND SKYLINE DRIVE (HOPKINSVILLE) (&quot;T&quot; INTERSECTION)</th>
<th>DIXIE HIGHWAY AND PAGES LANE (LOUISVILLE)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Intersection Delay</strong> (seconds per vehicle)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Hours</td>
<td>6.8</td>
<td>6.8</td>
<td>0</td>
</tr>
<tr>
<td>Peak Hours</td>
<td>11.3</td>
<td>11.2</td>
<td>-1</td>
</tr>
<tr>
<td>Non-Peak Hours</td>
<td>6.5</td>
<td>6.8</td>
<td>+5</td>
</tr>
<tr>
<td><strong>Side Street Delay</strong> (seconds per vehicle)</td>
<td>8.4</td>
<td>10.6</td>
<td>+26</td>
</tr>
<tr>
<td><strong>Opposing Approach Traffic Delay</strong> (seconds per vehicle)</td>
<td>2.0</td>
<td>4.5</td>
<td>+125</td>
</tr>
<tr>
<td><strong>Unopposed Approach Traffic Delay</strong> (seconds per vehicle)</td>
<td>4.0</td>
<td>1.0</td>
<td>-75</td>
</tr>
<tr>
<td><strong>Left-Turn Delay</strong> (seconds per vehicle)</td>
<td>22.1</td>
<td>32.7</td>
<td>+48</td>
</tr>
<tr>
<td>Peak Hours</td>
<td>48.8</td>
<td>36.8</td>
<td>-25</td>
</tr>
<tr>
<td>Non-Peak Hours</td>
<td>23.9</td>
<td>34.0</td>
<td>+12</td>
</tr>
<tr>
<td><strong>Left-Turn Conflicts</strong> (number)</td>
<td>50</td>
<td>12</td>
<td>-76</td>
</tr>
<tr>
<td><strong>Total Volume</strong></td>
<td>9057</td>
<td>8372</td>
<td>-8</td>
</tr>
<tr>
<td><strong>Left-Turn Volume</strong></td>
<td>481</td>
<td>492</td>
<td>+2</td>
</tr>
</tbody>
</table>
**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. It was previously shown that left-turn accidents were reduced by 85 percent after left-turn phasing, but rear-end accidents increased which offset part 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 the 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 summarized for various numbers of left-turn accidents (Table 5). An average cost of $7,112 per accident was used. This cost was calculated using National Safety Council accident costs and considering the distribution of fatalities, injuries, and property-damage-type accidents in the state. The operating cost considered was the increase in intersection delay. The 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 cost. Therefore, installation cost was not included. The 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) (Table 6). 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 (22). 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.

### TABLE 5. ACCIDENT SAVINGS RESULTING FROM LEFT-TURN PHASE

<table>
<thead>
<tr>
<th>NUMBER OF LEFT-TURN ACCIDENTS</th>
<th>ANNUAL ACCIDENT SAVINGS$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$8,800</td>
</tr>
<tr>
<td>4</td>
<td>17,700</td>
</tr>
<tr>
<td>6</td>
<td>26,500</td>
</tr>
<tr>
<td>8</td>
<td>35,400</td>
</tr>
<tr>
<td>10</td>
<td>44,200</td>
</tr>
<tr>
<td>15</td>
<td>66,300</td>
</tr>
<tr>
<td>20</td>
<td>88,500</td>
</tr>
</tbody>
</table>

$^a$Based on an average accident cost of $7,112 per accident.

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 in 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. The first question to answer when considering delay as a warrant is the appropriate unit of delay to use. Average delay per vehicle exceeding a specific level has been used. The level could be in terms of seconds or cycle lengths. This method has a limitation because volume is not considered. One left-turn vehicle in 1 hour could satisfy the specified delay criteria, but obviously a left-turn signal would not be warranted. A much better delay criteria would 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.
TABLE 6. ADDED INTERSECTION DELAY COST RESULTING FROM LEFT-TURN PHASE

<table>
<thead>
<tr>
<th>INTERSECTION AVERAGE DAILY TRAFFIC (AADT)</th>
<th>LEFT-TURN PHASING ON ONE APPROACH (&quot;T&quot; INTERSECTION)b</th>
<th>LEFT-TURN PHASING ON TWO APPROACHES (ONE STREET)c</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>$4,900</td>
<td>$24,700</td>
</tr>
<tr>
<td>20,000</td>
<td>9,900</td>
<td>49,400</td>
</tr>
<tr>
<td>30,000</td>
<td>14,800</td>
<td>74,100</td>
</tr>
<tr>
<td>40,000</td>
<td>19,800</td>
<td>98,800</td>
</tr>
<tr>
<td>50,000</td>
<td>24,700</td>
<td>123,400</td>
</tr>
</tbody>
</table>

aA delay cost of $4.87 per vehicle-hour was used.
bAn added delay of 1 second per vehicle was used.
cAn added delay of 5 seconds per vehicle was used.

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 (9). 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 then 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. The following formula is valid for this situation if the ratio of the mean to the standard deviation is less than 1.645:

$$\Sigma 90\text{ percentile} = \bar{X} + 1.645 \sigma$$

where $$\Sigma 90\text{ percentile}$$ = value of delay of the 90th percentile of a normal distribution (73 seconds),

$$\bar{X}$$ = mean value of delay, and

$$\sigma$$ = standard deviation of the distribution.

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. Substituting a value of $$\bar{X}/1.5$$ for $$\sigma$$ into the equation gave a value of 35 seconds for the mean delay. This value of 35 seconds was used as the minimum average delay necessary since this value 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 possible number of vehicles to 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. The 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. Actually, the total delay per hour was constant for any cycle length. 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. Delay studies were also conducted at several intersections in Lexington. From preliminary data, six intersections with the highest 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. Peak-hour delays for the critical approach varied from 1.76 to 5.96 vehicle-hours. The peak-hour delay was equal to or greater than 2.0 vehicle-hours 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.

The review of literature disclosed two peak-hour delay warrants for the installation of traffic signals which had been developed in terms of vehicle-hours of delay. These could be used as a guide in the development of left-turn delay warrants. A New Zealand warrant requires the average, side-street, vehicle delay in seconds, multiplied by side-street volume per hour, to equal or exceed 8,000 (10). This is equivalent to 2.2 vehicle-hours delay. The measurements apply to a weekday peak hour, or during three other hours (such as on a weekend). Box and Alroth also developed suggested peak-hour delay warrants in terms of vehicle-hours (10). For a single approach, which is analogous to the critical left-turn approach, the suggested warrant 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, using these two existing warrants as a guide.

Considering all sources of input, a left-turn delay of 2.0 vehicle-hours in the peak hour on a critical approach appeared to constitute a valid warrant for the installation of a separate left-turn phase.

VOLUME WARRANT

Relationship between Left-Turn Delay and Traffic Volumes — Many states indicated that the volume of left-turning vehicles was used as a guideline or warrant for the installation of a separate left-turn phase. Field experience has shown this type of warrant to be unacceptable because the difficulty in making a left turn is related to the opposing volume as well as the left-turn volume. A much better warrant which has been used in some states requires that a left-turn phase be installed when the product of left-turn demand and the conflicting opposing demand exceeds a certain value. A major use for this type of warrant would be to indicate need for left-turn phasing at an intersection where future signalization is planned. It would be more convenient and economical to include the left-turn phasing with the original installation if it could be proven necessary. This type of warrant could also be used to show if more detailed studies of an intersection should be made.

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 Figures 1 and 2. The curves were drawn by averaging delays between equal intervals of the volume product. 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 (Figure 1) than on the two-lane street (Figure 2). 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 – One state used a unique method to develop a left-turn phasing warrant for four-lane highways with left-turn lanes. A graph was drawn considering the variables of peak-hour left-turn volume, peak-hour opposing traffic volume, and posted speed. The graph was developed by plotting these variables for existing traffic signals on four-lane highways. Intersections with and without left-turn phases were plotted, and lines were then drawn to separate the signals with left-turn phases from those without left-turn phases. Determination of whether a phase was needed was made by plotting the point representing the leg of the intersection. This point was plotted using left-turn and opposing volumes. If the point was above the appropriate line for the posted speed on the highway, a left-turn phase was warranted. If the point was below the line, a left-turn phase was not warranted.

Similar plots were made for intersections on both four-lane and two-lane highways with data from Lexington (Figures 3 and 4). The plots considered the variables of left-turn and opposing traffic volumes. The posted speed was not included. 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 always 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 (2). 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.

First, data were taken to determine a critical gap, which was defined as the length of gap (t) at which the number of accepted gaps less than t was equal to the number of rejected gaps greater than t. 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 (Figure 5).

Using several assumptions, a rough 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. The results 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
Figure 1. Relationship between Volume Product and Left-Turn Delay (Four-Lane Street) (Intersection of Tates Creek Road and Lansdowne Shopping Center).

Figure 2. Relationship between Volume Product and Left-Turn Delay (Two-Lane Street) (Intersection of Rose Street and Euclid Avenue).
Figure 3. Comparison of Volumes at Intersections With and Without Left-Turn Phasing (Four-Lane Highways).

Figure 4. Comparison of Volumes at Intersections With and Without Left-Turn Phasing (Two-Lane Highways).
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 $r^2$ value measures the closeness of fit of the regression line to the points (21). The one exception was the plot of accidents versus the product of peak-hour left-turn and opposing volumes for four-lane streets (Figure 6); 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. The corresponding plot of the left-turn only volume is shown in Figure 7. The $r^2$ value there was 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.

Figure 5. Cumulative Distribution of Accepted and Rejected Gaps at Signalized Intersections.
Figure 6. Highest Number of Left-Turn Accidents in 1 Year versus Product of Peak-Hour Left-Turn Volume and Opposing Volume (Four-Lane Highway).

\[ \gamma = 9.55 \times 10^{-4} z^{17} \]
\[ r^2 = 0.50 \]

Figure 7. Highest Number of Left-Turn Accidents in 1 Year versus Peak-Hour Left-Turn Volume (Four-Lane Highway).

\[ \gamma = 162 + 0.02x \]
\[ r^2 = 0.19 \]
Capacity Analysis – The nomograph (4) shown in Figure 8 was used to develop warrant curves based on intersection capacity. The nomograph was based on the Highway Capacity Manual. With an assumed percentage of trucks and buses, a green-time-to-cycle-length ratio, and a cycle length, the left-turn capacity was determined in terms of the opposing volume. The capacity from both Chart A and B is determined for a set of values, and the greater of the two values is used. Chart B governs when the opposing volume becomes so heavy that almost all left turns are made during the amber phase. Assuming five percent trucks and buses, a green-time-to-cycle-length ratio of 0.6, and a cycle length of 60 seconds yielded the curve as shown in Figure 9. Points above this curve would represent intersections where the left-turn volume was above the left-turn capacity which would warrant a left-turn phase. Chart A governed the left-turn capacity up to a 1-hour opposing volume of about 600 where the capacity reached its maximum and Chart B controlled. The dashed line in Figure 9, depicting a product of 95,000 for the left-turning and opposing volumes, represented the average value of the points along the curve. Of course, the curve would vary with green-time-to-cycle-length ratio and cycle length. Still, 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 10). 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. A problem with 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 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.

Computer Simulation – The UTCS-1 Network Simulation Model was used as an alternate method of estimating left-turn delays. Data were simulated for an intersection on a four-lane and a two-lane street. The input intersection had a fixed cycle. During peak hours, volumes on the side street of a semi-actuated signal would be so heavy that a fixed cycle would be approximated. Volumes were input so that one main street approach had 100 percent of its volume turning left; this was done so that left-turn delay could be isolated. The opposing approach had 100 percent of its volume traveling through. Various combinations of left-turn and opposing volumes were simulated.

A prohibitive number of computer runs would have been necessary to simulate all the possible combinations of variables. Therefore, the number of computer runs was limited to consider the more important variables. Delays resulting from different volume combinations were simulated at a signal with different cycle lengths and different percentages of the cycle devoted to the main street. Cycles of 60, 90, and 120 seconds were used. Cycle splits of 60/40 (60 percent of the cycle devoted to main street) and 70/30 were used. Opposing volumes between 500 and 2,000 vehicles per hour on the four-lane street and between 250 and 1,000 vehicles per hour on the two-lane street were simulated. Left-turn volumes from 30 to 250 vehicles per hour were used. Free-flow speeds of 45 mph (20 m/s) and 35 mph (16.7 m/s) were used on the four-lane and two-lane streets, respectively.

The computer results confirmed field observations; for any given volume product, left-turn delays vary substantially. The cycle length affected left-turn delays to a large extent; delays increased during longer cycles. A table was developed which listed the volume product at which the average left-turn delay first exceeded 35 seconds (Table 7). This volume product was the average of the values obtained from the various volume combinations for each cycle length and cycle split. The critical product tended to decrease with increased opposing volumes. This level of delay corresponded, in most cases, to the point at which delays started to increase rapidly. Particularly for the 60-second cycle length, the volume products at which excessive delays began were higher than field data indicated; this was due to some of the assumptions used in the computer program. The program allowed more vehicles to turn left during or after the amber period than would be expected from field data. This would result in lower delays, particularly for shorter cycles where the number of amber periods are greater. There was a very large range in values for the critical product depending mainly on cycle length. The critical product was only valid for opposing volumes under the critical opposing volume. The critical opposing volume was the opposing volume
Figure 8. Design Capacity of a Separate Left-Turn Lane with No Separate Phase.
Figure 9. Capacity of a Left-Turn Lane as a Function of Opposing Volume (Based on Capacity Nomograph) \(T = 5\) percent, \(G/C = 0.6, C = 60\) seconds.

Figure 10. Capacity of a Left-Turn Lane Based on Capacity Nomograph \(T = 5\) percent.
at which the minimum number of left turns necessary to warrant a left-turn phase (50 vehicles per hour) first caused an average left-turn delay in excess of 35 seconds. This value was also given in Table 7. The warrant previously developed was basically for average conditions, and it only indicated that the intersection needed further study. The values given in Table 7, along with the capacity analysis from Figure 10, could be used to give a more thorough analysis of the need for a separate left-turn phase based on traffic volumes, especially at a new signal installation where delay data are not available.

**TRAFFIC CONFLICTS WARRANT**

A major reason for installing left-turn phasing is to provide improved safety. The obvious indicator used to warrant a left-turn phase because of a safety problem has been the number of left-turn accidents. This subject was dealt with in a preceding section. A weakness of that procedure 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 were listed in the procedure. 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

1. the total number of conflicts (all three types defined in the procedure) and
2. the basic left-turn conflicts (left-turn vehicle crossed directly in front of or blocked the lane of an opposing through vehicle).

Basically, the difference between these two categories is that total conflicts include red-light violations. Conflict counts were taken during peak-flow conditions for a 1-hour period. Several counts were done for each approach to obtain a consistent average. 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. As shown in Figure 11, left-turn accidents also reach a maximum during peak-volume hours, and it appeared reasonable that conflict counts should be conducted when accidents problems are most acute. It is important to again note that conflict data were taken during several peak hours at each approach so that a reliable average number of conflicts per hour could be obtained. Actually, more data were collected per approach than would have been if a standard method of collecting 15 minutes of data per approach per hour for 10 hours had been used. Collecting data only during peak hours rather than all day would provide a more economical method and would be more feasible on a large-scale, continuing basis.

### TABLE 7. RESULTS FROM COMPUTER SIMULATION

<table>
<thead>
<tr>
<th>CYCLE LENGTH (seconds)</th>
<th>60/40&lt;sup&gt;a&lt;/sup&gt; (CRITICAL VOLUME PRODUCT&lt;sup&gt;b&lt;/sup&gt;)</th>
<th>70/30 (CRITICAL OPPOSING VOLUME&lt;sup&gt;c&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FOUR LANE&lt;sup&gt;d&lt;/sup&gt;</td>
<td>TWO LANE</td>
</tr>
<tr>
<td>60</td>
<td>260,000 (1,550&lt;sup&gt;e&lt;/sup&gt;)</td>
<td>170,000 (800&lt;sup&gt;e&lt;/sup&gt;)</td>
</tr>
<tr>
<td>90</td>
<td>145,000 (1,300)</td>
<td>140,000 (800)</td>
</tr>
<tr>
<td>120</td>
<td>110,000 (1,000)</td>
<td>120,000 (750)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Sixty percent of the cycle time is devoted to the main street.

<sup>b</sup>Product of the peak-hour left-turning and opposing volumes at which the average left-turn delay first exceeded 35 seconds. Only valid for opposing volumes under the critical opposing volume.

<sup>c</sup>The peak-hour opposing volume at which the minimum number of left turns (50) necessary to warrant a left-turn phase first caused an average left-turn delay in excess of 35 seconds.

<sup>d</sup>Refers to the number of lanes on the highway. For a four-lane highway, there would be two opposing lanes.

<sup>e</sup>Maximum opposing volume per hour for the signal settings.
Plots were drawn of left-turn accidents versus left-turn conflicts (Figures 12-15). Conflict data were taken at 32 approaches. 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; although, 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 very 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. To calculate this range, the standard deviation of the difference between the predicted and actual number of conflicts was found. A range of about plus or minus five was found for total conflicts, and a range of about plus or minus four was found for basic conflicts. The various findings are summarized in Table 8.

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 comparison with data collected in studies by others would give an indication of the reliability of the conflict data collected in this study. 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 (23). In two studies, an attempt was made to relate the various types of conflicts to the corresponding type of accidents. The results, in terms of accidents per conflict, were: there were 20 left-turn accidents per 100,000 left-turn conflicts in one study (24) and 15 left-turn accidents per 100,000 left-turn conflicts in the other study (25). If those results are averaged (17.5 accidents per 100,000 conflicts) and if four left 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. It has been found that conflicts are very volume dependent; so, the number of conflicts in the peak hour may be found by assuming the percentage of conflicts to be directly related to the percentage of left turns in the peak hour. For comparison, volume data for Lexington showed that 14 percent of the daily left-turn volume occurred during
Figure 12. Left-Turn Accidents (Highest 1-Year Period) versus Total Left-Turn Conflicts (Peak-Hour).

Figure 13. Left-Turn Accidents (Highest 2-Year Period) versus Total Left-Turn Conflicts (Peak-Hour).
Figure 14. Left-Turn Accidents (Highest 1-Year Period) versus Basic Left-Turn Conflicts (Peak-Hour).

Figure 15. Left-Turn Accidents (Highest 2-Year Period) versus Basic Left-Turn Conflicts (Peak-Hour).
TABLE 8. RELATIONSHIPS BETWEEN LEFT-TURN ACCIDENTS AND LEFT-TURN CONFLICTS

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>LINEAR REGRESSION EQUATION</th>
<th>$r^2$</th>
<th>CRITICAL NUMBER OF CONFLICTS</th>
<th>RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Total Conflicts versus Highest 1-Year Period of Accidents</td>
<td>$Y = 1.26 + 1.87 \times$</td>
<td>0.50</td>
<td>8.7</td>
<td>±5.4</td>
</tr>
<tr>
<td>Number of Total Conflicts versus Highest 2-Year Period of Accidents</td>
<td>$Y = 1.58 + 1.17 \times$</td>
<td>0.61</td>
<td>8.6</td>
<td>±4.8</td>
</tr>
<tr>
<td>Number of Basic Conflicts versus Highest 1-Year Period of Accidents</td>
<td>$Y = 1.42 + 1.13 \times$</td>
<td>0.39</td>
<td>5.9</td>
<td>±4.1</td>
</tr>
<tr>
<td>Number of Basic Conflicts versus Highest 2-Year Period of Accidents</td>
<td>$Y = 1.70 + 0.69 \times$</td>
<td>0.45</td>
<td>5.8</td>
<td>±3.9</td>
</tr>
</tbody>
</table>

aY refers to number of conflicts.  
Y refers to number of accidents.  
b$^2$ is the coefficient of determination.  
cThe critical number of conflicts was determined using the critical number of left-turn accidents for one approach as given in Table 3.  
dProbability level of 95 percent.

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 correlation coefficients of 0.615 and 0.332, respectively, between left-turn accidents and conflicts. This would give $r^2$ 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 with studies by others.

As previously stated, 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 (Figures 16 and 17). 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 volumes 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.

SUMMARY AND CONCLUSIONS

1. Few states currently use numerical warrants for the installation of left-turn phasing; however, most use some type of guidelines.
2. Left-turn phasing has effectively reduced left-turn accidents while total accidents declined slightly.
3. Accident severity was reduced only slightly after installation of left-turn phasing.
4. The left-turn accident rate was much lower on intersection approaches which had separate left-turn phasing. However, the total intersection accident rate was almost identical for intersections with and without left-turn phases.
5. The critical number of left-turn accidents necessary to warrant installation of left-turn phasing was determined. For one approach, four left-turn accidents in 1 year or six accidents in 2 years were critical. When considering two approaches, six accidents in 1 year or ten accidents in 2 years were found to be critical.
6. Total intersection delay increased after installation of left-turn phasing.

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Figure 16. Number of Total Left-Turn Conflicts in Peak Hour versus Product of Peak-Hour Left-Turn Volume and Opposing Volume (Two-Lane Highway).

Figure 17. Number of Total Left-Turn Conflicts in Peak Hour versus Product of Peak-Hour Left-Turn Volume and Opposing Volume (Four-Lane Highway).
7. Exclusive left-turn phasing will only reduce left-turn delay during periods of heavy traffic.
8. Left-turn conflicts were reduced drastically after installation of left-turn phasing.
9. A benefit-cost analysis revealed that accident savings should offset increased delay costs when street geometry makes left-turn phasing necessary on only one approach which has a critical number of accidents. However, when a street has relatively high left-turn volumes on both intersection approaches, the increased delay costs will be much higher than the savings due to accident reduction.
10. A left-turn delay warrant, in terms of vehicle-hours of delay, was developed. Considering all sources of input, a left-turn delay of 2.0 vehicle-hours in the peak hour on a critical approach appeared to constitute a valid warrant. A minimum left-turn volume of 50 in the peak hour as well as a minimum, average left-turn delay of 35 seconds must also be met.
11. Use of the volume of left-turning vehicles as a warrant for adding separate phasing was found to be unacceptable. Consideration of both left-turn and opposing volumes provide a much better warrant. A warrant which specified a critical volume product of peak-hour left-turning and opposing volumes was developed. Critical volume products of 100,000 on a four-lane street or 50,000 on a two-lane street were found.
12. Data showed that average left-turn delay varied substantially between intersections for any given volume product. Therefore, even if a product was found to be above the specified warrant, a left-turn phase should not be added to an existing signal unless a delay study showed excessive delay.
13. The product of left-turn and opposing volumes was found to be a better estimator of left-turn accidents than just the left-turn volume.
14. The capacity analysis showed that the capacity of a left-turn lane is directly related to the cycle length and green-time-to-cycle-length ratio in addition to the opposing volume.
15. Computer simulation was used to estimate left-turn delay. Cycle length and cycle split had significant influence on the volumes at which excessive delays started to occur.
16. A relationship between left-turn conflicts and left-turn accidents was found. A warrant based on conflicts was developed; left-turn phasing should be considered when an average of 14 or more total left-turn conflicts on 10 or more basic left-turn conflicts occur in a peak hour.
17. The relationship between left-turn conflicts and volumes was found to be better than between left-turn accidents and volume.
18. A critical gap of 4.2 seconds was found for vehicles attempting to turn left at a signalized intersection.

RECOMMENDATIONS

It is recommended that the following warrants be used as guidelines when considering 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 20 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.

It is also recommended that a leading left-turn arrow be used instead of an exclusive left-turn phase at some trial installations. The exclusive left-turn phase has been used in virtually all installations. While this method provides maximum safety, it also increases intersection delay. Use of the leading left-turn arrow could make left-turn phasing more economically feasible. Of course, its use would be limited to intersections where it would not create an accident hazard due to certain intersection geometry such as restricted sight distance. It might be used most effectively at T-intersections.
REFERENCES

17. *Left Turns at Signalized Intersections in Wisconsin*, Report for the Wisconsin Section of the Institute of Traffic Engineers.
APPENDIX

ACCIDENT DATA BEFORE AND AFTER INSTALLATION OF SEPARATE LEFT-TURN PHASING
## ACCIDENT DATA BEFORE AND AFTER INSTALLATION OF SEPARATE LEFT-TURN SIGNAL PHASING

<table>
<thead>
<tr>
<th>LOCATION A</th>
<th>LENGTH OF BEFORE AND AFTER PERIODS (MONTHS)</th>
<th>TOTAL ACCIDENTS BEFORE</th>
<th>TOTAL ACCIDENTS AFTER</th>
<th>LEFT-TURN ACCIDENTS BEFORE</th>
<th>LEFT-TURN ACCIDENTS AFTER</th>
<th>REAR-END ACCIDENTS BEFORE</th>
<th>REAR-END ACCIDENTS AFTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Versailles Rd &amp; Alexandria Dr, Lexington</td>
<td>12 b</td>
<td>30</td>
<td>28</td>
<td>14</td>
<td>1</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Nicholasville Rd &amp; Malabu Dr, Lexington</td>
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<td>19</td>
<td>18</td>
<td>5</td>
<td>2</td>
<td>9</td>
<td>13</td>
</tr>
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<td>Broadway &amp; Loudon Ave, Lexington</td>
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<td>22</td>
<td>20</td>
<td>8</td>
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<td>New Circle Rd &amp; Liberty Rd, Lexington</td>
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<td>11</td>
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<td>10</td>
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<tr>
<td>Nicholasville Rd &amp; Reynolds Rd, Lexington</td>
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<td>36</td>
<td>25</td>
<td>12</td>
<td>1</td>
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<td>Richmond Rd &amp; Fontaine Rd, Lexington</td>
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<td>10</td>
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<td>2</td>
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<td>3</td>
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<td>Mason Headley Rd &amp; Broadway, Lexington</td>
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<td>Dr, Lexington</td>
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<td>15</td>
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<td>12</td>
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<tr>
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<td>26</td>
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<td>Dixie Hwy &amp; Blanton Lane, Louisville</td>
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<td>16</td>
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<td>US 41A &amp; Gate 6, Fort Campbell</td>
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<td>North Main St &amp; US 41A - KY 281, Madisonville</td>
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<td>US 41A &amp; Country Club Lane, Hopkinsville</td>
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<td>18</td>
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<tr>
<td>US 41 &amp; Marywood, Henderson</td>
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<td>1</td>
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</tbody>
</table>

The street listed first had a left-turn phase added.

The after period did not begin immediately after installation of the separate left-turn phase.

Left-turn phase added for both streets.

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