Research Report
526

# DEVELOPMENT OF WARRANTS FOR LEFT-TURN LANES

KYP-75-70; HPR-PL-1(15), Part III B

by

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16. Abstract


Warrants for the installation of separate left-turn lanes were developed. Literature was reviewed, and policies and practices in other states were surveyed. Accident analyses of locations with and without separate left-turn lanes were conducted. Computer simulation was used to determine the relationship between and among traffic delay and load factor and traffic volume, percent left-turns, cycle length, and cycle split. The relationship between left-tum accidents and conflicts was investigated.

Warrants were developed involving the following three general areas:

(1) accident experience,
(2) volumes (based on delay), and
(3) traffic conflicts.


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| | |
|---|---|
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| Left-Turn Accident | Delay |
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SUBJECT: "Development of Warrants for Left-Turn Lanes"; Research Report 526; KYP-75-70; HPR-PL-1(15), Part III-B

This report is one of a series concerning the left-turn problems at intersections. The preceeding reports were:

No. 446; K. R. Agent, "A Survey of the Use of Left-Turn-on-Red"; May 1976.

No. 456; K. R. Agent, "Development of Warrants for Left-Turn Phasing"; August 1976.

No. 519; K. R. Agent, "An Evaluation of Permissive Left-Turn Phasing"; April 1979.

In this study, warrants were developed for use as guidelines in determining when the need for left-turn lanes becomes critical. The addition of left-turn lanes always provides an improvement in the traffic flow; however, left-turn lanes cannot be built at all locations. The recommended warrants involved accident experience, traffic volumes, and traffic conflicts.

Respectfully submitted,

Jas. H. Havens
Director of Research

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Enclosure
cc's: Research Committee

## INTRODUCTION

A vehicle stopped in the traffic stream to turn left creates an accident potential and impedes the flow of through traffic. On divided highways without grade separation at crossings, a considerable reduction in accidents has been accomplished where the median was of sufficient width or could be widened so that left-turn lanes could be built. In locations where a left-turn lane cannot be cut into or substituted for the median, some form of flush median, delineated on the roadway to separate opposing streams of traffic and to mark separate turning lanes, has been used. The addition of left-turn lanes always provides an improvement in the traffic flow; however, left-turn lanes cannot be built at all locations, and warrants have not been established for determining when the need for left-turn lanes becomes critical.

This study was part of a larger study of the left-turn problem at intersections. Warrants for the addition of left-turn phasing were developed *(1)*, and a a survey of the use of left-turn-on-red was made *(2)*. In this study, warrants or guides were developed for installing separate left-turn lanes.

Computer simulation was used to determine the relationship between traffic delay and such variables as percentage left-turns, traffic volume, and cycle length. Accident data were compared at locations with and without left-turn lanes, and the average number of left-turn accidents for approaches with no left-turn lane was determined. The relationship between left-turn accidents and conflicts was also investigated. Using these sources of input, criteria for determining needed left-turn lanes were derived.

## REVIEW OF LITERATURE

Traffic accidents, delay, benefit-cost ratios, and left-turn capacities have been used to justify adding the left-turn lane. The number of left-turn and rear-end accidents in a certain time period was resolved as a warrant in one instance *(3)*. Unsignalized intersections having a total of four or more left-turn plus rear-end accidents in 12 months (involving vehicles from intersection legs to be channelized) or six or more left-turn plus rear-end accidents in a 24-month period qualified. Several warrants were tested at locations where left-turn lanes had been added. The warrant or criterion yielding the most cost effective results was selected.

An Index of Hazard was developed in another study *(4)*. It was based on the difficulty of a vehicle making a left-turn due to the lack of gaps in the oncoming vehicles and the physical features of the intersection. The Index of Hazard (I.H.) was stated mathematically as follows:

$$\text{I.H.} = V_L V_o (1 + F_c + F_e + F_{sa} + F_{so} + F_s + F_m)$$

in which
- $V_L$ = 8-hour maximum volume of left-turning vehicles,
- $V_o$ = through movement in opposition to the left-turn movement during the same 8-hour period,
- $F_c$ = clearance width factor (representing the increased hazard to left-turning vehicles crossing more than one lane of opposing traffic),
- $F_e$ = escape width factor (measuring the usable shoulder area for an overtaking vehicle to bypass to the right of a left-turning vehicle),
- $F_{sa}$ = sight distance ahead factor,
- $F_{so}$ = sight distance overtaking factor,
- $F_s$ = through vehicular speeds factor, and
- $F_m$ = miscellaneous factors.

The Oregon State Highway Department used this Index of Hazard to convert the original relative warrant to one independent of construction costs. The following formula was used:

$$\text{R.W.} = [\text{I.H.}\,(10 + A_p)]/124{,}000$$

in which
- R.W. = relative warrant and
- $A_p$ = number of preventable accidents in a 5-year period.

This warrant was used as a guide when comparing several alternative construction locations.

Computer simulation has been used to develop warrants for left-turn channelization *(5)*. Probability curves were developed to determine the delay likely to occur for a given set of conditions. The variables included the approach and opposing traffic volumes, percentage of left-turns, and traffic signal timing. Delays were given in terms of the percentage of all inside-lane vehicles delayed more than one signal cycle. By selecting the level of delay which would be permitted, probability charts indicate if a left-turn lane should be provided.

In another study, volume-based warrants were determined for left-turn storage lanes at unsignalized, at-grade intersections *(6)*. Charts developed from theoretical analyses and field studies included opposing and advancing volumes, percentage left-turns, number of lanes, and speed.

Benefit-cost ratios have been used to develop guidelines for inclusion of left-tum lanes at rural highway intersections *(7)*. Field data were analyzed by multiple regression to obtain equations for predicting stops and delays. Benefits to road users by reducing stops and delays to through and right-turning vehicles were added to the potential reduction in accident costs. These road-user benefits were then compared to the cost of providing a left-turn lane to determine the cost effectiveness of the construction.

Another study was based on benefits and costs as a method of establishing need and feasibility of constructing a median lane *(8)*. Multiple linear regression was used to develop expressions for predicting the seconds of delay per hour caused by left-turning vehicles to through vehicles and the number of accidents per million vehicles caused by left-turning vehicles at approaches to intersections in both rural and suburban areas. The benefit-cost analysis indicated that construction of median lanes was warranted at almost every intersection on a divided highway having a median width of 16 feet (4.9 m) or more and many intersections on other four- and two-lane highways.

The goals of one study were to assess the benefits of left-tum storage lanes in terms of accident reduction and to develop predictive equations for use in benefit-cost warrants *(9)*. It was found that left-tum lanes had no significant effect on rates for accidents involving left-turning vehicles, but some significance was observed with respect to total accident rates for gross classes of approaches. Models to predict the total number of accidents were developed

Elsewhere *(10)*, warrants were applied to signalized intersections on four-lane, major arterial streets. It was found that left-tum lanes are warranted when one of the following criteria is met: (1) more than two accidents per year are caused by left-turning vehicles, (2) when there is at least one leftturn per green interval for 75 percent or more of all green intervals in a peak hour, or (3) when the left-turn lane would provide the desired level of service.

A procedure based on left-turn
developed *(11)* to determine if a left-
warranted at a signalized intersection wl
on the street is permitted to move simul
common green indication. The total opp
green-time-to-cycle-length ratio, and num
ing through lanes were used to estimate t
a left-turn movement where no left-turn
tected signal phase is provided. If the lef
exceeds 80 percent of the estimated ca
turn lane is warranted. A level of s
assumed.

The method of calculating the cap
tum lane was developed by Leisch *(12)* a
for the procedure taught by the Traffi
Northwestern University *(13)*. The desig
the left-turn lane (the larger of values c
two charts) is determined for the sit
separate left-turn lanes are provided b
separate signal indication is provided. O
only the cycle length and the assump
vehicles will tum left on the amber a
each cycle to determine the design c
chart would govern conditions with he
volumes when most left-turns would hav
during the amber light. Another chart giv
design capacity where the opposing throu
relatively small. This chart uses t
volume, ratio of green time to cycle len
percentage of trucks and buses to determ
After choosing the level of service at whi
lane is needed, the left-turn capacity co
plied by the appropriate factor to determ
The level of service describes the quali
flow on a particular approach to the inters

The **Highway Capacity Manual** als
procedure for determining the capacity
turning lanes having no separate signal
In this procedure, the service volume o
lane (of adequate length) is given (in
passenger cars) as the difference bet
vehicles and the total opposing traffic volu
of passenger cars per hour of green, but
two vehicles per signal cycle. This proce
basis of the Leisch nomographs (with t
that minimum vehicles per signal cycle w
1.6).

## SURVEY OF OTHER STATES

Only six of the 45 states responding to an inquiry listed definite warrants. The warrants were as follows:

(1) When an intersection is designed, left-turn lanes are provided whenever left-turning volume exceeds 100 vehicles during the peak hour.

(2) When the individual movement is 25 vehicles or more per hour, a separate turning lane is warranted.

(3) A. On multilane, divided highways, left-turn lanes are warranted:

- (a) when the design speed is 40 mph (17.9 m/s) or higher.
- (b) if the access point serves an industrial, commercial, or a substantial trip-generating area or if the access point serves more than three residential units.
- (c) at all median openings.

B. On two-lane highways, left-turn lanes are:

- (a) not normally provided where the 20-year projected annual average daily traffic (AADT) is under 1,500 or the design hour volume (DHV) is under 400.
- (b) provided when the access is to a public road, an industrial tract, or a commercial center.
- (c) provided when there are more than five accidents per year involving left-turning vehicles.
- (d) provided when the projected two-way DHV exceeds 700.

(4) Controlled median openings with left-turn lanes are constructed:

- (a) for public roads and dedicated streets which are open and in use.
- (b) for drive-in theaters.
- (c) for shopping centers which provide off-street parking for 100 cars.
- (d) for hospitals, schools, industrial complexes, and cemeteries.

Openings warranted under b, c, and d would not be spaced less than 330 feet from any other median opening.

(5) Left-turn bays are provided on the main roadway where side-road volumes are in excess of an AADT of 100.

(6) At unsignalized locations, the procedure outlined in "Volume Warrants for Left-Turn Storage Lanes at Unsignalized Grade Intersections" is used *(6)*. At signalized locations, nomographs produced by the Traffic Institute at Northwestern University are used *(13)*.

Many states expressed the opinion that, on divided highways where sufficient right of way exists, left-turn lanes are warranted wherever a left-turn can be made. Some respondents indicated that left-turn lanes are provided at all median openings on four-lane divided highways with no control or semi-control of access as well as at all intersections of major routes on partially controlled access routes. Another respondent said that left-turn bays are constructed at each city street intersection, where practical, on urban projects with four or more lanes. However, this type of construction is limited by availability of funds; so analyses may be conducted to determine the locations which will yield the greatest benefits.

Although few specific warrants were listed, nearly all of the states gave guidelines (both general and specific) which were used to justify separate left-turn lanes. A list of the general guidelines (areas which should be considered) follows:

(1) accident experience,
(2) main-line volume,
(3) cross-traffic volume,
(4) left-turn volume,
(5) available right of way,
(6) benefit-cost ratio,
(7) capacity analysis,
(8) sight distance,
(9) speed limit,
(10) geometrics,
(11) left-turn, rear-end conflicts,
(12) delays,
(13) gaps,
(14) effect on surrounding intersections,
(15) opposing volume,
(16) queue lengths,
(17) type of facility,
(18) number of opposing lanes to cross, and
(19) left-turn volume versus opposing through volume.

Several states gave specific guidelines or methods which they used. There was a wide range in the volumes necessary to justify a left-turn lane. A summary of guidelines used to justify a separate left-turn lane follows:

(1) Opposing AADT of 850 or more and left-turn volume equal to at least 25 percent of the opposing volume,

(2) Left-turn volume of at least 25 vehicles per hour (two-lane streets),

(3) Left-turn volume of at least 25 vehicles per hour opposed by a volume of at least 600 (four-lane streets),

(4) Left-turn AADT of 500 or more (divided highways where funds are not available to construct all the left-turn lanes),

(5) At signalized intersections wherever possible unless the approach has very little left-turn traffic (AADT of under 50),

(6) In urban or rural areas where a continuous median of sufficient width (usually 16 feet (4.9 m) or greater) is available, one or two accidents would justify the minor construction,

(7) 100 left-turn vehicles during the peak hour (in urban areas),

(8) In rural areas, left-turn volume of at least 30 vehicles during the peak hour plus a related accident experience,

(9) A rural intersection accident rate higher than 12 per 10 million entering vehicles,

(10) Left-turn volume equal to 10 percent of the total intersection volume,

(11) Sum of left-turn and opposing volume equal to 800 vehicles during the peak hour,

(12) Side-road volume of 500 or more per day on a new two-lane highway with a design speed of 50 mph (22 m/s) or greater,

(13) Signalized intersections where left-turn signal phasing is required (non-divided roadways),

(14) High percentage of left-turning vehicles (20 percent or greater),

(15) Left-turn volume of 200 vehicles per hour, and

(16) A DHV value of approximately 100 vehicles making a left turn.

Two states listed guidelines for the use of double left-turn lanes. They were as follows:

(1) When left-turn volumes exceed 300 vehicles in the peak hour.

(2) When the left-turn volume exceeds about 1,500 ADT.

## PROCEDURE

### ACCIDENT DATA

The data base used here consisted of several years of accident analyses of intersections in Lexington. These analyses, including collision diagrams, were available for the years 1968 through 1972. Accident rates at locations with and without left-turn lanes were calculated. This was done using
sections for a 12-hour period
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occurred in this 12-hour peri
then multiplied by 1.25 to obt

Using the same data bas
left-turn accidents for the app
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A computer summary
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### TRAFFIC VOLUME

Computer simulation v
lationships between traffic
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cycle split. The simulation
UTCS-1 Network Simulation
Federal Highway Administ
intersection was input into
runs were made assuming b
signal control.

When a signal was spec
cycle split were given. Durin
the side street of a semi-act
heavy that a fixed cycle
Data were simulated for a
lane and a two-lane street.
for both main street appro
left-turns were varied on one
approach had 100 percent o
Cycles of 60, 90, and 120
splits of 70/30 (70 percent
main street), 60/40, and 50,
speed of 45 mph (20 m/s) w
and the load factor were
approach. Load factor is de
total number of green-sign
utilized by traffic during t
number of green intervals f
same period *(14)*. Its maxim

Graphs were drawn relating the variables to critical delay and load factors. The critical delay was found to be 30 seconds. This was found using a procedure given in another report *(16)*. In that study, engineers were asked 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 that 85 percent of all the left-turn approach vehicles be delayed less than this maximum level of 73 seconds was then used. Assuming the distribution of delays becomes approximately normal during peak-flow conditions, the following formula can be used:

$$85\text{th percentile} = X + 1.44\,\sigma$$

in which 85th percentile = value of delay of the 85th percentile of the normal distribution (73 seconds),

$X$ = mean value of delay, and

$\sigma$ = standard deviation of the distribution.

The assumption was made that the standard deviation was approximately equal to the mean. Substituting these values gave a value of 30 seconds for the mean delay. Thirty seconds was used as the minimum average delay necessary because this value constituted the lower bound of excessive delay. A critical load factor of 0.3 was used because it represents the upper bound of level of service C *(14)*, the upper limit of stable flow. Level of service D represents a zone of increasing restriction approaching instability.

An additional procedure was used for simulation of non-signalized intersections. One hundred percent of the volume on one approach turned left while 100 percent of the volume on the opposing approach went straight through the intersection. Volume on the left-turn approach was held constant while the opposing volume was changed. This permitted a plot of left-turn delay as a function of the left-turn and opposing volumes. Data were simulated for an intersection on a four-lane and a two-lane street.

The UTCS-1 model has been tested and validated. One test dealt specifically with the response of the model to variations in primary and opposing flow levels and left-turn percentages. The tests indicated that the model performed realistically with regard to left-turns at intersections. The delay per vehicle includes deceleration and acceleration as opposed to the stopped-time delay only.

### CONFLICT DATA

Conflict counts involving left-turn vehicles were taken at several intersections and related to the number of left-turn accidents and traffic volumes. The conflicts were classified into several categories *(17, 18)*. Basically, there were four types of left-turn related conflicts. The first occurred when a left-turning vehicle crossed directly in front of or blocked the lane of an opposing through vehicle (opposing left-turn conflict). The second was caused by a vehicle waiting to turn left (rear-end type). A third was a weave resulting when a vehicle, evading a left-turning vehicle ahead, veered into the path of another vehicle. The fourth involved running the red light. An attempt was made to classify the conflicts according to severity. However, in the analysis, no distinction by severity is made because of inconsistency of data taken by different observers.

## RESULTS

### ACCIDENT WARRANT

**Accident Rates at Intersections with and without a Left-Turn Lane** -- Using the Lexington data base, accident rates (left-turn accidents per million left-turning vehicles) were calculated for intersections with and without left-turn lanes (Table 1). Left-turn-related accidents were based on the following definitions: (1) when a left-turning vehicle turned into the path of an oncoming vehicle, (2) when a left-turning vehicle was struck in the rear while waiting to turn, or (3) when a vehicle weaving around a vehicle stopped to turn left was involved in an accident.

TABLE 1. COMPARISON OF ACCIDENT RATES AT LOCATIONS WITH AND WITHOUT LEFT-TURN LANES

| | ACCIDENT RATE (LEFT-TURN ACCIDENTS PER MILLION LEFT-TURN VEHICLES) |
|---|---|
| NO SIGNAL | |
| NO LEFT-TURN LANE | 5.7 |
| WITH LEFT-TURN LANE | 1.3 |
| WITH SIGNAL | |
| NO LEFT-TURN LANE | 7.9 |
| WITH LEFT-TURN LANE | 3.6 |
| WITH LEFT-TURN LANE AND PHASING | 0.8 |

The left-turn accident rate dropped significantly for intersections with left-turn lanes. For unsignalized intersections, the left-turn accident rate was 77 percent lower. The rate was 54 percent lower at signalized intersections. At signalized intersections, the rate dropped even lower when left-turn phasing was added.

**Critical Left-Turn Accident Number** -- Using the Lexington data, the average number of left-turn accidents for the approaches with no left-turn lanes was calculated. Separate averages were calculated for intersections with and without signals. Using the average number of left-turn accidents, the critical number of accidents was also determined. For unsignalized intersections, the average number of accidents was found to be 0.8 left-turn accidents per approach per year. This corresponded to an average of 1.2 at signalized intersections. The difference was probably due to higher volumes at signalized intersections.

The formula used to determine the critical number of accidents was derived from a formula for the average, critical accident rate *(1)*:

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

in which $N_c$ = 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 in 1 year for an approach was found to be four at an unsignalized intersection and five at a signalized intersection (Table 2).

TABLE 2. NUMBER OF LEFT-TURN ACCIDENTS NECESSARY TO BE A CRITICAL INTERSECTION (ONE APPROACH)

| | NUMBER OF LEFT-TURN ACCIDENTS (ONE YEAR) |
|---|---|
| NO SIGNAL | 4 |
| WITH SIGNAL | 5 |

## VOLUME WARRANT

**Excessive Delay at a Signalized Intersection** -- The computer simulation was used to determine the delay on an approach as a function of the opposing volume, percentage left turns on the subject approach, cycle length, cycle split, and number of opposing lanes. While all other variables were held constant, the percentage left turns was increased, resulting in relationships shown in Figure 1. The delay per vehicle on the left-turn approach increased as the percentage of left turns increased. The critical delay was found previously to be 30 seconds. As shown in Figure 1, this critical delay was reached at various percentage left turns as a function of the opposing volume. For this example, the critical delay was reached at three percent left turns for an opposing, peak-hour volume of 1,200 vehicles. This compared to the critical delay at about 20 percent left turns when the opposing peak hour volume was 800 vehicles.

The points at which delay became excessive were taken from data such as shown in Figure 1 and plotted as best-fit lines. One of the relationships found is in Figure 2. Given the cycle length and split and the total peak-hour, main-street volume (peak hour, both directions), the percentage left turns on an approach necessary to create excessive delay could be found. In Figure 2, for a main-street volume of 1,600 vehicles and a 60/40 cycle split, 19 percent left turns would be the point at which delay becomes excessive. Plots, such as Figure 2, were drawn for 60-, 90-, and 120-second cycle lengths for two- and four-lane highways. These figures are given in APPENDIX A.

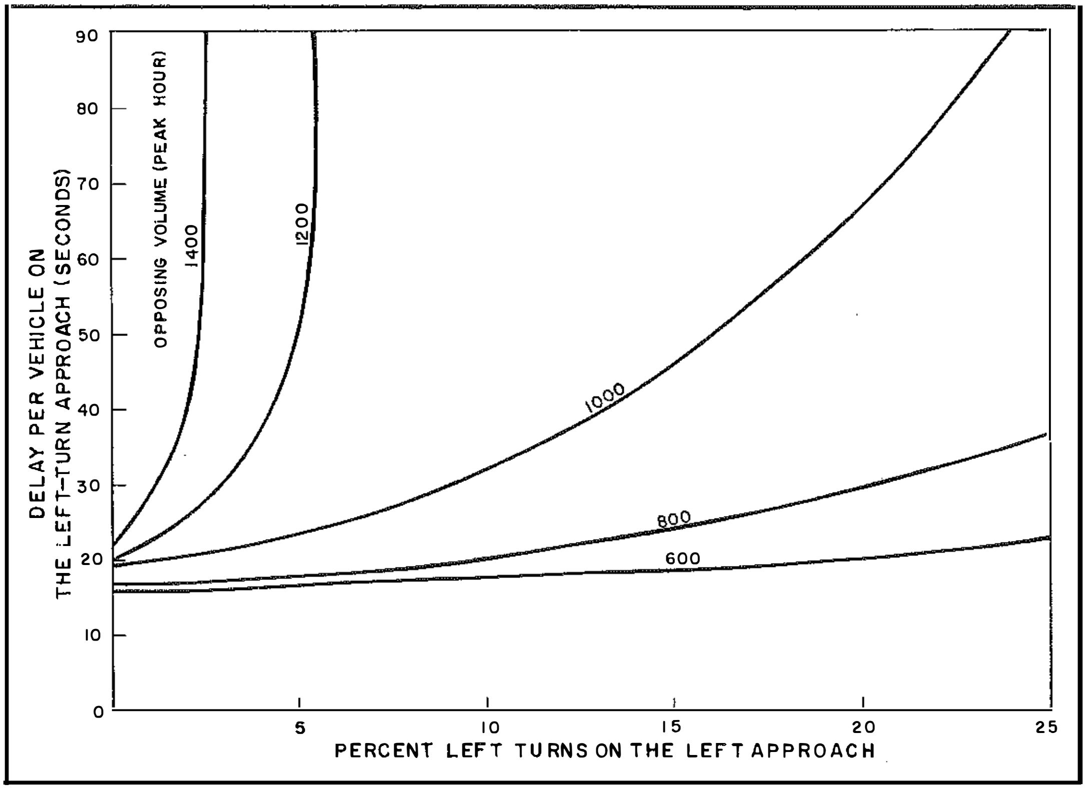


Figure 1. Relationship of Approach Delay to Opposing Volume and Percentage Left-Turns (Four-Lane Highway, 90-Second Cycle, 60/40 Cycle Split).

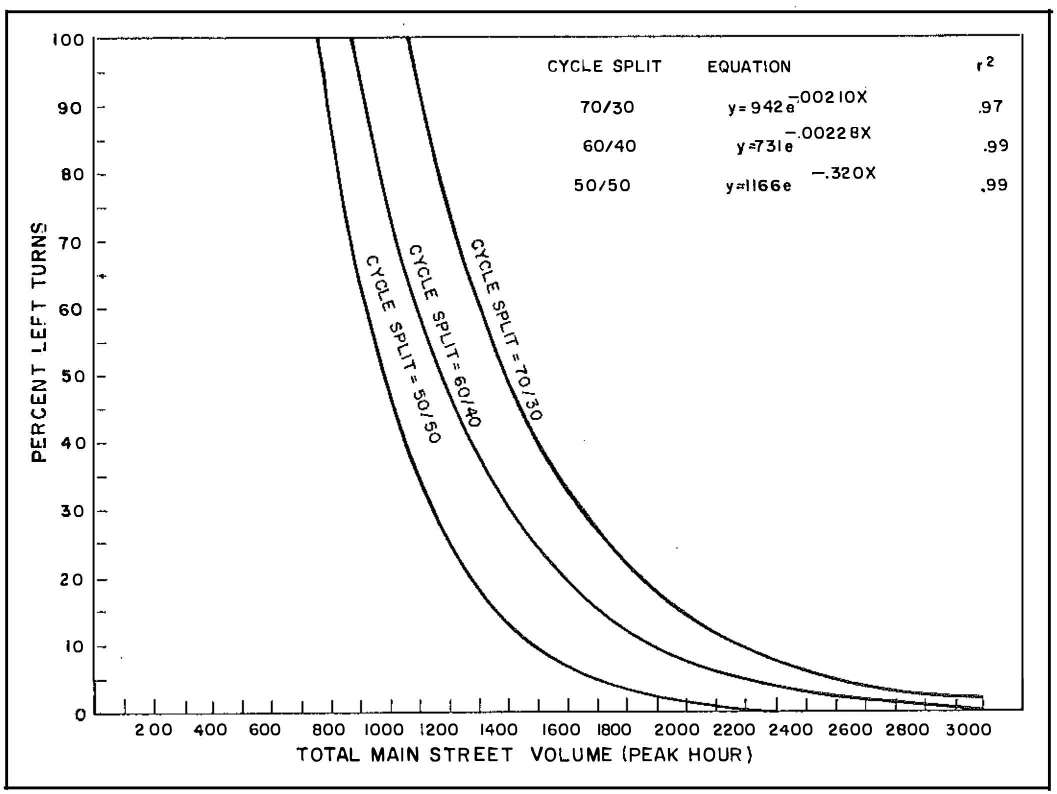


Figure 2. Percentage Left-Turns When Delay Becomes Excessive (Four-Lane Highway, 90-Second Cycle).

The total main-street volume was used because the volumes on both the left-turn and opposing approaches would be factors in determining where delay becomes excessive. Equal volumes were input for both approaches. This was done since it would have taken a prohibitive number of computer runs to consider all possible combinations of volumes. The data shown in Table 3 indicate that using equal volumes on both approaches gives a reasonable approximation of the delay which would result from different volume combinations. Therefore, given the necessary input, the figures given in APPENDIX A give a critical volume warrant for a left-turn lane at a signalized intersection based on excessive delay.

TABLE 3. VARIANCE OF DELAY PER VEHICLE ON THE LEFT-TURN APPROACH AS VOLUMES VARY*

| OPPOSING VOLUME | LEFT-TURN APPROACH VOLUME | DELAY PER VEHICLE ON LEFT TURN APPROACH (SECONDS) |
|---|---|---|
| 1000 | 1000 | 33.9 |
| 1500 | 500 | 28.7 |
| 500 | 1500 | 41.0 |
| 1200 | 800 | 40.9 |
| 800 | 1200 | 31.2 |
| 1300 | 700 | 33.3 |

*ALL COMBINATIONS OF OPPOSING AND LEFT-TURN VOLUMES YIELD A TOTAL OF 2000 VEHICLES IN A ONE-HOUR PERIOD.

**Excessive Load Factor** -- The critical load factor used was 0.3. This value represents the upper bound of level of service C, which is the upper limit of stable flow. The same procedure was used to relate the critical load factor to the variables under consideration as was used for excessive delay. Percentage left turns were increased while holding all other variables constant, giving relationships such as plotted in Figure 3. For this example, the critical load factor was reached at 3.5 percent left turns for an opposing peak-hour volume of 1,200 vehicles. This compared to the critical load factor at 22.5 percent left turns when the opposing peak-hour volume was 800 vehicles. It should be noted that the volumes necessary to exceed a load factor of 0.3 were slightly higher than those necessary to exceed the critical delay.

Data such as plotted in Figure 3 were plotted as best-fit lines to produce relationships as shown in Figure 4. The graphical procedure relating an excessive load factor to the variables considered was identical to that used when excessive delay was considered. In Figure 4, for a main-street peak-hour volume of 1,600 vehicles and a 60/40 cycle split, 23 percent left turns would be the point at which the load factor becomes excessive. Plots such as Figure 4 were drawn for 60-, 90-, and 120-second cycle lengths for two- and four-lane highways and are presented in APPENDIX B. These plots provide a critical volume warrant for a left-turn lane based on an excessive load factor.

**Unsignalized Intersection** -- Critical volume warrant curves based on excessive delays using a procedure similar to that for signalized intersections are given in Figures 5 and 6. The excessive delay criterion used for signalized intersections was 30 seconds. It would be logical that a lower delay would constitute excessive delay at an unsignalized intersection. Therefore, a curve representing a delay criterion of 20 seconds is included in Figures 5 and 6. However, there was only a small difference in the two curves. Higher volumes are necessary to create a critical condition at an unsignalized site compared to one signalized.

Another procedure was also used for simulating delays at a nonsignalized intersection. In this procedure, the computer input specified that 100 percent of the volume on the left-turn approach turned left while 100 percent of the opposing volume went straight through. Delay to the left-turn vehicles was determined as the left-turn volume was held constant while increasing the opposing volume (Figures 7 and 8). The point at which left-turn delay started to increase drastically represents the point at which a left-turn lane should be considered.

**Sum of Left-Turn and Opposing Volumes** -- The minimum sum of peak-hour left-turn and opposing volumes, which resulted in a critical left-turn delay, was determined (Table 4). To obtain these results, figures contained in APPENDIX A were used for signalized intersections, and Figures 5 - 8 were used for nonsignalized intersections. This table represents a simpler volume warrant which may be used to determine if further investigation is needed. The volumes there would tend to be lower than those given in the previous figures; it represents the minimum volumes necessary to create a left-turn delay problem. Of course, a minimum number of left-turns, such as 50 left turns per hour, would be necessary.

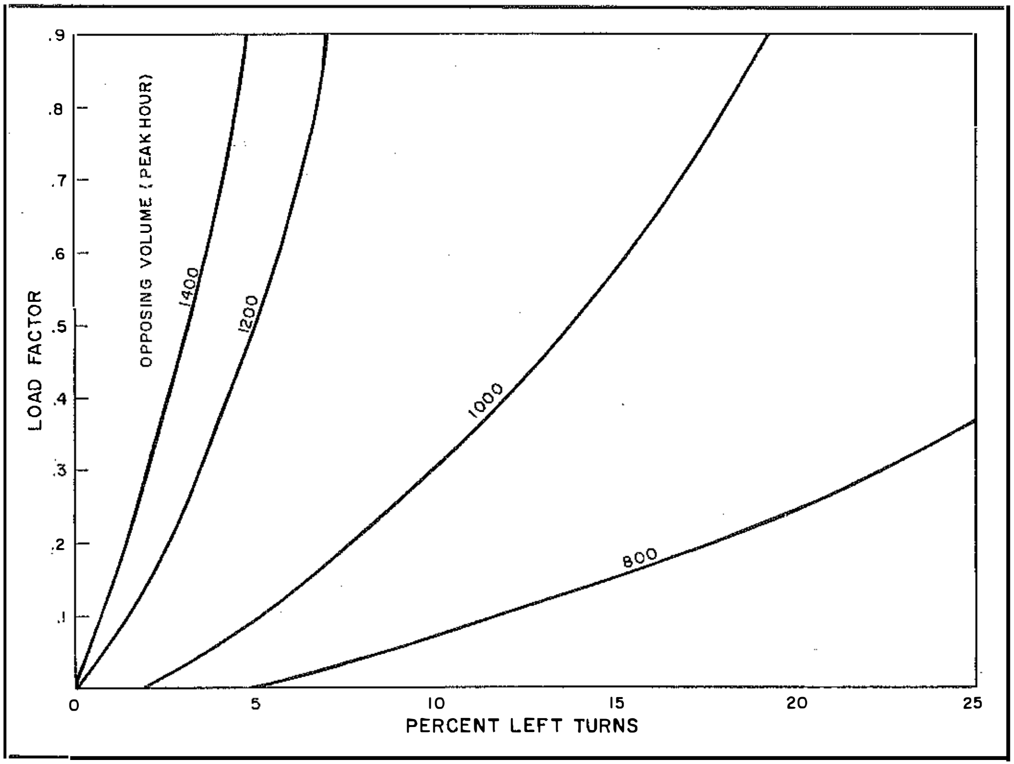


Figure 3. Relationship of Load Factor to Opposing Volume and Percentage Left-Turns (Four-Lane Highway, 90-Second Cycle, 60/40 Cycle Split).

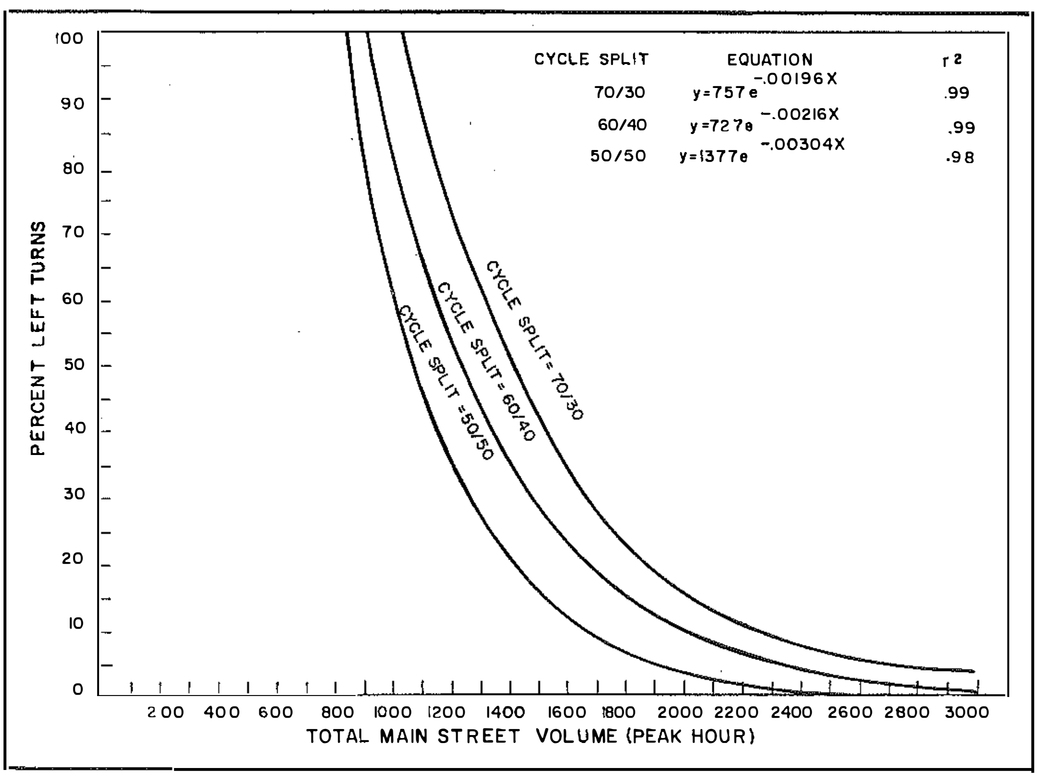


Figure 4. Percentage Left-Turns When Load Factor Becomes Excessive (Four-Lane Highway, 90-Second Cycle).

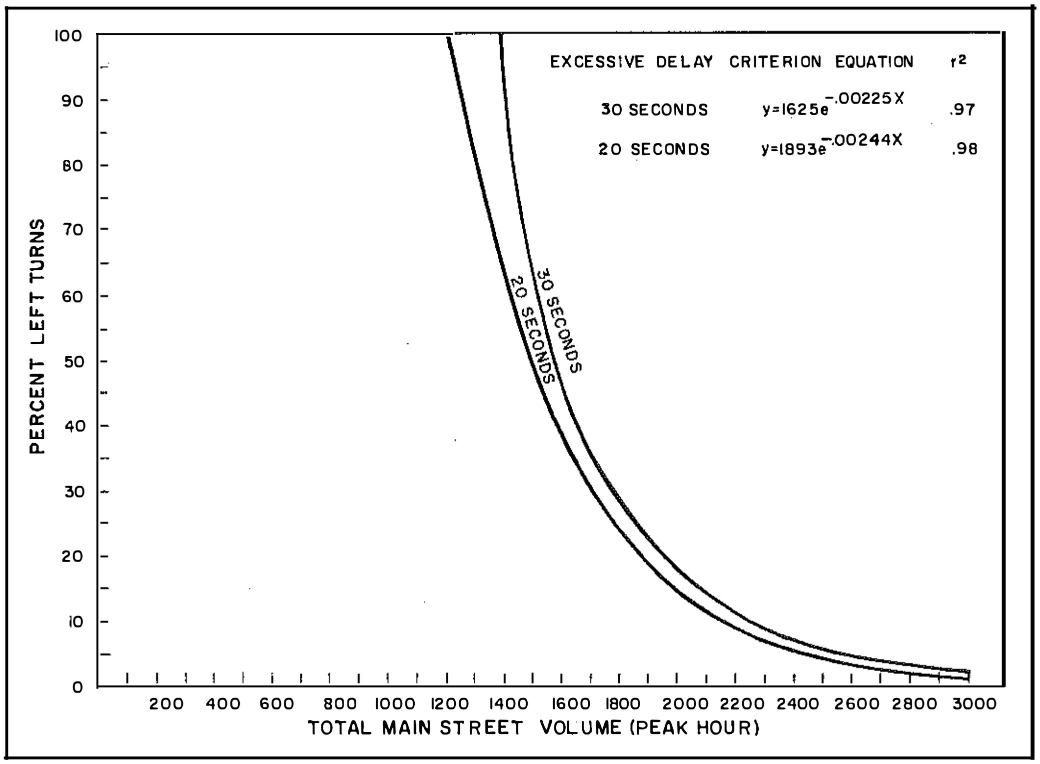


Figure 5. Percentage Left-Turns When Delay Becomes Excessive (Four-Lane Highway, No Signal).

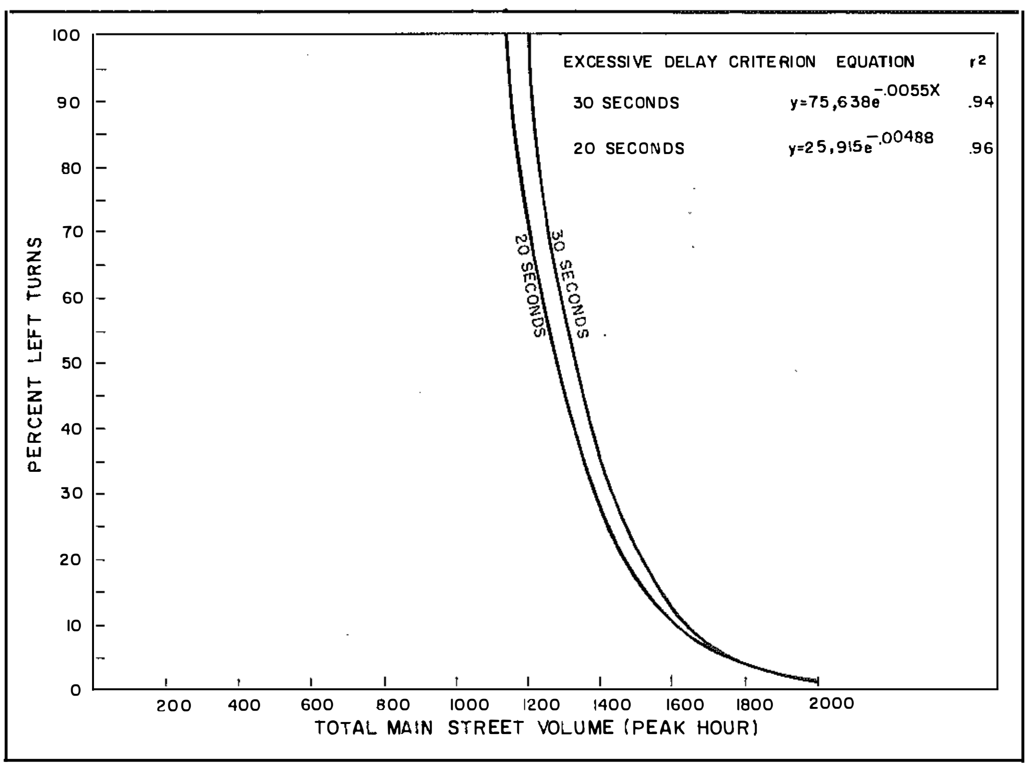


Figure 6. Percentage Left-Turns When Delay Becomes Excessive (Two-Lane Highway, No Signal).

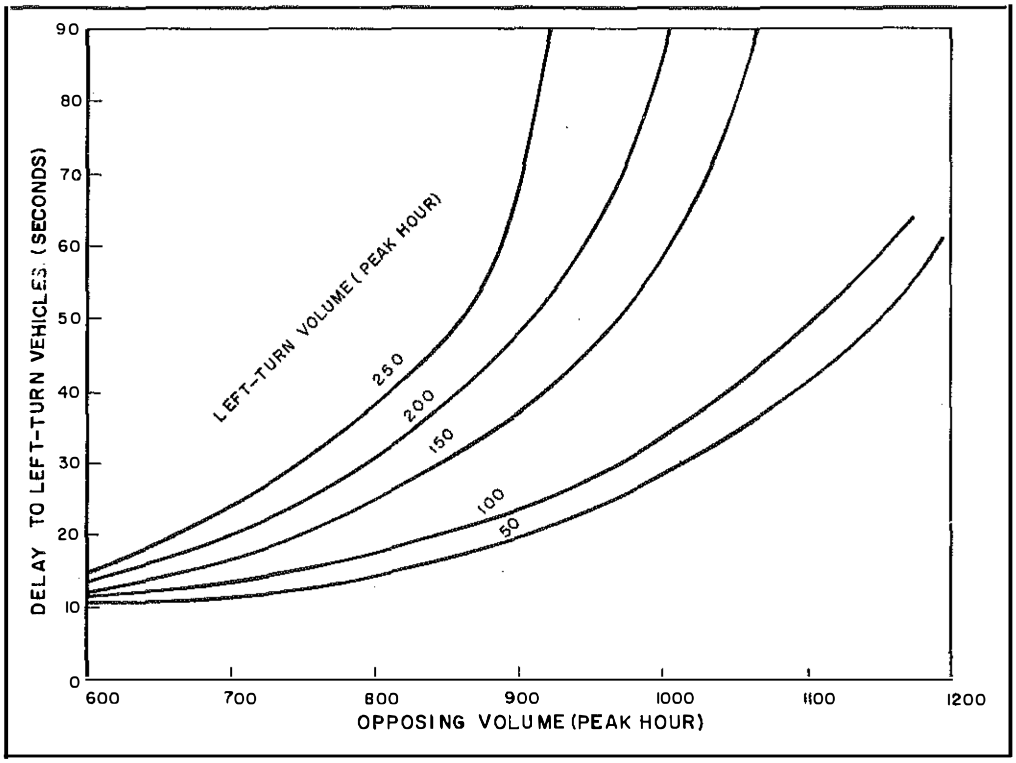


Figure 7. Left-Turn Delay as a Function of Opposing and Left-Turn Volume (Non-signalized Intersection, Four Lanes).

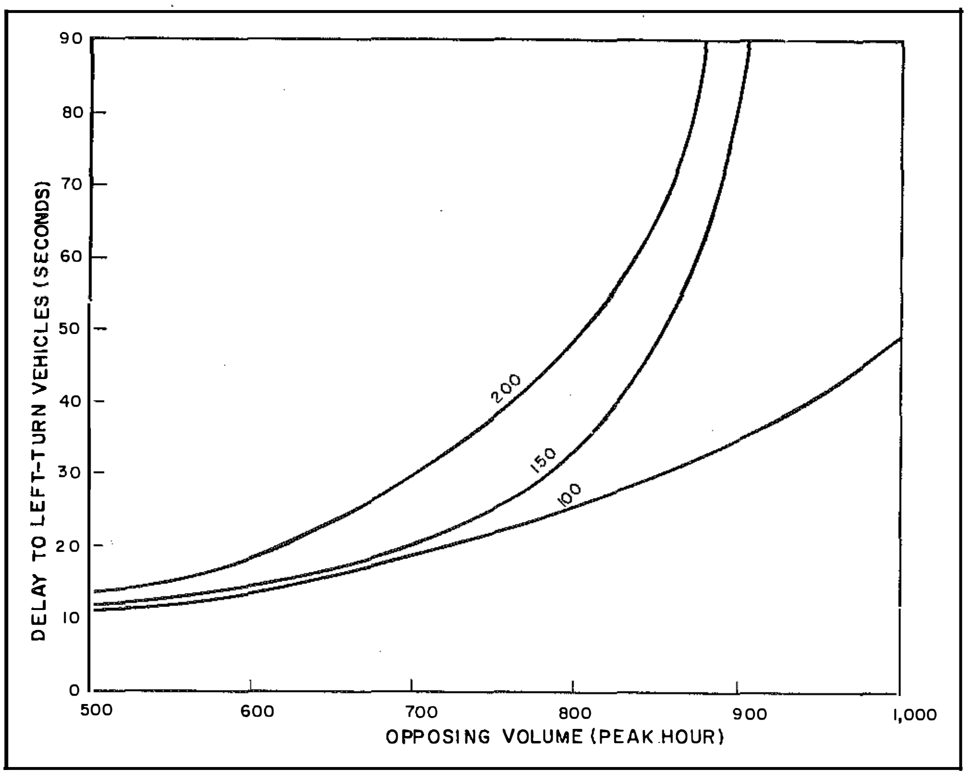


Figure 8. Left-Turn Delay as a Function of Opposing and Left-Turn Volume (Non-signalized Intersection, Two Lanes).

TABLE 4. SUM OF LEFT-TURN AND OPPOSING VOLUMES DURING THE PEAK HOUR NECESSARY TO CREATE A LEFT-TURN DELAY PROBLEM*

SIGNALIZED INTERSECTION (FOUR-LANE HIGHWAY)

| | CYCLE SPLIT | | |
|---|---|---|---|
| CYCLE LENGTH | 70/30 | 60/40 | 50/50 |
| 120 | 950 | 800 | 600 |
| 90 | 1000 | 850 | 700 |
| 60 | 1150 | 1000 | 850 |

SIGNALIZED INTERSECTION (TWO-LANE HIGHWAY)

| | CYCLE SPLIT | | |
|---|---|---|---|
| CYCLE LENGTH | 70/30 | 60/40 | 50/50 |
| 120 | 650 | 550 | 400 |
| 90 | 700 | 600 | 500 |
| 60 | 750 | 650 | 550 |

NON-SIGNALIZED INTERSECTION

| DELAY CRITERION | FOUR-LANE HIGHWAY | TWO-LANE HIGHWAY |
|---|---|---|
| 30 SECONDS | 1000 | 900 |
| 20 SECONDS | 900 | 800 |

*ASSUMING A MINUMUM LEFT-TURN VOLUME SUCH AS 50 LEFT-TURNS IN THE PEAK HOUR

## TRAFFIC CONFLICTS WARRANT

Traffic conflicts at 25 intersection approaches not having a separate left-turn lane were observed for three peak hours at each approach. In most instances, the data collection periods consisted of one morning rush hour (7:30 to 8:30 a.m.) and two afternoon rush hours (3:30 to 5:30 p.m.). The peak hours were found from traffic volume counts and varied from location to location. Data were recorded on forms developed for conflict studies *(18)*. All of the conflict types were recorded; however, only those relating to left-turn accidents were considered in the analysis. Those conflicts included in the analysis were as follows:

(1) opposing left-turn,
(2) weave (involving left-turning vehicle),
(3) slowed-for-left-turn,
(4) previous-left-turn, and
(5) ran-red-light (turning left).

Further descriptions of these conflict types are given in APPENDIX C. The sum of these five conflicts was referred to as the total left-turn-related conflicts.

The 25 intersection approaches were divided into two groups based on whether they met the previously developed accident warrant. Seven approaches did. The number of accidents used was the highest 1-year number of accidents at a particular approach. The average number of left-turn-related conflicts was determined for the two groups of locations. Six of the approaches were at unsignalized intersections. These approaches were not analyzed separately because there were very few conflicts directly involving the traffic signal (ran-red-light conflict). Also, six of the approaches were on two-lane streets. These approaches were not analyzed separately since weave conflicts were not a high proportion of the total.

A summary of the number of conflicts found at locations which did and did not meet the accident warrant is given in Table 5. For each conflict type, the averages of the number of conflicts found in the highest hour as well as all three hours for each approach were summarized. Also, the 95th-percentile confidence interval was calculated for each average value.

The slowed-for-left-turn type of conflict occurred most often. It was followed in frequency by the previous-left-turn and opposing-left-turn conflicts. There was a smaller number of weave conflicts and a very small number of ran-red-light conflicts. The number of conflicts was substantially higher at locations which met the accident warrant. However, there was a very large range in the data, as shown by the confidence intervals. An interesting comparison can be made between the upper bound of the confidence interval for the locations which did not meet the accident warrant and the average value at locations which did meet the accident warrant. With the exception of the ran-red-light conflict, the average value for locations meeting the warrant was above the upper bound of the confidence interval for locations not meeting the warrant. This indicates that using these average values as a guideline would not identify locations with a low accident potential. However, some potentially high-accident locations could be missed.

A determination of which types of conflicts to use in a traffic conflicts warrant must also be made. To benefit from all data available, it would be logical to include the total of all related conflicts in any warrant or guideline. In addition, any one type of conflict found to relate more to the accident potential should be included. Most accidents involved a left-turning vehicle turning into the path of an opposing vehicle. Therefore, the opposing left-turn conflict could be used as a guide.

To determine which types of conflicts related most directly with accidents, equations of the best-fit lines relating left-turn accidents and left-turn-related conflicts were determined (Table 6). When each approach was treated as a separate point, very poor relationships were found, as indicated by the coefficients of determination ($r^2$). The highest $r^2$ was 0.29. The equation showed that the total conflicts and opposing-left-turn conflicts related best to accidents.

The locations were also grouped by the number of accidents and related to conflicts. Five accident groupings were used. There were four locations having no accidents, four with one, seven with two, four locations with from three through five accidents, and six with six or more accidents. Much better relationships were found when this procedure was used. Substituting the number of accidents necessary to warrant a signal into the equations provided another procedure for determining critical traffic conflict numbers. Five accidents were used as input into the equations. Almost identical results were obtained for both groups of equations.

A summary of several alternate methods of developing traffic conflict warrants or guidelines is given in Table 7. These methods give similar results. Using both total conflicts and opposing-left-turn conflicts as guidelines would provide a suitable procedure. The total left-turn-related conflicts provides maximum input; on the other hand, opposing-left-turn conflicts are the most severe and are the most representative of the type of accidents which have occurred.

TABLE 5. COMPARISON OF CONFLICTS AT LOCATIONS WHICH DID AND DID NOT MEET THE ACCIDENT WARRANT

| | LOCATIONS MEETING ACCIDENT WARRANT | | LOCATIONS NOT MEETING ACCIDENT WARRANT | |
|---|---|---|---|---|
| TYPE OF CONFLICT | AVERAGE | CONFIDENCE INTERVAL (95TH PERCENTILE) | AVERAGE | CONFIDENCE INTERVAL (95TH PERCENTILE) |
| TOTAL[a] | | | | |
| PEAK HOUR[b] | 45 | 15 - 77 | 27 | 16 - 37 |
| AVERAGE[c] | 30 | 13 - 45 | 18 | 10 - 26 |
| OPPOSING LEFT TURN | | | | |
| PEAK HOUR | 8.7 | 2 - 16 | 3.2 | 1 - 5 |
| AVERAGE | 5.9 | 1 - 11 | 1.6 | 1 - 3 |
| SLOWED FOR LEFT TURN | | | | |
| PEAK HOUR | 23 | 10 - 36 | 15 | 8 - 22 |
| AVERAGE | 15 | 7 - 23 | 10 | 5 - 15 |
| PREVIOUS LEFT TURN | | | | |
| PEAK HOUR | 14 | 4 - 24 | 7.6 | 4 - 11 |
| AVERAGE | 8 | 5 - 11 | 4.9 | 2 - 8 |
| WEAVE[d] | | | | |
| PEAK HOUR | 4.4 | 1 - 8 | 1.9 | 1 - 3 |
| AVERAGE | 2.2 | 1 - 3 | 1.1 | 0.6 - 1.6 |
| RAN RED LIGHT[d] | | | | |
| PEAK HOUR | 0.57 | 0 - 1.3 | 0.50 | 0.2 - 0.8 |
| AVERAGE | 0.19 | 0 - 0.4 | 0.28 | 0 - 0.7 |

[a] TOTAL OF LEFT-TURN RELATED CONFLICTS

[b] AVERAGE OF THE HIGHEST NUMBER OF CONFLICTS FOUND IN ONE OF THE THREE PEAK HOURS STUDIED FOR THE LOCATIONS

[c] AVERAGE OF THE NUMBER OF CONFLICTS FOR THE THREE PEAK HOURS FOR EACH LOCATION

[d] INVOLVING LEFT-TURNING VEHICLES

TABLE 6. RELATIONSHIPS BETWEEN LEFT-TURN ACCIDENTS AND LEFT-TURN RELATED CONFLICTS

| TYPE OF CONFLICT | EACH LOCATION TREATED SEPARATELY | | LOCATIONS GROUPED BY NUMBERS OF ACCIDENTS | |
|---|---|---|---|---|
| | EQUATION[a] | $R^2$ | EQUATION | $R^2$ |
| TOTAL[b] | | | | |
| PEAK HOUR[c] | Y = 20.6 + 3.4 X | 0.18 | Y = 18.6 + 3.9 X | 0.85 |
| AVERAGE[d] | Y = 13.6 + 2.5 X | 0.21 | Y = 12.4 + 2.8 X | 0.80 |
| OPPOSING LEFT TURN | | | | |
| PEAK HOUR | Y = 1.8 + 0.91X | 0.26 | Y = 1.6 + 0.88X | 0.59 |
| AVERAGE | Y = 0.64 + 0.66X | 0.29 | Y = 0.6 + 0.64X | 0.71 |
| SLOWED FOR LEFT TURN | | | | |
| PEAK HOUR | Y = 11.7 + 1.8 X | 0.16 | Y = 10.0 + 2.0 X | 0.87 |
| AVERAGE | Y = 8.0 + 1.1 X | 0.15 | Y = 7.5 + 1.25X | 0.71 |
| PREVIOUS LEFT TURN | | | | |
| PEAK HOUR | Y = 5.6 + 1.1 X | 0.19 | Y = 5.5 + 1.27X | 0.62 |
| AVERAGE | Y = 3.6 + 0.66X | 0.15 | Y = 3.4 + 0.78X | 0.51 |
| WEAVE[e] | | | | |
| PEAK HOUR | Y = 1.24 + 0.43X | 0.18 | Y = 0.95 + 0.50X | 0.82 |
| AVERAGE | Y = 0.75 + 0.21X | 0.13 | Y = 0.45 + 0.25X | 0.86 |
| RUN RED LIGHT[e] | | | | |
| PEAK HOUR | Y = 0.58 - 0.02X | 0.005 | Y = 0.55 + 0.01X | 0.003 |
| AVERAGE | Y = 0.31 - 0.02X | 0.02 | Y = 0.31 - 0.01X | 0.02 |

[a] X = NUMBER OF ACCIDENTS
Y = NUMBER OF CONFLICTS
[b] TOTAL OF LEFT-TURN RELATED CONFLICTS
[c] HIGHEST NUMBER OF CONFLICTS IN THE THREE PEAK HOURS STUDIED
[d] AVERAGE OF THE THREE PEAK HOURS STUDIED
[e] INVOLVING LEFT-TURNING VEHICLE

TABLE 7. METHODS OF DEVELOPING TRAFFIC CONFLICT WARRANTS OF GUIDELINES

| TYPE OF CONFLICT | CRITICAL TRAFFIC CONFLICT LEVEL FOR GIVEN METHOD | | |
|---|---|---|---|
| | AVERAGE VALUE AT LOCATIONS MEETING ACCIDENT WARRANT | UPPER LEVEL OF CONFIDENCE INTERVAL AT LOCATIONS NOT MEETING ACCIDENT WARRANT | SUBSTITUTING FIVE ACCIDENTS INTO EQUATION RELATING CONFLICTS AND ACCIDENTS |
| TOTAL[a] | | | |
| PEAK HOUR[b] | 45 | 37 | 38 |
| AVERAGE[c] | 30 | 26 | 26 |
| OPPOSING LEFT TURN | | | |
| PEAK HOUR | 8.7 | 5 | 6.0 |
| AVERAGE | 5.9 | 3 | 3.8 |
| SLOWED FOR LEFT TURN | | | |
| PEAK HOUR | 23 | 22 | 20 |
| AVERAGE | 15 | 15 | 14 |
| PREVIOUS LEFT TURN | | | |
| PEAK HOUR | 14 | 11 | 12 |
| AVERAGE | 7.9 | 8 | 7.3 |
| WEAVE[d] | | | |
| PEAK HOUR | 4.4 | 3 | 3.4 |
| AVERAGE | 2.2 | 1.6 | 1.7 |

[a] TOTAL OF LEFT-TURN RELATED CONFLICTS
[b] THE HIGHEST ONE-HOUR NUMBER OF CONFLICTS
[c] AVERAGE NUMBER OF CONFLICTS IN THE THREE PEAK HOURS
[d] INVOLVING LEFT-TURNING VEHICLE

Based on these sources of input, the following warrant was developed: add a left-turn lane when a conflict study shows an hourly average of 30 or more total left-turn-related conflicts or 6 or more opposing-left-turn conflicts in a 3-hour study period during peak-volume conditions. Also, consider adding a lane if 45 or more total left-turn-related conflicts or 9 or more opposing-left-turn conflicts occur in any 1-hour period.

## SUMMARY AND CONCLUSIONS

1. Few states use numerical warrants for the installation of left-turn lanes; however, most use some type of guideline. The guidelines were usually based on either accidents, volume, or delay.

2. Left-turn accident rates were found to be significantly lower at intersections having left-turn lanes compared to those without left-turn lanes. This finding applied to both signalized and unsignalized intersections.

3. The critical number of left-turn accidents in one year necessary to warrant installation of a left-turn lane was found to be four at an unsignalized intersection and five at a signalized intersection.

4. Critical volume warrant curves for a left-turn lane at a signalized intersection were developed on the basis of excessive delay. Using a critical delay of 30 seconds per vehicle, plots were developed giving percentage left-turns necessary to create excessive delay as a function of total main-street volume. Plots were drawn for various cycle lengths and cycle splits for two-lane and four-lane highways (APPENDIX A).

5. Figures similar to those cited above were developed to give a critical volume warrant for a left-turn lane based on an excessive load factor (APPENDIX B). A critical load factor of 0.3 was used.

6. The volumes necessary to warrant installation of a left-turn lane were slightly higher when based on an excessive load factor than when based on excessive delay.

7. Critical volume warrant based on excessive delays were developed for unsignalized intersections (Figures 5 and 6).

8. An alternate type of volume warrant was based on the minimum sum of peak-hour left-turn and opposing volumes necessary to create a critical left-turn delay (Table 4). These volumes represent the lower bounds of the volumes necessary to create a left-turn delay problem and may be used to decide if further investigation is needed.

9. Traffic conflict studies were conducted at intersection approaches which did not have a separate left-turn lane. The data showed that the average number of left-turn-related conflicts was higher at locations which had a higher number of left-turn-related accidents. However, there was a very large range in the data, as shown by the confidence intervals which were found.

10. Equations of the best-fit lines relating left-turn accidents and left-turn conflicts were determined (Table 6). When each approach was treated as a separate point, very poor correlations were found. The highest $r^2$ was 0.29 when only the opposing-left-turn conflict was considered. However, much better correlations were found when the locations were grouped by number of accidents.

11. A warrant based on conflicts was developed. The warrant states that a separate left-turn lane should be considered when a conflict study shows an hourly average of 30 or more total left-turn-related conflicts or 6 or more opposing left-turn conflicts in a 3-hour study period during peak-volume conditions. Also, consideration should be given to adding a lane if 45 or more total left-turn-related conflicts or 9 or more opposing-left-turn conflicts occur in any 1-hour period.

## RECOMMENDATIONS

The addition of left-turn lanes always provides an improvement in the traffic flow; however, left-turn lanes cannot be built at all locations. It is recommended that the following warrants be used as guidelines to aid in determining when the need for left-turn lanes becomes critical:

1. **Accident Experience** -- Install a separate left-turn lane if the critical number of left-turn-related accidents (as defined in the text) has occurred. For one approach in 1 year, four left-turn accidents at an unsignalized intersection and five at a signalized intersection are critical.

2. **Volume** -- Install a separate left-turn lane when volumes meet the criteria given in the critical volume warrant graphs in APPENDIX A for signalized intersections. For signalized intersections, the number of lanes, cycle length, cycle split, total main-street volume (peak hour), and percentage left-turns must be known. For unsignalized intersections, the number of lanes, total main-street volume (peak hour), and percentage left-turns must be known. It is recommended that the curve representing a critical delay of 20 seconds be used for unsignalized intersections (Figures 5 and 6). Also, the volumes given in Table 4 representing minimum sums of peak-hour left-turn and opposing volumes giving critical left-turn delays may be used as a guideline to determine if further investigation is needed.

3. **Traffic Conflicts** – Consider adding a separate left-turn lane when a conflict study shows an hourly average of 30 or more total left-turn-related conflicts (as defined in APPENDIX C) or 6 or more opposing-left-turn conflicts (as defined in APPENDIX C) in a 3-hour study period during peak-volume conditions. Also, consider adding a lane if 45 or more total left-turn-related conflicts or 9 or more opposing-left-turn conflicts occur in any 1-hour period.

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## APPENDIX A

## FIGURES GIVING PERCENTAGE LEFT-TURNS WHEN DELAY BECOMES EXCESSIVE (SIGNALIZED INTERSECTION)

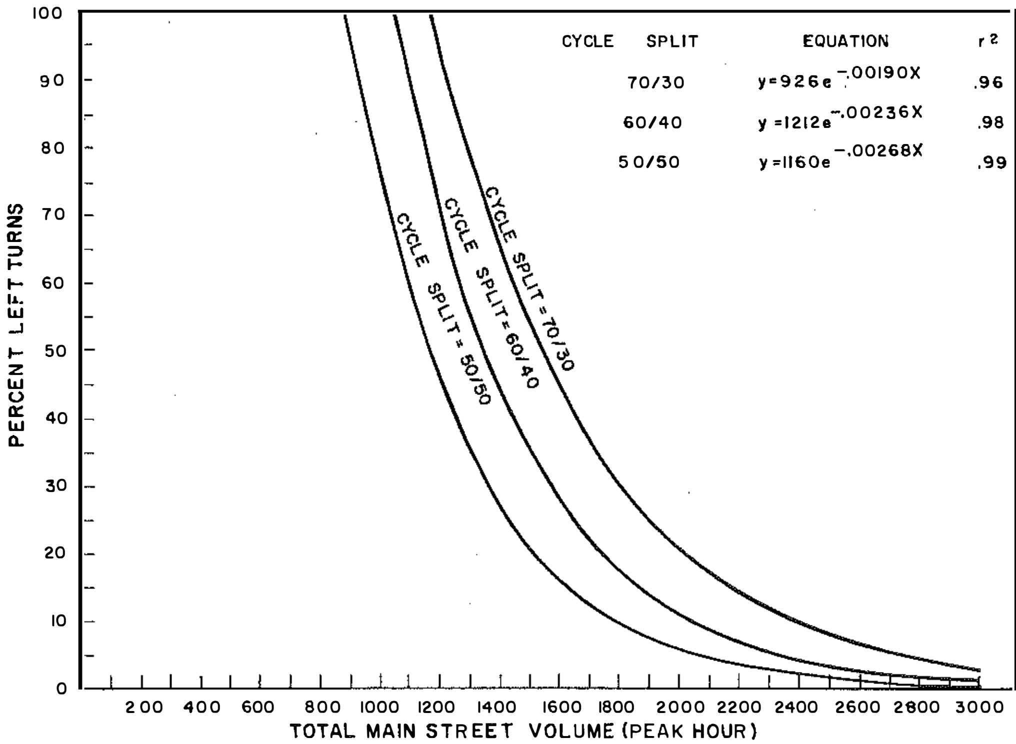


**Figure A1.** Percentage Left-Turns When Delay Becomes Excessive (Four-Lane Highway, 60-Second Cycle).

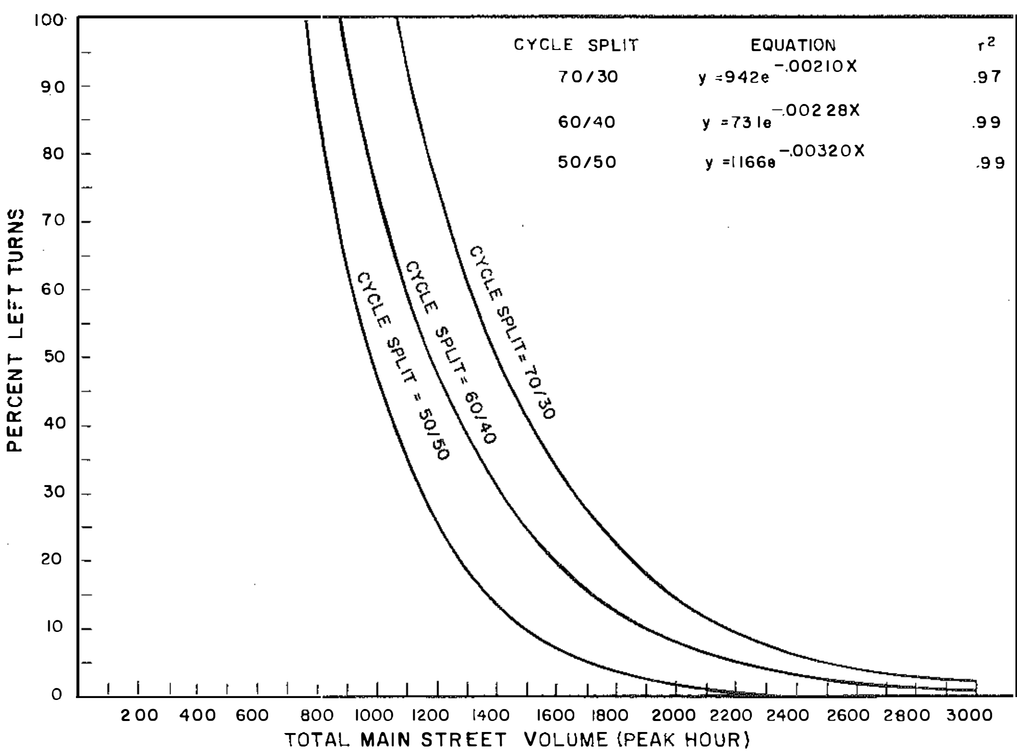


**Figure A2.** Percentage Left-Turns When Delay Becomes Excessive (Four-Lane Highway, 90-Second Cycle).

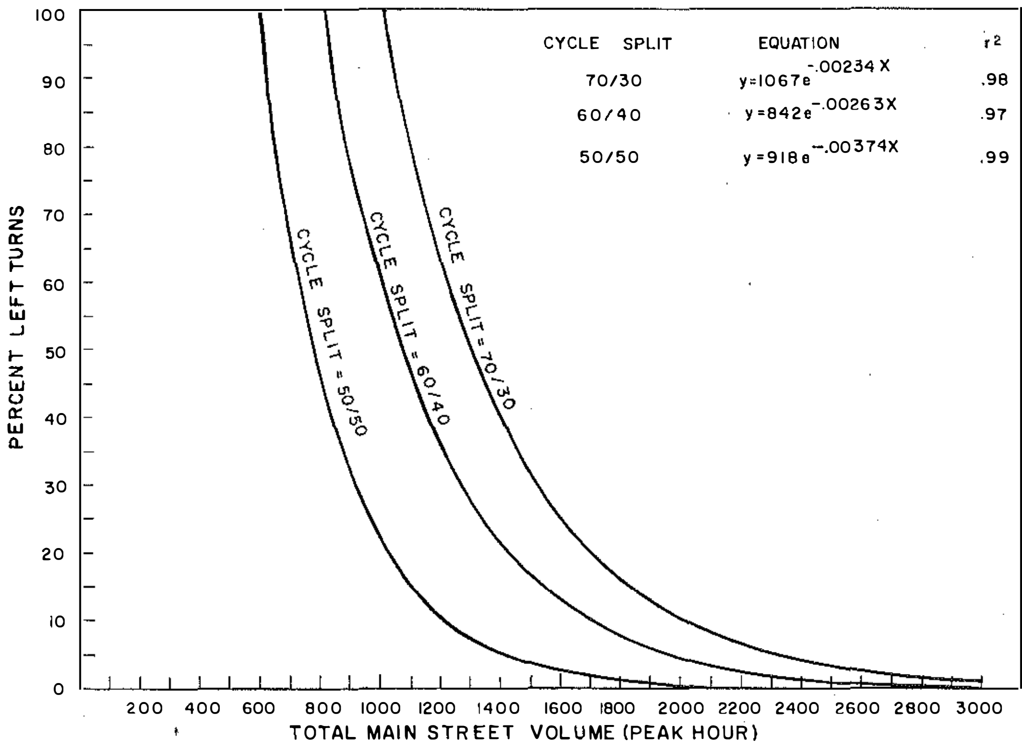


**Figure A3. Percentage Left-Turns When Delay Becomes Excessive (Four-Lane Highway, 120-Second Cycle).**

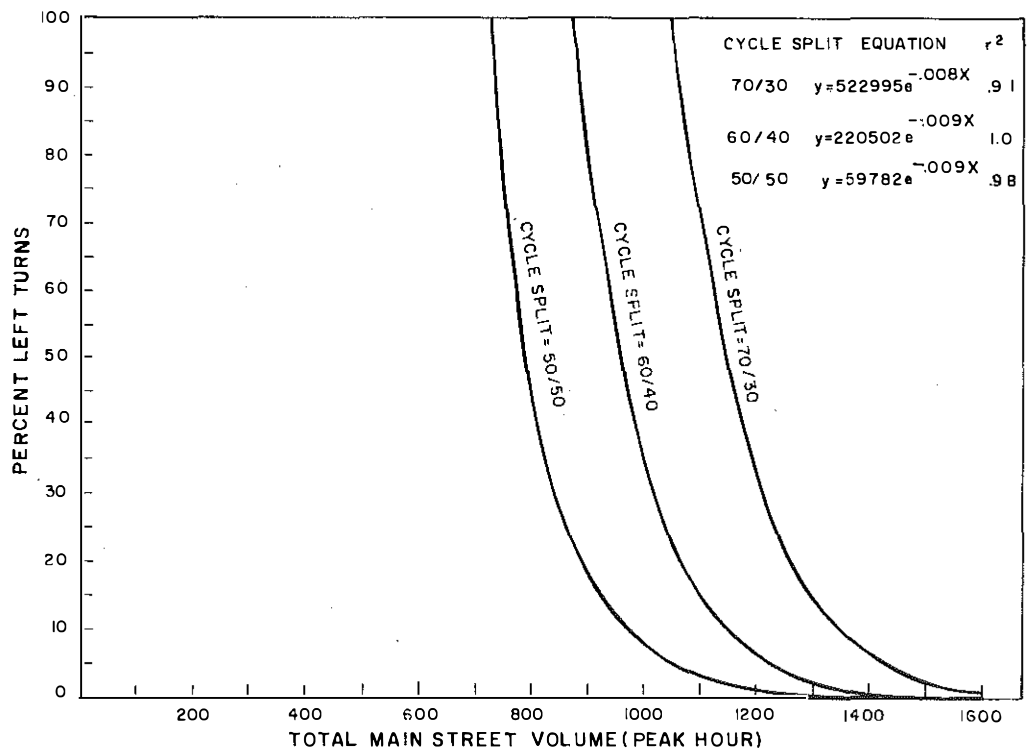


**Figure A4. Percentage Left-Turns When Delay Becomes Excessive (Two-Lane Highway, 60-Second Cycle).**

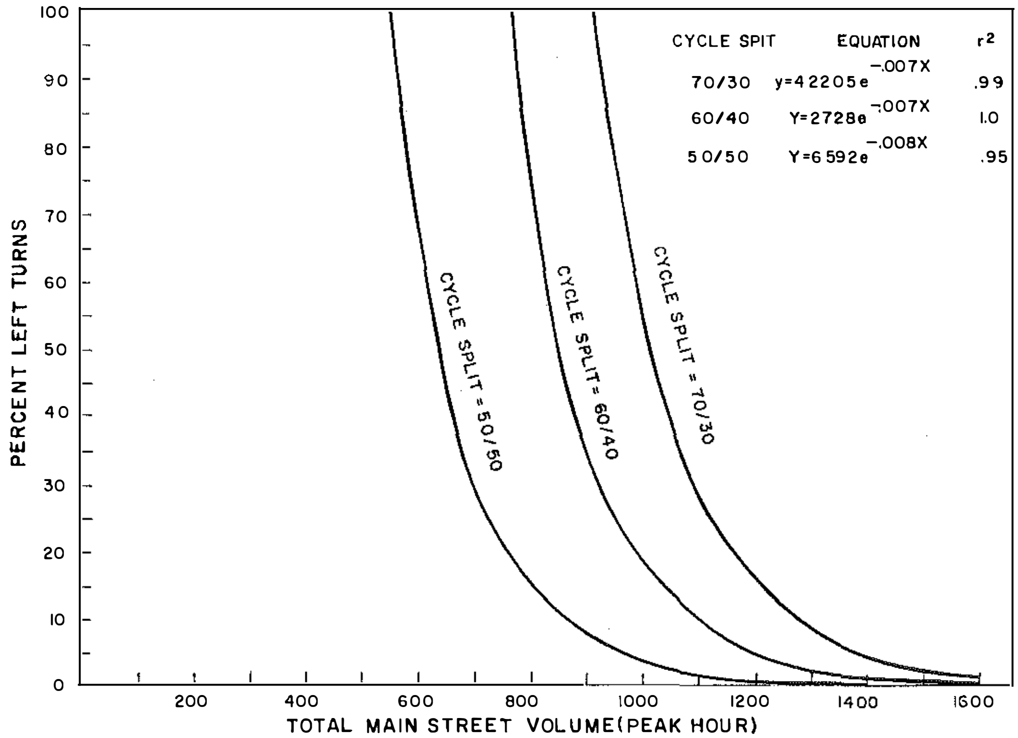


Figure A5. Percentage Left-Turns When Delay Becomes Excessive (Two-Lane Highway, 90-Second Cycle).

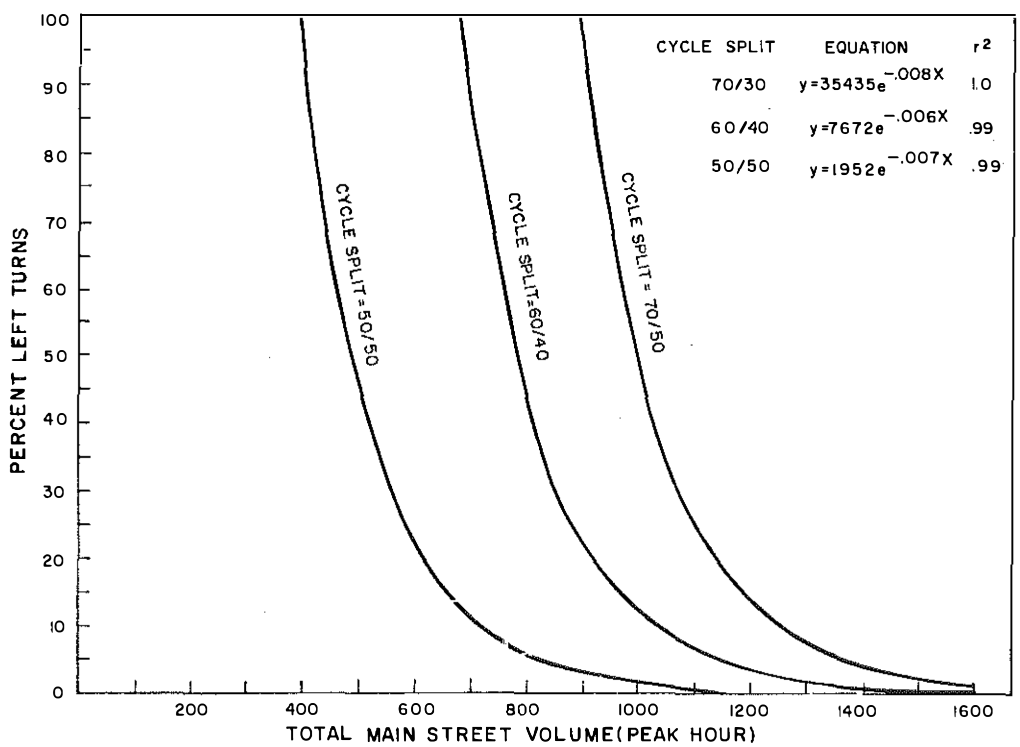


Figure A6. Percentage Left-Turns When Delay Becomes Excessive (Two-Lane Highway, 120-Second Cycle).

## APPENDIX B

## FIGURES GIVING PERCENTAGE LEFT-TURNS WHEN LOAD FACTOR BECOMES EXCESSIVE

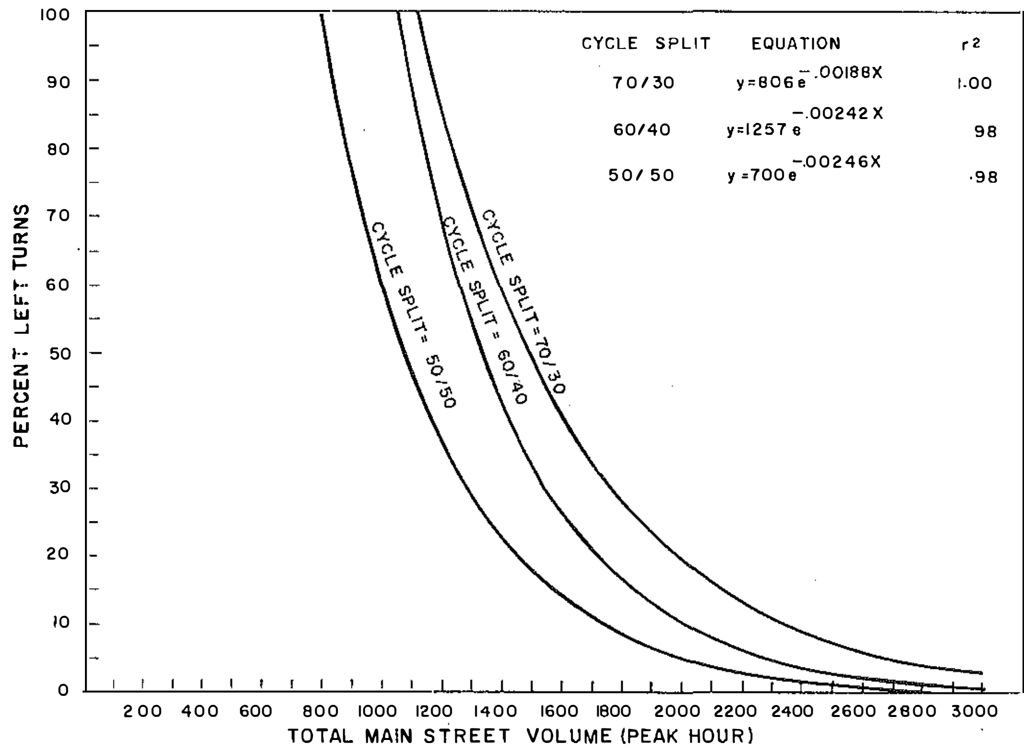


**Figure B1.** Percentage Left-Turns When Load Factor Becomes Excessive (Four-Lane Highway, 60-Second Cycle).

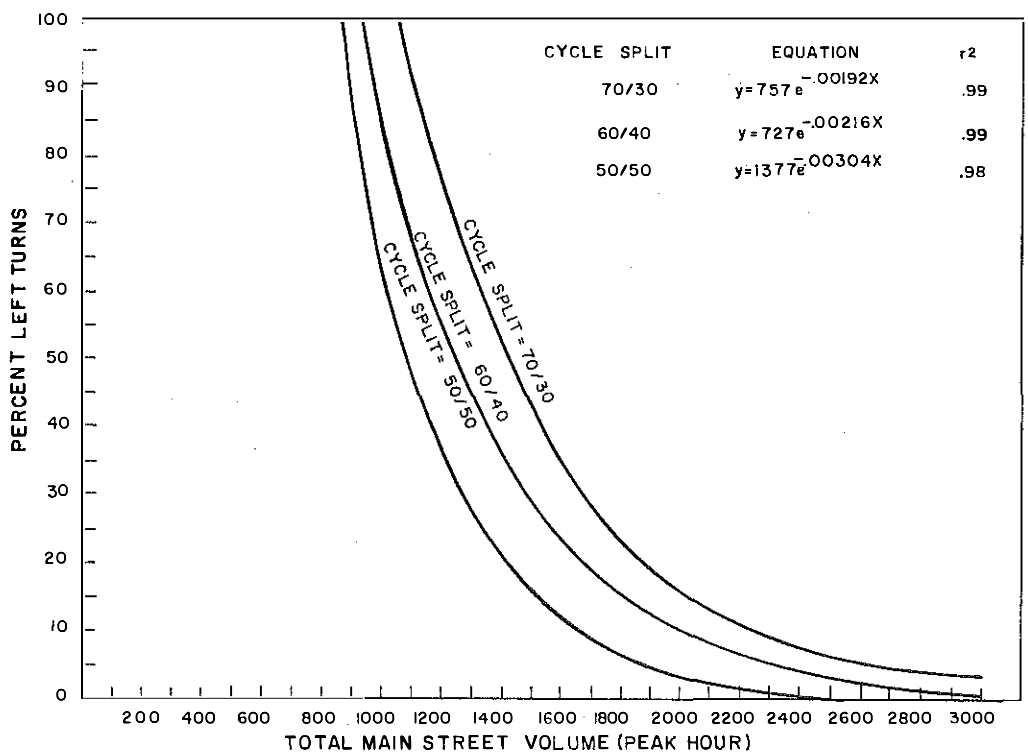


**Figure B2.** Percentage Left-Turns When Load Factor Becomes Excessive (Four-Lane Highway, 90-Second Cycle).

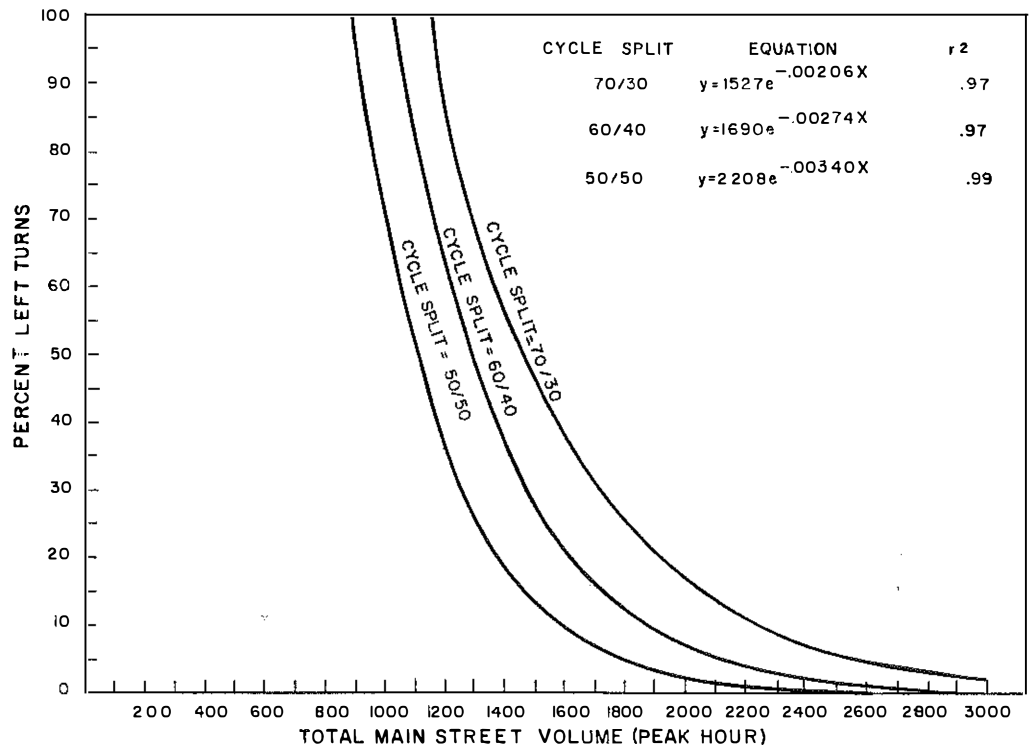


**Figure B3. Percentage Left-Turns When Load Factor Becomes Excessive (Four-Lane Highway, 120-Second Cycle).**

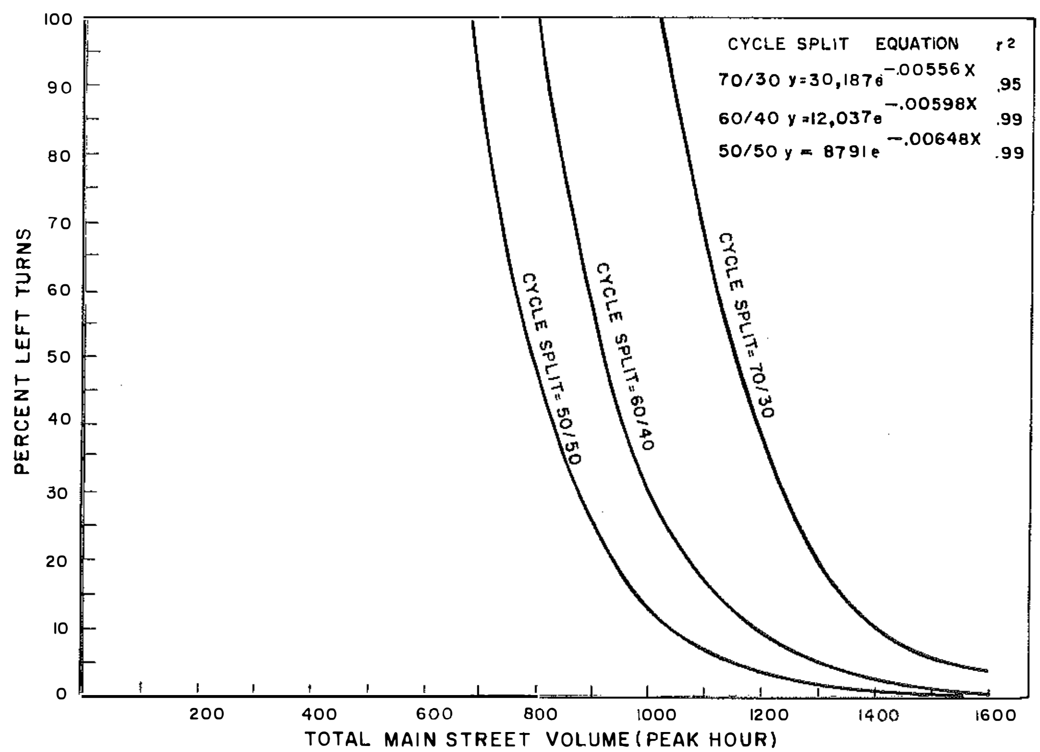


**Figure B4. Percentage Left-Turns When Load Factor Becomes Excessive (Two-Lane Highway, 60-Second Cycle).**

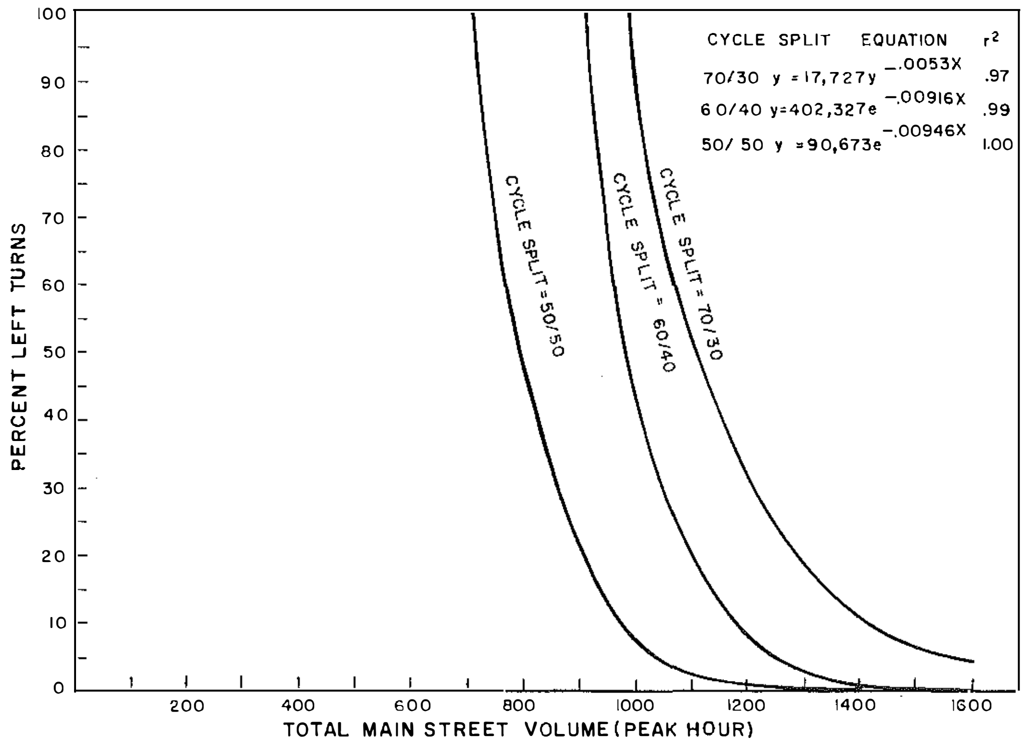


Figure B5. Percentage Left-Tnrns When Load Factor Becomes Excessive (Two-Lane Highway, 90-Second Cycle).

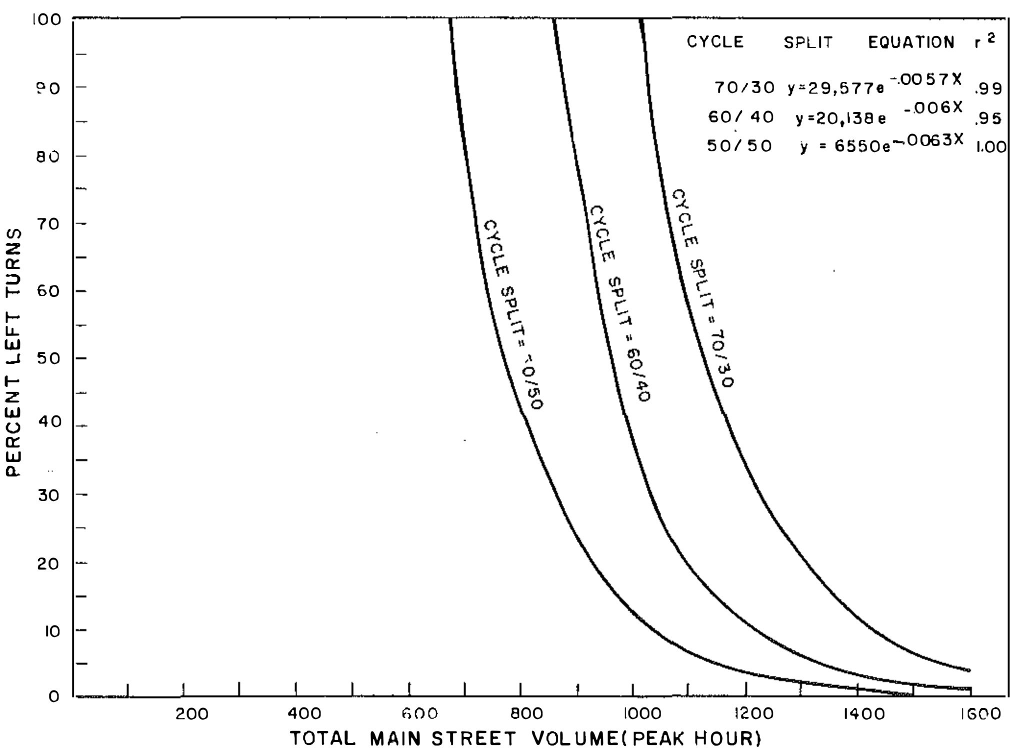


Figure B6. Percentage Left-Turns When Load Factor Becomes Excessive (Two-Lane Highway, 120-Second Cycle).

# APPENDIX C

## DESCRIPTION OF TRAFFIC CONFLICTS

Traffic conflicts data were accumulated using a procedure developed specifically for this purpose *(18)*. This involved observing and recording all the various types of conflicts. However, only those which related to left-turn accidents were used in the analyses for this study. Conflict types and weaves recorded are described as follows. Five types were referred to as the total left-turn-related conflicts.

1. **Opposing-Left-Turn Conflict** -- This occurs when a left-turning vehicle crosses directly in front of or blocks the lane of an opposing through vehicle. It is counted when the through vehicle brakes or weaves.

2. **Weave Conflict (involving left-turning vehicle)** -- This conflict involves a vehicle veering into another lane to avoid a vehicle waiting ot turn left. It occurs when the vehicle veers into the rightward lane into the path of another vehicle, causing that vehicle to brake or weave.

3. **Slowed-for-Left-Turn Conflict** -- This conflict occurs when a through vehicle brakes to avoid a slow moving or stopped vehicle waiting to complete a left turn.

4. **Previous-Left-Turn Conflict** -- This type of conflict only occurs after a slowed-for-left-turn conflict. The first vehicle which slows or stops behind a left-turning vehicle is counted as a slowed-for-left-turn conflict. If one or more vehicles must slow for the same left-turner, a previous-left-turn conflict is counted. For one left-turning vehicle, a maximum of one slowed-for-left-turn and one previous-left-turn conflict is possible. The number of slowed-for-left-turn conflicts must equal or exceed the number of previous-left-turn conflicts.

5. **Ran-Red-Light Conflict (turning left)** -- This conflict was counted when a left-turning 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.

Weaves involving left-turning vehicles were also used in the analyses. A weave was counted when an approaching vehicle weaved into the right lane or veered around a left-turning vehicle to avoid having to stop.