Guidelines for Selecting Type of Left-Turn Phasing

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ABSTRACT

At the present time, there is no uniform method of application of left-turn signal phasing throughout the United States. Different jurisdictions use different approaches to determine which type of left-turn phasing--permissive, exclusive, or exclusive/permissive--should be used. Guidelines for selecting the appropriate type of left-turn signal phasing are presented. The guidelines are based on the effect of different types of phasing on left-turn delay, through delay, and safe intersection operation. The effect of different types of left-turn phasing on left-turn and through delay was determined from observing six arterial-arterial intersections. Time-lapse photography was used to observe volume, number of vehicles stopping, total delay, average delay per stopped vehicle, and average delay for all approach vehicles for each turning movement. The guidelines presented select the type of left-turn phasing based on left-turn volume, opposing volume, number of opposing lanes, cycle length, approach speed, sight distance restrictions, and accident history.

Left turns at signalized intersections have a significant impact on capacity and safety. The introduction or use of a separate left-turn phase can be used to increase safety and to satisfy large left-turn demands. Vehicular delays to all entering vehicles and capacity are also affected by the use of left-turn phasing or the lack of such phasing.

At the present time, there is no uniform method of application of left-turn phasing throughout the United States. Different jurisdictions use different approaches to determine which type of left-turn phasing--permissive, exclusive, or exclusive/permissive--should be used. Universal application of suitable guidelines would enhance uniformity in use throughout the United States and would lead to improved intersection safety and capacity and reduction of delay.

There are three types of left-turn phasing in general use. They are as follows:

• Permissive: Vehicles are allowed to make a turn on a circular green indication but must yield to opposing traffic.
• Exclusive: Vehicles are allowed to make a turn only on a green arrow indication and have the right of way while the green arrow is displayed.
• Exclusive/permissive: Vehicles are allowed to make a turn either on a green arrow indication or on the circular green after the green arrow has been terminated but on the latter they must yield to oncoming traffic.

The basic objective of the study was to develop suitable guidelines for selecting left-turn signal phasing so that decision makers can decide, on a rational basis, when and where to commit resources to install left-turn phases at signalized intersections.

WARRANTS, GUIDELINES, AND CRITERIA USED BY OTHERS

Other states' warrants, guidelines, criteria, techniques, policies, and procedures for selecting left-turn signal phasing throughout the United States were reviewed and evaluated. The review showed two main points. First, there is great variety in the warrants or guidelines used in various jurisdictions--no universally accepted standard. Second, in many cases current warrants or guidelines are based mostly on habit and individual engineering judgment and preference rather than on strong, objectively based research.

An excellent summary of other states' warrants or guidelines was prepared in a 1978 study by K.R. Agent (1). He surveyed 45 states to determine their procedures for determining the need for left-turn phasing. Only 6 of the 45 states had numerical warrants for left-turn phasing.

A review of two dozen additional sources showed certain criteria that were more commonly used and therefore believed to be most important by the traffic engineering community. They are delay (along with associated congestion), volume of traffic accommodated (capacity), and accident experience or observed vehicle conflicts.

CRITERIA FOR OPTIMIZING INTERSECTION OPERATION

The intent in developing guidelines for left-turn signal phasing was to prepare a method for selecting the left-turn phasing type that will result in optimum intersection operation. Based on review of previous research and warrants and guidelines being used by other jurisdictions, three basic criteria were selected for optmizing intersection operation:

1. Provide some minimum level of service or maximum delay time for left-turning vehicles,
2. Minimize delay on the intersection approach (left, through, and right-turn movements combined) consistent with Objective 1, and
3. Minimize left-turn-related accidents to the extent practicable and consistent with Objectives 1 and 2.

For practical application of warrants or guidelines it is important that choice of left-turn phasing type be a function of easily and quickly measured intersection characteristics or variables. On the

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basis of the literature review, the most promising potential candidate variables appeared to be

* Left-turn volume,
* Adjacent through volume,
* Opposing volume,
* Number of lanes, and
* Number of left-turn-related accidents.

Other characteristics or variables that were found to have been used by other agencies included conflicts, vehicle speed, geometric characteristics, and sight distance. In addition, delay has occasionally been used. It is not as quickly and easily measured as volume, for example, and thus is not as promising for practical application.

SELECTION OF INTERSECTIONS

In the previous paragraphs the criteria for optimizing intersection operation and the intersection variables that were of interest were described. The variables included volume and delay. To obtain accurate data on delay and volume relationships for different types of left-turn phasing, the study approach was to use time-lapse photography at field study locations.

Six intersection locations were selected to represent the three types of left-turn phasing and a variety of other intersection characteristics. The intersections selected for study were chosen to provide a range of values for the following variables:

* Type of left-turn phasing,
* Number of opposing lanes,
* Left-turn volume, and
* Volume of opposing traffic.

All six intersections had separate left-turn lanes. The six intersections included two with permissive phasing, two with exclusive/permissive phasing, and two with exclusive phasing. For each type of phasing one intersection was selected with two opposing lanes and the other intersection was selected with three opposing lanes.

Intersections were matched so that they were similar in terms of the number of lanes of opposing traffic, signal display and signing, speed, traffic composition, and geometry. A wide range of left-turn volumes and opposing volumes was desired for the study and was a factor in intersection selection.

The six intersection locations selected were all in the Phoenix, Arizona, urban area (2).

INTERSECTION INVENTORY AND DATA COLLECTION

An inventory of each intersection was compiled. Posted speed limits were 35 to 45 mph at all six intersections. Two-way traffic volumes on the streets at the six intersections ranged from 23,000 to 49,000 vehicles per day. Accident records provided an accident inventory.

Additional data were collected by using time-lapse photography at each site. Time-lapse photography was used because it was the only practical data collection method for accurately obtaining information on volume and associated vehicle delay. The films were used to determine left-turn volumes, opposing volumes, and delay (both to left-turn and through vehicles).

The time-lapse camera was located on a lift truck adjacent to the right-hand lane of an approach and approximately 300 ft in advance of the intersection. The height of the camera above the roadway was approximately 30 ft. From this location the through and left-turn movements on two opposite approaches were observed and recorded on film.

Approximately 7 hr of film were exposed at each intersection. Filming was conducted from about 8:00 a.m. to 5:00 p.m. on weekdays in March and April 1984. The hours filmed included portions or all of the a.m. or p.m. peak period or all of both. A speed of 1 frame/sec was used for all filming. Filming was continuous in order to be able to calculate delays based on 1-sec intervals. Each roll of film had 3,600 frames (50-ft roll) and ran for 1 hr.

DATA REDUCTION

Time-Lapse Film

The basic types of information obtained from the time-lapse films were volume data and delay data. Stopped-time delay was the specific type of delay calculated in this study. It is a measure of the time a vehicle is stopped and does not include time losses caused by deceleration and acceleration. Wherever the term "delay" is used in this paper, it refers to stopped-time delay.

The 45 hr (real time) of time-lapse film exposed at the six field sites were projected by using a time-lapse projector at a slow rate of speed. Viewing of the films, observation of vehicle movements, and tabulation of data resulted in the collection of data on volume, the number of vehicles stopping, the number of vehicles not stopping, total delay, average delay per stopped vehicle, average delay per approach vehicle, and the percentage of vehicles that stopped. These data were collected separately for left-turn and through movements and for the near-side and far-side approaches to the intersection. These data were tabulated for 5-min intervals. Viewing of the films was extremely time consuming; each real-time hour of intersection operation required several hours of film viewing.

Although the time-lapse film was exposed at a rate of 1 frame/sec, 5-sec intervals were used for recording volume and delay data. This interval facilitated data reduction and analysis. A 5-sec interval of film was projected and the number of vehicles was observed and tallied that (a) had stopped, (b) had previously stopped or would later stop, and (c) would not stop at all while traversing the intersection. A stopped vehicle was defined as one that was stopped and waiting for the signal to turn to green or for a suitable gap (in the case of left-turn vehicles).

Stopped-time delay was used for calculating delay. In this study, stopped vehicles (in through or left-turn lanes) were counted every 5 sec. The total delay (for all vehicles on the approach) was calculated as the total number of vehicles observed multiplied by the observation interval (5 sec).

Volume and delay data were summed for 5-min periods, which were used so that relationships between volume and delay could be developed over short time intervals. Average delay per stopped vehicle, average delay per approach vehicle (vehicles on the approach), and the percentage of vehicles that stopped were calculated from the volume and delay data.

Accident Data

Accident rates were calculated based on accidents per 1 million entering vehicles. Left-turn accident rates (defined as left-turn-related accidents per 1 million entering left-turn vehicles) were calculated

TABLE 1 Accident Rates at Six Study Sites

	Type of Left-Turn Phasing						
	Permissive		Exclusive/Permissive		Exclusive		
	Intersection A	Intersection B	Intersection C	Intersection D	Intersection E	Intersection F	Year
Left-turn accident rate on observed approaches	1.06	–[a]	2.75	–[a]	0.60	0.48	1981
(left-turn-related accidents/1 million	6.37	2.76	2.06	0.59	1.21	1.45	1982
entering left-turn vehicles)	6.37	1.84	4.12	1.78	0.60	1.45	1983
Accident rate (all approaches)	0.91	–[a]	2.12	–[a]	3.57	1.31	1981
(total accidents/1 million entering	1.51	2.07	1.42	0.70	1.60	0.87	1982
vehicles)	1.51	1.77	1.82	1.48	1.60	1.86	1983

Note: Intersections A, C, and E had two opposing lanes. Intersections B, D, and F had three opposing lanes.

[a]Data not available.

for each left-turn movement. Accident rates are shown in Table 1.

ANALYSIS OF DATA AND FINDINGS

The thrust of the effort in data analysis was to compare and distinguish among the three different types of left-turn phasings on the basis of their effects on intersection operation. The important observations made in analyzing data will be described in this section.

The data reduction process was described in the previous section. Five items of data generated by the data reduction process (total delay, number of vehicles stopping, average delay per stopped vehicle, average delay per approach vehicle, and percentage stopped) were the principal items evaluated in the data analysis phase. This phase attempted to identify meaningful relationships among type of left-turn phasing, number of opposing lanes, left-turn delay, through delay, total intersection delay, left-turn volume, and opposing volume.

Several combinations of the foregoing variables were analyzed to determine whether there were mean-

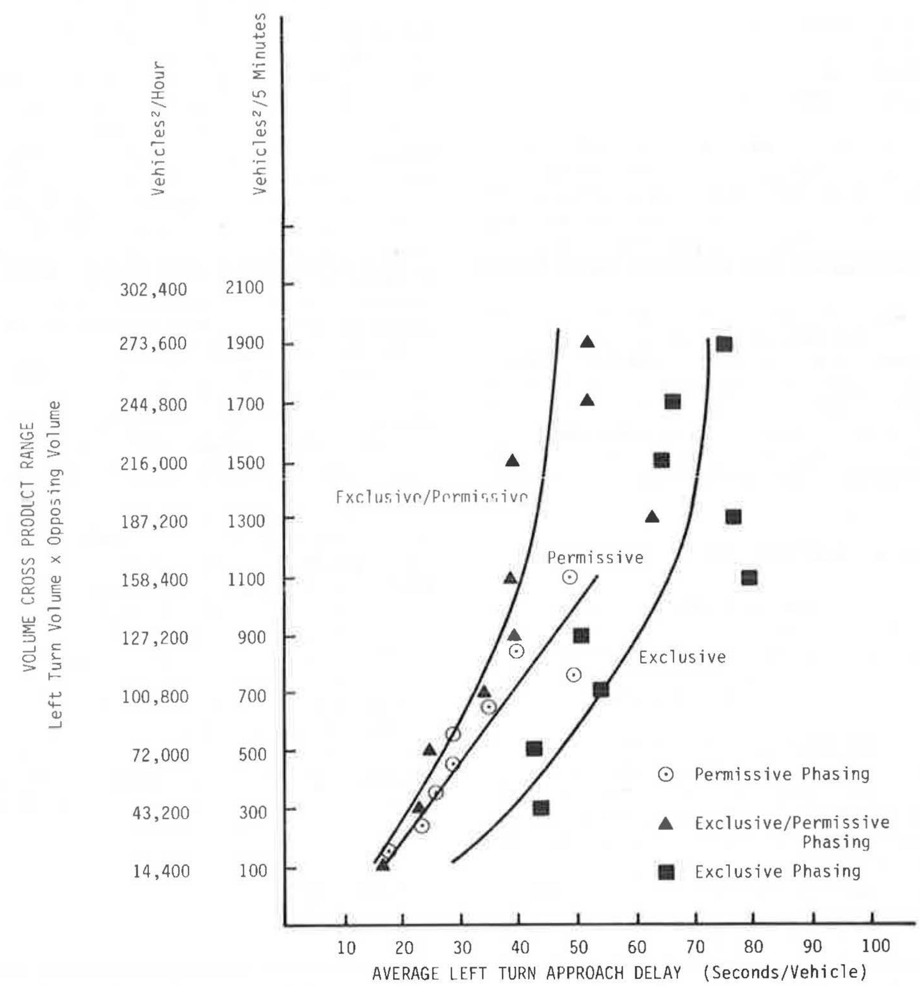

FIGURE 1 Plot of average left-turn delay versus volume cross product: two opposing lanes.

ingful relationships or correlations. The combinations included:

- Left-turn delay versus opposing volume,
- Left-turn delay versus left-turn volume,
- Through delay versus left-turn volume, and
- Left-turn delay versus volume cross product.

(Volume cross product is the left-turn volume multiplied by the opposing through volume.) For each of these combinations, data (by 5-min intervals) were separately plotted for each of the six intersections. Thus, each plot had approximately 180 data points (7 1/2 hr of filming times 12 five-minute intervals per hour times two approaches). Plots for permissive phasing, exclusive/permissive phasing, and exclusive phasing were then compared to determine whether the type of left-turn phasing had different impacts.

Most of the combinations analyzed displayed no meaningful relationships of interest in this study. Two important exceptions were (a) the relationship between left-turn delay and volume cross product and (b) the relationship between through delay and volume cross product. Volume cross product was used as a variable because it presents the opportunity to consider the effect of both left-turn volume and opposing volume at the same time. The combination of both left-turn volume and opposing volume has greater significance than either one used alone.

Figures 1 and 2 show the relationship between the average left-turn approach delay (the average delay for all left-turning vehicles) versus the volume cross product (left-turn volume multiplied by the opposing through volume).

These figures (as well as Figures 3 and 4) represent a simplification of the original plots in that not all of the original 180 data points for each type of left-turn phasing are plotted. Each point shown in Figures 1 and 2 represents the mean of the left-turn approach delay values for a range of volume cross product values. For example, the lowermost exclusive/permissive point (a triangle) in Figure 1 shows that for cases when the volume cross product was between 0 and 200 the mean value of average left-turn approach delay was 16 sec/vehicle. The scale on these figures shows the volume cross product in terms of 5-min intervals used in data reduction (vehicles^2/5 min) as well as the equivalent hourly values (vehicles^2/hr).

Figures 1 and 2 produce some very interesting

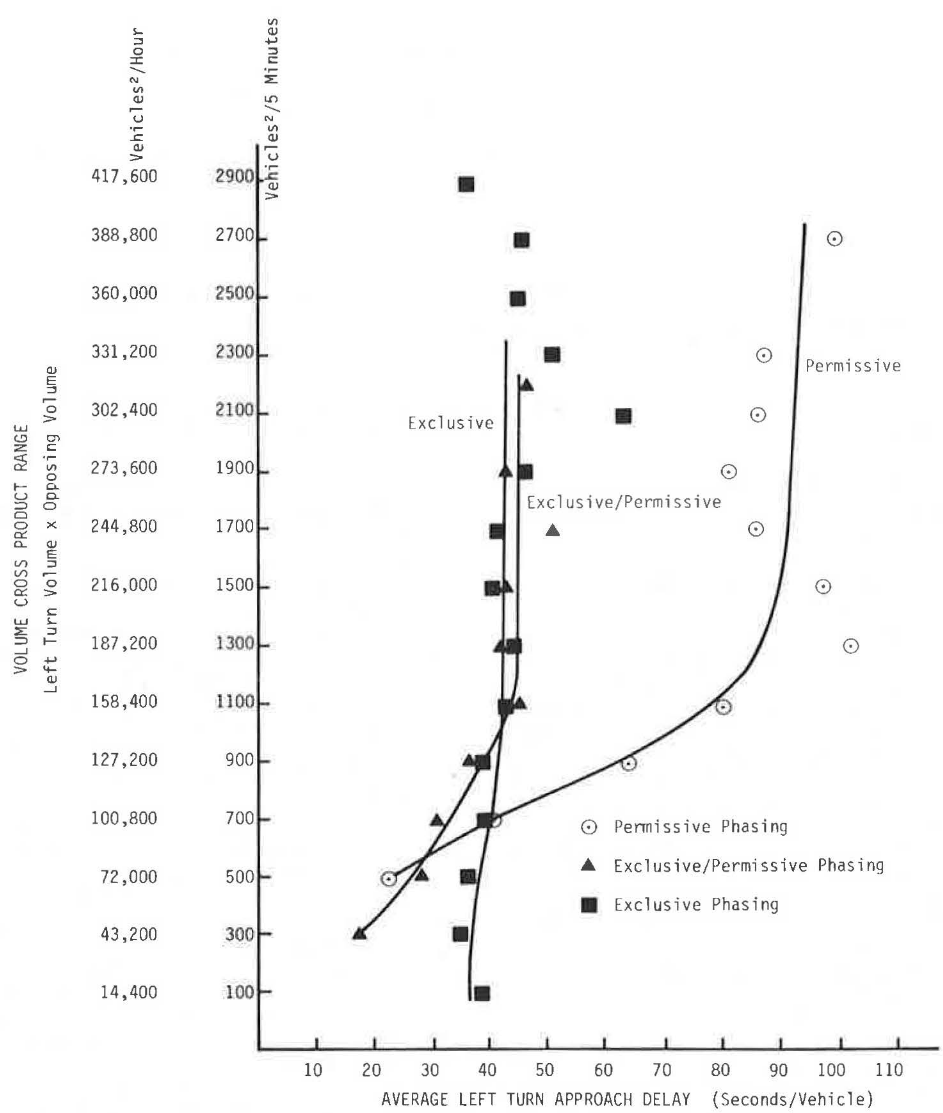

FIGURE 2 Plot of average left-turn delay versus volume cross product: three opposing lanes.

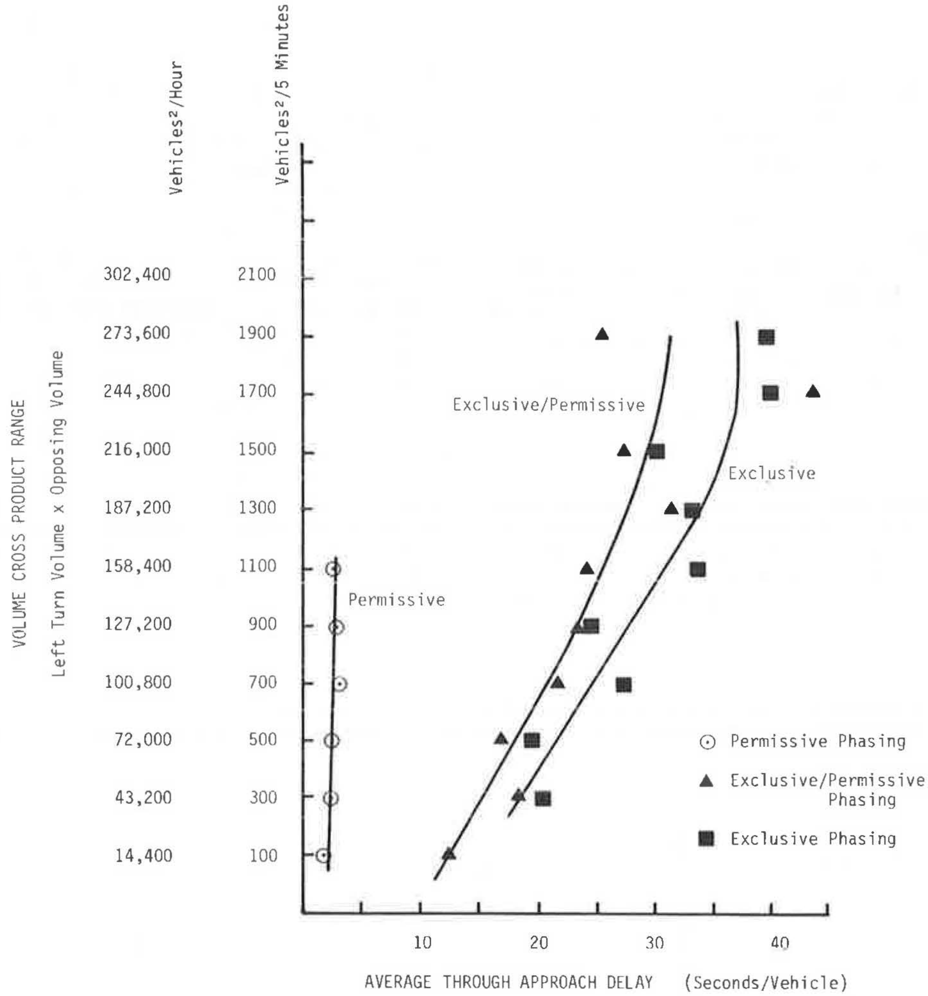

FIGURE 3 Plot of average through delay versus volume cross product: two opposing lanes.

observations. Figure 1, the case of two opposing lanes, shows the following:

1. A change from permissive phasing to exclusive phasing would increase left-turn delay. With exclusive phasing left-turning vehicles must wait until that small portion of the cycle with an exclusive left-turn movement; with permissive phasing they may turn during nearly one-half of the cycle.
2. At low-volume levels (less than about 1,000 vehicles²/5 min), exclusive/permissive phasing results in very little reduction in left-turn delay as compared with permissive phasing. In these cases left-turn demand is so low that most left turners are turning on the circular green anyway and the exclusive portion of the phase offers very little reduction in average left-turn delay.
3. At higher levels (greater than 1,000 vehicles²/5 min), exclusive/permissive phasing results in a significant reduction in left-turn delay. In these cases left-turn demand or opposing volume or both are so high that the exclusive portion of the phase is used much more.
4. Exclusive/permissive phasing results in much less left-turn delay than exclusive phasing at all volume levels. With exclusive/permissive phasing left-turning vehicles have opportunities to make left turns during the permissive portion of the cycle as well as the exclusive portion, thus reducing delay.

The case of three opposing lanes is illustrated in Figure 2 and the following relationships are shown:

1. At low volumes (less than about 700 vehicles²/5 min) permissive phasing works very effectively.
2. At higher volume levels left-turn delay increases rapidly when permissive phasing is used.
3. At low volumes (less than about 700 to 900 vehicles²/5 min) exclusive/permissive phasing results in less left-turn delay than exclusive phasing. As volume decreases, exclusive/permissive phasing performs increasingly better than exclusive phasing because more and more left-turning vehicles can make their maneuver on the circular green.
4. At high volumes (greater than 1,000 vehicles²/5 min) there is no significant difference in left-turn delay between exclusive phasing and exclusive/permissive phasing. At these volume levels opposing volumes are so high that there are inadequate gaps for vehicles to execute left turns on the circular green. Therefore, the exclusive/permissive phasing functions as if it were exclusive phasing. Many jurisdictions, by policy, do not install exclusive/permissive phasing when there are three opposing lanes. This observation suggests that those jurisdictions are not sacrificing great reductions in left-turn delay by using only exclusive phasing.
5. The curves representing left-turn delay for permissive phasing and exclusive phasing intersect

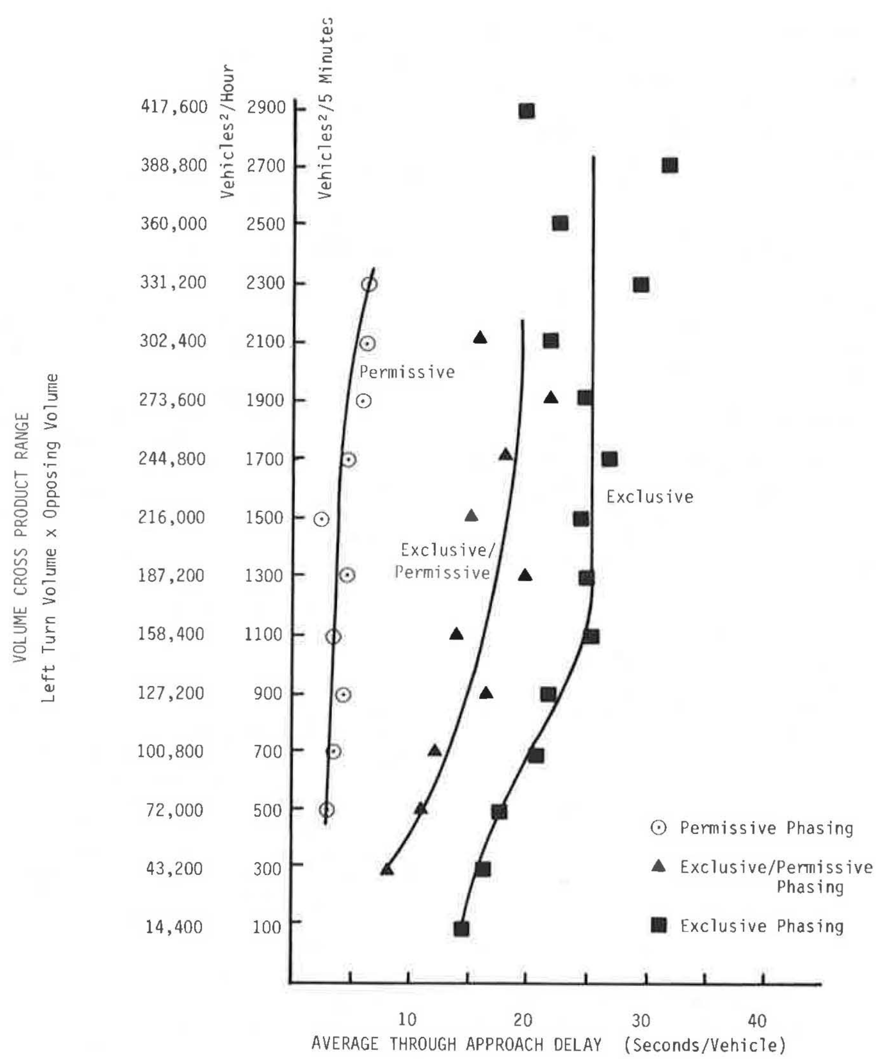

FIGURE 4 Plot of average through delay versus volume cross product: three opposing lanes.

at a volume cross product of 700 vehicles^2/5 min, which is equivalent to 100,800 vehicles^2/hr. This value is remarkably close to the volume cross product criterion of 100,000 used by many jurisdictions to install exclusive left-turn phasing.

A comparison of Figures 1 (two opposing lanes) and 2 (three opposing lanes) shows that there are substantial differences in the relationships between types of left-turn phasing. For two opposing lanes (Figure 1) exclusive/permissive phasing performs substantially better than exclusive phasing. For three opposing lanes there is virtually no difference in performance. This suggests that when there are three opposing lanes of traffic, left turners are much more reluctant to make a turn on a circular green indication. With three opposing lanes it is more difficult for the driver to see and judge suitable gaps. The driver must check three lanes rather than two and there is a greater chance that one vehicle will mask out another. A further factor is that with three opposing lanes, longer gaps are necessary because vehicles must cross three lanes instead of two.

The relationship between the average through-approach delay (the average delay for all through vehicles) versus the volume cross product (left-turn volume multiplied by the opposing through volume) is detailed in Figures 3 and 4. The reader should note that the horizontal scale is different for Figures 3 and 4 and Figures 1 and 2.

The following observations may be made for the case of two opposing lanes (Figure 3):

1. Average through-approach delay is very small for permissive phasing. It is 2 to 3 sec per vehicle, regardless of the size of the volume cross product.
2. Average through-approach delay is much smaller for permissive phasing than for either exclusive/permissive or exclusive phasing. A change from permissive phasing to either exclusive/permissive or exclusive phasing would increase through delay.
3. Exclusive/permissive phasing results in about 4 to 5 sec less delay to through vehicles than does exclusive phasing.
4. The magnitude of the delay to through vehicles increases with increasing volume cross product.

Observation of both Figures 1 and 3 shows that exclusive phasing results in the greatest delay for both left-turn and through vehicles.

The following observations may be made for the case of average through-approach delay with three opposing lanes:

1. Average through-approach delay is 3 to 6 sec per vehicle for permissive phasing.

2. Average through-approach delay is much smaller for permissive phasing than for either exclusive/permissive or exclusive phasing. A change from permissive phasing to either exclusive/permissive or exclusive phasing would increase through delay.

3. Exclusive/permissive phasing results in about 6 to 8 sec less delay to through vehicles than does exclusive phasing.

4. The magnitude of the delay to through vehicles increases with increasing volume cross product.

Comparison of Figures 3 (two opposing lanes) and 4 (three opposing lanes) shows that the effect of the three types of left-turn phasing on through delay is basically the same regardless of the number of opposing lanes.

Analysis of the data on accident rates at the limited number of intersections studied suggests that left-turn phasing has a significant effect on left-turn accidents at signalized intersections.

Table 1 shows the accident rates per 1 million entering left-turn vehicles. The left-turn accident rate was calculated using left-turn volumes. The accident rate for the entire intersection was also calculated.

As shown in the following tabulation, the type of left-turn phasing appears to have an effect on the left-turn accident rate. (Each value represents an average of the annual accident rate at two intersections in 1981, 1982, and 1983.)

Type of Left-Turn Phasing	Left-Turn Accident Rate
Permissive	3.68
Exclusive/permissive	2.24
Exclusive	0.97

Exclusive phasing has the lowest left-turn accident rate. This is because left turns are permitted only on the green arrow. Left-turn vehicles do not enter the intersection at the end of the through green and attempt left turns during the clearance interval. The potential for conflicts and accidents with opposing through or cross traffic is relatively low.

Exclusive/permissive phasing also shows a reduction in left-turn accident rates as compared with permissive phasing. Most left turns are made on the left-turn arrow (exclusive condition) and few are required to make left turns on the circular green (permissive condition) or on the clearance interval following it. The opportunity for conflicts and collisions is reduced because during most cycles, the left-turn demand is satisfied by the exclusive portion of the cycle.

It appears that the accident reduction potential of exclusive and exclusive/permissive phasing can be an important consideration in the selection of signal phasing.

RECOMMENDED GUIDELINES

The basic objective of this study was to develop suitable guidelines for selecting the type of left-turn signal phasing. Development of the guidelines considered a variety of information from two sources: that obtained from the review of the warrants, guidelines, and criteria used by others and that produced in this study. The important points of information that directly influenced the guidelines developed are as follows:

1. It is generally accepted in the traffic engineering community that with permissive phasing, two left-turning vehicles can clear the intersection at the end of the circular green. If left-turn demand in the peak hour is greater than two vehicles per cycle, on the average, then either exclusive or exclusive/permissive phasing is required to accommodate left turns.

2. In this study it was shown that, for intersections with two opposing lanes:

   a. Permissive phasing works well when the volume cross product is less than 1,000 vehicles^2/5 min (144,000 vehicles^2/hr),

   b. Exclusive/permissive phasing significantly reduces left-turn delay (as compared with permissive phasing) when the volume cross product exceeds 1,000 vehicles^2/5 min. (144,000 vehicles^2/hr), and

   c. Exclusive/permissive phasing results in significantly less left-turn delay than exclusive phasing at all volume levels.

3. In this study it was shown that, for intersections with three opposing lanes:

   a. Permissive left-turn phasing works well when the volume cross product is less than 700 vehicles^2/5 min (100,000 vehicles^2/hr), and

   b. Above 100,000 vehicles^2/hr, use of exclusive phasing results in the lowest left-turn delay.

4. In several instances guidelines, warrants, and criteria used by other agencies recommend that exclusive phasing, rather than exclusive/permissive phasing, be used when left-turning traffic must cross three or more lanes of opposing through traffic. One such study is the report by the Florida Section of the Institute of Transportation Engineers (3).

5. Similarly, it is suggested that exclusive phasing, rather than exclusive/permissive phasing, be considered when the speed limit of opposing traffic is greater than 45 mph. At high speeds it is more difficult for left-turning motorists to judge acceptable gaps.

6. Restricted sight distance to opposing traffic creates potential accident situations. Sight distance may be restricted because of roadway geometry or opposing left-turning vehicles. The Florida report (3) recommends use of exclusive left-turn phasing when sight distance fails to meet the following criteria: 250 ft for speeds of 35 mph or less and 400 ft for speeds greater than 35 mph.

7. Separate left-turn phasing can reduce left-turn accidents. This study presented accident rates for a limited number of intersections (six).

A pragmatic factor was involved in the development of these guidelines. Although guidelines must be somewhat sophisticated so that the appropriate type of left-turn phasing will be selected, they must also be of a form that is easily used. They should establish a quick and easy means of evaluating an individual intersection to determine what type of left-turn signal phasing is best for its particular characteristics.

The data required to use the guidelines developed in this study are

- Left-turn volume (hourly) during the peak hour (use the hour of highest left-turn demand if it is not the peak hour),
- Cycle length,
- Opposing volume during the peak hour (or hour of highest left-turn demand),
- Number of opposing lanes,
- Speed of opposing traffic,
- Available sight distance, and
- Accident history, including left-turn accidents.

All these data are usually easily acquired and readily available.

The guidelines developed in this study are based on the factors described earlier and are presented in the form of a flowchart (Figure 5). The following steps describe application of the guidelines. (Note that the guidelines apply only to locations that have a separate left-turn lane.)

I. Determine the left-turn volume in the hour of highest left-turn demand and divide by the number of cycles per hour. Determine whether the answer is greater than 2.0.

II. Determine the number of lanes of traffic opposing the left-turn movement. These would all be lanes on the opposite approach with through or right-turning vehicles or both.

III. Multiply the left-turn hourly volume by the hourly volume for opposing through traffic. Use the same hour as in Step I. Compare the answer with either 100,000 or 144,000, as appropriate.

IV. Determine whether the speed on the opposing approach is greater than 45 mph.

V. Determine whether sight distance is restricted. Restricted sight distance is <250 ft when speeds are 35 mph or less and <400 ft when speeds are 40 mph or more.

VI. Determine whether there is a severe left-turn accident problem that could be corrected by exclusive phasing. There are no clear-cut criteria for a severe left-turn accident problem that can apply to all jurisdictions. Each jurisdiction should develop its own accident-rate criterion. The following data may be useful in determining whether the number of left-turn accidents is unusually high.

a. In this study the following accident rates were calculated at six intersections (two for each type of phasing):

Type of Left-Turn Phasing	Left-Turn-Related Accidents/Million Entering Left-Turn Vehicles
Permissive	3.68
Exclusive/permissive	2.24
Exclusive	0.97

b. In a second study (3) the following annual average number of left-turn angle accidents at a sample of 28 intersections was found:

Type of Left-Turn Phasing	Avg Annual No. of Left-Turn Angle Accidents/Approach
Exclusive/permissive	3.38
Exclusive	0.48

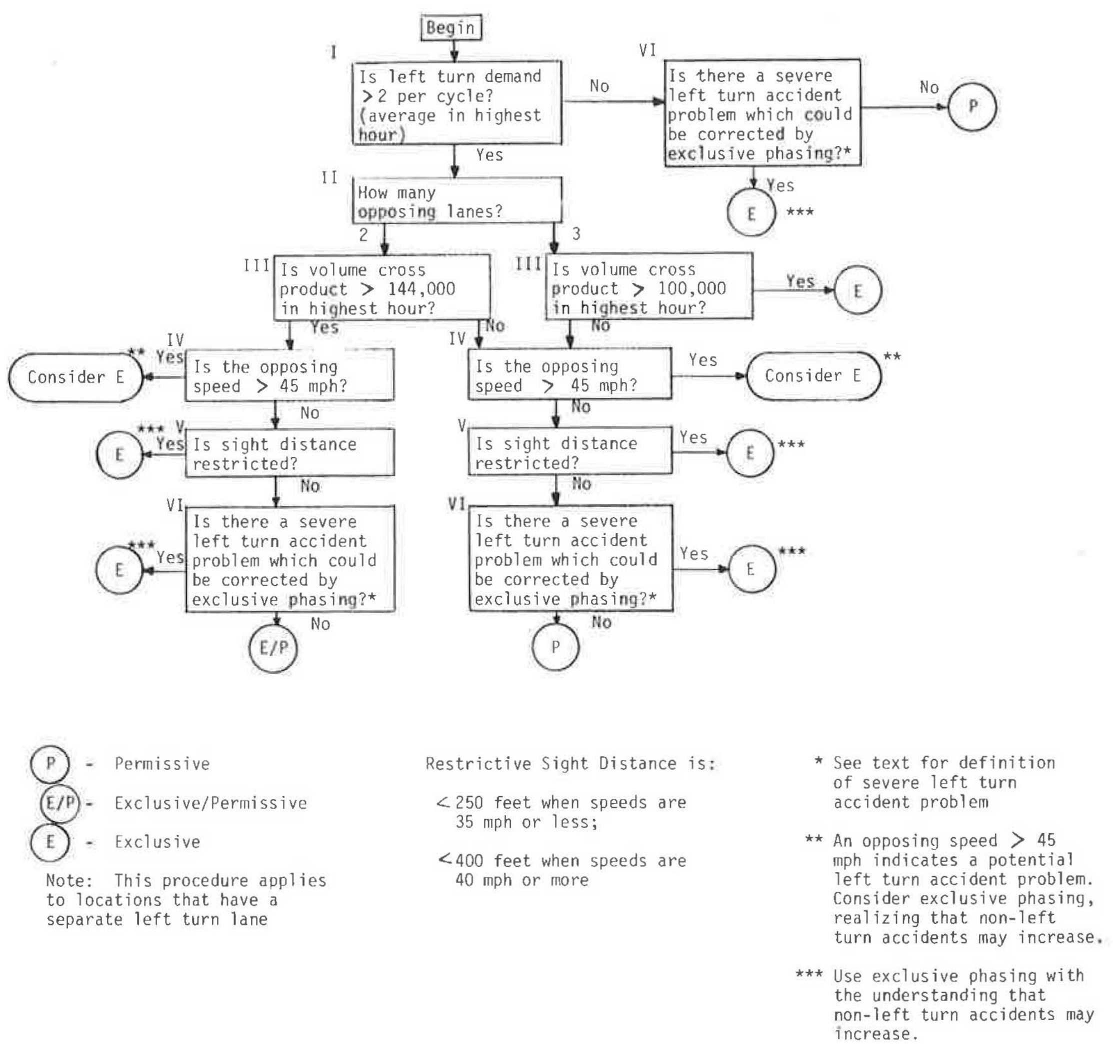

FIGURE 5 Recommended procedure for determining type of left-turn phasing.

It must be recognized that although changing the type of left-turn phasing will reduce left-turn accidents, other types of accidents may increase.

It is recommended that when exclusive or exclusive/permissive phasing is installed, it be traffic actuated with left-turn phase lengths varied according to actual demand on any cycle.

ACKNOWLEDGMENT

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