be modified into a timing tool by considering the variation from the regression line.

In summary, the ITE formula is based on a very shaky theoretical ground and it has a poor ability to explain the variation in the driver needs for the change interval. I do not recommend continued use of either T + V/(2a) to determine the yellow interval or the ITE formula to determine the entire change interval.

REFERENCE

1. M.S. Chang, C.J. Messer, and A.J. Santiago. Timing Traffic Signal Change Intervals Based on Driver Behavior. In Transportation Research Record 1027, TRB, National Research Council, Washington, D.C., 1985, pp. 20-30.

Guidelines for Protected/Permissive Left-Turn Signal Phasing

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ABSTRACT

Guidelines for the use of protected/permissive left-turn signal phasing were developed by collecting and analyzing data on traffic and roadway conditions for protected-only, protected/permissive, and permissive left-turn phasings to identify relationships among these conditions and signal phasings. The following left-turn signal aspects are addressed: (a) traffic volume based on the peak-hour minimum left-turn volume and the product of the peak-hour left-turn and opposing volumes with lower and upper limits, (b) annual left-turn accident experience based on the critical number and rate, (c) left-turn traffic conflict experience based on the critical number and rate, (d) left-turn delay, (e) site condition, (f) user cost savings for protected/permissive versus protected-only left-turn phasing, and (g) traffic engineering judgment.

Protected/permissive (P/P) left-turn signal phasing is a combination of a protected phase, in which a green arrow indicates a protected turn, and a permissive phase, in which the left-turning vehicles must yield to the opposing traffic during the green indication. The primary intent is to increase the efficiency of traffic flow by permitting left-turning movements through gaps in the opposing traffic at intersections where traffic volumes warrant a separate left-turn phasing. P/P phasing also reduces delay and energy consumption.

However, in two research efforts it was found that accidents involving left-turning vehicles increased after the installation of P/P signals (1,2). The number of accidents appeared to decrease as drivers became familiar with the signals, and driver understanding of the P/P phasing was identified as an important factor. However, because at some intersections operational and accident problems have not decreased over time, it appears that factors other than unfamiliarity cause problems.

Because the guidelines for a separate left-turn signal found in the literature vary considerably, no clear, consistent set of guidelines could be derived from a synthesis. Moreover, the quantitative guidelines are only for a separate left-turn phase and do not specify the selection of P/P versus protected-only (PO) phasing. The P/P guidelines lack quantitative measures that would eliminate much of the judgment and potential for error involved in selecting a P/P phasing.

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OBJECTIVE AND SCOPE

In light of the foregoing, research was undertaken to develop guidelines for the use of P/P left-turn phasing. This was achieved by collecting data on traffic and roadway conditions for the three left-turn phasings and then analyzing the data to identify relationships between the left-turn phasing and traffic and roadway conditions.

Because the majority (about 95 percent) of the P/P left-turn signals designed by the Virginia Department of Highways and Transportation contain a leading green arrow, only leading-arrow phases were considered. Study sites were limited to signalized intersections along arterial routes in suburban areas because these are of primary interest to the Department.

In establishing the guidelines for use of P/P left-turn phasing, guidelines for the use of permissive (P) and PO left-turn phasings were indirectly addressed.

DATA COLLECTION PROCEDURE

The data collection was divided into five parts: selection of sites, traffic volumes and conflicts, delay, site conditions, and accidents. The procedures and measures of performance used are discussed in the following paragraphs.

Selection of Sites

The selection of sites is discussed in two parts: sample size and criteria for selecting sites.

Sample Size

In 1982, 130 P/P signals were available for the study; for the other types, no accurate estimate of the population size could be obtained. Nevertheless, within the arterial system in Virginia there are very few P signals, largely because of the traffic volumes typical of this system. Furthermore, experience with and warrants for PO phasing suggested that even though the number of signals in this category is relatively large, careful selection of sites would enable the drawing of reasonable inferences about these signals for comparison with the P/P type. Consequently, the total sample size for the PO and the P signals was limited to 25.

Although little was known about the distribution of key traffic variables for the 130 P/P signals, information from a study by Perfater was found to indicate that the range of basic left-turn conflicts is 0.7 to 14.33 per 1,000 left-turn vehicles (2). Assuming the population to be normally distributed, 99.7 percent of the values of conflict rates lie between the sample mean and ±3 standard deviations (σ), and $6\sigma = 14.33$, or $\sigma = 2.39$. Using Equation 1, the sample size required for a predetermined level of confidence and degree of precision with respect to the conflicts rate that might be expected was calculated as

$$n = Z_\alpha \sigma^2 / 2E^2 \quad (1)$$

where

- n = required sample size,
- Z_α = standard normal variable for a (100 − α) percent level of confidence, and
- E = desired precision or error limit (3, pp.200-225).

Thus, for a 95 percent level of confidence and the same degree of precision of ±1 conflict per 1,000 left turns,

$$n = 1.96\,(2.39)^2 / 2(1)^2 \quad (2)$$

Consequently, a 15 percent sample (20 P/P sites) was selected.

Criteria for Selecting Sites

A total of 45 sites were examined; 20 sites for P/P, 15 sites for PO, and 10 sites for P left-turn phasings. For each study site it was required that the signal display and displacement conform with Department standards and that a left-turn lane be provided. The first requirement was intended for P/P signals under the control of municipalities. The P/P signal should (a) be of the five-section cluster (or house) design, (b) have the sign "Left Turn Must Yield on (green ball symbol)" mounted near the signal, and (c) be installed overhead on the left-turn lane line extended. Figure 1 shows the standard P/P signal installation. It is noted that since the field study, the standard sign legend has been changed to "Left Turn Yield on Green (green ball symbol)." Because urbanized areas have more signalized intersections, more potential sites were located in or near urban areas. The sites were concentrated in four of the nine highway construction districts in Virginia, and because the majority of signalized arterials are on four-lane roads, the majority of the study sites were on four-lane roads.

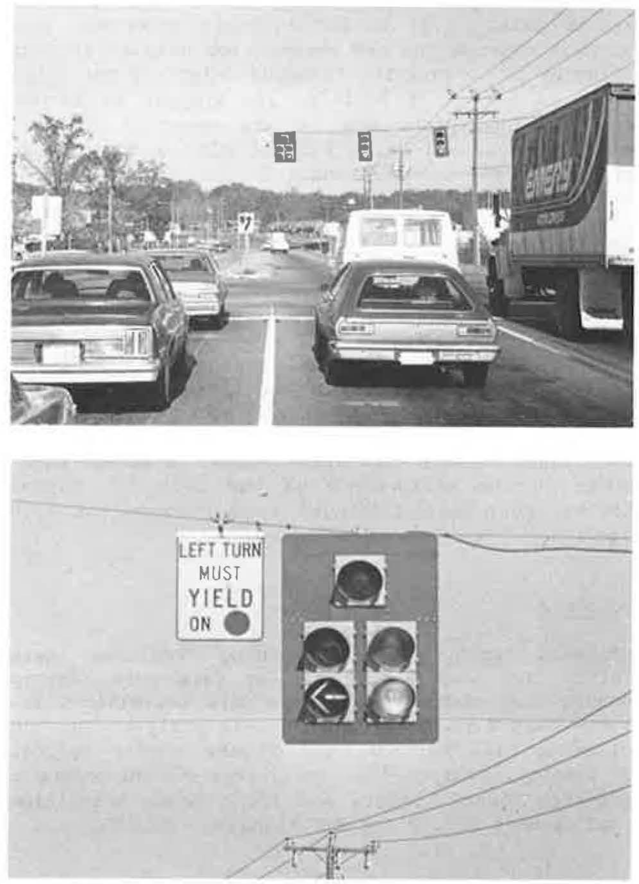

FIGURE 1 Standard P/P installation.

Traffic Volumes and Conflicts

Data on traffic volumes and conflicts were collected at each site with respect to the study left-turn approach, that is, the approach with the highest volume. Data were collected during six 45-min intervals of the off-peak period and continuously during the 2-hr peak period (recorded in 15-min intervals) of the day defined by the sum of the left-turn and opposing volumes of the study approach. The total opposing volume was recorded by a mechanical traffic counter.

Five types of conflicts were observed (4). A Type 1 conflict is the basic left-turn conflict where the left-turning vehicle crosses in front of an opposing through vehicle whose driver has to brake or weave to avoid the left-turn vehicle. In the Type 2 conflict, the second through vehicle following the first through vehicle also has to brake. A truck conflict is one in which a through truck is involved in a Type 1 or 2 conflict. Type 3 conflicts are violations where vehicles enter the intersection and turn left on red, and a Type 4 conflict is a rear-end conflict in the left-turn lane that results when the following vehicle brakes after the lead vehicle begins its left turn and then stops. Incidents of left-turn vehicles overflowing the storage lane and blocking the through lane are Type 5 conflicts. Left-turn volumes on the green arrow and green ball were counted. The total left-turn conflicts is the sum of Types 1 through 5.

Left-Turn and Total Intersection Delay

The point-sample-stopped-delay method was used to measure delay (5,6) in three 15-min intervals (two off-peak samples and one peak-period sample) in 2-hr cycles by two observers. "Stopped delay" is the total amount of time that vehicles are stopped at an intersection approach, and it was measured for the left-turn approach being studied plus each approach (or leg) to the intersection.

Site Conditions

Site conditions describe the road and intersection environment in which the left-turn signal phasing is operating. The following site conditions were examined: signal placement, number of lanes of opposing through volume, speed limit, intersection type and size, median width, sight distance and alignment, adjacent lane use, and length of left-turn lane. These factors were investigated to assess their impact on the performance of the left-turn signal phasing. They were displayed in a diagram for each site.

Accidents

Accidents involving left-turning vehicles were analyzed for each site. Accident data were limited because many of the P/P signals were installed within the last 2 years. Accidents were analyzed for the following time periods: (a) recent 2-year period, (b) recent 1-year period, (c) 1-year period before a left-turn signal change, and (d) 6-month transition or adjustment period for P/P signals.

ANALYSIS

The analysis is divided into two sections--statistical and traffic engineering analyses.

Statistical Analysis

The Statistical Package for the Social Sciences, a collection of computer programs for the application of statistical techniques, was employed to perform Pearson correlation, regression analysis, and analysis of variance (7). Also, statistical tests to compare mean traffic measures by signal type were conducted manually.

Although the statistical tests provided insight into the relationships between traffic and roadway variables, the results did not lend themselves to direct use as guidelines. Two conclusions were as follows:

1. The values for P/P phasing were significantly lower than the PO phasing values for the total left-turn delay for the peak and average off-peak hours, and for the mean left-turn delay for the average off-peak hour. The values for the P/P phasing were significantly greater than the PO phasing values for the annual number of left-turn accidents and the peak-hour total conflict rate.
2. There was no linear correlation between left-turn accidents and traffic conflicts.

Traffic Engineering Analysis

The traffic engineering analysis examined the study sites relative to existing guidelines for left-turn signal phasing and evaluated the safety and operational aspects of the intersections for the left-turn phasings.

There were five areas in the traffic engineering analysis: (a) before-and-after analysis of two sites converted from PO to P/P phasing, (b) causes of left-turn traffic conflicts and accidents, (c) truck conflict analysis, (d) relationships among the traffic data, and (e) user cost savings for P/P versus PO phasings. Conclusions for the first four are as follows:

1. For the before-and-after analysis, the expected trends were found for the total period for both sites. The total traffic conflict rate increased (21 and 35 percent), the left-turn delay [in vehicle seconds per vehicle (veh-sec/veh)] decreased (43 and 77 percent), and the mean total intersection delay decreased (16 and 38 percent). Also, the number of left-turn accidents increased (200 and 700 percent).
2. On the basis of the accident reports reviewed, driver inattention was the major factor contributing to accidents involving left-turning vehicles and opposing through vehicles. It is suspected that contributing factors were driver perception errors, impatience, confusion, aggressiveness, and site conditions.
3. Neither traffic conflicts nor accidents involving opposing through trucks were overrepresented or more hazardous than the remaining conflicts and accidents.
4. Four P/P sites had a posted speed limit of 55 mph. There were no accident problems at any of the four sites. At one of the four, traffic conflict problems were experienced, probably because of access management. It was concluded that speed limits greater than 45 mph do not cause safety problems. It is noted that speed is considered in determining adequate sight distance.

The remaining area is discussed in the next section.

DEVELOPMENT OF THE GUIDELINES

In this section, the guidelines are developed based on the previous sections and additional analysis. The section is divided into seven parts: guidelines for accidents, traffic conflicts, volume, left-turn delay, site conditions, user cost savings for P/P versus PO phasings, and traffic engineering judgment.

Accident Guidelines

The number of accidents occurring annually is commonly used to assess the magnitude of an accident problem. However, a comparison of the numbers of accidents at different locations is inadequate because differences in the traffic volumes at the locations are not considered. The consideration of traffic volumes is significant with wider ranges of traffic volumes and high volumes (8).

The annual left-turn accident rate--left-turn accidents per 100 million left-turn and opposing-volume vehicles (LT+OV)--is the best available measure for taking vehicle exposure into account when determining whether an intersection has an unusually high left-turn accident experience. The critical number and the rate for conflicts and accidents are determined by Equations 3 and 4 on the basis of the rate quality control method (8).

$$N_c = N_a + K(N_a)^{1/2} - 0.5 \quad (3)$$

where

N_c = critical number for a type of left-turn signal phasing,
N_a = average number for all left-turn signal phasings, and
K = constant that determines the level of confidence at which rates (or numbers) are significant and have not resulted by chance. For a 95 percent level of confidence, K = 1.645.

$$R_c = R_a + K(R_a/V)^{1/2} - 0.5/V \quad (4)$$

where

R_c = critical rate (number per exposure volume) for a site,
R_a = average rate for all left-turn signal phasings, and
V = exposure volume, in vehicles at a site. For conflicts, V = number of left-turning vehicles; for accidents, V = number of LT+OV.

The critical number should serve as a caution that the accident experience is high, whereas the combination of the critical number and rate confirms that the accident experience is unusually high.

The critical number of annual left-turn accidents for one approach is 2 for PO and P phasings and 6 for P/P phasing. The average annual left-turn accident rate for an approach (i.e., accidents per 100 million LT+OV) is 14.0 for PO phasing, 16.8 for P phasing, and 55.8 for P/P phasing. Therefore, it is usual for a P/P phasing to experience more left-turn accidents than the PO or P phasings. Consequently, with regard to accidents the primary concern is focused on P/P phasing.

The mean accident experience for all left-turn signal types was used as the basis for computing the critical values. Compared with the mean accident experience by signal type, this approach would increase the critical accident values for PO and P phasings and decrease the critical values for P/P phasing. This alternative narrows the range of acceptable left-turn accident experience for all left-turn signal types. Thus, it addresses the problem of accepting an unusually high mean accident experience for a given signal type, such as P/P.

A ranking of P/P sites by peak-hour product of left-turning and opposing volumes (LTOV) and accident data is shown in Table 1. Based on the mean accident number for all signal types, the critical number was 4 and was exceeded by 6 of 18 P/P sites (33 percent of total) compared with a critical number based on P/P sites of 6, which was exceeded by 4 of 18 P/P sites (22 percent). The number of P/P sites that exceeded the critical rate increased from 5 of 15 P/P sites (33 percent of the sites) to 8 (53 percent) when the rate basis was changed from P/P signals to all types of signals. Similarly, the number of P/P sites with accident problems increased from 5 (33 percent) to 6 (40 percent). For Sites 20 and 34, the rate was exceeded but not the number. This explains the difference of 2 between the number of sites that exceed the rate and the number of sites with accident problems.

It is concluded that there is only a very small increase in the number of P/P sites that have accident problems when the critical values are based on the mean for all signals compared with the mean for all P/P sites.

On the basis of the mean values for all signal types, the four sites with the highest LTOVs had unusually high accident experiences, with both the critical number and rate being exceeded. In other words, it appears that unusually high accident ex-

TABLE 1 Ranking of P/P Sites by Peak-Hour LTOV with Accident Data

Site No.	LTOV (000s)	LTOV/NL (000s)	No. of Left-Turning Vehicles	No. of Accidents	Rate (accidents/ 100 MV)	Critical Rate[a] (accidents/ 100 MV)	Problem[a]	Critical Rate[b] (accidents/ 100 MV)	Problem[b]
17	1,030	515	595	7	96.0	60.5	x	94.5	x
26[c]	598	299	459	6	157.7	67.6	x	97.4	x
16[d]	474	158	192	9	95.6	57.9	x	90.6	x
19[e]	405	203	246	13	176.1	60.4	x	94.3	x
22	384	192	222	3	52.3	63.1		98.4	
25	369	185	419	4	64.6	62.3	x	97.1	
35	320	160	303	0	NA	NA		NA	
23[e]	293	147	142	8	92.4	59.5	x	92.9	x
31	289	145	203	3	34.0	58.6		91.5	
20	216	108	141	3	74.0	66.9		104.5	
18	159	80	84	0	0	62.7		97.7	
28	133	67	180	0	NA	NA		NA	
33	114	114	138	0	0	70.4		110.6	
21	111	56	142	1	27.2	68.0		106.4	
27	108	54	76	1	23.0	66.2		103.3	
34	98	98	145	3	76.9	67.3		105.2	
29	97	49	145	3	NA	NA		NA	
30	34	68	104	NA	NA	NA		NA	
24	30	59	143	1	62.0	75.6		121.6	
32	44	44	71	0	0	58.6		110.2	

Note: A site is considered to have an accident problem when both the critical number and rate are exceeded. NL = number of opposing through lanes. MV = million vehicles.

[a]Based on a mean rate for all signal types of 32.6 and a critical number of 3.5 (rounded to 4).
[b]Based on a mean rate for P/P signals of 55.8 and a critical number of 5.6 (rounded to 6).
[c]Based on data for a 7 1/2-month period; therefore this site is not included in the mean.
[d]Three lanes of opposing through volume.
[e]Not included in mean because of signal timing problem.

periences occur when the LTOV exceeds 400,000. Of these four sites, only Site 16, with three lanes of opposing through traffic, had an LTOV/NL under 200,000, where NL is the number of opposing through lanes. Two sites, 25 and 23, with an LTOV under 400,000 or an LTOV/NL under 200,000, had unusually high accident experiences. Site 25 appeared to have a timing problem. Site 23 appeared to have a high peak-period delay, 34.5 veh-sec/veh, for a P/P signal. It is noted that exclusive of Site 16, peak-hour left-turn volumes above 200 vehicles appeared to result in accident problems.

A second alternative approach, basing the critical values on PO and P/P signals, may result in more appropriate critical values because the traffic conditions are similar for PO and P/P signals. Use of this approach results in a mean accident rate of 35.4 and a critical number of 3.8. Because the increase in the critical values when using PO and P/P signals compared with all three signal types is minimal, the use of critical values based on all left-turn signal types is reasonable. In the Manual on Uniform Traffic Control Devices, one part of the accident experience warrant is satisfied when five or more reported accidents of types susceptible to correction by traffic signal control have occurred in 1 year (9). If the critical annual number of five or more accidents is used, the results are the same. In the interest of uniformity and consistency with national standards, a critical number of five or more accidents is suggested. The effect of increasing the critical number by 1 is expected to be minimal because only one site, 25, would no longer be labeled as a problem.

Traffic Conflict Guidelines

Because traffic conflict guidelines are also based on critical values, they are also based on the mean traffic conflict experience for all left-turn signal types. The sites with conflict problems are identified in Table 2. The conclusion drawn from Table 2 is the same as that drawn with critical values based on P/P signals only, which is that traffic conflict problems are more likely to occur at P/P sites with peak-hour LTOVs equal to or above 320,000 or an LTOV/NL of 160,000. It is noted that these values are lower than the LTOV = 400,000 and LTOV/NL = 200,000 that appear to define the threshold above which accident problems occur. Use of the critical numbers of conflicts and mean total traffic conflict rates, which are based on all left-turn signal types, is suggested for both the peak hour and total period. The total period includes 4.5 hr during the off-peak period plus the 2-hr peak period. Because the total period is longer and therefore provides a larger sample size, the guideline should be based on the total period.

	Critical No.	Mean Traffic Conflict Rate
Peak hour	12	5.0
Total period	39	4.0

The use of traffic conflict studies is optional when the left-turn signal phasing type is being selected.

Volume Guidelines

The minimum left-turn volume should be greater than two vehicles per cycle during the peak hour. This is based on the assumption that two vehicles will turn left on the clearance interval during each cycle when there are no acceptable left-turn gaps in the opposing through traffic. Consequently, the left-turn demand is satisfied for each cycle when the left-turn volume is below the minimum. When this demand is above the minimum, a P/P or PO left-turn phasing should be considered, provided that the following guidelines are satisfied:

1. If desired, a rough estimate of the lower limit of LTOV/NL for which a P/P signal should be considered based on capacity may be determined by Equations 5, 6, and 7 (4):

LT = minimum left-turn volume
= 2 veh/cycle x no. of cycles/hr (5)

OV/L = opposing volume per lane = maximum green time in the peak hour for the opposing through volume in seconds divided by 4.2 sec/veh (critical headway = critical gap) (6)

TABLE 2 Ranking of P/P Sites by Peak-Hour LTOV with Traffic Conflict Data

Site No.	LTOV (000s)	LTOV/NL (000s)	No. of Left-Turning Vehicles	No. of Conflicts	Exceed Nc	Total Period Conflict Data: Rate (no./100 LT)	Total Period Conflict Data: Critical Rate (no./100 LT)	Exceed Rc	Problem
17	1,030	515	595	84	x	5.0	4.8	x	x
26	598	299	459	51	x	2.7	4.7		
16	474	158	192	55	x	5.1	5.0	x	x
19	405	203	246	41	x	3.0	4.9		
22	384	192	222	85	x	6.6	4.9	x	x
25	369	185	419	79	x	6.7	4.9	x	x
35	320	160	303	82	x	5.5	4.8	x	x
23	293	147	142	18		2.3	5.1		
31	289	145	203	23		2.5	5.0		
20	216	108	141	30		3.8	5.1		
18	159	80	84	31		6.6	5.4	x	
28	133	67	180	19		2.1	5.0		
33	114	114	138	21		3.6	5.3		
21	111	56	142	46	x	6.3	5.2	x	x
27	108	54	76	7		2.0	5.6		
34	98	98	145	36		3.2	4.9		
29	97	49	145	25		3.3	5.1		
30	68	34	104	12		2.5	5.4		
24	59	30	143	24		3.7	5.2		
32	44	44	71	11		4.1	5.8		

Note: Nc = critical number for all signal types of 38.6. Rc = critical rate for all signal types based on mean rate of 4.0. x = the critical value was exceeded. LT = left turns.

LTOV/NL = LT x (OV/L) (7)

2. If this rough estimate is exceeded by the actual or projected LTOV/NL, then a P/P phasing should be considered. This estimate may be useful when the actual or projected LTOV/NL is between 30,000 and 70,000. When deemed appropriate, a value greater than 2 veh/cycle may be used.

Although a single critical value for all sites is simpler to use, the procedure for determining a rough estimate should provide a better approximation of the critical LTOV per lane. The accuracy of the rough estimate depends on the validity of the assumptions used. The median of the range, 53,000, when rounded off is equal to 50,000. When a single critical value is desired for all sites, 50,000 is used. This value has been verified in the literature (4,10).

The upper limit of the peak-hour LTOV is based on safety guidelines such as accidents and traffic conflicts. From the previous discussions, an upper limit of LTOV = 400,000 or LTOV/NL = 200,000 is suggested.

P/P phasing is suggested for a peak LTOV/NL range of 50,000 to 200,000.

The volume guidelines are graphed in Figure 2.

Left-Turn Delay Guidelines

Because this research effort did not adequately address delay, peak-hour delay guidelines were derived from the literature. P/P phasing should be considered if, as a minimum, (a) the mean delay per left-turning vehicle exceeds 35 veh-sec, (b) the total left-turn delay exceeds 2.0 veh-hr, and (c) the 90th-percentile left-turn delay is greater than or equal to 73 sec (4). The mean delay per vehicle was determined on the basis of the 90th-percentile minimum. It is noted that higher levels of delay may be acceptable or tolerated at intersections with exceptionally high volumes that exceed their capacity.

Site Condition Guidelines

The influence of site conditions on traffic performance was examined in both the traffic engineering and statistical analyses. In the traffic engineering analysis, access management problems, intersection geometrics (especially the angle of the intersection), and the number of lanes of opposing traffic were identified. The statistical analysis indicated that intersection size influences the safety of P and P/P signals, whereas intersection type and the number of lanes of opposing volumes influence PO sites. Generally speaking, the safety problems increase with increasing intersection size for P and P/P signals. Traffic volumes also tend to increase with increasing intersection size. In general, safety is not a problem at PO signals. The number of opposing lanes reflects the intersection size for the route on which left-turning traffic is traveling. The sample sizes for some of the site conditions were small. Therefore, the site conditions considered were those that resulted from the traffic engineering analysis, namely, access management problems, intersection geometrics, and number of lanes of opposing through traffic (no more than two lanes). Also, an adequate sight distance was deemed mandatory for P and P/P signals.

Problems with access management were noted where vehicles using commercial or private entrances and exits or service roads near the intersection interfered with the safe and efficient flow of traffic.

Intersection geometrics, especially the angle of the intersection of the two roads, may cause a safety problem. Additional time may be required to negotiate a left turn greater than 270 degrees compared with a turn of 270 degrees (Figure 3). When the need for additional time is not perceived, a left-turning driver may accept an inadequate gap and thus create a hazardous situation. Additional time and therefore longer gaps are required to traverse three lanes as compared with two lanes.

Both accident and conflict problems were identified at the one P/P site that had three lanes of opposing traffic. This site also had access management problems. Additional P/P sites with three lanes of opposing traffic were unavailable because of the prevailing practice of using P/P phasing with no more than two lanes of opposing traffic. On the basis of the data, it is not possible to recommend the use of P/P phasing for sites with three lanes of opposing through traffic. It is emphasized that this conclusion is based on a sample size of 1 and on current

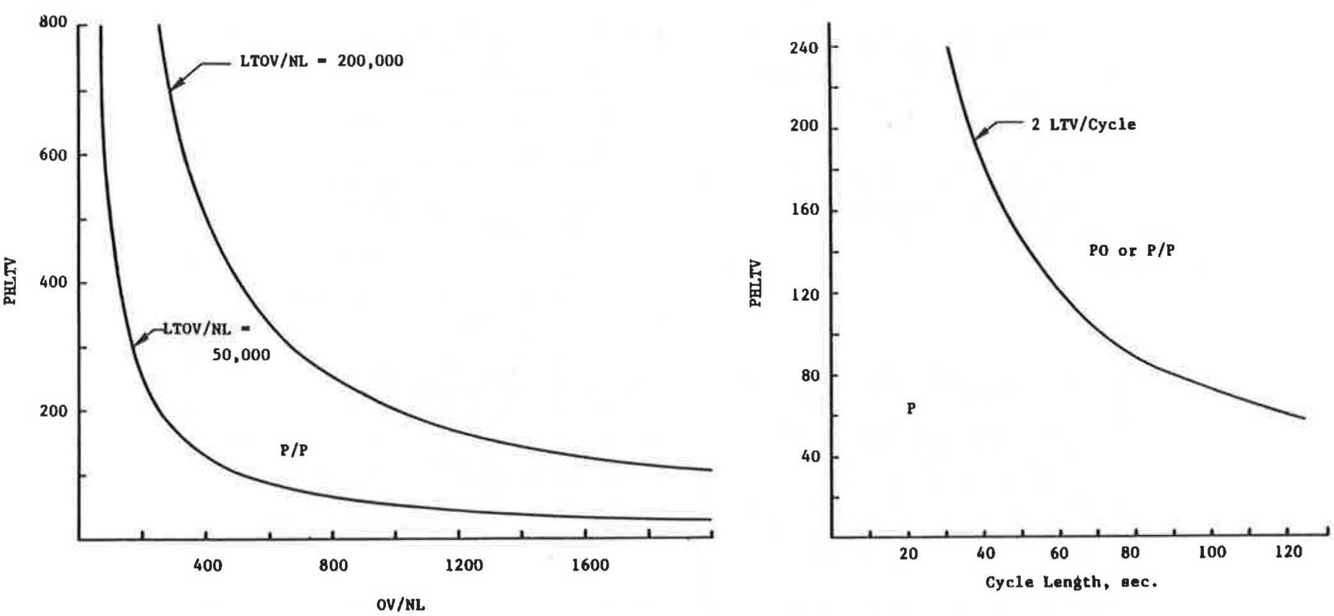

FIGURE 2 Volume guidelines based on peak-hour volume (PHLTV = peak-hour left-turn volume).

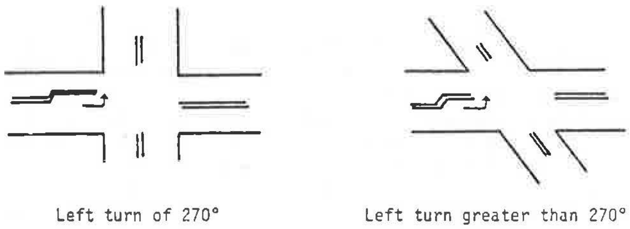

FIGURE 3 Comparison of two intersection angles.

practice. Traffic engineering judgment would indicate that there may be locations where P/P and P phasings are appropriate for three lanes of opposing through volume given compliance with the volume guidelines.

User Cost Savings for P/P Versus PO Phasing

One method of justifying the installation of a left-turn phasing is to demonstrate that the benefits or user cost savings exceed the installation costs. When a separate left-turn phasing is warranted, the alternatives are PO or P/P. In general, the user cost savings for P/P are associated with a reduction in delay and the savings for PO are associated with a reduction in accidents.

A survey of the Department's district highway and traffic safety engineers revealed that it costs approximately $500 more to install a P/P than a PO signal.

The average delay savings for P/P for the total period is 20.1 veh-sec/veh. Using the mean value of 1,006 left-turning vehicles for PO and P/P for the total period and an adjustment factor of 2.6 to expand the period to 24 hr (11), the annual total vehicle hours of delay saved was calculated as follows:

Annual delay savings: 20.1 veh-sec/veh
x (1 hr/3,600 sec) x (1,006 x 2.6) veh/day
x 365 days/year = 5,330 veh-hr.

Using values established by FHWA (6), the following savings in user costs were calculated:

Vehicle operating cost: $312.64/1,000 veh-hr
x 5,330 veh-hr = $1,666.

Volume

Use P/P when left-turn volume exceeds 2 vehicles per cycle during the peak hour, and the peak-hour LTOV/NL is between 50,000 and 200,000.

Left-Turn Accidents

If at a P/P site, the number of annual left-turn accidents is greater than 5, and the critical accident rate based on a mean of 32.6 accidents per 100 million left-turn and opposing volume is exceeded, conduct a traffic engineering investigation; otherwise use P/P phasing.

Traffic Conflicts

If at a P/P site, the number of total left-turn conflicts in the total period exceeds 39, and the total left-turn conflict rate is greater than the critical rate based on a mean of 4.0 left-turn conflicts per 100 left turns, consider a traffic engineering investigation; otherwise, use a P/P phasing.

Left-Turn Delay

A P/P phasing should be considered when the mean peak-hour delay per left-turning vehicle exceeds 35 veh sec/veh and the total peak-hour left-turn delay exceeds 2.0 veh/hr.

Site Conditions

A P/P phasing should be considered if all of the following exist:
- Adequate sight distance for the left-turning vehicles or opposing through traffic (mandatory)
- No more than 2 lanes of opposing through traffic
- Intersection geometrics that do not promote hazardous conditions
- Good access management

Delay-Accident Trade-off

If P/P phasing is suggested for all the guidelines except accidents, then consider P/P if the annual P/P delay savings is greater than or equal to the annual PO accident savings; othewise, use a PO phasing.

Traffic Engineering Judgement

Traffic engineering judgement should be used in conjunction with the guidelines. This is especially true when one signal phasing is not clearly preferred.

FIGURE 4 Guidelines for P/P phasing.

Fuel: \$1.10/gal x 650 gal/1,000 veh-hr x 5,330 veh-hr = \$3,811.

Vehicle travel time: \$1 per hour x 5,330 veh-hr = \$5,330.

Total = \$10,807.

It is noted that the reduction in total intersection delay was not included in the savings because total intersection volume data were not collected. After the \$500 difference in installation cost has been subtracted, the estimated annual cost savings for a P/P signal is \$10,300.

The annual cost savings estimate for PO signals is based on a mean accident reduction of 2.5 accidents per year. Unfortunately, no data are available on the mean cost of a left-turn accident. However, to provide a benefit greater than that of a P/P signal, the mean accident cost must be greater than \$10,300 per year divided by 2.5 accidents per year, or \$4,120.

When applied to a particular intersection, the estimated savings can be improved by using the actual left-turn average daily traffic and delay measures, the mean cost of prior accidents at that intersection, total intersection delay measures, and updated unit cost figures (6). Moreover, reliable methods for predicting differences in delay and accidents would be helpful.

Traffic Engineering Judgment

Traffic engineering judgment should be exercised in conjunction with the guidelines. This is especially true when one signal phasing is not clearly preferred on the basis of the guidelines.

Application of the Guidelines

The guidelines should be applied as follows:

1. Existing P/P phasing: use accident and site condition guidelines;
2. Existing PO or P phasing: use volume, site condition, and delay guidelines; and
3. New signal: use volume and site condition guidelines.

The use of other parts of the guidelines is optional.

CONCLUSION

The guidelines for the use of P/P phasing, summarized in Figure 4, are useful because (a) they are based on data from actual roadway conditions and identify the optimal conditions for P/P left-turn phasing, (b) they are based on statistical and traffic engineering analyses, (c) they provide quantitative measures to the extent possible, and (d) they are easy to use.

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