Developmental Study of Implementation Guidelines for Left-Turn Treatments

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At signalized intersections, the common treatment for improving left-turn performance is to increase left-turn capacity by installing a left-turn bay or a separate left-turn phase. However, under given traffic conditions and geometric configurations, there have been no universally accepted guidelines for ascertaining the need for a left-turn treatment. In this research, the TEXAS traffic simulation model is employed to study the capacity and performance of left-turn movements at signalized intersections in order to devise warrants for left-turn treatments. Since left-turn performance is germane to left-turn capacity, existing methods for estimating left-turn capacity are thoroughly reviewed and a new method that can yield reasonable estimates for left-turn capacity under general conditions of left-turn movements is proposed. Furthermore, different measures of effectiveness are used to evaluate the performance of left-turn movements under various traffic conditions. With a set of delay criteria, critical conditions of left-turn movements are identified. Finally, a new capacity-based warrant is derived from the relationship between the critical left-turn volume and left-turn capacity.

Left-turn maneuvers at signalized at-grade intersections have been recognized as highly problematic. Numerous guidelines have been used to indicate the need for separate left-turn lanes and signal phases, yet none seems to have achieved general acceptance. This paper represents a summary of some significant findings of a three-year research effort directed toward development of guidelines for implementation of left-turn treatments. The study was sponsored by the Texas Department of Highways and Public Transportation in cooperation with the Federal Highway Administration, U.S. Department of Transportation.

REVIEW OF WARRANT CONCEPTS

At signalized intersections, the common treatment for improving left-turn performance is to increase left-turn capacity by adding a bay or a separate left-turn phase. However, under given traffic conditions and geometric configurations, there have been no universal guidelines for traffic engineers to determine whether a bay or a separate left-turn phase is justified. The variations in existing guidelines stem from different methodologies and criteria adopted for evaluating left-turn performance. The methodologies could be analytical models, simulation models, or field observations, whereas the criteria may be a certain level of delay, conflict, or accidents. The resulting guidelines usually will fall into five categories of warrants: delay, volume, capacity, conflict, and accident. Although conflict and accident warrants are useful for the trade-off analysis of a left-turn treatment, study of them by analytical or simulation analysis is very difficult. Thus, only the first three types of warrants will be discussed here. Existing left-turn warrants will be reviewed, and by applying a set of delay criteria to left-turn performance curves (1), critical conditions of left-turn operations can be defined. Efforts will be devoted to developing a general form of left-turn warrant that can identify the need for a left-turn treatment under various traffic conditions and geometric configurations.

SEPARATE LEFT-TURN PHASE

Agent and Deen (2) conducted a survey of warrants currently being used by state highway agencies for installing a separate left-turn phase and found that numerous discrepancies exist:

Type of Warrant	Left-Turn Warrant
Delay	Left-turn delay in excess of two cycles
	One left-turner in 1 h being delayed more than one cycle
Volume	Product of left-turn and opposing volumes < 50 000
	Product of left-turn and opposing volumes > 100 000
	More than two vehicles per approach per cycle during peak hour
	50 or more left-turn vehicles in 1 h on one approach and average speed of through traffic > 45 mph
	> 100 left-turn vehicles during peak hour
	Left-turn volume > 90 vph
	Left-turn ADT > 500 for two-lane roadway
	100-150 left-turn vehicles during peak hour (small cities)
	150-200 left-turn vehicles during peak hour (large cities)
	120 left-turn vehicles in design hour
	90-120 left-turn vehicles in design hour
	> 100 turns per hour
Accident	Five or more left-turn accidents within 12-month period

It has also been observed (3,4) that a left-turn phase, when not required, will cause more delay to drivers during other phases and even to left-turners. Therefore, it is very important to have clear and effective guidelines for implementing a separate left-turn phase.

In order to develop warrants, a set of criteria must be chosen. If criteria on delay are employed, left-turn warrants in terms of delay, volume, and capacity can be obtained. A volume warrant may be a minimum left-turn volume level or a product of the left-turn and opposing volumes. The latter is also called the volume-product warrant. From the tabulation above, it can be seen that a minimum left-turn volume level is the most popular type of left-turn warrant. However, this type of warrant does not include the interactive effect of opposing traffic volume and the number of opposing lanes. It also makes no distinction between the left-turn and the opposing volumes. For example, if a left-turn phase is justified when the product of the left-turn and the opposing volumes is greater than 50 000, it does not matter whether there are 500 vph and 100 vph of opposing and left-turn volumes, respectively, or the other way around. Moreover, for a single opposing flow of 100 vph, according to the volume-product warrants shown below, the warranted left-turn volumes would be higher than the left-turn capacity estimated by any of the commonly used estimation methods discussed elsewhere (1):

No. of Opposing Lanes	Product of Opposing and Left-Turn Peak-Hour Volumes Agent and Deen (2)	SSITE	Texas Transportation Institute (5)
1	50 000	45 000	50 000
2	100 000	90 000	90 000
3		135 000	110 000

A recent report (5) presented a capacity warrant in which a separate left-turn phase is recommended if the ratio of left-turn demand to capacity is greater than 0.7. This capacity warrant can be misleading, as pointed out by Lin (1), because two traffic conditions with the same degree of left-turn saturation may not be equally severe for left-turn operations.

Left-turn operations evaluated with different performance measures by using the TEXAS traffic simulation model have been studied (1). For the purpose of developing warrants, the following left-turn delay criteria are used to define critical conditions for left-turn operations:

1. The average left-turn delay reaches 35 s,
2. The 90th-percentile left-turn delay reaches 73 s,
3. Five percent of left-turners are delayed more than two cycles, and
4. Four left-turners in 1 h are delayed more than two cycles.

Performance curves were developed that related each of these criteria to left-turn and opposing flow volumes by using the TEXAS model. Examples of the curves are presented here as Figures 1 and 2, and they illustrate the relationships for 90th-percentile left-turn delay when opposing flows consist of two and three lanes, respectively. Each plotted point of each performance curve represents the arithmetic mean of eight repetitions of 45 min of simulated observation time.

By applying each of these criteria to its corresponding left-turn performance curve (1), critical left-turn volumes can be determined as shown in Table 1. It can be seen that the criteria of 35 s for the average left-turn delay and 73 s for the 90th-percentile left-turn delay will usually generate the lowest critical left-turn volumes. On the other hand, the criteria of 5 percent of left-turners delayed more than two cycles and four left-turners in 1 h delayed more than two cycles generally will lead to the highest critical left-turn volumes. Traffic engineers may choose any level between the highest and lowest critical left-turn volumes as the warranted left-turn volume depending on which criterion they regard as more important. The decision regarding a separate left-turn phase can be made as follows: A separate left-turn phase is required if all four delay criteria are met; no separate left-turn phase is needed if none of the four criteria is satisfied. When some but not all of the four delay criteria are satisfied, a judgment is required by the traffic engineer. A typical decision chart is shown in Figure 3.

Figure 1. The 90th-percentile left-turn delay under various traffic conditions at four-by-four signalized intersections with adequate length of bay.

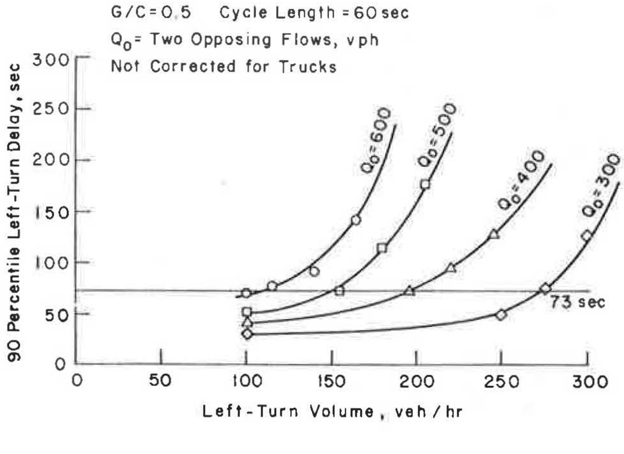


Figure 2. The 90th-percentile left-turn delay under various traffic conditions at six-by-six signalized intersections with adequate length of bay.

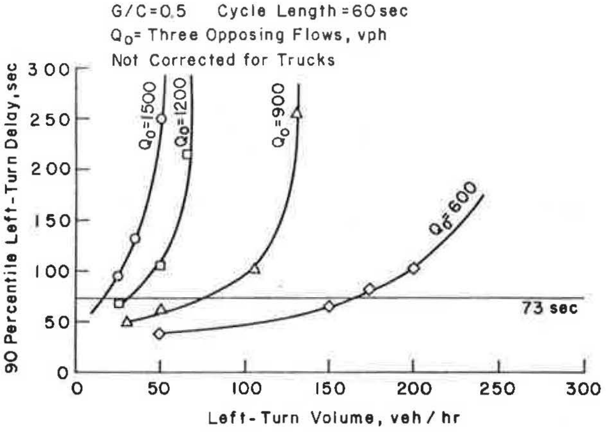
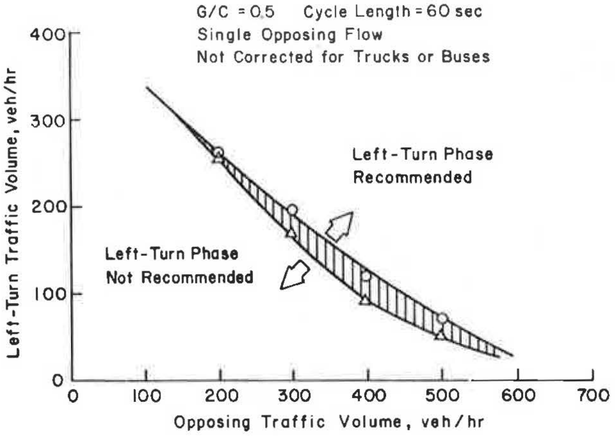


Table 1. Critical left-turn volumes based on different criteria for three types of signalized intersections with adequate length of bay.

Criterion	Opposing Traffic Volume (vph) 200	300	400	500
Two-by-Two Signalized Intersection				
Average left-turn delay, 35 s	255	170	90	50
90th-percentile left-turn delay, 73 s	255	170	90	50
Five percent of left-turners delayed more than two cycles	255	195	120	70
Four left-turners in 1 h delayed more than two cycles	260	180	110	70
Ratio of left-turn demand and capacity, 0.7	222	176	128	85
Product of left-turn and opposing volume, 50 000	250	167	125	100
Four-by-Four Signalized Intersection				
Average left-turn delay, 35 s	275	200	155	110
90th-percentile left-turn delay, 73 s	275	195	155	110
Five percent of left-turners delayed more than two cycles	290	220	170	130
Four left-turners in 1 h delayed more than two cycles	275	195	160	120
Ratio of left-turn demand and capacity, 0.7	217	179	153	122
Product of left-turn and opposing volumes, 90 000	300	225	180	150
Six-by-Six Signalized Intersection				
Average left-turn delay, 35 s	165	65	25	15
90th-percentile left-turn delay, 73 s	165	75	30	15
Five percent of left-turners delayed more than two cycles	195	90	40	30
Four left-turners in 1 h delayed more than two cycles	175	75	55	35
Ratio of left-turn demand and capacity, 0.7	147	93	68	45
Product of left-turn and opposing volumes, 110 000	183	122	92	73

Notes: Green per cycle (G/C) = 0.5; C = 60 s. Not corrected for trucks and buses.

Figure 3. Typical decision chart for implementing left-turn treatment.



With these critical left-turn volumes, Tables 2 and 3 show that neither the volume products nor the volume-to-capacity ratios remain constant over opposing volumes. This is not surprising, since these two types of warrants were found inadequate in the previous discussions. The question is what kind of left-turn warrant could appropriately describe the results shown in Table 1; in other words, what type of left-turn warrant might apply if it is not a volume-capacity ratio or a cross product of volumes. The answer might be revealed by examining the relation between the left-turn capacity and the opposing volume from a different viewpoint.

It was found that the left-turn capacity Q_L can in general be obtained from a linear equation as follows (1):

$$Q_L = Q_c (G/C) - e_0 Q_0 \qquad (1)$$

where Q_c and e_0 assume different values over different ranges of opposing volume. Equation 1 can also be written as follows:

$$Q_L + e_0 Q_0 = Q_c (G/C) \qquad (2)$$

The physical meaning of Equation 2 can be explained as follows. The coefficient e_0 (1) is the equivalence factor for converting opposing to left-turn vehicles. Thus, the left-hand side of Equation 2 is the sum of total conflicting flows in terms of left-turn vehicles produced by converting opposing to left-turn vehicles by using the equivalence factor e_0. In this sense, the right-hand side of Equation 2 is the maximum volume of total conflicting flows that can be processed through the signalized intersection or can be regarded as the capacity of the conflict area. It follows that Q_c will be the maximum volume of conflicting flows that can be processed in 1 h of green time, or it can be called the effective capacity of the conflict area. When the capacity of the conflict area is used, opposing vehicles not only have priority over left-turn vehicles but also have a weight less than that of left-turn vehicles.

Note that if Equation 2 is divided by e_0, it will become

$$Q_L/e_0 + Q_0 = (Q_c/e_0)(G/C) \qquad (3)$$

Let $e_L = 1/e_0$ and $Q_c' = Q_c/e_0$. Then Equation 3 will become

$$e_L Q_L + Q_0 = Q_c' (G/C) \qquad (4)$$

Table 2. Ratios of critical left-turn volumes to left-turn capacities under different levels of opposing volumes and number of opposing lanes.

		Criteria for Determining Critical Left-Turn Volumes			
No. of Opposing Lanes	Opposing Volume (vph)	Avg Left-Turn Delay, 35 s	90th-Percentile Left-Turn Delay, 73 s	5 Percent of Left-Turners Delayed > Two Cycles	Four Left-Turners in 1 h Delayed > Two Cycles
Single	200	0.80	0.80	0.80	0.82
	300	0.67	0.67	0.77	0.71
	400	0.49	0.49	0.65	0.60
	500	0.41	0.41	0.58	0.58
Two	300	0.87	0.87	0.92	0.87
	400	0.78	0.76	0.86	0.76
	500	0.71	0.71	0.78	0.74
	600	0.69	0.63	0.74	0.69
Three	600	0.79	0.79	0.93	0.83
	900	0.49	0.56	0.68	0.56
	1200	0.26	0.31	0.41	0.57
	1500	0.23	0.23	0.47	0.54

Notes: G/C = 0.5; C = 60 s. Not corrected for trucks and buses.

Table 3. Cross products of critical left-turn volumes and opposing volumes under different levels of opposing volumes and number of opposing lanes.

		Criteria for Determining Critical Left-Turn Volumes			
No. of Opposing Lanes	Opposing Volume (vph)	Avg Left-Turn Delay, 35 s	90th-Percentile Left-Turn Delay, 73 s	5 Percent of Left-Turners Delayed > Two Cycles	Four Left-Turners in 1 h Delayed > Two Cycles
Single	200	51 000	51 000	51 000	52 000
	300	51 000	51 000	58 500	54 000
	400	36 000	36 000	48 000	44 000
	500	25 000	25 000	35 000	35 000
Two	300	82 500	82 500	87 000	82 500
	400	80 000	78 000	88 000	78 000
	500	77 500	77 500	85 000	80 000
	600	72 000	66 000	78 000	72 000
Three	600	99 000	99 000	117 000	105 000
	900	58 500	67 500	81 000	67 000
	1200	30 000	36 000	48 000	66 000
	1500	22 500	22 500	45 000	52 500

Notes: G/C = 0.5; C = 60 s. Not corrected for trucks and buses.

Equation 4 has a physical meaning similar to that of Equation 2 except that the total conflicting flows are represented in terms of opposing vehicles by converting left-turn to opposing vehicles with the left-turn equivalence factor e_L. A left-turn equivalence factor of 1.6 has been used in the literature and found suitable for single opposing flow less than 1000 vph in the TEXAS model. However, the left-turn equivalence factor e_L, as will be shown later, is not a constant value for all opposing volumes and geometric configurations.

In order to preclude critical conditions of left-turn operations, left-turn demand or the total conflicting flows should not be near capacity. Let Q_w be a critical left-turn volume at signalized intersections that have adequate length of bay without a separate left-turn phase. Let f_c be the allowable utilization factor of the conflict area, defined as follows:

$$f_c = (Q_w + e_0 Q_0)/Q_c (G/C) \qquad (5)$$

Hence, for any critical left-turn volume $Q_w < Q_L$, there exists an allowable utilization factor of the conflict area $f_c < 1.0$ such that the following equations hold:

$$Q_w + e_0 Q_0 = f_c Q_c \,(G/C) \quad (6)$$

or

$$Q_w = f_c Q_c \,(G/C) - e_0 Q_0 \quad (7)$$

As Q_W approaches Q_L, f_c will approach 1.0. In this case, Equation 6 is reduced to Equation 2. If values of e_0, f_c, and Q_c under various traffic conditions and geometric configurations are known, the critical left-turn volume Q_W can be determined from Equation 7. Therefore, Equation 7 can serve as a left-turn warrant. Typical values of e_L, e_0, Q_c, and f_c are shown in Table 4. To assist traffic engineers in using their judgement, f_c-values for predicting the lowest and highest critical left-turn volumes are provided. From Table 4, the following conclusions can be drawn:

1. For a given intersection geometry and cycle split, the left-turn equivalence factor $[e_L \; (= 1/e_0)]$, the effective capacity of the conflict area (Q_c), and the allowable utilization factor of the conflict area (f_c) have different values for different ranges of opposing volume.
2. The left-turn equivalence factor varies from 1.6 for low volumes of single opposing flow to 8.9 for high volumes of three opposing flows. Generally, the fewer the number of acceptable gaps, the larger the left-turn equivalence factor will be.
3. The effective capacity of the conflict area varies from 465 to 930 vehicles/green hour. For the same opposing volume, the effective capacity increases with the number of opposing lanes.
4. The allowable utilization factor of the conflict area varies from 0.79 to 0.96. For a given intersection geometry, the allowable utilization factor of the conflict area decreases as the opposing volume increases.

Table 4. Values of e_L, e_0, f_c, and Q_c for different opposing volumes and number of opposing lanes.

No. of Opposing Lanes	Opposing Volume Q_0 (vph)	Equivalence Factor e_L	e_0	Effective Capacity of Conflict Area Q_c (vehicles/green hour)	Allowable Utilization Factor f_c
Single	$0 < Q_0C/G < 1000$	1.6	0.634	879	0.84-0.87
	$1000 < Q_0C/G < 1350$	2.9	0.348	590	0.79-0.82
Two	$0 < Q_0C/G < 1000$	2.0	0.500	930	0.86-0.92
	$1000 < Q_0C/G < 1350$	2.8	0.353	780	0.82-0.87
	$1350 < Q_0C/G < 2000$	6.0	0.167	465	0.79-0.84
Three	$0 < Q_0C/G < 1000$	2.2	0.448	930	0.91-0.96
	$1000 < Q_0C/G < 1350$	3.4	0.297	780	0.88-0.94
	$1350 < Q_0C/G < 2400$	8.9	0.112	465	0.72-0.84

Table 5. Recommended left-turn warrants for separate left-turn phase under different levels of opposing volumes and number of opposing lanes.

No. of Opposing Lanes	Opposing Volume Q_0 (vph)	Critical Left-Turn Volume Q_W (vph)
Single	$0 < Q_0C/G < 1000$	$770(G/C) - 0.634Q_0$
	$1000 < Q_0C/G < 1350$	$480(G/C) - 0.348Q_0$
Two	$0 < Q_0C/G < 1000$	$855(G/C) - 0.500Q_0$
	$1000 < Q_0C/G < 1350$	$680(G/C) - 0.353Q_0$
	$1350 < Q_0C/G < 2000$	$390(G/C) - 0.167Q_0$
Three	$0 < Q_0C/G < 1000$	$900(G/C) - 0.448Q_0$
	$1000 < Q_0C/G < 1350$	$735(G/C) - 0.297Q_0$
	$1350 < Q_0C/G < 2400$	$390(G/C) - 0.112Q_0$

From Equation 7, the relation between the critical left-turn volume and the left-turn capacity can be obtained as follows:

$$\begin{aligned} Q_w &= f_c Q_c \,(G/C) - e_0 Q_0 \\ &= [Q_c \,(G/C) - e_0 Q_0] - [Q_c \,(G/C) - f_c Q_c \,(G/C)] \\ &= Q_L - (1 - f_c)\, Q_c \,(G/C) \end{aligned} \quad (8)$$

Let

$$M = (1 - f_c)\, Q_c \,(G/C) \quad (9)$$

Then

$$Q_w = Q_L - M \quad (10)$$

Equation 10 reveals that the critical left-turn volume is M vehicles less than the left-turn capacity. This implies that there exists a threshold located at M vehicles lower than the left-turn capacity and that once the left-turn demand reaches this threshold, the left-turn operations will become critical. The value of M depends on the geometric configuration, the signal-timing scheme, and the level of the opposing volume. Left-turn warrants for a separate left-turn phase under various traffic conditions and geometric configurations can be obtained from Table 5 by using Table 4. Decision charts for a separate left-turn phase are provided in Figures 4 through 6. If a left-turn demand is greater than the warranted left-turn volume obtained from Table 5 or Figures 4 through 6, the four left-turn delay criteria are all satisfied. Thus, a separate left-turn phase is required.

Compared with simulation results from the TEXAS model, the recommended left-turn warrants in Table 5 predict the highest critical left-turn volume within about 10 vehicles for the case of a 0.5-cycle split and a 60-s cycle length. The volume-product warrant, the volume-capacity-ratio warrant, and the recommended warrant are compared in Figures 7 through 9.

LEFT-TURN BAY

An adequate length of bay has been assumed in studying warrants for a separate left-turn phase. Should a left-turn bay not be adequately long or not be provided at all, left-turn and through vehicles will incur more delay due to interactions among them. Moreover, through vehicles impeded by the left-turn queue may attempt hazardous lane changes. A left-turn bay is always desired; however, the construction of a left-turn bay usually involves redesigning the intersection and thus is costly. Therefore, it is important to know when a left-turn bay is required and how long the bay should be. This section will concentrate on developing warrants for a left-turn bay, and the bay length will be left for discussion in the next section.

For unsignalized intersections, Failmezger (6) and Harmelink (7) proposed a relative warrant and volume warrants, respectively, for the construction of a left-turn bay. The relative warrant is based on an index of hazards, construction costs, and past traffic accident data. If the numerical value of the indicator parameters of the relative warrant is greater than 1, a left-turn bay is recommended. The volume warrants developed by Harmelink are based on queuing-theory analysis and field studies of traffic behavior. If the opposing and left-turn volumes are known, the bay length required can be determined

Figure 4. Decision chart for implementing separate left-turn phase at signalized intersections for which G/C = 0.4 and C = 60 s.

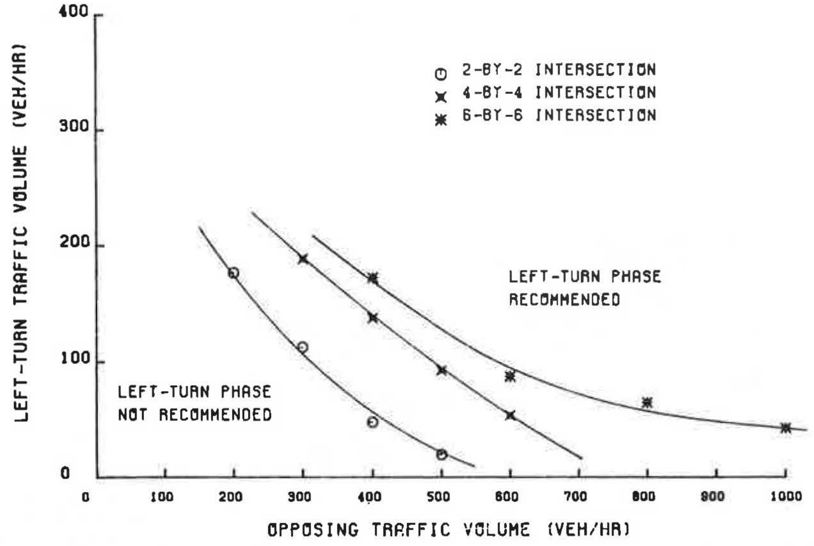


Figure 5. Decision chart for implementing separate left-turn phase at signalized intersections for which G/C = 0.5 and C = 60 s.

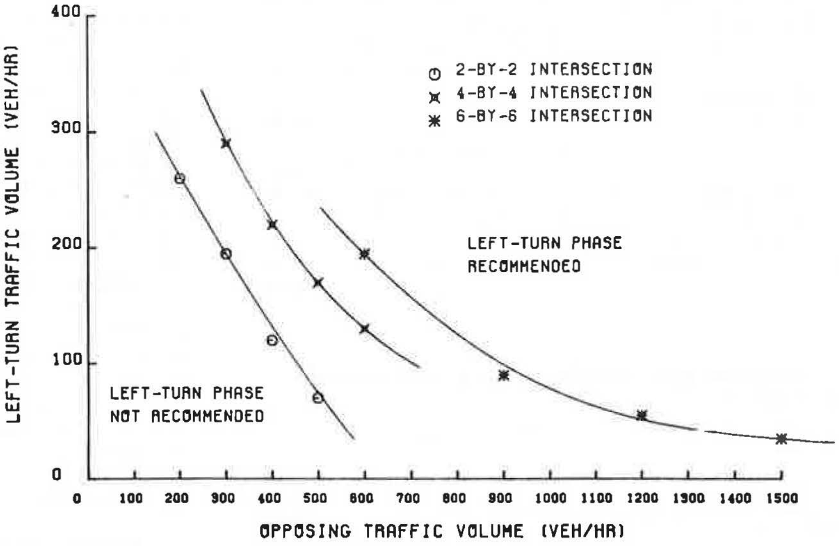


Figure 6. Decision chart for implementing separate left-turn phase at signalized intersections for which G/C = 0.6 and C = 60 s.

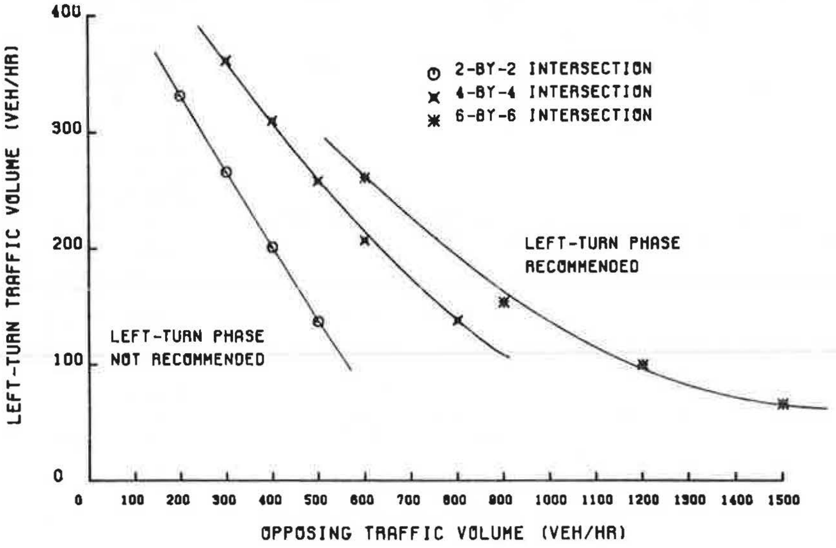


Figure 7. Comparisons among different warrants for separate left-turn phase at two-by-two signalized intersections.

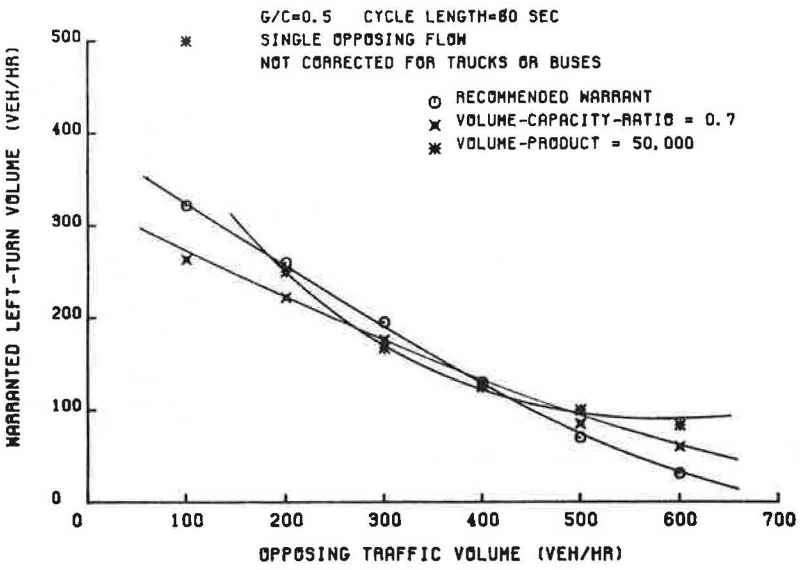


Figure 8. Comparisons among different warrants for separate left-turn phase at four-by-four signalized intersections.

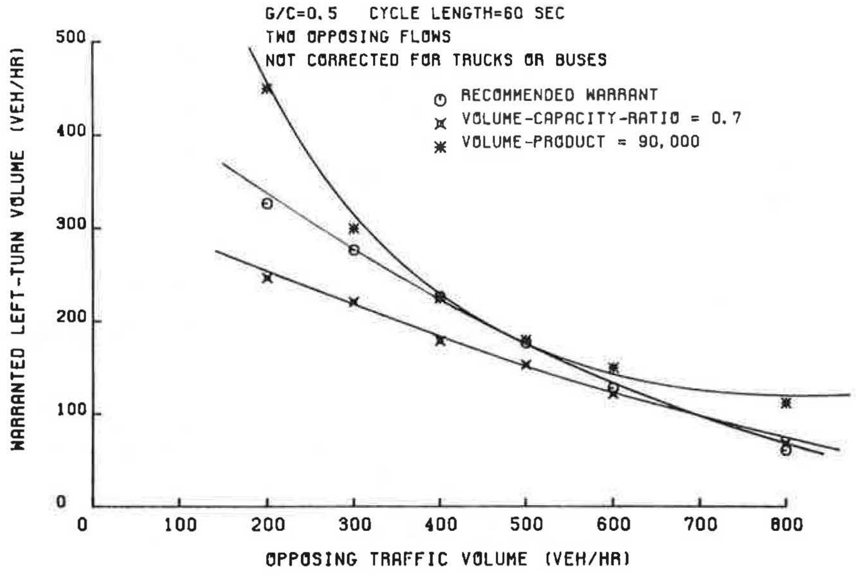


Figure 9. Comparisons among different warrants for separate left-turn phase at six-by-six signalized intersections.

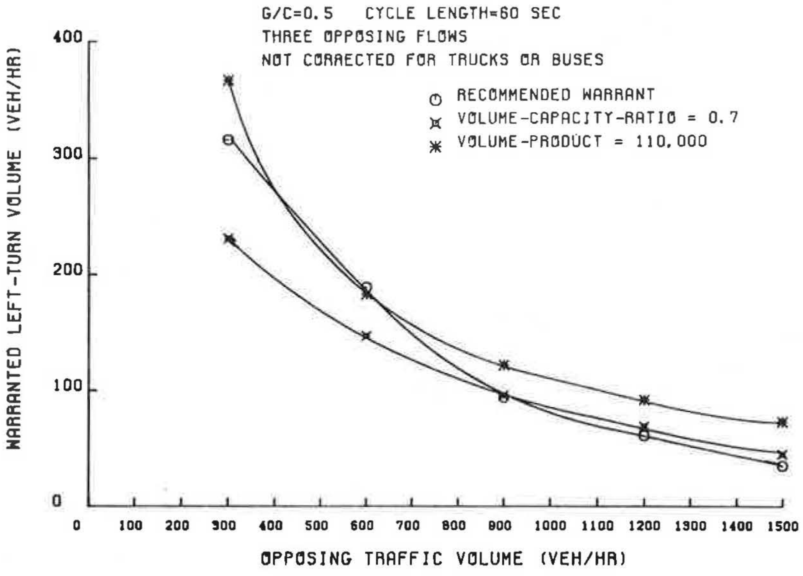


Table 6. Values of $\tilde{e}_L$, $\tilde{e}_o$, $\tilde{Q}_c$, and $\tilde{f}_c$ for single opposing flow.

Opposing Volume Q_0 (vph)	Through Volume in Median Lane (vph)	$\tilde{e}_L$	$\tilde{e}_0$	$\tilde{Q}_c$	$\tilde{f}_c$
$0 < Q_0C/G < 1000$	100	1.6	0.634	855	0.84-0.87
	200	1.7	0.593	820	0.84-0.87
	300	1.9	0.526	680	0.84-0.87
	400	2.2	0.455	560	0.84-0.87
$0 < Q_0C/G < 800$	500	2.9	0.340	415	0.84-0.87
$1000 < Q_0C/G < 1350$	100	3.2	0.310	530	0.79-0.82
	200	3.7	0.270	460	0.79-0.82
	300	4.5	0.220	375	0.79-0.82
	400	5.6	0.180	300	0.79-0.82
$800 < Q_0C/G < 1350$	500	4.0	0.250	295	0.79-0.82

Table 7. Values of $\tilde{e}_L$, $\tilde{e}_o$, $\tilde{Q}_c$, and $\tilde{f}_c$ for two opposing flows.

Opposing Volume Q_0 (vph)	Through Volume in Median Lane (vph)	$\tilde{e}_L$	$\tilde{e}_0$	$\tilde{Q}_c$	$\tilde{f}_c$
$0 < Q_0C/G < 1000$	100	2.0	0.507	910	0.86-0.92
	200	2.1	0.483	840	0.86-0.92
	300	2.3	0.443	740	0.86-0.92
	400	2.6	0.380	615	0.86-0.92
$0 < Q_0C/G < 800$	500	3.3	0.305	455	0.86-0.92
$1000 < Q_0C/G < 1600$	100	2.7	0.370	770	0.82-0.87
	200	2.9	0.340	695	0.82-0.87
	300	3.4	0.290	590	0.82-0.87
	400	4.4	0.230	465	0.82-0.87
$800 < Q_0C/G < 1600$	500	5.3	0.188	365	0.82-0.87
$1600 < Q_0C/G < 2000$	100	6.3	0.160	435	0.79-0.84
	200	7.1	0.140	375	0.79-0.84
	300	8.7	0.115	310	0.79-0.84
	400	11.1	0.090	240	0.79-8.84
	500	16.7	0.060	160	0.79-0.84

Table 8. Values of $\tilde{e}_L$, $\tilde{e}_o$, $\tilde{Q}_c$, and $\tilde{f}_c$ for three opposing flows.

Opposing Volume Q_0 (vph)	Through Volume in Median Lane (vph)	$\tilde{e}_L$	$\tilde{e}_0$	$\tilde{Q}_c$	$\tilde{f}_c$
$0 < Q_0C/G < 1000$	100	2.2	0.450	910	0.91-0.96
	200	2.3	0.430	840	0.91-0.96
	300	2.5	0.400	745	0.91-0.96
	400	2.9	0.343	615	0.91-0.96
$0 < Q_0C/G < 800$	500	3.6	0.280	460	0.91-0.96
$1000 < Q_0C/G < 1600$	100	3.2	0.317	775	0.88-0.94
	200	3.4	0.297	705	0.88-0.94
	300	3.9	0.260	605	0.88-0.94
	400	4.8	0.210	485	0.88-0.94
$800 < Q_0C/G < 1600$	500	5.8	0.173	375	0.88-0.94
$1600 < Q_0C/G < 2000$	100	9.1	0.110	445	0.72-0.84
	200	10.0	0.100	395	0.72-0.84
	300	11.1	0.090	335	0.72-0.84
	400	14.3	0.070	260	0.72-0.84
	500	20.0	0.050	105	0.72-0.84

from charts provided. As to signalized intersections, Dart (8) performed a computer simulation to develop warrants for a left-turn bay. If delay is used as a design criterion, the need for a bay can be ascertained. In this section, warrants for a left-turn bay will be explored from its relation to left-turn capacity.

Before warrants for a left-turn bay are developed, criteria for defining critical conditions when there is no bay must be chosen. The four left-turn delay criteria used in developing warrants for a separate left-turn phase seem to remain relevant in this case. However, the through delay in the median lane should also be an important concern since through vehicles in the median lane will be impeded by left-turning vehicles if there is no bay. The question is what an appropriate through delay criterion would be. It has been found (1) that the average through delay in the median lane is not considerably greater than that in the curb lane so long as no more than 5 percent of the left-turners are delayed more than two cycles. In view of this, the four left-turn delay criteria alone would be appropriate for developing warrants for a left-turn bay.

Since the same criteria are used, warrants for a left-turn bay can be derived through an approach similar to that for a separate left-turn phase. For the convenience of discussion, left-turning vehicles in the opposing flows are ignored first and then taken into consideration later.

Case 1: No Left-Turning Vehicles in Opposing Flows

If we refer to Lin's study (1), the left-turn capacity for the no-bay case when there are no left-turning vehicles in opposing flows in general can be obtained as follows:

$$\tilde{Q}_L = \tilde{Q}_c (G/C) - \tilde{e}_0 Q_0 \quad (11)$$

By the same argument as in the previous section, warrants for a left-turn bay can be expressed as follows:

$$\tilde{Q}_w = \tilde{Q}_L - (1 - \tilde{f}_c) \tilde{Q}_c (G/C) \quad (12)$$

Typical values of $\tilde{e}_L$, $\tilde{e}_0$, $\tilde{Q}_c$, and $\tilde{f}_c$ are summarized in Tables 6 through 8.

Case 2: Left-Turning Vehicles in Opposing Flows

The left-turn capacity when there is no bay and there are V_{0L} and Q_0 left-turning and through vehicles per hour in opposing flows will be as follows (1):

$$\hat{Q}_L = \tilde{Q}_L - aQ_0 \quad (13)$$

where

$\hat{Q}_L$ = left-turn capacity with no bay when there are V_{0L} left-turning vehicles per hour in opposing flows,
$\tilde{Q}_L$ = left-turn capacity with no bay when there are no left-turning vehicles in opposing flows as defined in Equation 11,
a = 0.317 (P_c - 1.0/N),
P_c = percentage of opposing traffic in curb lane, and
N = number of opposing lanes.

Thus, the warrant for a left-turn bay when there are left-turning vehicles in opposing flows can be obtained as follows:

$$\hat{Q}_w = \tilde{Q}_w - aQ_0 \quad (14)$$

Since the warranted left-turn volume Q_w can be obtained from Equation 12, the left-turn volume Q_w required for construction of a bay when there are left-turning vehicles in opposing flows can be determined from Equation 14.

REQUIRED LENGTH OF LEFT-TURN BAY

Once a decision has been made regarding the con-

Figure 10. Maximum number of left-turn vehicles stored in bay under various traffic conditions at two-by-two signalized intersections.

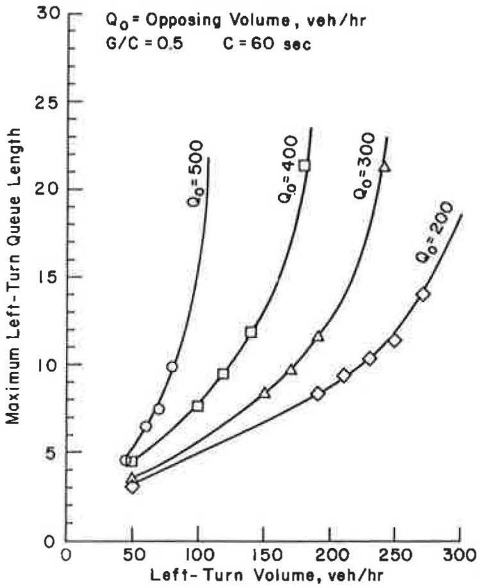


Figure 11. Maximum number of left-turn vehicles stored in bay under various traffic conditions at four-by-four signalized intersections.

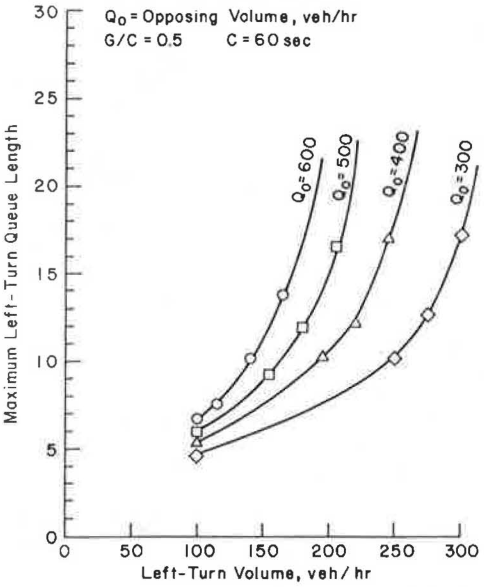
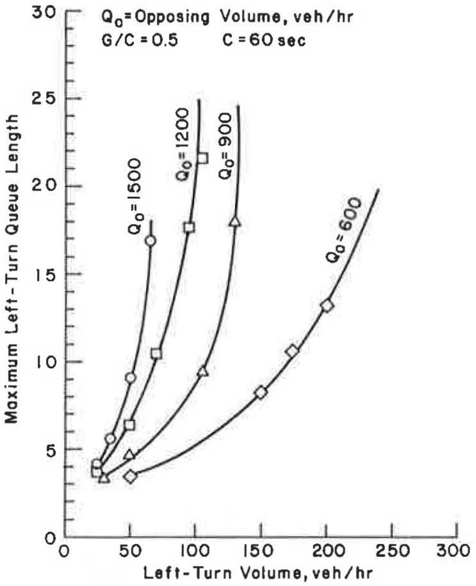


Figure 12. Maximum number of left-turn vehicles stored in bay under various traffic conditions at six-by-six signalized intersections.



struction of a left-turn bay at a signalized intersection, the next step would be to determine how long the left-turn bay should be. The American Association of State Highway and Transportation Officials (AASHTO) (9) states that storage length should be 1.5-2.0 times the average number of vehicles that would be stored per cycle based on design volume. Unfortunately, this guideline may not clearly recognize the fact that the average number of left-turning vehicles stored per cycle will depend on the opposing volume and the signal-timing scheme. For the same left-turn demand, the number of left-turning vehicles stored in the bay for high opposing volume will be much larger than that for low opposing volume. Messer (10) used a combination of theory and traffic simulation to develop the relation between left-turning volume and left-turn bay length required for a protected left-turning movement. In this section, the bay length required for an unprotected left-turn movement will be derived based on the simulation results from the TEXAS model.

From the study of left-turn queuing (1), it was found that the relationship between the average and the maximum values of left-turn queue length can be approximately represented by the following equations:

Based on the average condition:

$$L_m = 5.5\bar{L}^{0.58} \quad (R^2 = 0.95) \tag{15}$$

Based on 95 percent confidence level:

$$L_m = 7.4\bar{L}^{0.55} \quad (R^2 = 0.86) \tag{16}$$

where L_m is the maximum left-turn queue length in vehicles and $\bar{L}$ is the average left-turn queue length in vehicles.

If the bay length is designed based on the average condition, the bay length will be exceeded under a given traffic condition with a probability of 0.5. On the other hand, if the bay length is designed based on the 95 percent confidence level, the bay length will be exceeded with a probability of 0.05. Any bay length in between will have a probability greater than 0.05 but less than 0.5 of being exceeded.

On the assumption that a passenger car and a truck or a bus will occupy w_c ft and w_T ft of bay length, respectively, the required bay length can be determined from the following equation:

$$L_B = w_T p_T L_m + w_c (1 - p_T) L_m \tag{17}$$

where p_T is the percentage of trucks in the left-turning traffic flow (decimal).

Figures 10 through 12 are charts for determining the required bay length based on the 95 percent confidence level.

CORRECTIONS FOR TRUCKS AND BUSES

So far, it has been assumed that the traffic population consists of passenger cars only. For traffic

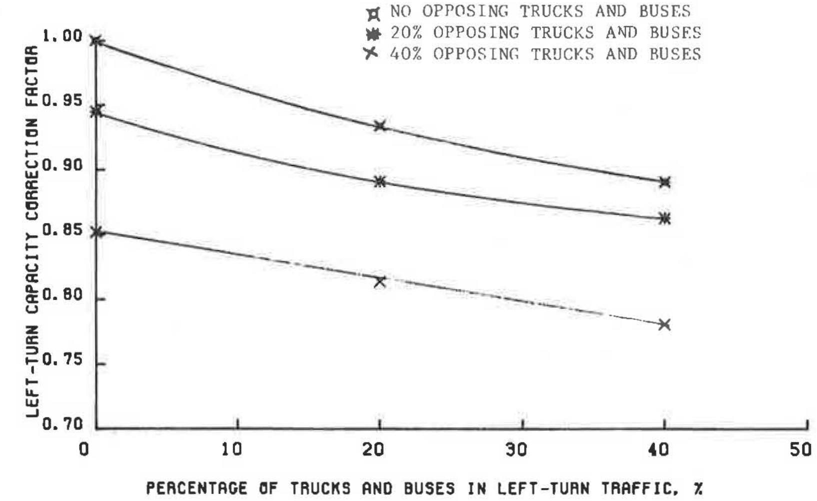


Figure 13. Factors for adjusting left-turn capacity for different combinations of opposing and left-turn truck percentages.

flows in which passenger cars are mixed with trucks and buses, the left-turn warrants obtained in the previous sections have to be modified. From Lin's study (1), the left-turn capacity for mixed traffic flows can be obtained by adjusting the "truck-free" capacity as follows:

$$Q_L^* = f_T Q_L \qquad (18a)$$

where

Q_L^* = left-turn capacity for mixed traffic flows (vph),
Q_L = left-turn capacity for traffic without trucks and buses (vph), and
f_T = correction factor for trucks and buses obtained from Figure 13.

Therefore, the left-turn warrant for mixed traffic will be

$$Q_w^* = Q_L^* - M \qquad (18)$$

DISCUSSION

Although the four left-turn delay criteria adopted in this study have been suggested by researchers and practicing engineers, it is recognized that different criteria and methodologies might bring out different left-turn warrants. It seems appealing to have simplified left-turn warrants such as constant volume-capacity ratios or cross products of volumes. However, simulation results from the TEXAS model show little evidence of such simple relations. Alternatively, this study reveals a new type of capacity warrant. The warranted left-turn volume is at some margin from the left-turn capacity, whereas the margin may have different constant values over different ranges of opposing volume. This type of left-turn warrant, though more complicated, is more reasonable. It is hard to believe that complicated left-turn operations can be characterized by a single numerical value with reasonable accuracy, especially over a wide range of traffic conditions.

Another important problem would be how to establish the phasing plan for a signal that has a separate left-turn phase. As in the case of no left-turn bay, the required bay length must be known once a left-turn bay is warranted. In fact, to know how to implement a left-turn treatment effectively is more important than to know when to implement it. In many field studies, it has been found that the left-turn delay is increased after a separate left-turn phase has been implemented. This might happen when the left-turn phase is not really justified or, more likely, the left-turn phase is not properly designed. Hence, it is necessary to have guidelines for phasing the left-turn signal.

The Texas Transportation Institute (5) provided guidelines for choosing a phasing scheme, such as leading, lagging, or skipping (actuated) left-turn phase for a single left-turn movement. However, how to determine the cycle length and duration of a left-turn phase is not quite clear. A simple guideline for timing the left-turn phase might be as follows: The total time available for left turns in 1 h after addition of a separate left-turn phase should not be less than that before it was added. For example, for an opposing traffic flow of 400 vph at a two-by-two signalized intersection, the transparency [ratio of accepted gap time to total time (1)] is 0.22. That means the total time available for left turns in 1 h is 792 s. Thus, the total time for the separate left-turn phase, either pretimed or actuated, should not be less than 792 s. Otherwise, the left-turn delay would be increased after a separate left-turn phase had been implemented. When left turns are prohibited during the through green phase, the duration of the left-turn phase should be at least 11 s if a cycle length of 70 s is used. For protective or permissive left turns, the duration of the left-turn phase can be less than 11 s since some part of the green phase for opposing traffic is used by left-turners. As to an actuated left-turn phase, the maximum extension for the phase can be set at 11 s. When the left-turn demand is saturated, the actuated signal would perform as pretimed so that the total available time for left turns in 1 h would be 792 s. Moreover, for the pretimed signal, whether the left-turn phase should be added to or taken out of the original cycle length is not a trivial question. Since the cycle split for opposing flows is critical to the left-turn delay, a rule of thumb would be to keep the cycle split as near the original cycle split as possible.

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reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Determining Capacity and Selecting Appropriate Type of Control at One-Lane Two-Way Construction Sites

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The problem of determining the most appropriate type of traffic control at one-lane two-way construction sites (i.e., on two-lane two-way roadways where one lane is temporarily closed for repairs and the other must be shared by both directions of traffic) is addressed. Capacity and performance tables and figures are presented for stop-sign, signal, or flagger control. These were developed by a microscopic simulation program that was adjusted and calibrated from field data. Following safety and visibility constraints, selection of the most appropriate control type can be made from the capacity and performance estimations obtained from the methodology presented here along with some practical considerations. An overview of existing practices followed by most states is also presented.

Traffic control at construction and maintenance zones has become particularly important in recent years, especially in view of increased government liability for accidents and incidents on public road systems and the reduced tolerance for inefficient operating conditions. Despite the attention recently given to the development of design standards and improved traffic control at construction and maintenance zones, few guidelines are currently available for determining capacity and the most appropriate type of control at two-lane two-way roadways where one lane is temporarily closed and the other must be shared by both directions of traffic. Such is frequently the case for two-lane two-way bridges during deck repairs.

The Minnesota Department of Transportation, recognizing the need for further research in this area, sponsored a research project to (a) determine capacity and select the most appropriate type of control (including optimal timing plans in the case of signal control) and (b) develop guidelines for increasing safety by appropriate signing. In this paper only the first issue is addressed, but it should be noted that all the results of this study are described in a final report (1), which may be consulted for further details not included here due to space limitations.

Selection of the most appropriate type of control (i.e., among stop sign, pretimed or actuated signal, and flagger) requires performance evaluation of each alternative, which in turn is dependent on capacity estimations. An extensive literature search combined with a survey of practices in all states revealed the absence of any well-established methodology for dealing with problems of capacity, performance evaluation, and selection of the most appropriate type of control. For this reason, a more systematic procedure was developed and is described here. It should be kept in mind that although the basic research was geared toward one-lane bridges during the construction or maintenance operations, the results are general and apply to any similar situation in which a single lane is alternately used by both directions of travel.

The problems of capacity determination and performance evaluation with stop-sign control were resolved by generating tables based on simulation, whereas the signal-control case (pretimed or actuated) was treated both analytically and by simulation. Finally, flagger control was assumed to be similar to actuated-signal control, at least from the capacity and performance points of view (i.e., excluding visibility and safety aspects), and therefore it was not treated separately. Naturally this assumption is only an approximation, but in view of the difficulties involved in realistically modeling flagger control, it was felt that such approximation should suffice. It should be pointed out that the simulation programs and their results were tested against actual data collected at 15 sites by time-lapse photography, and model calibrations and adjustments were made. Similar comparisons were also made with the analytical results.