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Design of Left-Turn Lanes for Priority Intersections

JOE LEE AND THOMAS MULINAZZI

There is general agreement that a left-turn lane should be warranted on a benefit-cost basis. However, existing documents do not provide accurate techniques for the prediction of the two items that are needed for such an approach—the reduction of delay and the length of the left-turn lane. This study shows that the problem can be solved by using the results of two simulation models. These two models attempt to duplicate the traffic of an uncontrolled approach at a two-lane by two-lane priority intersection. A priority intersection is an intersection at which only the two minor approaches are controlled by stop or yield signs—in other words, the major flow has been assigned priority. One model represents a without-left-turn condition and the other represents a with-left-turn condition. Design charts and tables were produced from these models. These charts and tables are presented in this paper to give the user a systematized guide to design problems for the left-turn lane. Application of the study results are intended for use in Kansas and are limited to a two-lane priority intersection. Although the approach and methodologies reported in the study are considered applicable to other locations and for other purposes, users are cautioned to observe the limits of the study results.

A priority intersection is an intersection at which only the two minor approaches are controlled by stop or yield signs. In other words, it is an intersection at which the major flow is assigned priority. Highway engineers involved with the design of left-turn lanes for priority intersections are confronted by two major design consideration issues. The first issue is to determine the conditions (i.e., approach volumes, left-turn percentages, and accidents) under which a left-turn lane is warranted. The second issue is to determine the appropriate length of the left-turn lane. The questions involved in these two issues are complex because of the randomness with which vehicles arrive at an intersection to make left turns and the incidental number of vehicles that turn left at one time when a left-turn lane is provided. Past research efforts regarding these two issues are relatively inadequate.

REVIEW OF LITERATURE

Failmezger (1) developed a warrant for left-turn-refuge construction based on ratings of many geometric and traffic parameters. However, no analytical rationale was provided. Harmelink (2) calculated the arrival and release rate of a combination of through and left-turning vehicles. He proposed that construction of a left-turn lane is warranted when the probability of having more than one of the vehicle combinations waiting in the system is less than 0.005. However, he failed to consider all the other numerous vehicle combinations, such as two consecutive left-turning vehicles, one left-turning vehicle followed by two through vehicles, and two left-turning vehicles followed by one through vehicle, and he did not explain the rationale behind the selection of the 0.005 probability level.

Hammer (3) suggested that a left-turn lane is warranted from an accident consideration point of view but neglected to consider delay. Shaw and Michael (4) as well as Ring and Carstens (5) employed a more-comprehensive approach for the left-turn-lane problem. Both teams considered the reduction in delay and accidents to be the benefits of a left-turn lane. They then compared the benefits with the construction cost of the left-turn lane to see whether the left-turn lane was justified. The approach was undoubtedly rational for an isolated intersection; however, because they assumed that the delay varied linearly with approach volume, opposing volume, and left-turn volume, they underestimated delays for high-volume ranges. This shortcoming would make their findings applicable only to low and moderate volumes.

Numerous studies of delay caused by left-turning vehicles at signalized intersections (6) have shown that delays increase curvilinearly with increases of left-turn, approaching, and opposing volumes. Delay approaches infinity when volumes are so high that left-turning vehicles could not find enough acceptable gaps in the opposing traffic stream. This characteristic of the delay function seems to point out the need for an accurate method of predicting delay if the use of the benefit-cost approach is to be expanded.

An important problem associated with the consideration of stopped delay is capacity. Once vehicles must stop and wait for their release from an intersection, the lane that they have occupied is temporarily blocked. The longer the delay, the shorter the time that the lane would be open for vehicles to go through the intersection, and the greater would be the reduction in capacity. Because delay varies curvilinearly with volumes, the capacity of the lane may be reduced to less than that of the approaching volume (a total breakdown of traffic) sooner than many people have believed. Even if the critical condition has not been reached, the reduction of capacity would cause the volume-capacity ratio to rise. This would result in the reduction of the level of service for the lane. For many lightly traveled highways, capacity may not be a serious problem. The level-of-service consideration, however, would certainly be of interest to highway engineers.

Because of the emphasis on safety and safety improvements, some left-turn lanes have been warranted based only on a consideration of accident reductions, and the reduction of delay is just an added benefit. Methods for handling this have been documented comprehensively in a National Cooperative Highway Research Program (NCHRP) report (7).

A benefit-cost approach is probably the most desirable way to handle a left-turn-lane design problem at a priority intersection. In order to effectively implement this approach, an estimate of the three most important quantifiable parameters (reduction of accidents, reduction of delays, and the length of the designed left-turn lane) with an acceptable accuracy appears to be essential.

STUDY APPROACH

For the purpose of predicting delay reduction, an experimental approach requires that delay data be collected before and after a left-turn lane is installed. Because delay data before installation are not generally required in a left-turn-lane construction, an intersection that has left-turn lanes would provide delay data only for the after-installation condition. If we could choose some intersections that are scheduled to have their left-turn lanes constructed in the future, it would be possible to collect both before and after delay data. Nevertheless, a long period of time would be required to accumulate an adequate number of cases to make the experimental results statistically significant. Certainly, an adequate number of intersections that do and do not have left-turn lanes could be located and their delay data collected to derive statistical trends on delay reductions. This method is costly, however, because a large amount of data are needed to discount the effect of local geometric and traffic conditions. In addition, existing facilities may be clustered within a small range of traffic conditions so that results developed from their data might not be applicable when traffic conditions outside of the range have to be dealt with. As for the estimation of the length of the left-turn lane, the experimental approach would face the same kind of difficulties as the delay-reduction consideration, even though only intersections that have left-turn lanes would be involved.

In view of the difficulties encountered by the experimental approach and since a simple deterministic formula cannot be developed to handle the probabilistic nature of the left-turn-lane design problem, simulation becomes the only logical solution. We have developed two computer-simulation programs for traffic on an uncontrolled approach at a two-lane by two-lane priority intersection. These programs can accurately predict vehicular delays caused by left-turn vehicles and the reduced capacity of an uncontrolled approach with and without a left-turn lane. By comparing the results from the two models, one will be able to see the improvement, in terms of delay and capacity, by providing left-turn lanes at an uncontrolled approach. Therefore, the benefits of building a left-turn lane could be established. Because outputs of the simulation model for the left-turn-lane condition show the queuing characteristics of the left-turning vehicles (i.e., lengths and frequencies of queues), the use of the model alone will provide the needed information on the length requirement for left-turn lanes. The main thrust of this paper is to use results generated from the two simulation models as a base and systematically look into the left-turn-lane design problem so that guidelines may be developed.

Many study results are available for predicting accident reductions due to construction of a left-turn lane. We, therefore, do not actively pursue this topic in this study.

SIMULATION MODELS

Although the simulation models were documented in several articles (8,9), a brief presentation is provided as a quick and usable reference. The first model is an attempt to duplicate the traffic operating characteristics of an uncontrolled approach at a priority intersection without a left-turn lane. The second model attempts to simulate the traffic conditions of the same intersection approach when a left-turn lane of infinite length is available. The conceptual flow of the two models is presented in Figures 1 and 2, respectively. In an attempt to validate the simulation models, delay data were collected in two Kansas locations. Since these two locations did not have left-turn lanes, only the first model was used to generate simulated results to compare with the collected data.

Table 1 is the result of this comparison. Five computer runs were used to generate simulated data so that the average and the standard deviation of simulated results could be developed. A significance test has been conducted by using a normal approximation. This approximation test had a significance level of about 5 percent. The test results showed that, in 12 of the 16 sets compared, the simulated results are not significantly different from the observed data. In view of the complexity of traffic behavior and the widely varied headway patterns that actual traffic has exhibited, it is felt that the simulation models have an acceptable accuracy.

SAMPLE SIMULATION RESULT

Various assumed traffic conditions were used as input to the simulation models to generate needed information for developing design guidelines for left-turn lanes. The results were summarized into the following graphs and tables. Figures 3, 4, and 5 indicate the volume-capacity ratio of an approach if no left-turn lane is available. Figures 6 and 7 illustrate the savings in delay due to the construction of a left-turn lane. Figure 8 specifies the length requirement of an approach if a left-turn lane is warranted. Graphs 3-7 were derived by using a 4.5-s critical gap for all left-turning vehicles and assuming that the opposing volume is either equal to or one-half of the approach volume. Delay-saving adjustments for conditions other than those specified are suggested in the tables below. The adjustment factors for the reduction of delay for various critical gaps are as follows:

Critical Gap (s)	Adjustment Factor
4.0	0.80
4.5	1.00
5.0	1.25
5.5	1.56

The adjustment factors for the reduction of delay for the difference between actual opposing volume and the opposing volumes shown in Figures 6 and 7 are as follows:

Difference (vehicles/h)	Adjustment Factors
+500	2.49
+400	2.07
+300	1.73
+200	1.44
+100	1.20
0	1.00
-100	0.83
-200	0.69
-300	0.58
-400	0.48
-500	0.40

Figure 8 is derived from simulated results of using a negative experimental headway distribution and a 4.5-s critical gap. However, adequate safety margins were included so the figure would be suitable for general use. In graphs 3 through 7, the symbol α represents the percentage of traffic that is assumed to be nonfree flowing in a composite headway-distribution model. The formula $\alpha = 1 - e^{-0.001\,55V}$ (where V is the volume of a traffic flow) was suggested by Lewis (10). The formula $\alpha = 1 - e^{-0.000\,39V}$ was derived from data collected at two Kansas locations.

These tables and graphs were the simulated results of the various described traffic conditions. They were used to

Figure 1. Conceptual flow of the simulated model without a left-turn lane.

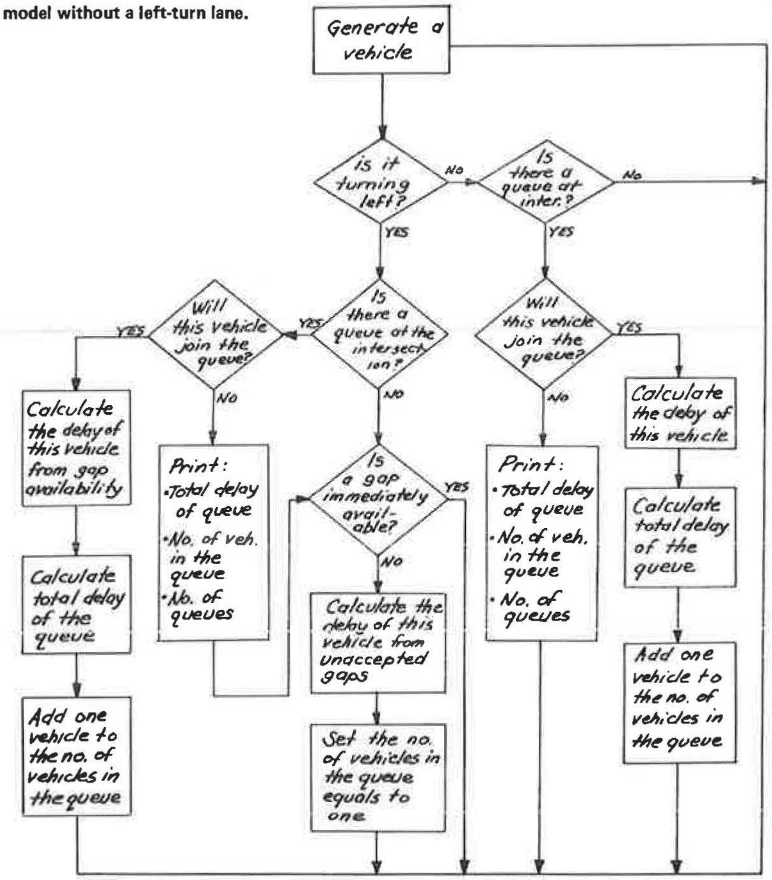
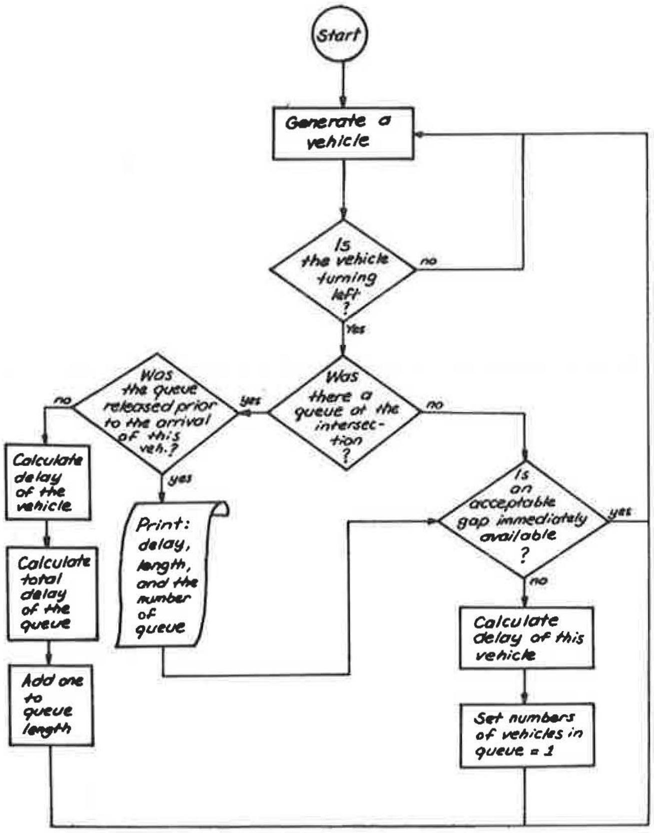


Figure 2. Conceptual flow of the simulation model with a left-turn lane.



illustrate the capability of the simulation models. If traffic conditions other than those described are of interest or greater accuracies are required, direct use of the models to obtain needed information would be desirable.

SUGGESTED DESIGN PROCEDURES FOR LEFT-TURN LANES

The overall approach for designing left-turn lanes at a priority intersection described in this paper is based on the concept of the benefit-cost ratio. The two developed traffic-simulation models are the basis for estimating many of the needed quantitative values for a benefit-cost analysis if such a design is considered. Design charts and tables derived from the simulated data were provided for normal traffic conditions (Figures 3-8 and the tables above). These charts and tables can help designers find needed information faster and more efficiently than can the direct use of the simulation models.

A conceptual model that illustrates the overall left-turn-lane design process on a systems basis is presented in Figure 9. Note that a precondition for using the process is that the intersection under consideration be a two-lane by two-lane priority intersection. However, the simulation models, design charts, and tables are considered applicable to some other situations if minor modifications are made. The user of this process should judge whether it is applicable to his or her particular case. Once the precondition is met and a designer must decide whether left-turn lanes should be built for the uncontrolled approaches, he or she should follow the steps outlined below.

1. Collect or estimate the following information about the traffic: (a) directional hourly volumes, (b) directional truck percentage, (c) directional right-turn

Table 1. Comparison of actual and simulated delays.

Approach Volume (vehicles/h)	Left Turn (%)	Opposing Volume (vehicles/h)	Observed Delay (s)	Simulated Results (s): Delay, Run 1	Run 2	Run 3	Run 4	Run 5	Avg	SD	Significant Difference
216	0.9	234	0	0	0	0	0	0	0	0	No
234	20.5	216	73.7	88.5	65.6	32.4	48.4	92.4	65.5	25.9	No
209	4.3	332	59.9	39.5	10.5	4.3	11.9	45.5	22.4	17.7	Yes
332	29.0	209	101.07	285.8	158.0	166.2	126.9	197.7	186.9	30.4	Yes
314	2.8	360	44.4	43.0	6.6	9.0	21.0	74.1	30.7	29.0	No
360	25.9	314	467.3	469.9	241.1	234.7	230.6	261.7	287.6	102.9	No
314	3.5	423	65.4	38.4	9.1	8.4	38.4	70.8	33.0	26.8	No
423	39.5	314	418.7	820.8	527.8	550.6	577.1	519.3	599.1	129.6	No
166	2.6	204	0	11.1	33.0	5.5	2.7	28.9	16.2	13.0	No
204	31.6	166	154.4	111.0	46.9	69.6	69.1	76.1	74.5	27.6	Yes
207	3.0	211	0	3.8	11.0	26.5	7.2	4.6	10.6	9.8	No
211	24.8	207	23.6	43.9	89.9	60.0	34.1	56.8	56.9	23.9	No
236	5.3	376	0	10.7	36.6	80.9	9.8	13.4	30.3	30.5	No
376	20.2	236	543.8	95	214.3	183.2	165.7	100.9	151.8	51.3	Yes
313	3.0	249	0	8.7	20.4	51.6	2.6	7.9	18.2	21.1	No
249	10.7	313	48.9	41.4	60.6	73.4	56.2	82.9	64.1	17.8	No

Figure 3. Variation of the volume-capacity ratio due to changes of approach volume and percentage of left turns (negative exponential headway distribution).

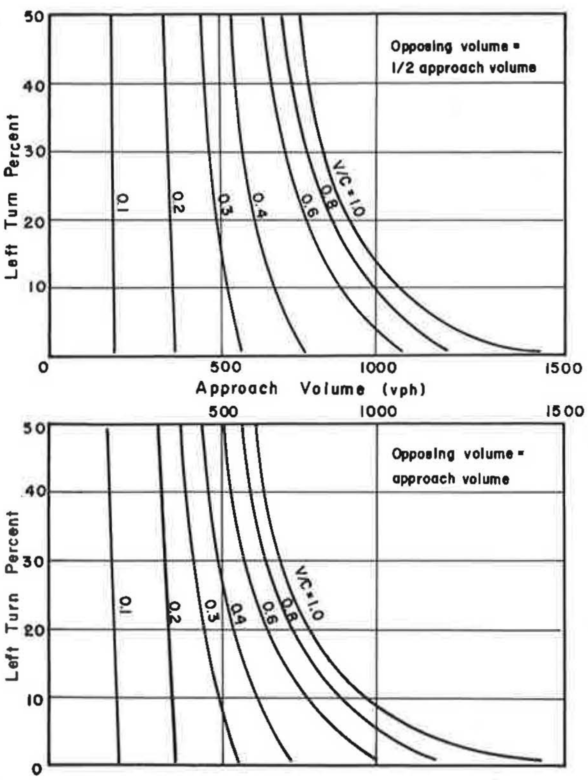
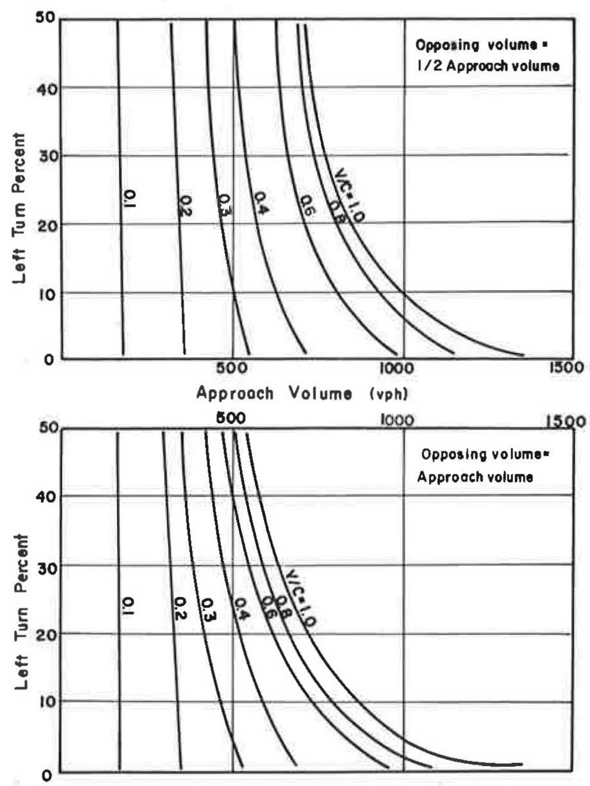


Figure 4. Variation of the volume-capacity ratio due to changes of approach volume and percentage of left turns (composite exponential headway distribution with $a = 1 - e^{-0.000\,39V}$).



percentage, (d) directional left-turn percentage, and (e) approach width.

2. Assume the traffic is composed of a group of free-flowing vehicles and a group of restrained vehicles. The percentage of restrained vehicles (α) is assumed to be equal to $1 - e^{-0.000\,39V}$ unless otherwise proven by collected data (V is volume in vehicles/h).

3. Assume the traffic has a critical gap equal to 4.5 s unless a different value is obtained from actual traffic data.

4. Use Figures 3, 4, or 5 with the design-hour values [expressed as average daily traffic (ADT)] defined above and read the corresponding volume-capacity values for the critical direction (the one with a higher directional volume).

5. Determine the capacity-adjustment factors for trucks, right turns, and approach width from the Highway Capacity Manual (11). The capacity adjustment factor for trucks, right turns, and approach width is given by the following equation:

$$F_c = F_t \times F_r \times F_w \quad (1)$$

where

F_c = total capacity adjustment factor,
F_t = truck adjustment factor,
F_r = right-turn adjustment factor, and
F_w = approach width adjustment factor.

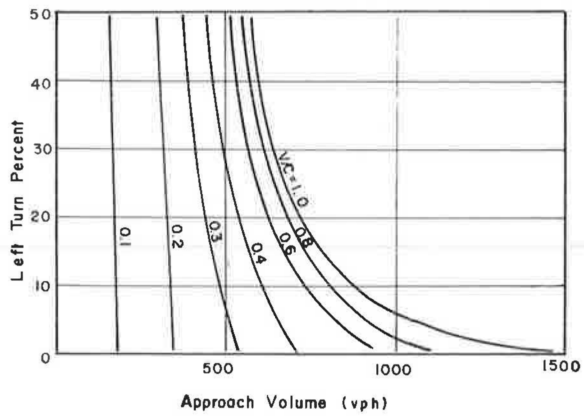


Figure 5. Variation of the volume-capacity ratio due to changes of approach volume and percentage in left-turn lane (composite exponential headway distribution with $a = 1 - e^{-0.00155V}$).

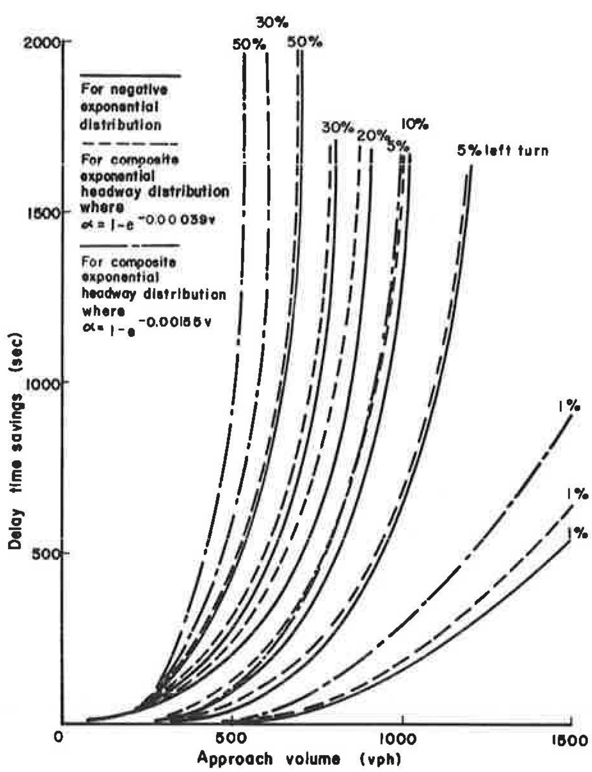


Figure 6. Delay time savings due to the construction of a left-turn lane for varied approach volume and percentage of left turns (opposing volume = half the approach volume).

The table below gives the values for F_t (11).

Trucks (%)	F_t	Trucks (%)	F_t
0	1.00	11	0.89
1	0.99	12	0.88
2	0.98	13	0.87
3	0.97	14	0.86
4	0.96	15	0.85
5	0.95	16	0.84
6	0.94	17	0.83
7	0.93	18	0.82
8	0.92	19	0.81
9	0.91	20	0.80
10	0.90		

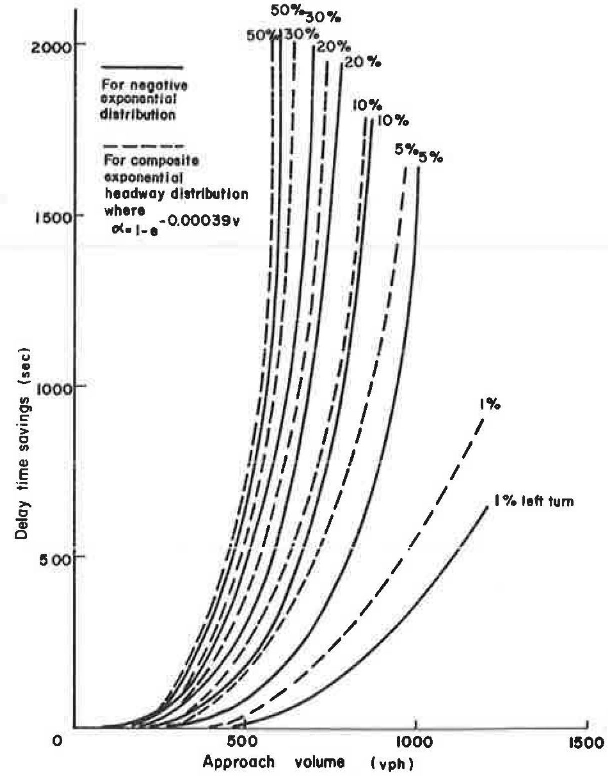


Figure 7. Delay time savings due to the construction of a left-turn lane for a varied approach volume and percentage of left turns (opposing volume = approach volume).

The table below gives the values for F_r (11).

Right Turns (%)	F_r	Right Turns (%)	F_r
0	1.00	14	0.80
1	0.98	15	0.79
2	0.97	16	0.78
3	0.95	17	0.78
4	0.93	18	0.77
5	0.92	19	0.76
6	0.90	20	0.75
7	0.88	22	0.74
8	0.87	24	0.73
9	0.85	26	0.73
10	0.83	28	0.72
11	0.83	30+	0.71
12	0.82		
13	0.81		

The table below gives the values for F_w (1 m = 3.28 ft) (11).

F_w	Approach Width (m)
0.82	3.05
0.91	3.35
1.00	3.66
1.09	3.96
1.18	4.27

6. Calculate a modified volume-capacity value by considering the correction factors obtained above. If this modified volume-capacity value is greater than one or represents an unacceptable level of service, left-turn lanes should be built for the intersection and no more analysis is needed. If this modified volume-capacity value is less than one, proceed to the next step.

7. Obtain hourly time savings for every hour of the

Figure 8. Length requirement for left-turn lane for varied opposing volumes and numbers of left-turning vehicles.

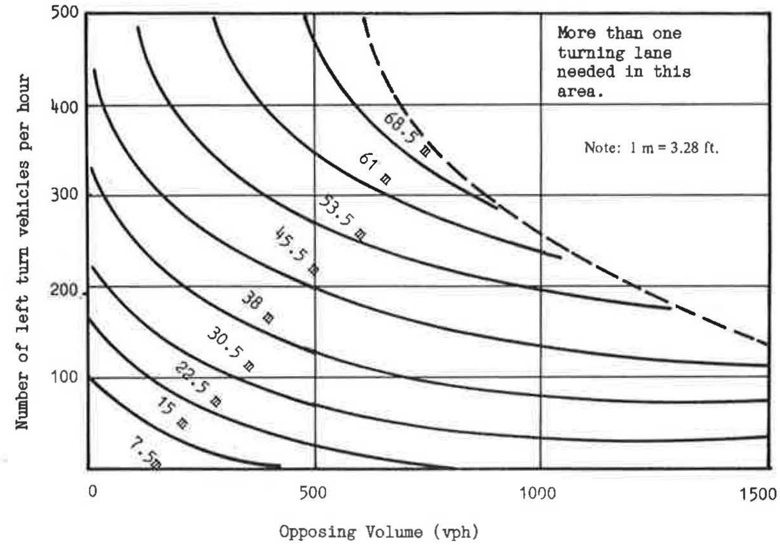


Figure 9. Systems model for designing left-turn lanes for a priority intersection.

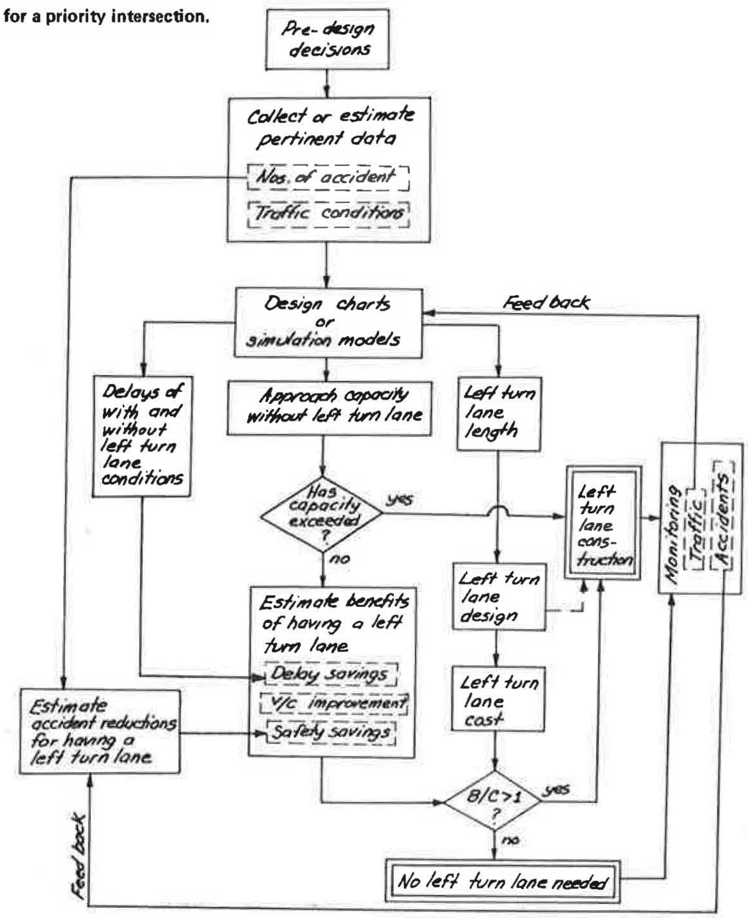


Table 2. Accident reduction forecast as a result of adding a left-turn lane without a signal.

		Accident Reduction (%)		
Area	Number of Lanes	All Accidents	Fatal-Injury Accidents	Property-Damage Accidents
Urban	2	1.9[a]	80[a]	
Urban	2+	6	54[a]	18[a]
Rural	2+	-6	-1[b]	

[a]Rough estimate; accurate percentage is in a range of 30-70 percent of this figure.
[b]Very rough estimate; accurate percentage is in a range of 70-150 percent of this figure.

day from Figures 6 or 7, assuming that a left-turn lane is available. Use the simulation models directly to obtain the hourly time savings if conditions specified for Figures 6 and 7 are not met.

8. Obtain total daily time savings by adding the hourly time savings.

9. Obtain the number of accident reductions from Table 2 (7, p. 140) and the calculation and tables below, which use methods derived from various existing sources. Be cautious in selecting the method used.

For suburban areas, the following calculation can be used (4):

Reduced numbers of accidents per million vehicles = 3.6203 - 1.1407 (number of approach lanes) + 1.2446 (approach ADT) - 0.7723 (opposing ADT) + 0.0371 (total intersection ADT).

For accident reduction due to left-turn channelization, use the table below (3):

Channelization Type	Accident Reduction (%)
Paint	32
Physically protected	64

Ring and Carstens (5, p. 71) found that construction of a left-turn lane prevented about one property-damage accident each year and one personal-injury accident every five years at each of four rural intersections studied.

The accident reduction forecasts used by the California Division of Highways (7, p. 141) show the following reductions (as a percentage of all accidents) for new left-turn channelization of unsignalized intersections:

Type of Channelization	Average Accident Reduction (%)
With curbs or raised bars	
Urban area	70
Suburban area	65
Rural area	60
With painted channelization	
Urban area	15
Suburban area	30
Rural area	50

10. Convert the time and accident savings into dollar values based on state economic analysis policies. American Association of State Highway and Transportation Officials (AASHTO) and National Highway Traffic Safety Administration (NHTSA) policies can be used if no state policies are available.
11. Obtain the left-turn-lane length requirement from Figure 8.
12. Design the left-turn-lane arrangement.
13. Compute the cost of installing the left-turn lanes.
14. By using benefit values obtained from step 10 and the cost value obtained from steps 11-13, conduct a benefit-cost analysis. An annual computation of the benefit-cost ratio is suggested.
15. If the calculated benefit-cost ratio is greater than one, the building of a left-turn lane is warranted. If the calculated benefit-cost ratio is less than one, the building of a left-turn lane may not be warranted. When the calculated benefit-cost ratio is close to one, redesign or recomputation is suggested for reaching a final decision.

For conditions that are not included in the charts and tables presented in this paper, the developed simulation models are suggested for use for left-turn-lane design purposes. Since the designer is likely to have a set of traffic parameter values different from those used in producing the charts and tables, he or she is urged to study the computer models carefully before making the necessary modifications. Lee (8,9) has a detailed description of model logics and other technical details.

CONCLUSION

This study has pointed out a new approach to highway design. Two simulation computer models for two-lane by two-lane priority intersections, one with and the other without left-turn lanes, were used as decision tools. The computer models tend to indicate that they have an acceptable degree of accuracy in duplicating the actual traffic condition. The models enable highway engineers to predict reduction of delays due to the construction of a left-turn lane if needed. The results enable us to develop design guidelines for priority intersections. Guidelines suggested in this paper are an attempt to systematize design procedures for left-turn lanes. The information presented should be a great improvement over the existing design methods. The more notable contributions of this study to the left-turn-lane design area can be summarized as follows:

1. Opposing volumes can be more adequately considered;
2. More realistic and complicated headway distributions can be accommodated;
3. Reduced delay, not the delay of without-left-turn-lane conditions alone, can be considered;
4. Left-turn-lane length recommendations are more realistic; and
5. Traffic conditions not suitable for simple queuing theories are more easily dealt with.

The result of this study is also further evidence that simulation is a vital and useful tool for highway designers. The quickness of computers makes them much more efficient for obtaining needed design information than are field observations. Four hours of traffic data collected were simulated on the computer (Honeywell 66/60 at the University of Kansas) in about 2.5 s.

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