Analysis of Left-Turn-Lane Warrants at Unsignalized T-Intersections on Two-Lane Roadways

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At an unsignalized T-intersection, where a major two-lane roadway intersects a minor roadway, criteria that justify a left-turn lane on the major roadway are analyzed. Three criteria are considered: (a) probability that one or more waiting through vehicles are present on the approach; (b) delay (average delay to the "caught" through vehicles, average delay to all through vehicles, and delay savings due to the left-turn lane); and (c) degradation of the level of service. The volume combinations (through, left-turn, and opposing flow) that would justify a left-turn lane under each of the criteria are presented. The current AASHTO guidelines are based on the probability that one or more through vehicles are in the queue behind a waiting left-turn vehicle. The original mathematical formulation of the AASHTO guidelines is examined and corrected, and a new set of volume warrants is developed. A simulation model of the movements of the vehicles on the approach is simulated, and delays to through vehicles with and without a left-turn lane for different traffic volumes are computed. Finally, a set of traffic volumes at which the level of service of the approach changes from A to B is developed. The warrant volumes based on the three criteria are different. Delay and the level of service are more easily understandable measures of traffic performance than probability, so the volume combinations based on these two criteria should also be considered. The result provides a range of volume combinations within which an engineering judgment should be made. Discussions of other considerations for justification of a left-turn lane are also provided.

A rapid increase in the number of residential developments, shopping centers, and professional centers in the suburbs has added many unsignalized T-intersections on two-lane roadways. The left-turn movements made from a major roadway to a minor roadway create various negative effects on the flow of the through movements on the two-lane roadways. They include delay, reduction of capacity, accident potential, increased fuel consumption due to deceleration and acceleration, and the general annoyance associated with the possibility of delay. Many states require that developers prepare traffic impact reports that evaluate the effects of the left-turn movements on the existing through traffic and the need for a left-turn lane. This paper examines the left-turn-lane warrants practiced in different states and develops and compares different warrant criteria for installing a left-turn lane on the major roadway approach at an unsignalized T-intersection as shown in Figures 1 and 2.

The 1984 and 1990 AASHTO Green Books (*1*,*2*) provide a set of traffic volumes to be used as a guide when installing a left-turn lane at an unsignalized intersection. The guide is based on the probability that one or more through vehicles are present in the queues created by vehicles waiting to turn left. The guide provides the combinations of traffic volumes consisting of advancing, opposing, and left-turn percentages for the given probability.

However, it does not give a clue about the corresponding delay and delay savings with the lane, nor does it provide the level of service on the approach at the traffic volume. If delay is known, the warrant would be more meaningful to the public as well as to engineers and planners, because delay is an easily understood measure of inconvenience. Furthermore, as a comprehensive measure of the efficiency of the approach, the reduction of the level of service can be used as a criterion for justifying a left-turn lane.

Other criteria, such as hazard and energy consumption, must be taken into account in justifying a left-turn lane at an unsignalized T-intersection. Some studies, such as one by Failmezger (*3*), attempted to use empirical equations to quantify hazards caused by left-turning vehicles. Although these aspects are important, site-specific elements—such as geometric characteristics of the intersection—affect the relative importance of these factors. A more general discussion of design considerations at an unsignalized intersection is found in a study by Kimber (*4*).

PURPOSE

This study focuses on criteria that are quantitative and basic to all intersections. Its purpose is to evaluate different warrant criteria for justifying a left-turn lane, those that are currently used, and those that can be considered. First, the existing criteria used in different states are examined. Second, three different criteria are examined:

1. Probability that a queue containing one or more through vehicles is present on the approach lane,
2. Average delay experienced by all through vehicles; average delay experienced by through vehicles caught by the queue; potential delay savings with the left-turn lane, and
3. Level of service on the approach lane.

Based on a threshold value given to each of these criteria, the traffic volumes that warrant the left-turn lane are calculated and compared. Possible problems with applying any of

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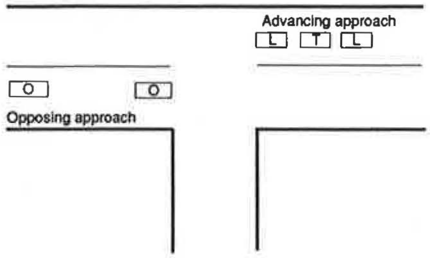

FIGURE 1 Schematic diagram of T-intersection with no left- turn lane.

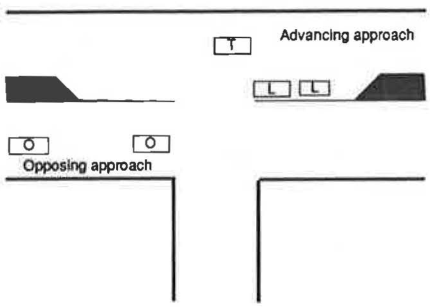

FIGURE 2 Schematic diagram of T-intersection with left-turn lane.

these criteria are discussed, and the general ranges of the traffic volume combinations for which a left-turn lane should be considered are presented.

To prepare for the analysis of the three criteria, this study (a) reviews the criteria practiced in different states, (b) reviews the current AASHTO warrants, (c) develops a simulation model that estimates delays to through vehicles, and (d) reviews a procedure for calculating the shared lane capacity on an approach to an unsignalized T-intersection (*5*).

CRITERIA FOR JUSTIFYING A LEFT-TURN LANE

The current criteria for justifying a left-turn lane are presented. They are the AASHTO guidelines and the warrants practiced by transportation departments in the United States and Canada.

AASHTO Green Book Guidelines

The 1984 and 1990 AASHTO Green Books (*1,2*) provide combinations of three traffic volumes (through, left-turn, and opposing) as a guide for installing a left-turn lane at an unsignalized T-intersection (Table 1). Sets of volume combinations for approach speeds of 40, 50, and 60 mph are given. According to Table 1 if, for example, the opposing volume is 400 vehicles per hour (vph) and the percentage of left-turn vehicles in the advancing flow is 10 percent, a left-turn lane is justified when the total advancing volume exceeds 380 vph for 40-mph approach speed. The source of the AASHTO guide is a study published by Harmelink (*6*) in 1967. The values are also adopted in an NCHRP report (*7*, p. 51). Detailed discussions of Harmelink's work are presented in the next section.

TABLE 1 AASHTO'S GUIDE FOR LEFT-TURN LANES ON TWO-LANE HIGHWAYS (*2*)

	Advancing Volume			
Opposing Volume	5% Left Turns	10% Left Turns	20% Left Turns	30% Left Turns
	40-mph Operating Speed			
800	330	240	180	160
600	410	305	225	200
400	510	380	275	245
200	640	470	350	305
100	720	575	390	340
	50-mph Operating Speed			
800	280	210	165	135
600	350	260	195	170
400	430	320	240	210
200	550	400	300	270
100	615	445	335	295
	60-mph Operating Speed			
800	230	170	125	115
600	290	210	160	140
400	365	270	200	175
200	450	330	250	215
100	505	370	275	240

Warrants Used by Different Departments of Transportation

A survey was conducted to examine the types of criteria different states use to justify a left-turn lane. Inquiries were sent in 1989 to the transportation departments of all states in the United States and provinces in Canada. A total of 25 responses were obtained. Sixteen departments responded that they did not have a specific volume warrant for installing a left-turn lane. Accident experiences, public complaints, and engineer judgments were cited as the bases for these decisions. Among the states that use volume warrants, most cited the AASHTO criteria (Table 1). Others cited volume criteria different from AASHTO's; these include daily volume and one of the three volumes only. None of the states reported that delay, delay savings to the through vehicles, or the reduction of the level of service were used to justify a left-turn lane.

PROBABILITY-BASED MODELS

This section examines and conducts a critical review of the criterion based on the probability that through vehicles are delayed.

Discussion of AASHTO Guidelines (Harmelink's Model)

The AASHTO warrants (those proposed by Harmelink) are based on the probability that one or more through vehicles are present in queues formed by left-turning vehicles waiting for gaps in the opposing flow. The values of the maximum allowable probabilities were determined on the basis of the judgment of a panel of traffic engineers. The values of the probability are different depending on the approach speeds; they are as follows:

Approach Speed (mph)		
Design	*Operating*	*Probability*
50	40	.02
60	50	.015
70	60	.01

For each value of the probability, the combination of three volumes (opposing, left-turn, and through) that result in the value is computed assuming a queueing system.

The original queueing model is based on the following parameters:

- Advancing volume (V_A),
- Percentage of left-turn volume in the advancing volume (L),
- Opposing volume (V_O),
- Critical gap (G_c),
- Time required for a left-turning vehicle to clear itself from the advancing stream (t_e), and
- Time taken to complete a left-turn maneuver (t_1).

The queueing system as defined by Harmelink assumes that the arriving units are the through vehicles behind the vehicles waiting to turn left and that the service is the departure of the left-turning vehicles. More specifically, the arrival and service rates are defined as

$$\lambda = L \cdot (1 - L) \cdot V_A \cdot \frac{t_w + t_e}{(2/3)t_A} \tag{1}$$

and

$$\mu = \frac{\text{unblocked time/hr}}{t_1} \tag{2}$$

where λ is the arrival rate and μ is the service rate.

The equation for the arrival rate (λ) is derived based on the following:

- Each left-turning car blocks the intersection for $t_w + t_e$ sec, where t_w is the average time a left-turning vehicle waits to find a suitable gap in the opposing flow. It is given by

$$t_w = \frac{3{,}600}{V_O} \cdot \left(e^{\frac{V_O}{3{,}600} \cdot G_c} - \frac{V_O}{3{,}600} \cdot G_c - 1\right) \tag{3}$$

- The total time the advancing approach is blocked by left-turning vehicles is

$$T_B = (L * V_A)(t_w + t_e) \tag{4}$$

- The number of advancing cars that arrive during the time period T_B is

$$C_A = \frac{(L \cdot V_A)(t_w + t_e)}{(2/3)t_A} \tag{5}$$

where $(2/3)t_A$ is the median headway of the advancing stream.

- Out of these C_A advancing cars, the number of through vehicles is

$$(1 - L) \cdot C_A = (1 - L) \cdot \frac{L \cdot V_A(t_w + t_e)}{(2/3)t_A} \tag{6}$$

The expression of the service rate (μ) is derived on the basis of the following:

- The unblocked time in Equation 2 is the total amount of time during which left turns can be made. This is equivalent to the sum of headways greater than G_c in the opposing flow minus an adjustment factor.
- Therefore, the number of left turns that can be made per hour is derived by dividing the unblocked time by t_1 as seen in Equation 2.

Given λ and μ in the queueing system, the probability of k units in the system is derived by

$$P(k) = \left(\frac{\lambda}{\mu}\right)^k \cdot \left(1 - \frac{\lambda}{\mu}\right) \tag{7}$$

From Equation 7, $1 - P(0)$ represents the probability that one or more units are in the system. The criterion for installing a left-turn lane is based on the probability that one or more units in the system will be less than a given value α. Therefore,

$$1 - P(0) = \frac{\lambda}{\mu} \leq \alpha \tag{8}$$

where the value of α is the preset probability defined in Table 2. The probability can be restated as the proportion of the time during which through vehicles are present in the queueing system or the probability that a through vehicle is delayed due to the left-turn vehicles.

Critical Evaluation and Limitation of Harmelink's Model

There are two problems in Harmelink's formulation. They are (a) inconsistent definitions of λ and μ, and (b) incorrect representation of the total number of possibilities of making a left turn in μ.

Problem 1

In Harmelink's model, λ denotes the arrival rate of through vehicles while one or more left-turning vehicles are waiting and μ denotes the rate at which vehicles can make left turns per unit of time. In queueing theory, the arrival rate and the service rate must refer to the same units in the system. In this case, λ refers to the through vehicles, but μ does not refer to the discharge rate of the through vehicles. This apparent inconsistency can be explained with the help of an example. Suppose that in 1 hr there are 10 possibilities of making a left turn, and assume that there are 10 left-turning vehicles. Assume also that every time a left-turning vehicle is waiting, three through vehicles arrive. Then λ, which counts each of the through vehicles as separate units, would take on the value

TABLE 2 VOLUME COMBINATIONS JUSTIFYING A LEFT-TURN LANE ON BASIS OF MODIFIED HARMELINK'S MODEL

	Advancing Volume			
Opposing Volume	5% Left Turns	10% Left Turns	20% Left Turns	30% Left Turns
40-mph Operating Speed				
800	434	300	219	189
600	542	375	272	234
400	682	472	343	293
200	863	600	435	375
100	946	679	493	424
50-mph Operating Speed				
800	366	257	185	162
600	460	320	234	202
400	577	403	294	255
200	735	513	373	324
100	830	576	424	365
60-mph Operating Speed				
800	294	207	154	146
600	365	259	187	165
400	461	324	238	206
200	586	414	303	263
100	663	468	344	297

of 30, whereas μ would represent the discharge rate of the leading left-turning vehicle and be equal to 10. This means that the system would never reach a steady state, because λ is greater than μ. But this is not correct, because every time a left-turning vehicle is discharged, more than one through vehicle can be discharged.

The inconsistency in the definitions of λ and μ in Equations 1 and 2 ceases to be critical only when there is no more than one through vehicle waiting behind a left-turning vehicle. Under this condition, the number of opportunities for turning left equals the discharge rate of through vehicles, and thus the units represented in λ and μ become consistent. Alternatively, the definitions are consistent only when the probability that two or more through vehicles waiting behind a left-turning vehicle is very small. This condition could occur when the proportion of through vehicles in the advancing stream is very small. Under such conditions, however, the question of installing a left-turn lane is not relevant, because the approach is essentially used as the left-turn lane.

Problem 2

The value of μ represents the total number of possibilities (per hour) of making left turns based on the available gaps in the opposing flow. It is an aggregated value in Harmelink's model; in other words, μ is derived by dividing the sum of gaps that are greater than the critical gap by the time required to make a left turn (t_1). A problem in this derivation is that the residual gaps (the remainder of individual gap size divided by t_1) are added and the sum is also considered to be part of the time available for making left turns. This would make μ represent more left-turn opportunities than are actually available. For example, if there were four consecutive 6-sec gaps, the value of μ would be 6: $4 \times 6 \div t_1$, where t_1 equals 4 sec. In reality, however, there are only four left-turning possibilities because each 6-sec gap can accommodate one left turn, assuming t_1 equals 4.

Thus, even when λ and μ are consistent, as pointed out, the value of λ, derived from Equation 8, is overestimated because of this definition of μ.

Modified Formulation of Harmelink's Model

In this section Harmelink's model is modified so that the definitions of λ and μ are consistent and μ represents real-world conditions more closely. One left-turning vehicle followed by one or more through vehicles is considered as an arriving unit. The modified arrival rate of units (λ^*) is

$$\lambda^* = L \cdot V_A \left[1 - e^{\frac{-(1-L)V_A}{3{,}600}(t_{lw} + t_e)} \right] \qquad (9)$$

where the term in brackets represents the probability of one or more through vehicles' arriving behind a waiting left-turning vehicle.

The corresponding service rate (μ^*) should then be the total number of left-turning possibilities. It is assumed that in a headway between $[G_c + (\eta - 1) \cdot G_s]$ and $(G_c + \eta \cdot G_s)$, η left turns are possible, where G_s is the follow-up gap size, assumed to be 3 sec. This assumption is based on a suggestion made by Baass in his 1987 paper (*8*). Therefore, μ^* can be expressed as

$$\mu^* = \left[1 - e^{-3\left(\frac{V_O}{3{,}600}\right)} \right] \cdot V_O \cdot \sum_{\eta=1}^{N} \eta \left\{ e^{-\frac{V_O}{3{,}600}[G_c + 3(\eta - 1)]} \right\} \qquad (10)$$

where the value of N is the maximum number of left-turning opportunities per single headway. It is approximated by solving the following for N:

$$\text{Probability } \{\text{headway} \geq G_c + N \cdot G_s\} \approx 0 \qquad (11)$$

Based on the modified arrival rate (λ^*) and service rate (μ^*) and the threshold probability shown earlier, the volume combinations that warrant a left-turn lane are computed using Equation 8. The results are presented in Table 2, in the same format as the current AASHTO guide (Table 1).

Tables 1 and 2 provide warrant volumes based purely on probability and do not provide a reference to the delays experienced by through vehicles.

DELAY-BASED MODELS

In this section, expressions are derived that compute delays to the through vehicles under different volume combinations. Savings in time accrued by providing a separate left-turn lane are also computed. To compute the delays, a simulation model is developed. The approach is to build the simulation model and, from many runs of the model, develop a set of regression equations that expresses delay as a function of the volume combination. The simulation model, its validation, and the values of delays are presented in the following.

Simulation Model and its Validation

Before the development of the simulation model, TRAF-NETSIM was tested to determine whether it could be used to derive delay for this problem. However, the TRAF-NETSIM model did not provide a reasonable and consistent set of delay values. It is believed that TRAF-NETSIM may not be suited for computing delay to the vehicles in the advancing stream of an isolated, unsignalized T-intersection on a two-lane roadway (as shown in Figure 1). Because the problem with TRAF-NETSIM could not be resolved, a separate simulation model was developed. The assumptions of the model are as follows:

1. The arrivals of all three types of vehicles follow the Poisson distribution.
2. The basic time unit for simulation is 1 sec. For each time unit the arrival of vehicles is checked according to the Bernoulli experiment.
3. The acceptable gap in the opposing flow for making a left turn is 6 sec.
4. A waiting left-turning vehicle initiates the turning movement only when the first acceptable gap becomes available. The time at which the vehicle initiates the movement is referred to as the "departure time."
5. If a gap is long, more than one left-turning vehicle can use the same gap. In this case, the next left-turning vehicle in the queue makes the turn 1 sec after the preceding left-turning vehicle departs.
6. The difference in departure time between a left-turning vehicle and the succeeding through vehicle, which is in the queue, is 1 sec.
7. The difference between the departure times of consecutive through vehicles in the queue is 1 sec.
8. The delay to a left-turn or through vehicle is measured by the time difference between the time of arrival at the intersection and the time of departure from the intersection.
9. The time loss to the through vehicles is computed based on a linear acceleration and deceleration pattern (all vehicles are assumed to travel at a designated speed before and after the delay). The rates of acceleration and deceleration used are 5.4 ft/sec^2 and 8 ft/sec^2, respectively.

The output of the simulation model includes the following:

- Total hourly delay (TD),
- Average delay to left-turning vehicles (ALTD),
- Average delay to through vehicles caught in the queue (ACTHD),
- Average delay to all through vehicles, caught and not caught (ATD),
- Total delay savings per hour as a result of the left-turn lane (DS), and
- Distributions of queue lengths, times of queue dissipation, and frequency of queue formation.

The performance of the model was verified by checking the values of selected parameters. For those parameters, the values computed from previously developed equations are compared with the values obtained from the simulation model. The selected parameters are ALTD and NTVC, which is the number of through vehicles caught behind waiting left-turn vehicles per hour.

For NTVC, the data from the model were compared with the value of λ in Equation 1, and the comparison is shown in Figure 3. In this figure, NTVC and λ are calculated for different volume combinations and compared. If the values of

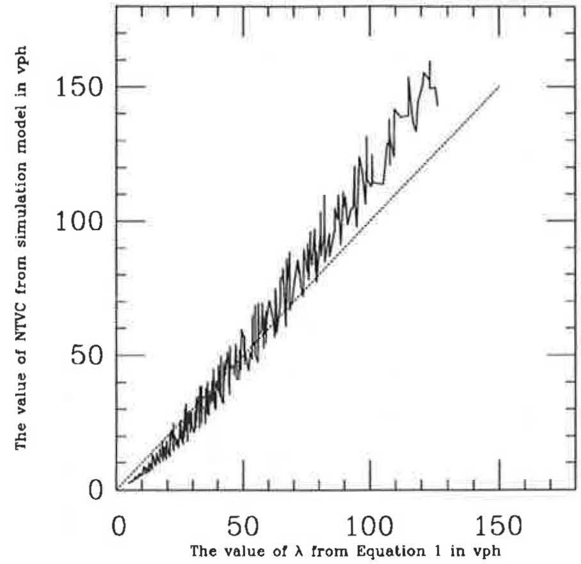

FIGURE 3 Comparison of λ (Equation 1) and NTVC (simulated result).

NTVC and λ were an ideal match, the plot would be a 45-degree line through the origin.

For ALTD, the data from the model were compared with the results from the expression of vehicle waiting time at the merge point of two traffic streams, Equation 3. This equation has been presented by many studies, among them Drew (*9*) and Tanner (*10*). The comparison is shown in Figure 4. In this figure, t_w from Equation 3 and ALTD are plotted against the opposing volume (V_O). The value of ALTD presented in this figure corresponds to the situation in which the proportion of through vehicles in the advancing approach is zero in the simulation model.

Development of Equations on Delay and Delay Savings

For the same set of traffic volumes, the simulation model was run many times to attain the average value of delay. A regression analysis was conducted to develop the general relationships between the volume combinations and TD, ACTHD, ATD, and DS.

The regression equations express these delays in terms of the three input volumes (opposing, left-turn, and through). Total delay (TD) refers to the sum of all delays faced by vehicles in the advancing stream, and it is expressed in seconds per hour. The average delay to the through vehicles caught in the queue (ACTHD) refers to the average time the through vehicles must wait in the queue; it is expressed in seconds per vehicle. The average delay to the left-turn vehicles (ALTD) is the expected delay to any left-turning vehicles, including those that do not have to wait for a gap in the opposing stream and hence suffer no delay. It too is expressed in seconds per vehicle. The average delay to the through vehicles (ATD) is the average time the through vehicles spend in the system, irrespective of their being caught in the queue. It is measured in seconds per vehicle. Delay savings (DS) refers to the delay that would be eliminated by providing a left-turn lane; it is

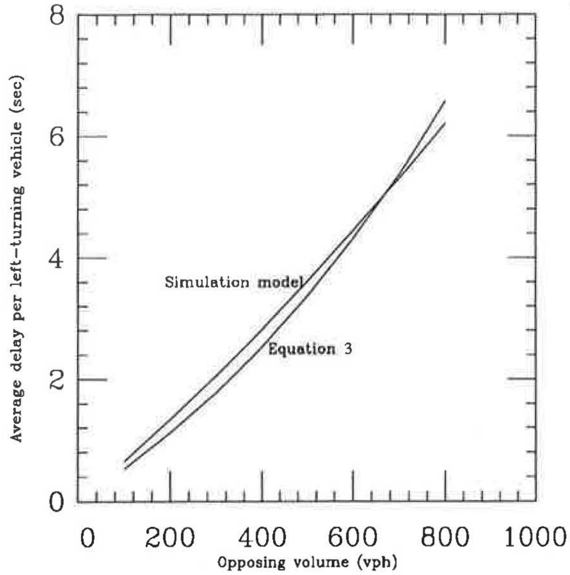

FIGURE 4 Comparison of t_w (Equation 3) and ALTD (simulated result).

expressed in seconds per hour. All of these delays account for the time loss due to deceleration and acceleration.

In formulating each equation, the influencing factors for the delay are identified and arranged in a polynomial form. Once the basic forms of the equation are determined, regression analyses are conducted to determine the coefficients of the equations. The regression equations and the R^2 values obtained are

$$\text{TD} = 0.087 \cdot (V_O/100)^2 \cdot (V_l/10)^2 \cdot (V_t/100) + 3.147 \cdot (V_O/100)^2 \cdot (V_l/10) + T_l \cdot \text{PTHC}\, V_t \qquad R^2 = .88 \tag{12}$$

$$\text{ACTHD} = 0.016 \cdot (V_O/100)^2 \cdot (V_l/10) + 1.39 \cdot (V_O/100) + T_l \qquad R^2 = .9 \tag{13}$$

$$\text{ALTD} = 22.86 \cdot [(V_O/3{,}600) + (V_O/3{,}600)^2] + 222.65 \cdot \text{PT} \cdot (V_O/3{,}600)^2 \qquad R^2 = .83 \tag{14}$$

where

V_l = left-turn volume,
V_t = through movement volume, and
T_l = time loss due to deceleration and acceleration.

Once these equations are developed, ATD and DS are developed as follows:

$$\text{ATD} = \text{ACTHD} \cdot \text{PTHC} \tag{15}$$

where PTHC is the proportion of the through vehicles caught in the queue, and its value is again computed from a regression equation of the form

$$\text{PTHC} = 14.19 \cdot 10^{-10} V_O \cdot V_l \cdot V_t + 46.511 \cdot V_O^2 \cdot V_l \tag{16}$$

DS consists of two elements:

1. The total delay to the through vehicles. This is given as ACTHD · NTVC, where NTVC = PTHC · V_t, and
2. The delay experienced by the left-turning vehicles because of missed gaps. This is due to the presence of through vehicles in the queue. ALTD, given by Equation 14, consists of two terms. The first term represents the delay due to waiting for acceptable gaps in the opposing stream. For this reason it is dependent only on the opposing volume. The second term represents the delay caused by the presence of through vehicles in the queue. Hence, this term depends on the proportion of through vehicles in the advancing stream. This latter delay will be saved when a separate left-turn lane is provided.

Thus, the delay savings is expressed as

$$\text{DS} = \text{ACTHD} \cdot \text{NTVC} + 222.365 \cdot (1 - L) \cdot (V_O/3{,}600)^2 \cdot V_l \tag{17}$$

Delays and Delay Savings at Warrant Volumes Based on Probability Models

By using the regression equations derived in the previous subsection, delays and delay savings for volume combinations of the AASHTO guidelines and of the modified Harmelink's model are now computed. For each volume combination ACTHD, ATD, and DS are computed and are shown in Tables 3 and 4.

Delays at AASHTO Guidelines

Table 3 shows the ACTH, ATD, and DS for each volume combination shown in Table 1. ACTHD ranges from 10 to 28 sec, ATD from less than 0.1 to 4 sec, and DS from 22 sec/hr to nearly 500 sec/hr. The existence of these variations indicates that the installation of a left-turn lane based on the AASHTO warrant volumes would not result in the consistent reduction of delay. It is particularly interesting to see that the total delay savings vary more than 20 times for the same threshold probability (α).

Delays at Warrant Volume Combinations Based on Modified Harmelink's Model

Table 4 shows ACTHD, ATD, and DS for the volume combinations shown in Table 2, which is derived after modifying the original formulation of Harmelink's model. When comparing Tables 3 and 4, the values of delay are higher in Table 4 than in Table 3. This reflects the fact that the warrant volume conditions based on the modified formulation are more re-

TABLE 3 DELAYS AT VOLUME COMBINATIONS OF AASHTO'S GUIDE FOR LEFT-TURN LANES

Opposing Volume	Advancing Volume: 5% Left Turns	10% Left Turns	20% Left Turns	30% Left Turns
40-mph Operating Speed				
800	330 (22/1.2/550)	240 (22.6/1.8/615)	180 (23.8/2.7/704)	160 (25/3.7/787)
600	410 (18.6/0.8/418)	305 (19/1.1/475)	225 (20/1.6/518)	200 (21/2.2/573)
400	510 (15.3/0.4/259)	380 (15.6/0.6/284)	275 (16/0.8/289)	245 (16.5/1.0/316)
200	640 (12/0.1/105)	470 (12.1/0.2/103)	350 (12.3/0.2/102)	305 (12.4/0.3/104)
100	720 (10.5/0/43)	575 (10.5/0.1/46)	390 (10.5/0.1/34)	340 (10.6/0.1/33)
50-mph Operating Speed				
800	280 (24/1.1/439)	210 (25/1.7/519)	165 (26/2.7/642)	135 (27/3.3/626)
600	350 (21/0.7/339)	260 (21.2/1.0/386)	195 (22/1.6/434)	170 (22.6/2.0/464)
400	430 (17.5/0.4/206)	320 (17.7/0.5/227)	240 (18.1/0.7/248)	210 (18.5/1.0/263)
200	550 (14.3/0.1/87)	400 (14.4/0.2/84.4)	300 (14.5/0.2/86)	270 (14.6/0.3/93)
100	615 (12.8/0/35)	445 (12.8/0/30)	335 (12.8/0.1/29)	295 (13/0.1/28)
60-mph Operating Speed				
800	230 (26/1.0/331)	170 (26.5/1.4/385.5)	125 (27.4/2.1/431)	115 (28.3/3.0/506)
600	290 (23/0.6/260)	210 (23.2/0.9/286)	160 (24/1.4/332.5)	140 (24.4/1.8/358)
400	365 (19.7/0.3/165)	270 (20/0.5/182)	200 (20.3/0.7/196)	175 (20.6/0.9/209)
200	450 (16.6/0.1/64)	330 (16.7/0.1/65)	250 (16.8/0.2/68.2)	215 (16.9/0.2/68.5)
100	505 (15.1/0/25)	370 (15.1/0/23.2)	275 (15.2/0.1/22)	240 (15.2/0.1/22)

Notes: Delays (a/b/c)
a: Average delay per through vehicle caught in the queue (in sec/veh)
b: Average delay per through vehicle (in sec/veh)
c: Total delay savings with a left-turn lane (in sec/hour)

TABLE 4 DELAYS AT VOLUME COMBINATIONS OF MODIFIED HARMELINK'S MODEL

Opposing Volume	Advancing Volume: 5% Left Turns	10% Left Turns	20% Left Turns	30% Left Turns
40-mph Operating Speed				
800	434 (22.5/1.7/922)	300 (23.4/2.3/922)	219 (24.8/3.4/988)	189 (26.1/4.6/1047)
600	542 (19.1/1.1/724)	375 (19.7/1.5/697)	272 (20.7/2.1/725)	234 (21.6/2.7/892)
400	682 (15.6/0.6/472)	472 (15.9/0.7/432)	343 (16.5/1.0/430)	293 (17.0/1.3/434)
200	863 (12.2/0.2/209)	600 (12.3/0.3/173)	435 (12.5/0.3/155)	375 (12.6/0.4/152)
100	946 (10.6/0.1/86.1)	679 (10.6/0.1/69)	493 (10.7/0.1/56)	424 (10.7/0.1/51)
50-mph Operating Speed				
800	366 (24.4/1.5/716)	257 (25.2/2.1/740)	185 (26.3/3.1/779)	162 (27.5/4.2/847)
600	460 (21.1/1.0/568)	320 (21.6/1.3/561)	234 (22.4/1.9/592)	202 (23.2/2.5/618)
400	577 (17.7/0.5/371)	403 (18/0.7/350)	294 (18.5/0.9/355)	255 (19/1.2/365)
200	735 (14.4/0.2/166)	513 (14.5/0.2/141)	373 (14.7/0.3/129)	324 (14.8/0.4/128)
100	830 (12.9/0.1/73)	576 (12.9/0.1/55.1)	424 (12.9/0.1/47)	365 (13.0/0.1/43)
60-mph Operating Speed				
800	294 (26.3/1.3/508)	207 (26.9/1.8/537)	154 (28/2.7/602)	146 (29/3.7/677)
600	365 (23.1/0.8/395)	259 (23.5/1.1/409)	187 (24.2/1.6/428)	165 (24.9/2.2/467)
400	461 (19.8/0.5/259)	324 (20.1/0.6/253)	238 (20.5/0.8/263)	206 (20.8/1.1/272)
200	586 (16.7/0.2/113)	414 (16.7/0.2/101)	303 (16.9/0.3/96)	263 (17/0.3/97)
100	663 (15.1/0.1/48.3)	468 (15.1/0.1/39)	344 (15.2/0.1/34)	297 (15.2/0.1/32)

Notes: Delays (a/b/c)
a: Average delay per through vehicle caught in the queue (in sec/veh)
b: Average delay per through vehicle (in sec/veh)
c: Total delay savings with a left-turn lane (in sec/hour)

laxed. Although delays are higher in Table 4, the ranges of individual delays and delay savings are similar between the two cases (i.e., AASHTO and modified Harmelink). Discussions on the variation in the values of delays are presented in more detail later.

Delay as Warrant Criterion

It is now attempted to establish a set of volumes that can be considered as warrants on the basis of a given value of delay. A given value of ACTHD, ATD, or DS can be selected, and the regression equations 12, 14, or 16, respectively, can be used to compute the volume combinations for the selected value of the parameters. Shown in Figure 5, as an example, are the volume combinations that would result in 14, 19, 24, and 29 sec of ACTHD. These delay values include the acceleration and deceleration time loss, which for a 40-mph approach speed is 9 sec. If for a given value of ACTH the volume combination points to the upper right of the line in Figure 5, a left-turn lane is justified; if it points to the lower left of the line, the lane is not justified.

LEVEL OF SERVICE AS WARRANT CRITERION

In this section, the reduction of level of service (LOS) from A to B on the advancing approach is considered as the criterion for justifying a left-turn lane. On the basis of the transition from LOS A to LOS B, a set of volumes (V_O, V_A, L) are computed and presented as warrant conditions.

The procedure to determine the level of service of an approach on the major road where through and left-turn movements share the same lane is not clearly explained in the *Highway Capacity Manual* (5). The shared lane capacity of an approach lane at an unsignalized intersection (C_{SH}) is defined in the manual as

$$C_{SH} = \frac{V_l + V_t + V_r}{\dfrac{V_l}{c_{ml}} + \dfrac{V_t}{c_{mt}} + \dfrac{V_r}{c_{mr}}} \tag{18}$$

where V_l, V_t, and V_r are left-turn, through, and right-turn flow rates, and c_{ml}, c_{mt}, and c_{mr} are the movement capacities for left-turn, through, and right-turn flows. (in this case, $V_r = 0$).

It is not clear if c_{mt} can represent the capacity of the advancing through movements that have no conflicting flow but are affected by the presence of the left-turning movement. In this analysis, it is assumed that c_{mt} represents the capacity of the through movement. Assuming V_r equals 0, Equation 18 can be written as

$$C_{SH} = \frac{1}{\dfrac{L}{c_{ml}} + \dfrac{(1 - L)}{c_{mt}}} \tag{19}$$

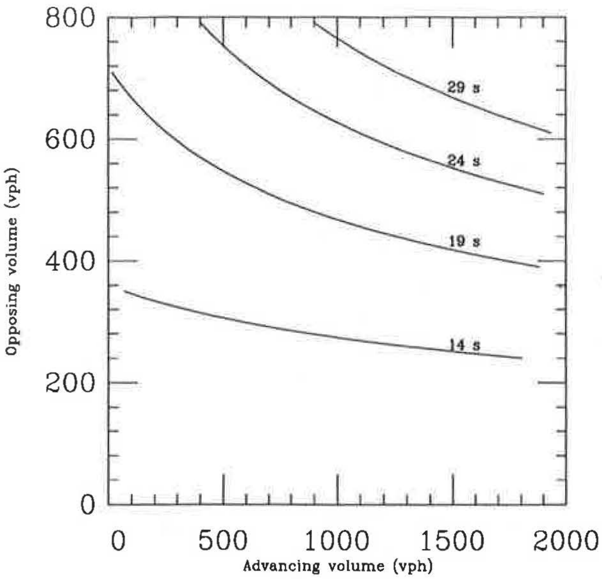

FIGURE 5 Volume combinations (V_O and V_A) at different values of ACTHD for L = 10 percent.

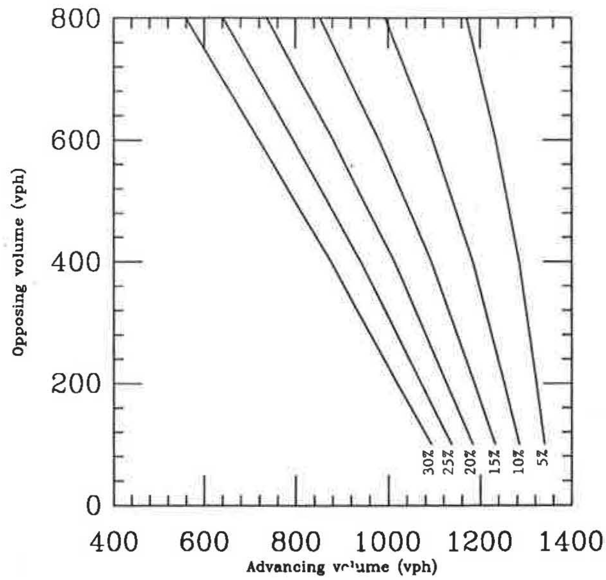

FIGURE 6 Volume combinations (V_O and V_A) at boundaries of LOS A and LOS B for different values of *L*.

In this equation, C_{SH} is computed as the weighted average of the minimum headways of the through and left-turn movements. It is, however, very difficult to decide what value of c_{mt} should be used. It would depend on many factors and, as such, can take on a wide range of values. This study presents the warrant conditions for c_{mt} = 1,800 vph. This value is chosen because it is the maximum capacity that can be attained on such a roadway.

For LOS A, the minimum reserve capacity is 400 vph. Thus, the combination of three volumes that results in a reserve capacity 400 vph can be computed from

$$C_{SH} - V_A = 400 \qquad (20)$$

The volume combinations that satisfy Equation 20 are plotted in Figure 6. As the percentage of left-turn volume increases, the effect of opposing volume on the level of service becomes more pronounced. This is not surprising: with the increase of L, the effect of c_{ml} on C_{SH} becomes greater, so, as mentioned earlier, C_{SH} becomes more strongly dependent on the opposing volume. In the figure, if the volume combination (V_O, V_A, L) points to the upper right of the line (corresponding to L), then a left-turn lane should be provided; if the combination points to the lower left of the line, the left-turn lane is not required.

It should be noted that peak hour factor (PHF) can be included in this analysis by dividing the hourly volumes by the PHF and then using these values as V_O and V_A.

DISCUSSION OF CRITERIA FOR LEFT-TURN-LANE WARRANTS

The characteristics and problems are discussed of using each of the three criteria for justifying a left-turn lane based on (a) a given probability that waiting through vehicles are present on the approach, (b) a given value of delay, and (c) the reduction of the level of service from A to B.

Comparison of Probability- and Delay-Based Criteria

The probability-based criterion does not take into account how long individual vehicles must wait. For the same value of probability depending on the combination of V_O, V_A, and L, the delay to the through vehicles can vary significantly. This can be seen from the delay values (ACTHD, ATD, and DS) calculated at the warrant volume based on the probability and presented in Tables 3 and 4. As seen in the tables, the values of ACTHD, ATD, and DS have large variations for the same probability of .02 (for the 40-mph approach speed). For the modified Harmelink's model, for example, at an approach speed of 40 mph, ACTHD varies for 10 to 25 sec, ATD from 0.1 to 5 sec, and DS from 51 to 1,050 sec/hr. The wide variation in the DS, in particular, suggests that if the probability-based warrant were applied, the economic justification for installing a left-turn lane would not be consistent for different volume combinations.

Comparison of Probability-Based Criterion and Level of Service–Based Criterion

When the reduction of the level of service from A to B is used as a criterion, the values of volume combination at which a left-turn lane is justified are much greater than the ones for the probability-based criterion. For example, as seen in Table 2, at V_O equals 600 vph and L equals 10 percent, V_A is 375 under the probability criterion of .02; under the level of service-based criterion, V_A is 1,100, as seen in Figure 6. A possible explanation for this discrepancy is that the level of service is a macroscopic analysis, considering the average condition during 1 hr, whereas the probability-based criterion is a more microscopic analysis of flow characteristics. The volume combination that corresponds to the level of service criterion should be considered as the minimum limit.

Comparison of Three Criteria

To compare the volume combinations for the three criteria, Figure 7 is provided. It shows the volume combinations when the probability is .02; ACTHD is 19 sec and level of service changes from A to B at c_{mt} = 1,800 vph; in all cases the percentage of left turns in the advancing flow (L) is 10 percent.

The volume combinations developed on the basis of these three criteria provide a range in which a left-turn lane can be considered under the threshold values stated above. The volume combination based on the level of service is perhaps the minimum acceptable criterion, and the volume combination based on the probability (as seen in AASHTO or the modified Harmelink's model) is the most luxurious criterion; in other words, the latter is an ideal criterion. The volume combinations based on the delay criterion fall between the volume combinations for the other two criteria. This is applicable when the advancing volume is between 500 and 1,250 vph.

Justifying a left-turn lane on the basis of a given probability is difficult to comprehend. Justification based on delay is easier to understand; however, depending on which criterion is used (the average delay or the total delay savings), the volume combination that justifies the left-turn lane will be significantly different. Justification based on the degradation of the level of service can also be a reasonable concept that the public understands.

The volume combinations based on these three criteria should provide the general volume range for which the left-turn lane should be considered. The precise limits should vary based on the standards of the community and other factors, such as the accident experience and the number of buses included in the through vehicles. The delay experienced by the persons rather than the vehicles involved should also be an important consideration. Thus, if the percentage of transit vehicles is large, the more stringent considerations should be used.

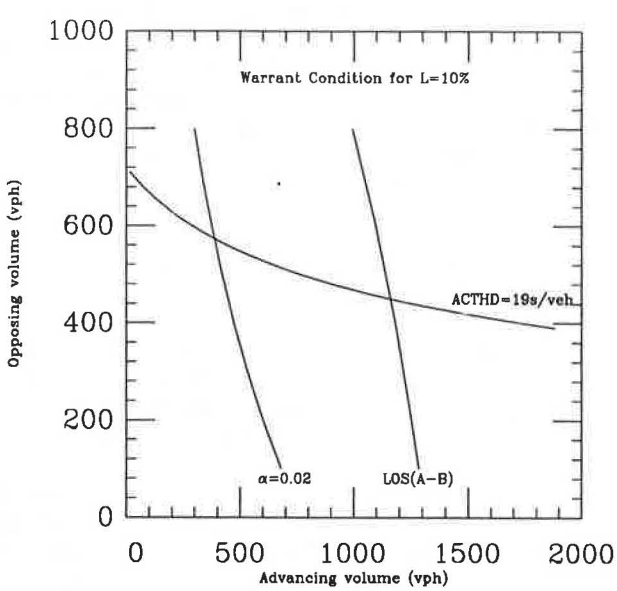

FIGURE 7 Volume combinations for justification of left-turn lane for the three criteria.

CONCLUSIONS

This paper has examined the criteria that should be considered when justifying a left-turn lane on the major approach of an unsignalized T-intersection. They are (a) probability that one or more waiting through vehicles exist on the approach, (b) delay to the through vehicles and delay savings as a result of the left-turn lane, and (c) degradation of the level of service. For each case, combinations of three volumes (opposing, left-turn, and through movements) that result in a given condition are computed and presented. During the process of developing the volume combination, the mathematical model on which the existing AASHTO guidelines are based is reviewed, and modifications to the model are made. Furthermore, a set of regression equations is developed that represents delay to the through vehicles and delay savings. A computation procedure for the level of service on a shared lane approach to an unsignalized T-intersection is examined.

The problem of the left-turn-lane justification will continue to be a matter of engineering judgment; however, this study should help the decision-making process. In addition to the volume warrant, particular attention should be paid to (a) an appropriate value of the threshold values for probability and delay, (b) delay based on the number of passengers in vehicles, in the case of large percentages of transit vehicles among the through vehicles, (c) the length of time for which the warrant conditions exist, and (d) environmental and energy issues.

ACKOWLEDGMENTS

The authors are grateful to the Delaware Department of Transportation for its assistance in collecting survey responses. The authors are also thankful to Mohammad Dzulkifli for his help with the development of the simulation model.

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Publication of this report sponsored by Committee on Methodology for Evaluating Highway Improvements.