Lengths of Left-Turn Lanes at Signalized Intersections

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The required length of the left-turn lane at signalized intersections is analyzed, and the recommended lengths for different conditions are presented. The presently available guidelines for the length of the left-turn lane are rather vague and not comprehensive. Lane lengths are analyzed from two aspects: (*a*) the probability of overflow of vehicles from the turning lane and (*b*) the probability of blockage of the entrance to the turning lane by the queue of vehicles in the adjacent through lane. The factors affecting each of these conditions are identified, and a model that computes the probability of occurrence of each of these conditions is developed. A set of tables is prepared for the recommended left-turn lane lengths for different parameters, including signal timing, left-turn volume, through volume, and threshold probabilities. Field surveys are conducted to obtain values of turning maneuver time and the space requirement per vehicle on the lane. The observed values are incorporated in the recommended lengths. The proposed models not only provide the recommended lane lengths but also help evaluate the existing conditions and the effectiveness of different improvement measures.

Suburbanization has brought about a multidirectional traffic pattern in the suburban road network. As a result, suburban intersections are handling an increasing share of turning movements. Left-turning movements, in particular, require close examination since they significantly influence the capacity, safety, and design of the intersection. The adequacy of the length of the left-turn lane, for example, affects the efficiency of movements of through as well as left-turning vehicles. This paper proposes a set of models that determines the required length of the left-turn lane at signalized intersections and presents a set of tables for the recommended lengths.

Whereas the problem is fundamental to intersection design and operation, the currently available guidelines are different among themselves, some are rather vague, and some, such as AASHTO (*1*), suggest that the length should be based on a probabilistic analysis. A brief discussion of the existing standards is provided in the next section.

In this paper, the length of the left-turn lane is analyzed on the basis of probabilities of occurrence of two cases: (*a*) overflow of the left-turn lane and (*b*) blockage of the entrance of the left-turn lane by backed-up through vehicles on the adjacent through movement lane. The models compute these probabilities as a function of left-turn volume, through-vehicle volume, signal timing (cycle length and phasing), vehicle turning time, and the length of the left-turn lane. Given an acceptable probability for each of the two cases, the required lane length is computed for that case. The recommended length is the longer of the two required lengths. The time required to complete a left-turn maneuver and the space requirement for vehicles while standing in the lane are determined on the basis of field observations.

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LITERATURE REVIEW

A literature search was conducted through HRIS and DIALOG, but no analytical model dealing with both the problems of overflow and blockage was found. The existing guidelines deal with the lane overflow problem, but they do not consider the lane blockage problem. AASHTO (*1*), however, states that blockage of the entrance to the left-turn lane should be considered when designing the turning lane. In the following, four of the existing guidelines are discussed.

1. AASHTO (*1*) suggests that the lane length should be 1.5 to 2 times the average number of vehicles that would store during one cycle.
2. NCHRP (*2*) presents a chart that is based on 2 times the average number of arrivals during one signal cycle. From a probabilistic standpoint these two guidelines do not provide a uniform standard of design. It can be easily shown that, other factors remaining constant, the probability that the lanes (designed according to the above guidelines) will overflow reduces as arrival rate increases. In other words, one would be overdesigning when arrival rates are high and underdesigning when arrival rates are low.
3. The Ontario Ministry of Transportation (*3*) offers slightly different standards. The lane length is calculated to store the average number of arrivals per cycle 95 percent of the time. In other words, the probability of lane overflow should be less than 0.05. This, although more specific than AASHTO and NCHRP guidelines, has some shortcomings. The suggested lane length is no longer valid if the existing protected phase length is less than the phase length obtained from the guideline for the existing left-turn volume and cycle length.
4. The *Highway Capacity Manual* (*4*) presents a relationship between left-turn flow rate and the required left-turn lane length based on a 0.05 threshold probability of overflow. This relationship appears also in an article by Messer and Fambro (*5*). They suggest a left-turn lane length that accounts for the average number of vehicles that remain at the end of the left-turn green phase as well as the average number of left-turn vehicles that arrive during the red time. This approach, though more comprehensive than the others, does

not include detailed analysis of lane entrance blockage by the through vehicles.

NATURE OF THE PROBLEM AND APPROACH

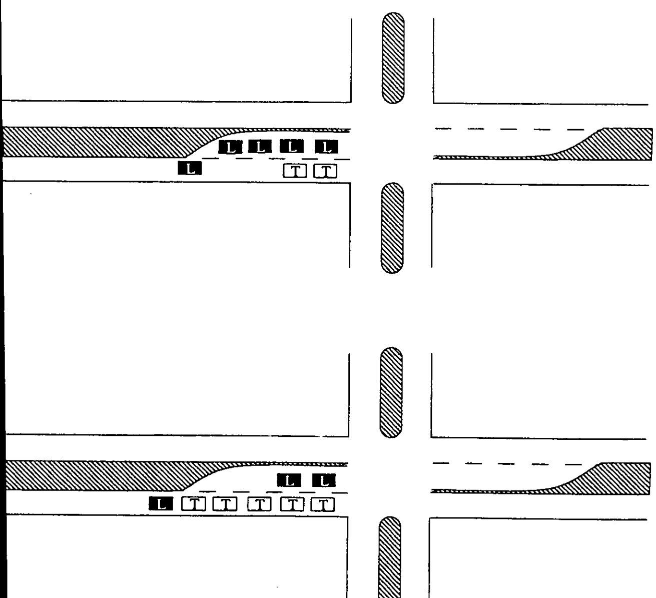
The problem is to determine the adequate length of a single left-turn lane at a signalized intersection. Inadequate lane length results in two cases: (*a*) lane overflow and (*b*) blockage of the access to the left-turn lane by the queue of through vehicles on the adjacent through lane. These situations are illustrated in Figure 1.

The causes of these cases are different. The overflow problem is heavily dependent on left-turn volume, protected phase duration, cycle length, opposing volume (if permitted phase is present), and the layout of the intersection; these factors affect the arrival and service rates of left-turning vehicles. The blockage problem is influenced more by through-vehicle volume and through red time.

Not only are the causes different, but two problems adversely affect two different populations. The overflow problem affects the smooth flow of through vehicles, whereas blockage generally increases the delay and frustration experienced by left-turning vehicles. Later, we will discuss the relative importance of these two problems.

In this paper a probabilistic approach is used to develop recommendations for left-turn lane length. The number of vehicles that arrive at an intersection and the pattern in which they arrive are assumed to be random. The implication of any probabilistic modeling is that the design is never foolproof; in other words, no matter how long the lane is, there is always a chance that the queue length will exceed the lane length. Thus, a threshold value of probability that indicates the tolerable frequency of failure is used to set the guidelines. The suggested procedure for developing the recommended length of the left-turn lane involves the following steps:

1. Determine the values of the threshold probabilities (the tolerable frequency of occurrence) of lane overflow and lane entrance blockage.
2. Identify the values of all input parameters, including cycle length, signal phasing, turning volume, through volume, and so forth.
3. Compute the necessary lane lengths by the proposed model. The lengths are given in number of vehicles.
4. Take the maximum of the two lane lengths (in number of vehicles) for the two cases (lane overflow and lane blockage) as the recommended lane length.
5. Determine the lane lengths in distance by multiplying the recommended lane length in number of vehicles by the factor that takes the length of the vehicles and the vehicle mix into account.



IGURE 1 Lane overflow and blockage of lane entrance at a ignalized intersection.

FACTORS THAT AFFECT LENGTH OF THE LEFT-TURN LANE

The major factors affecting the length of the left-turn lane are as follows:

- Traffic volumes—left-turn, through, and opposing;
- Vehicle mix—percentage of trucks, buses, recreational vehicles, and passenger cars;
- Signal timing—cycle length and phase length, protected phase, and permitted phase;
- Time required to make a left turn; and
- Space requirement for a standing vehicle (vehicle length and the gap between vehicles).

Traffic Volumes

The effect of left-turn volume on left-turn lane length is obvious. The through volume affects the lane length requirements because the queue of through vehicles on the lane adjacent to the left-turning lane may prevent left-turning vehicles from entering the lane. The opposing volume affects the requirements for the left-turn lane length if the signal phases include a permitted phase for the left-turn movement.

Vehicle Mix

The type and the mix of the vehicles influence the required length, both from the lane overflow and the lane blockage standpoints. Obviously, a large proportion of trucks will increase the probability of lane overflow for a given lane length. The probability of lane blockage also increases if the proportion of trucks in the through flow is large. Furthermore, the time required to make the turning movement differs with the vehicle type. Therefore, vehicle mix is relevant to the analysis of left-turn lane length. (In this paper, the analysis and the models are based on the number of vehicles. The vehicle mix is taken into account when the length, expressed as the number of vehicles, is converted to the actual distance.)

Signal Phases and Cycle Length

The number of vehicles that accumulate in the left-turn lane depends on the signal phases and the cycle length. It also depends on whether the left turn is protected. The number of vehicles that accumulate on the through lane depends on the duration of the red phase on the through movement. Generally, the longer the cycle length, the greater the number of vehicles that accumulate, and the longer the left-turn lane required. Thus, if the space for building the left-turn lane is limited, the signal timing should be adjusted to keep the probability of lane overflow and lane blockage below an acceptable level.

Time Required To Make a Left Turn

This time affects the maximum number of left turns that can be made during a protected phase. If T is the time required by a passenger car to complete a left-turn maneuver, RT is the perception/reaction time of the first vehicle in the queue (that is, the time gap between the signal changing to green and the first vehicle starting to move), and D is the duration of the protected green, the maximum number of left-turns, m, that can be made during D is

$$m = \text{nearest integer to } \left(\frac{D - RT}{T}\right) \quad (1)$$

The values of RT and T were determined through a field survey by video recording. The average value obtained is 2.66 sec for RT and 2.42 sec for T. These values were obtained from the following equation derived through linear regression:

$$\Delta = 2.66 + 2.423 \times (\text{total number of vehicles that made the turn}) \quad (2)$$

where Δ is the time between the onset of green and the moment when the last vehicle (that completed the left turn) initiated the turn. The R^2 value for this regression equation is 0.92. The data were collected at an intersection where the left-turn movement crosses two opposing lanes.

Space Requirement per Vehicle

The total space a vehicle requires when it is stopped on the lane is important in determining the necessary lane length. The space includes the space for the vehicle itself and the additional buffer space that a vehicle requires before it. The space required per average passenger car is estimated to be 7 m on the basis of 35 sets of observations. Queue length in the observations varied between 3 and 12 vehicles.

THE MODELS

Model for Determining the Lane Length from the Lane Overflow Standpoint

Figure 2 shows the patterns of cumulative arrivals (Line 1) and departures for the case of permitted and nonpermitted green phase (Lines 2 and 3, respectively). The queue length is represented by the vertical distance between Lines 1 and 2 and Lines 1 and 3, for permitted and nonpermitted green phases, respectively.

Assuming that the arrivals of left-turn vehicles are random, we model the fluctuation of the number of left turns in the queue at the beginning of each protected green phase (i.e., points at A, A + C, A + 2C, etc.) as a Markov process.

Assumptions

The assumptions used in the model are as follows:

1. Arrivals of left-turn vehicles are random and follow a Poisson distribution.
2. The signal phases are pretimed and thus the cycle time is constant. It includes a protected left-turn phase.
3. The maximum number of vehicles that can make left turns during the permitted phase, s, is calculated using the following equation adapted from Equation 9-22 of the 1985 HCM (*4*):

$$s = \max\left[\frac{(1{,}400 - v_o)g}{3{,}600}, 2\right] \quad (3)$$

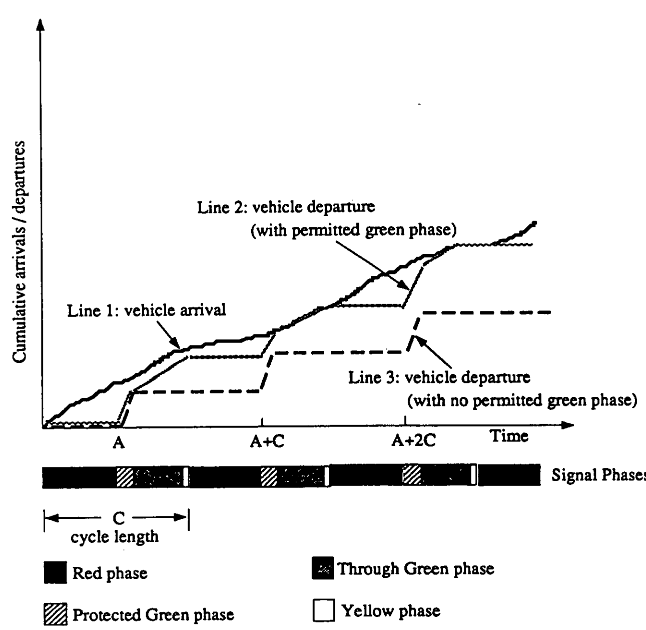


FIGURE 2 Cumulative arrival and departure processes on a left-turn lane.

where v_o is the opposing through plus right-turn volume in vph and g is the effective green time for the permitted phase.

4. The mean arrival rate of left turns is less than the capacity of the intersection to handle such movements (i.e., $\lambda_\ell C < (m + s)$, where λ_ℓ is the arrival rate of left-turn vehicles, C is the cycle length of the intersection, and m is the maximum number of vehicles that can make left turns during the protected green time). That is, the queue length will not become infinity.

5. The number of vehicles on the left-turn lane is likely to be a maximum at the beginning of the protected phase. Hence, the time points considered for the Markov process are A, A + C, A + 2C, . . . (see Figure 2). A is the beginning of the protected green phase.

Markov Chain Formulation

The system is defined in terms of states and time points. The states are the number of vehicles waiting to make a left turn at time points of analysis (i.e., A, A + C, A + 2C, . . .). The following variables are used:

- λ_ℓ is the arrival rate of left-turning vehicles in vehicles per second.
- **P** is the one-step transition probability matrix representing the probability of a change in queue length (in number of vehicles) from one time point to the next (for example, from A + C to A + 2C).
- p_{ij} are elements of **P**.
- p_α^D is the probability that α vehicles arrive during D, where D is the duration of protected green in seconds.
- p_α^R is the probability that α vehicles arrive during R, where R is the duration of protected green in seconds.
- p_α^C is the probability that α vehicles arrive during C, where C is the cycle length in seconds.
- Π is the vector $\{\pi_0, \pi_1, \pi_2, \pi_3, \ldots\}$, where π_i, $i = 0, 1,$ 2, 3, . . . , is the probability that i vehicles are waiting in the queue at one time point.
- m is the maximum number of left turns that can be made during one protected phase.
- s is the maximum number of vehicles that can turn left during one permitted phase.

Note that under the Poisson arrival with mean arrival rate of λ_ℓ, p_α^D, p_α^R, and p_α^C are given by

$$p_\alpha^\beta = \frac{(\lambda_\ell \beta)^\alpha e^{-\lambda_\ell \beta}}{\alpha!} \qquad (4)$$

where β is D, R, or C.

Matrix **P** is divided into three submatrices (I, II, and III), as shown in Figure 3. Submatrix I represents the case in which the number of vehicles waiting to make a left turn (just before the start of the protected phase), i, is less than the maximum number of vehicles that can make the turn during the protected phase, m. Submatrix II represents the case in which i is greater than or equal to m but less than or equal to $m + s$, where $m + s$ is the total number of turns that can be made during the whole cycle. Submatrix III represents the case in which i is greater than the total number of turns that can be made during the whole cycle, that is, $i > m + s$. The individual elements p_{ij} of each submatrix are given below.

	0 1 . . m-1 m . m+s m+s+1 . .
0 1 . . m-1	Submatrix I
m . m+s	Submatrix II
m+s+1 . . .	Submatrix III

FIGURE 3 One-step transition matrix P.

Submatrix I applies when $i < m$. If $s > 0$,

$$p_{ij} = \begin{cases} \sum_{k=0}^{m-i} p_k^D \cdot \sum_{k=0}^{s} p_k^R + \sum_{\ell=1}^{s} \left(p_{m-i+\ell}^D \cdot \sum_{k=0}^{s-\ell} P_k^R \right) & \text{if } j = 0 \\ \sum_{k=0}^{m-i} P_k^D \cdot P_{j+s}^R + \sum_{\ell=0}^{j+s-1} p_\ell^R \cdot p_{m-i+j+s-\ell}^D & \text{if } j > 0 \end{cases} \qquad (5)$$

If $s = 0$,

$$p_{ij} = \begin{cases} p_0^R \cdot \sum_{k=0}^{m-i} p_k^D & \text{if } j = 0 \\ \sum_{k=0}^{m-i} P_k^D \cdot p_j^R + \sum_{\ell=0}^{j-1} p_\ell^R \cdot p_{m-i+j-\ell}^D & \text{if } j > 0 \end{cases} \qquad (6)$$

Submatrix II applies when $m \leq i \leq m + s$.

$$p_{ij} = \begin{cases} \sum_{k=0}^{m+s-i} p_k^C & \text{if } j = 0 \\ p_{m+s-i+j}^C & \text{if } j > 0 \end{cases} \qquad (7)$$

Submatrix III applies when $i > m + s$.

$$p_{ij} = \begin{cases} 0 & \text{if } j < i - (m + s) \\ p_{m+s-i+j}^C & \text{if } j \geq i - (m + s) \end{cases} \qquad (8)$$

In the following the derivation of the elements of the Submatrix I is explained using p_{i0}, the probability of finding 0 vehicles in the queue at the next time point given that there are i vehicles in the queue at the current time point, as an example.

p_{i0} = Prob{(at most $m - i$ vehicles arrive during the protected green D
and at most s vehicles arrive during the permitted phase, R),
or
($m - i + 1$ vehicles arrive during the protected green D
and $s - 1$ vehicles arrive during the permitted phase, R),

or
($m - i + 2$ vehicles arrive during the protected green D
and $s - 2$ vehicles arrive during the permitted phase, R)
or . . .
($m - i + s$ vehicles arrive during the protected green D
and 0 vehicles arrive during the permitted phase, R)}.

To calculate the limiting distribution of this Markov chain, we define an arbitrarily large number, ψ, as the upper bound of the queue length (the value of ψ is selected such that in the steady state, $\pi_\psi \approx 0$). In this case the matrix **P** becomes a $\psi \times \psi$ matrix. The elements $p_{i\psi}$ of the transition matrix now become $p_{i\psi} = 1 - \Sigma_{j=0}^{\psi-1} p_{ij}$, where p_{ij} is given by the expressions defined earlier. The conditions for **P** to be a regular transition matrix are satisfied; thus, a limiting distribution exists.

Determining the Probability of Lane Overflow

As the system reaches the steady state (in other words, the pattern of vehicle arrivals and departures is stable), the probability that a given number of vehicles exists in the lane in each time point can be computed using the following steady state equation of the Markov chain:

$$\mathbf{\Pi}\,\mathbf{P} = \mathbf{\Pi} \tag{9}$$

where $\mathbf{\Pi}$ is a vector and each of its elements $\{\pi_0, \pi_1, \pi_2, \pi_3, \ldots, \pi_\psi\}$ represents the steady-state probability of a given queue length existing in the left-turn lane. This equation indicates that the system is the same (in terms of probability of its states) at two adjacent points. By solving the equation with respect to $\mathbf{\Pi}$, the probability of a given number of vehicles in the lane is obtained. Therefore, $1 - \Sigma_{i=0}^{N} \pi_i$ is the probability that the number of vehicles in the lane is greater than N.

Required Lane Length from Lane Overflow Standpoint

Given the tolerable probability of overflow, τ_1, the recommended length of the lane in vehicles, N^* is obtained by

$$N^* = \min\left\{N \mid \left(1 - \sum_{i=0}^{N} \pi_i\right) \leq \tau_1\right\} \tag{10}$$

Model for Determining the Lane Length from the Lane Blockage Standpoint

This section develops a model that determines the required lane length on the basis of the probability that the entrance to the left-turn lane is blocked by the queue of through vehicles on the adjacent lane. The assumptions, formulation of the model, and calculation of the probability are presented, and they are followed by the required lane length for this case.

Description of the System and Assumptions

Given a left-turn lane length of N vehicles, the event of interest is the following: the number of vehicles in the left-turn lane is less than N, but more than N through vehicles are already waiting on the adjacent through lane, and a left-turning vehicle arrives. In this case the left-turn vehicle cannot enter the partially occupied turning lane. We will refer to this event as blockage of a left-turn lane of length N vehicles and its probability is denoted $P_B(N)$:

$P_B(N)$ = Prob{number of through vehicles $\geq N$, and the number of left-turning vehicles already in the lane $< N$, and a left-turn vehicle arrives}.

The basic assumptions made here are the same as those made for the overflow conditions. An additional assumption is that all the left-turning and through vehicles that accumulate during their red phases clear during the immediately following green phases. Also, the arrival process of through vehicles is assumed to follow a Poisson distribution with mean arrival rate of λ_t.

Model Formulation and Analysis

The probability $P_B(N)$ can be rephrased as the probability of blockage when the left-turn lane length is sufficient to store at most N vehicles. Using the ideas of conditional probability we can write $P_B(N)$ as

$$p_B(N) = \sum_{L=1}^{\infty} \sum_{T=N}^{\infty} p_N^{(T,L)} \tag{11}$$

where

$p_N^{(T,L)}$ = P{blockage occurs|L turning vehicles, T through arrived} $P_L P_T$,
P_L = P {L left turns arrive during the through red R} and
P_T = P {T throughs arrive during the through red R}.

Note that the summation for T in Equation 11 is from N to ∞, because if the total number of through vehicles that arrive while the through phase is red is less than N, blockage cannot occur. In the following, the probability of lane blockage is derived by enumerating the different combinations of T, N and L that will cause a blockage

For $L = 1$,

$$p_N^{(T,1)} = \left\{\prod_{i=0}^{N-1} \frac{T - i}{\phi - i}\right\} \cdot \mathcal{F}(T, 1) \tag{12}$$

For $1 < L \leq N$,

$$P_N^{(T,L)} = \left\{ \prod_{i=0}^{N-1} \frac{T-i}{\phi - i} + \sum_{k=1}^{L-1} \binom{N}{k} \prod_{i=0}^{N-1} \frac{T-i}{\phi - i} \cdot \prod_{i=N}^{N+k-1} \frac{L-(i-N)}{\phi - i} \right\} \cdot \mathcal{F}(T, L) \quad (13)$$

For $L > N$,

$$P_N^{(T,L)} = \left\{ \prod_{i=0}^{N-1} \frac{T-i}{\phi - i} + \sum_{k=1}^{N-1} \binom{N}{k} \prod_{i=0}^{N-1} \frac{T-i}{\phi - i} \cdot \prod_{i=N}^{N+k-1} \frac{L-(i-N)}{\phi - i} \right\} \cdot \mathcal{F}(T, L) \quad (14)$$

where

$$\mathcal{F}(T, L) = P_T \cdot P_L = \frac{(\lambda_t \mathrm{R})^T e^{-\lambda_t \mathrm{R}}}{T!} \cdot \frac{(\lambda_\ell \mathrm{R})^L e^{-\lambda_\ell \mathrm{R}}}{L!}$$

$\phi = T + L$;
T = total number of through vehicles that arrive during the through red, R; and
L = total number of left-turn vehicles that arrive during the through red, R.

Required Lane Length from Lane Blockage Standpoint

Given the tolerable probability of lane blockage, τ_2, the required length in vehicles from the lane blockage standpoint, N^{**}, is calculated by

$$N^{**} = \min\{N \mid P_{\mathrm{B}}(N) \leq \tau_2\} \quad (15)$$

RECOMMENDED LENGTHS OF LEFT-TURN LANE

Recommended Lengths in Number of Vehicles

Here we present a set of tables that show the required length (in number of vehicles) of a left-turn lane for different combinations of volumes and signal conditions. The required lengths are presented separately for the prevention of lane overflow and the prevention of blockage of lane entrance. Tables 1 to 3 are for the lane overflow consideration; each table corresponds to a different value of s. Table 4 is for the blockage of lane entrance consideration.

For a given set of conditions, the user first obtains the required lane lengths for the two cases separately and then adopts the greater of the two values for design. That is,

Recommended lane length in number of vehicles,

$$\mathrm{RN}, = \max [N^*, N^{**}] \quad (16)$$

where N^* is obtained from Tables 1 to 3 and N^{**} is obtained from Table 4.

The tables are based on the following assumptions:

- The vehicle arrival pattern for both left-turn and through vehicles follows the Poisson distribution,
- The threshold probability (tolerable frequency of occurrence) for overflow is $\tau_1 = 0.02$, and
- The threshold probability (tolerable frequency of occurrence) for lane blockage is $\tau_2 = 0.10$.

The values of τ_1, τ_2, and other parameters are chosen to develop the tables provided here. For conditions other than the ones provided, a new set of tables should be developed using the models and considering practical and site-specific

TABLE 1 Recommended Lane Length at Signalized Intersections, Overflow Consideration: Probability of Overflow < 0.02; Number of Vehicles During Permitted Phase = 0/cycle

Left Turn Volume (vph)	Cycle Time (in seconds)															
	90				120				150				180			
	Green Time (sec.)				Green Time (sec.)				Green Time (sec.)				Green Time (sec.)			
	10	15	20	25	10	15	20	25	10	15	20	25	10	1 5	20	25
50	4	4	3	3	5	4	4	4	7	5	5	5	13	6	6	6
70	5	4	4	4	10	6	5	5	38	7	6	6	-	9	7	7
90	9	5	5	5	-	7	6	6	-	10	8	7	-	22	9	8
110	24	6	6	5	-	10	7	7	-	25	9	8	-	-	13	10
130	-	8	6	6	-	17	8	8	-	-	12	10	-	-	30	12
150	-	10	7	7	-	-	10	9	-	-	22	11	-	-	-	17
170	-	15	8	7	-	-	14	10	-	-	-	14	-	-	-	35
190	-	34	9	8	-	-	24	11	-	-	-	21	-	-	-	-
210	-	-	11	9	-	-	-	13	-	-	-	-	-	-	-	-
230	-	-	14	9	-	-	-	18	-	-	-	-	-	-	-	-
250	-	-	21	10	-	-	-	30	-	-	-	-	-	-	-	-

Note 1: "-" indicates that the required pocket becomes infinitely long for the combination of parameters.
Note 2: For conversion to length in meters under different vehicle mix, see the section on Recommended Lengths in Actual Distance.

TABLE 2 Recommended Lane Length at Signalized Intersections, Overflow Consideration: Probability of Overflow < 0.02; Number of Vehicles During Permitted Phase = 2/cycle

Left Turn Volume (vph)	Cycle Time (in seconds)															
	90				120				150				180			
	Green Time (sec.)				Green Time (sec.)				Green Time (sec.)				Green Time (sec.)			
	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
50	2	2	1*	1*	3	2	2	2	3	3	3	3	4	4	4	4
70	3	2	2	2	4	3	3	3	5	4	4	4	7	5	5	5
90	3	3	3	3	5	4	4	4	8	6	5	5	20	7	7	6
110	4	4	4	3	8	6	5	5	24	8	7	6	-	11	8	8
130	6	5	4	4	15	7	6	6	-	11	8	7	-	28	10	9
150	8	5	5	5	-	9	7	7	-	20	10	9	-	-	15	11
170	13	6	6	5	-	12	8	7	-	-	12	10	-	-	34	13
190	34	7	6	6	-	22	9	8	-	-	19	11	-	-	-	19
210	-	9	7	6	-	-	12	9	-	-	39	14	-	-	-	37
230	-	12	8	7	-	-	16	10	-	-	-	20	-	-	-	-
250	-	20	9	7	-	-	28	12	-	-	-	35	-	-	-	-

Note 1: "-" indicates that the required pocket becomes infinitely long for the combination of parameters.

Note 2: For conversion to length in meters under different vehicle mix, see the section on Recommended Lengths in Actual Distance.

Note 3: "*" It should be noted that the values are obtained from the models for the given input values, and thus, they should be adjusted with practical and site specific considerations. In particular, the lengths less than 2 vehicles (marked by *) should not be used for most conditions.

TABLE 3 Recommended Lane Length at Signalized Intersections, Overflow Consideration: Probability of Overflow < 0.02; Number of Vehicles During Permitted Phase = 3/cycle

Left Turn Volume (vph)	Cycle Time (in seconds)															
	90				120				150				180			
	Green Time (sec.)				Green Time (sec.)				Green Time (sec.)				Green Time (sec.)			
	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
50	1*	1*	0*	0*	2	1*	1*	1*	2	2	2	2	3	3	3	3
70	2	1*	1*	1*	3	2	2	2	4	3	3	3	5	4	4	4
90	2	2	2	2	4	3	3	3	5	5	4	4	8	6	6	5
110	3	3	3	2	5	4	4	4	9	6	6	5	24	8	7	7
130	4	4	3	3	7	5	5	5	20	8	7	6	-	12	9	8
150	5	4	4	4	12	7	6	6	-	11	8	7	-	31	11	9
170	7	5	5	4	32	8	7	6	-	19	10	9	-	-	16	11
190	9	6	5	5	-	11	8	7	-	-	12	10	-	-	35	14
210	16	7	6	5	-	17	9	8	-	-	19	11	-	-	-	20
230	36	8	6	6	-	36	11	9	-	-	37	14	-	-	-	38
250	-	10	7	6	-	-	14	10	-	-	-	19	-	-	-	-

Note 1: "-" indicates that the required pocket becomes infinitely long for the combination of parameters.

Note 2: For conversion to length in meters under different vehicle mix, see the section on Recommended Lengths in Actual Distance.

Note 3: "*" It should be noted that the values are obtained from the models for the given input values, and thus, they should be adjusted with practical and site specific considerations. In particular, the lengths less than 2 vehicles (marked by *) should not be used for most conditions.

factors. In particular, lengths less than two vehicles (marked by asterisks in Tables 1 to 3) should not be used for most conditions.

Recommended Lengths in Actual Distance

The analysis so far refers to the required or recommended lane length in number of vehicles. This value should be converted to the actual lane length in meters by taking the vehicle length and the buffer distance between vehicles into account. In this conversion the effect of large vehicles must be considered because a large vehicle not only requires a longer space but also takes more time to complete the turning movement

The first point is obvious, and we have developed passenger car equivalency factors that account for the difference in siz between a large vehicle and a passenger car on the basis o AASHTO's standard (*1*) on vehicle lengths. Their values ar given in the following table:

Vehicle Type	*Symbol*	*Equivalency Factor*
Passenger car	E_{pc}	1.0
Bus	E_B	2.1
Truck	E_T	2.9
Recreational vehicle	E_{RV}	2.2

TABLE 4 Recommended Left-Turn Lane Length in Number of Vehicles, Blockage Consideration: Probability of Blockage < 0.1

Left-Turn Volume (vph)	Duration of Through Red = 45 seconds, Through Volume (in vphpl)								Duration of Through Red = 60 seconds, Through Volume (in vphpl)							
	500	600	700	800	900	1000	1100	1200	500	600	700	800	900	1000	1100	1200
50	6	7	8	9	10	11	13	14	9	10	12	13	14	16	17	19
75	7	8	9	10	12	13	14	15	9	11	13	14	16	17	19	20
100	8	9	10	11	12	13	14	16	10	11	13	15	16	18	19	*
125	8	9	10	11	13	14	15	16	10	12	13	15	17	18	20	*
150	8	9	10	12	13	14	15	16	10	12	14	15	17	19	20	*
175	8	9	11	12	13	14	16	17	10	12	14	15	17	19	20	*
200	8	9	11	12	13	14	16	17	10	12	14	15	17	19	*	*
225	8	9	11	12	13	15	16	17	10	12	14	15	17	19	*	*
250	8	9	11	12	13	15	16	17	10	12	14	15	17	19	*	*
Left-Turn Volume (vph)	**Duration of Through Red = 75 seconds, Through Volume (in vphpl)**								**Duration of Through Red = 90 seconds, Through Volume (in vphpl)**							
	500	600	700	800	900	1000	1100	1200	500	600	700	800	900	1000	1100	1200
50	11	13	15	17	18	20	*	*	13	16	18	20	*	*	*	*
75	12	14	16	18	20	*	*	*	14	16	19	*	*	*	*	*
100	12	14	16	18	20	*	*	*	14	17	19	*	*	*	*	*
125	12	14	17	19	20	*	*	*	15	17	20	*	*	*	*	*
150	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
175	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
200	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
225	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
250	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*

Note 1: "*" indicates that the required lane length is large. A better way of dealing with the blockage problem may be changing the signal time. In most of these cases the value from this table will not be critical, since required lane length from overflow consideration will be greater.

Note 2: For conversion to length in meters under different vehicle mix, see the section on Recommended Lengths in Actual Distance.

The recommended lane length in meters, RL, is computed as follows:

$$RL = RN \times \xi \times K \quad (17)$$

where K is the required length per passenger car and ξ is computed as follows:

$$\xi = 1 + (E_B - 1)\,\mathrm{Prop}_B + (E_T - 1)\mathrm{Prop}_T + (E_{RV} - 1)\mathrm{Prop}_{RV} \quad (18)$$

where Prop_B, Prop_T, and Prop_{RV} are proportions of buses, trucks, and recreational vehicles in the left-turning volume, respectively. The values of E_B, E_T, and E_{RV} are taken from the preceding table. The required length per passenger car, K, is found to be 7 m from the survey. This distance includes the buffer. Thus, given the vehicle mix, the recommended lane length is RN $\times\ \xi \times$ 7 (meters).

The second aspect, the effect of the longer turning time for a large vehicle, requires further research. The maximum number of left turns that can be made during the protected phase, n, should decrease as the proportion of large vehicles in the left-turning volume increases. It is our belief that the value of RN will not increase by more than two vehicles because of the excess turning time of large vehicles under normal conditions.

ISSUES

This section discusses issues that must be taken into account in determining left-turn lane lengths and some issues that need further research.

Significance of Lane Overflow and Blockage of Lane Entrance

A decision on the criterion, lane overflow or blockage of lane entrance, depends on which of the movements, turning or through, is the primary flow. In most intersections, the through volume is much greater than the turning volume (although the percentage of turning movements is steadily increasing in many suburban intersections). Thus, frequent disturbances in the movement of through vehicles are not desirable. Such disturbances are caused when turning vehicles overflow into the through lane. The blockage of the entrance of the left-turn lane, on the other hand, affects mainly the flow of turning vehicles.

The basic difference in dealing with these two cases is as follows. If through vehicles are of primary importance, lane overflow becomes the more serious of the two problems, and thus this condition should be prevented. If, on the other hand, the turning movements are of primary importance, the lane blockage is the more serious problem. Thus, the threshold probabilities of overflow and lane blockage should be set according to these priorities. In developing Tables 1 to 4, primary importance has been given to the smooth flow of the through vehicles. In other words, the value of τ_1 is assumed to be much smaller than the value of τ_2 ($\tau_1 = 0.02$, $\tau_2 = 0.1$).

Selection of Threshold Probabilities

In selecting the values of the threshold probability, many factors must be taken into account, including economic, capacity, safety, and site-specific conditions. The required length is sensitive to the threshold probability; a small decrease in the value will result in a substantial increase in the length of the lane (and thus an increase in the cost of construction). A value between 0.01 and 0.02 has been used for justifying a left-turn lane at an unsignalized intersection (*6*). Both the HCM and the Ontario Ministry of Transportation guidelines use 0.05.

Comparison with the Results Obtained from NETSIM

In our model of lane blockage, we have assumed that all vehicles in the queue clear in each cycle. Reasonableness of this assumption is checked using a simulation model. For this purpose NETSIM, a network simulation model supported by FHWA, was used to simulate the blockage condition. Since NETSIM does not provide information on the probability of events, the frequency of blockage was observed by running NETSIM 100 times for a given set of traffic parameters. This was performed for 10 sets of parameters. For each of the sets of parameters, Table 5 provides the results from NETSIM of the required lane length such that the frequency of blockage is less than 10 percent. The table also provides the value of N^{**}, the required lane length from the proposed model of blockage. As can be seen, the results from the proposed lane blockage model and NETSIM are in agreement except for one case, where the difference is one vehicle.

Comparison with Existing Guidelines

The result of the proposed model is compared with those of the existing guidelines, namely AASHTO (*1*) and HCM (*4*), for the same input conditions. Figure 4 shows the suggested lane lengths for the three cases: the proposed model, HCM, and AASHTO, for different left-turn volumes. The assumed range of values for the input parameters are as follows: left-turn protected green = 10 to 25 sec, no permitted phase, cycle length = 90 sec, through red time = 45 sec, through volume = 500 to 800 vphpl, probability of overflow ≤ 0.05, and probability of blockage ≤ 0.1.

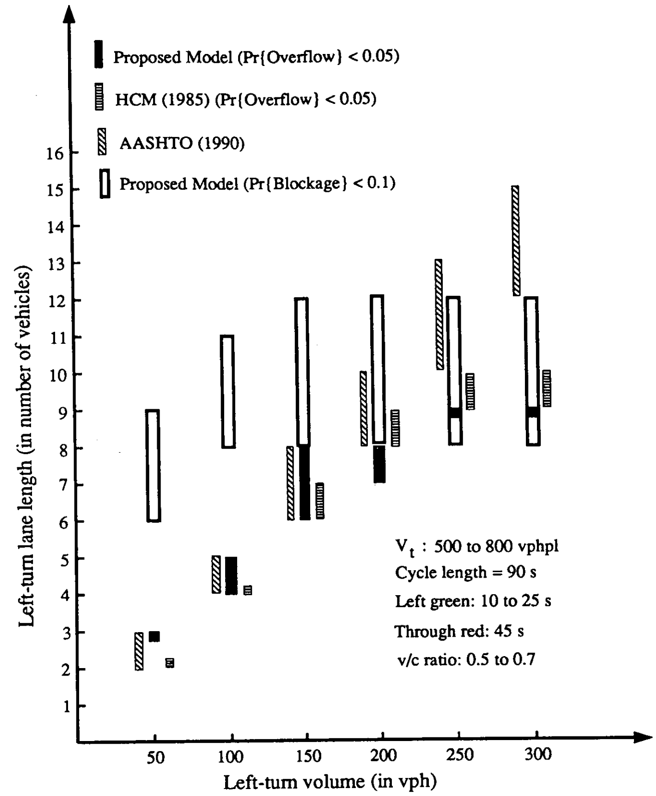


FIGURE 4 Comparison of proposed model with existing guidelines.

These assumed values of through volume and through red time are used only for our blockage model. To use the HCM guidelines, the v/c ratio for the left-turn movement is required. The v/c ratio corresponding to the above set of input parameters is between 0.5 and 0.7; thus this range of v/c is used when calculating the length on the basis of HCM guidelines.

The AASHTO and HCM guidelines are derived from the standpoint of preventing overflow of the left-turn lane only. Therefore, we first compare the result of our proposed overflow model with those of AASHTO and HCM. Figure 4 shows

TABLE 5 Comparison of NETSIM with Proposed Model Results

Spot Check Point			NETSIM Results			Proposed
LT. Vol.	Thru' Vol.	Thru' Red	L / P	L / P	RL	Model: RL
50	500	45	5 / 0.11	6 / .03	6	6
50	1000	45	10 / 0.18	11 / 0.09	11	11
90	800	45	10 / 0.1	11 / 0.06	11	11
150	1000	45	13 / 0.22	14 / 0.08	14	14
190	700	45	10 / 0.15	11 / 0.06	11	11
50	900	60	13 / 0.1	14 / 0.04	14	14
70	500	60	7 / 0.18	8 / 0.08	8	9
110	800	60	14 / 0.2	15 / 0.1	15	15
150	700	60	13 / 0.1	14 / 0.02	14	14
50	500	75	10 / 0.12	11 / 0.05	11	11

L / P : Probability of Blockage= P when lane length (in number of cars)= L
RL : Recommended lane length in number of vehicles.

Note 1: RL listed under Proposed model is the value of N^{**} obtained from Equation 15.
Note 2: RL listed under NETSIM model is the required length derived from simulation, such that frequency of blockage is less than 10%.

that the recommended length based on AASHTO is longer than that based on the other two models, and the difference increases as the left-turn volume increases. The results from our proposed model and the HCM model are close for most values of left-turn volume. However, in addition to the lane overflow, when the lane blockage is considered, the recommended lane lengths (indicated by the hollow bars) are considerably different from the existing AASHTO and HCM guidelines (which are based solely on overflow consideration).

The comparison suggests that for a small left-turn volume, attention should be paid to the possibility of lane blockage, whereas for a large left-turn volume, attention should be given to the possibility of lane overflow. This analysis emphasizes that the length of a left-turn lane is influenced by both overflow and blockage conditions.

CONCLUSIONS

This study has developed a methodology to determine the ength of the left-turn lane at signalized intersections. Two ases are considered: (*a*) the left-turning vehicles from the urning lane overflow onto the adjacent through lane and (*b*) he queue of through vehicles prevents the left-turning venicles from entering the turning lane. The parameters affectng each case are identified, and models that compute the robabilities that these cases occur are developed. A set of ables of recommended lane lengths is presented on the basis of threshold probabilities that limit the occurrence of these ases.

In addition to developing the lane lengths, the models can be used to evaluate the conditions of the existing intersections. The probabilities of lane overflow and lane entrance blockage can be computed for the existing conditions. Furthermore, alternative ways of mitigating these cases can be evaluated. For example, the appropriate signal timing, when available space for the storage lane is limited, can be analyzed.

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