Lengths of Left-Turn Lanes at Unsignalized Intersections

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The required length of left-turn lanes at unsignalized intersections of two-lane roadways is analyzed, and recommended lengths are presented for different conditions. Increasing volumes of turning movements along suburban roadways due to residential and commercial developments warrant an analysis of the adequate length of turn lanes. The existing guidelines and standards for determining lane lengths at unsignalized intersections are incomplete, and the practices of various state agencies are not uniform. A model is developed which calculates the probability that a given length of turning lane will result in overflows. Lane lengths are suggested such that the probability of lane overflow is less than a given threshold value. The parameters considered in the model are the volume of turning vehicles, volume of opposing vehicles, critical gap, threshold probability, and vehicle mix. The validity of the model is checked by computer simulation. The recommended lengths are compared with lengths suggested by AASHTO, and the effects of considering opposing volume and changing the values of the threshold probability are discussed. The results of a field survey on the required space per vehicle in the turn lane are also presented. Recommended lane lengths for various conditions are presented in a set of tables.

As residential and commercial developments proliferate in the suburbs, turning movements, particularly left-turns into and out of minor roadways, are posing significant negative effects on traffic flow and safety of major roadways. A procedure to compute the adequate length of left-turn lanes on major roads at unsignalized intersections is presented. This study was conducted as a part of a series of examinations by the authors of the guidelines on channelization of intersections (*1*,*2*).

Although the issue of adequate lane length is critical for highway planning, little has been done to develop a consistent volume-based criterion for its selection. Neither AASHTO (*3*) nor the Highway Capacity Manual (*4*) (HCM) provide any definitive guidelines for the selection of lane length. A survey of several states indicates that practices differ widely across the country: some states follow very simple ad hoc criteria, while others use the rigid guide suggested by Harmelink (*5*).

In studying left-turning movements at unsignalized intersections, two questions arise:

1. Is a separate left-turn lane warranted?
2. If it is warranted, what should be the length of the lane?

The work presented addresses the second question. The first question has been dealt with in detail by Kikuchi and Chakroborty (*1*).

The following sections include: a review of existing procedures and practices; identification of the factors relevant to the determination of the length of left-turn lane; analysis of the queueing pattern of the turning vehicles using a generalized queueing model; validation of model results by simulation model; presentation of the suggested left-turn lane lengths; and discussion of the effects of changes in the input parameters with a comparison of the proposed model's results with previously suggested AASHTO values.

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PROBLEM STATEMENT AND APPROACH

Figure 1 shows an unsignalized intersection in which a major two-lane roadway intersects a minor road. The through traffic on the major road does not stop at the intersection, requiring left-turning vehicles on the major road to wait until a suitable gap is found in the opposing flow. The task is to determine the vehicle storage length L that minimizes the chance of lane overflow; the probability of overflow must be less than a specified threshold value. Lane length L is called the adequate lane length.

EXISTING GUIDELINES

Despite the importance of determining adequate lane length, guidelines for the left-turn lane length at unsignalized intersections have not been systematically compiled.

AASHTO (*3*) suggests the following procedure to calculate lane length: "the storage length, exclusive of taper, may be based on the number of turning vehicles likely to arrive in an average 2-min period within the peak hour." This procedure is obviously ad hoc, and AASHTO acknowledges this when it refers to the 2-min period as "somewhat arbitrary (*3*)." AASHTO recognizes that guidelines on left-turn lane length should be based on the turning as well as the opposing volume, but offers no specifics. NCHRP Report 279, *Intersection Channelization Design Guide* (*6*), also follows the AASHTO guidelines.

When their research revealed a lack of comprehensive guidelines on the subject the authors conducted a survey of various state departments of transportation regarding lane length. Of the fifty questionnaires that were sent out, 25 states responded. It was found that most states follow the rule-of-thumb approach to determine lane lengths. Some states, however, use the lane lengths suggested by Harmelink (*5*).

Harmelink provides a set of figures on recommended lengths for left-turn lanes in his 1967 study (*5*). The suggested lengths are derived based on the criterion that the probability of lane overflow be less than a given value. Harmelink considers most of the relevant factors in his model; however, his derivation suffers from critical errors in the mathematical treatment of probability, which undermine the validity of his recommendations. The shortcomings of Harmelink's derivation were discussed in detail by Kikuchi and Chakroborty (*1*).

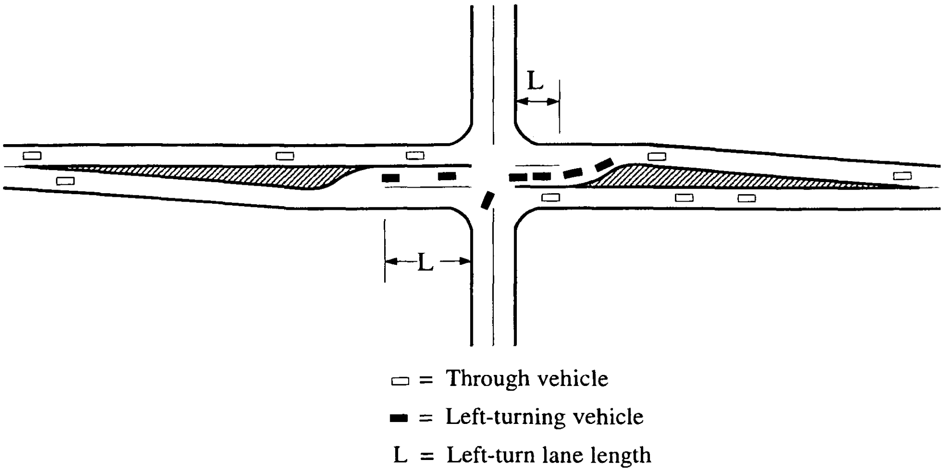


FIGURE 1 Schematic of unsignalized intersection with turning lanes.

Factors Considered in the Analysis

The major factors that must be considered when selecting the left-turn lane length at an unsignalized intersection are:

- Traffic volumes and vehicle mix: left-turn, through, and opposing volume, and composition of vehicle types,
- Critical gap size,
- Space requirement per vehicle, and
- Threshold probability.

Each of these factors is discussed in the following sections.

Traffic Volumes and Vehicle Mix

Left-turn volume is an obvious factor in selecting left-turn lane length. The opposing flow determines the frequency of gaps available to a left-turning vehicle. The type and mix of left-turning vehicles influences the required length in that (*a*) large vehicles require a longer space for storage and (*b*) they often take longer to complete the turn because of a lower acceleration rate and the need for careful maneuvering, which affects their critical gap size.

Critical Gap Size

Critical gap size is the minimum time headway in the opposing flow that is required for a driver to complete a left-turning maneuver. Its value (in seconds) is influenced by several factors, including geometric design, speed of approaching vehicle, dynamic characteristics of the turning vehicle, and driver characteristics. A longer critical gap results in fewer turning opportunities, and hence, the length of the queue increases.

The geometric design of the intersection affects the sight distance of the turning vehicle. The critical gap increases inversely with the available sight distance (*4*). The approach speed of the opposing vehicles also affects the critical gap size. Empirical research has shown that the critical gap size increases with increasing approach speed of the opposing vehicles (*4*). The HCM (*4*) provides guidelines, based on empirical findings, on the value of the critical gap size under different approach speeds and geometric designs. Values ranging from 5 to 7 sec are suggested and shown in Table 1.

Space Requirement Per Vehicle

The space a vehicle requires while standing affects the actual lane length required. The required space per vehicle includes the length of the vehicle and the buffer distance in front of the vehicle. Field surveys were conducted to determine the space requirement of a standing vehicle. The results are provided in the section on the determination of adequate lane length in units of distance.

Threshold Probability of Overflow

The threshold probability defines the acceptable frequency of overflow of vehicles from the left-turn lane into the adjacent through lane. The greater the value of this probability, the greater the chance of lane overflow, and vice versa. A value of 0.015 is used. The selection criteria for the threshold probability and its implications are discussed in a subsequent section.

THE PROPOSED APPROACH

A queueing model of the turning vehicles is constructed and the adequate lane length is then derived by anticipating the probability of lane overflows, which must be less than a given threshold value.

TABLE 1 Critical Gap Size Under Various Conditions

Approach Speed of Opposing Flow	No. of Lanes (in each direction) 1	2
30 mph	5.0 sec	5.5 sec
55 mph	5.5 sec	6.0 sec

Note: In case of restricted sight distance increase the above values by a maximum of 1.0 seconds
Source: HCM [4], Table 10-2.

The proposed procedure for determining the adequate lane length involves:

1. Determining the threshold probability of lane overflow based on the acceptable frequency of lane overflow.
2. Identifying the values of the input parameters based on traffic conditions and intersection characteristics: left-turning volume, opposing volume, critical gap, vehicle mix, and vehicle space requirements.
3. Computing the adequate lane length in units of number of vehicles using the model. The probability of lane overflow (or a queue length greater than the lane length) should be less than the threshold value.
4. Converting the lane length to distance by multiplying the adequate lane length in vehicle units (obtained in step 3) by the factor that converts the vehicle units to the distance requirements considering vehicle mix and the buffer between vehicles.

NOTATION

The following notations are used in explaining the model:

- λ_o = Arrival rate of opposing vehicles in vehicles per second,
- λ_l = Arrival rate of left-turning vehicles in vehicles per second,
- T_c = Critical gap in seconds,
- t_i = Time headway of the ith gap in the opposing flow,
- τ = Threshold probability of lane overflow,
- μ = Service time for a left-turning vehicle (service time of the first vehicle in the queue),
- ν = The number of left-turning vehicles in the queue. The term queue includes the vehicle that is being served (i.e., the vehicle at the top of the queue, as well as the other vehicles waiting behind it),
- N_i = Arbitrary value of the lane length in number of vehicles,
- N^* = The adequate lane length in number of vehicles,
- IN^* = Nearest integer to N^*,
- L = The adequate lane length in units of distance,
- χ = Factor accounting for the vehicle mix while calculating L, and
- S = Space required by a stationary passenger car in meters.

Model Formulation

The queueing process being modeled is as follows:

Left-turning vehicles arrive randomly at the intersection and form a queue. The first vehicle in the queue waits for an acceptable gap in the opposing flow. The service time of this queueing process is actually the waiting time of the first vehicle with no apparent server. The queueing system is assumed to be an M/G/1 system. That is, the arrival process is Poisson distributed, and the service time distribution is unspecified; the queue discipline is first-in-first-out (FIFO). Because of the unique service pattern and service time distribution, the queue distribution is complex. The M/G/1 queue is analyzed using the concept of Markov chains. The outcome of the analysis is the mean and variance of the queue length. From the knowledge of the mean and variance of the queue length, an upper bound probability of lane overflow is obtained using Chebyshev's inequality.

Vehicle Arrival Process

The left-turning and opposing vehicles are assumed to arrive according to the Poisson distribution. The probability of k vehicles arriving within a time period t is given as

$$P(k) = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{1}$$

where λ is either λ_l or λ_o depending on the flow being considered.

Vehicle Departure (Service) Process

A left-turning vehicle at the top of the queue waits until a suitable gap (i.e., gap size $\geq T_c$) becomes available in the opposing flow and then accepts it to make the turn. In this queueing model, the time a vehicle spends at the top of the queue is considered the service time. That is, if the first gap (t_1) is greater than the critical gap size ($t_1 < T_c$), the service time is zero. If the second gap (t_2) is the first acceptable gap ($t_1 < T_c$ and $t_2 > T_c$), the service time is t_1 seconds (i.e., the driver rejects the first gap and immediately accepts the second).

Under the assumption of Poisson arrival for the opposing flow, the time headways in the opposing flow are distributed exponentially with parameter λ_o. Assuming that the critical gap T_c is the same for all drivers and is independent of how long the driver has waited, the following equations are obtained from the moment-generating function of the service time distribution according to Drew (*7*).

$$E[\mu] = \frac{e^{\lambda_o T_c} - 1 - \lambda_o T_c}{\lambda_o} \tag{2}$$

where $E[\mu]$ is the mean service time for the left-turning vehicles (or the mean time a left-turning vehicle waits at the top of the queue).

Subsequently, $E[\mu^2]$ and $E[\mu^3]$ are obtained as follows:

$$E[\mu^2] = \frac{2\{\lambda_o E[\mu]\}^2 + 2\lambda_o E[\mu] - \{\lambda_o T_c\}^2}{\lambda_o} \tag{3}$$

$$E[\mu^3] = \frac{6}{\lambda_o^3}\left[2\lambda_o E[\mu]\left\{\lambda_o E[\mu] - \frac{(\lambda_o T_c)^2}{2}\right\} + \{\lambda_o E[\mu]\}^3 + \left\{\lambda_o E[\mu] - \frac{(\lambda_o T_c)^2}{2} - \frac{(\lambda_o T_c)^3}{6}\right\}\right] \tag{4}$$

Also note that the variance of the service time, var[μ], is obtained from Equations 2 and 3 as

$$\mathrm{var}[\mu] = E[\mu^2] - E[\mu]^2 = \frac{e^{2\lambda_o T_c} - 2\lambda_o T_c e^{\lambda_o T_c} - 1}{\lambda_o^2} \tag{5}$$

Queue Length: Mean and Variance

This section focuses on two consecutive left-turning vehicles (the first and second vehicles) at the top of the queue and studies the queue length (the number of vehicles) during the time in which they are served. The following identity holds:

$$\nu' = \nu - \delta + \alpha \tag{6}$$

where

v = number of vehicles in queue when first vehicle reached top of queue,
v' = number of vehicles in queue just after first vehicle's departure,
α = number of arrivals of left-turning vehicles during particular service time, and
δ = dummy variable that takes a value of 1 if $v > 0$, and a value of 0 if $v = 0$.

In the steady state (i.e., when the initial fluctuations are cleared), the following identities hold: $E[v'] = E[v]$, $E[v'^2] = E[v^2]$, and $E[v'^3] = E[v^3]$. The reason is that, in the long run, the distinction between v and v' is lost and they have the same distribution. From these and the preceding identity expressions for $E[v]$, var[v] can be obtained. The expression for $E[v]$ is called the Pollaczek-Kintchine equation and its derivation can be found in many textbooks of probability theory; among them is Taylor and Karlin (*8*). The expression for $E[v]$ is given as

$$E[v] = \lambda_l E[\mu] + \frac{\lambda_l^2 E[\mu^2]}{2(1 - \lambda_l E[\mu])} \tag{7}$$

Using similar logic, the following relationship for the variance of the queue length, var[v], may be determined.

$$\mathrm{var}[v] = 2(E[v] - \lambda_l E[\mu]^2 + 3E[v] - 2\lambda_l E[\mu] + \frac{\lambda_l^3 E[\mu^3]}{3(1 - \lambda_l E[\mu])} - E[v]^2 \tag{8}$$

DETERMINATION OF ADEQUATE LANE LENGTH IN NUMBER OF VEHICLES

Derivation

The adequate lane length is defined as the minimum lane length in number of vehicles N^* for which the probability of lane overflow is less than an acceptable value:

$$N^* = \min_i \{N_i \mid P(v > N_i) \leq \tau\} \tag{9}$$

where

v = the number of vehicles in the left-turn queue,
N_i = the left-turn lane length in number of vehicles, and
τ = the threshold probability of overflow.

To compute the probability $P(v > N_i)$ precisely, the probability density function (PDF) of the number of left-turn vehicles in the queue must be determined. However, determining the PDF is difficult given the complex distribution of the service time. Chebyshev's inequality formula allows the computation of this probability without any specific assumption about the PDF.

According to Chebyshev's inequality (9),

$$P(v > E[v] + \alpha) \leq \frac{\mathrm{var}[v]}{\mathrm{var}[v] + \alpha^2} \tag{10}$$

where α is any real number. The preceding inequality holds for any probability distribution for v.

Substituting $E[v] + \alpha$ by N_i, Equation 10 can be written as

$$P(v > N_i) \leq \frac{\mathrm{var}[v]}{\mathrm{var}[v] + (N_i - E[v])^2} \tag{11}$$

Thus, in the worst case, the probability that the number of vehicles in the queue, v, is greater than the given lane length, N_i (the overflow condition), is found by treating Equation 11 as an equality.

Hence, for the condition $P\{v > N_i\} \leq \tau$ (Equation 9) to be satisfied, the following should hold:

$$P(v > N_i) = \frac{\mathrm{var}[v]}{\mathrm{var}[v] + (N_i - E[v])^2} \leq \tau \tag{12}$$

When Equation 12 is an equality, the value N_i is equal to N^*. That is, when $N_i = N^*$, Equation 12 may be rewritten as

$$(N^*)^2 - 2E[v]N^* + E[v]^2 + \mathrm{var}[v] - \frac{1}{\tau}\mathrm{var}[v] = 0 \tag{13}$$

By solving Equation 13 with respect to N^*

$$N^* = E[v] + \sigma[v]\sqrt{\frac{1}{\tau} - 1} \tag{14}$$

where $E[v]$ is the mean queue length and $\sigma[v] = \sqrt{\mathrm{var}[v]}$ is the standard deviation of the queue length.

The preceding relation is obtained by considering only one of the two possible roots of Equation 13. The other root is discarded because the lane length required should increase when τ decreases, and not vice versa as is suggested by the discarded root.

The values of $E[v]$ and $\sigma[v]$ in Equation 14 are obtained from Equations 7 and 8, respectively, which are in turn determined by Equations 2 and 3. Hence N^*, the adequate lane length in number of vehicles, can be calculated when a set of values for λ_o, λ_l, and T_c is given.

Recommended Lane Lengths for Selected Input Values

Tables 2 through 6 show the adequate lane length obtained from the model for different sets of input values. In the tables, the numbers shown are the nearest integer to N^*, IN^*. The tables are developed for $\tau = 0.015$, and for different combinations of T_c, λ_l, and λ_o: T_c = 5.0, 5.5, 6.0, 6.5, and 7.0 sec; λ_l = 40 vph to 400 vph; λ_o = 100 vph to 1,000 vph.

The tables show that the adequate lane length increases as the left-turn volume increases for the same opposing volume and critical gap size, as expected. Similarly, for a given left-turning volume and critical gap size, the adequate lane length increases for a higher opposing volume. And as the critical gap size increases so does the adequate lane length (for the same left-turning and opposing volumes).

Model Validation

The validity of the proposed model was tested by comparing the recommended left-turn lane lengths in the tables with the results

TABLE 2 Adequate Lane Length at Unsignalized Intersections (in Number of Vehicles), Critical Gap = 5.0 sec, Threshold Probability = 0.015

Left-Turn	Opposing Volume (in vph)															
Volume (vph)	100	160	220	280	340	400	460	520	580	640	700	760	820	880	940	1000
40	0[a]	0[a]	0[a]	0[a]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	2	2	2
80	0[a]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	2	2	2	2	2	2	3	3	3
120	0[a]	1[b]	1[b]	1[b]	2	2	2	2	2	3	3	3	3	4	4	4
160	1[b]	1[b]	1[b]	2	2	2	2	3	3	3	4	4	4	5	5	6
200	1[b]	1[b]	2	2	2	3	3	3	4	4	4	5	5	6	6	7
240	1[b]	1[b]	2	2	3	3	3	4	4	5	5	6	6	7	8	9
280	1[b]	2	2	3	3	4	4	4	5	6	6	7	8	8	9	11
320	1[b]	2	2	3	3	4	4	5	6	6	7	8	9	10	11	13
360	1[b]	2	3	3	4	4	5	6	6	7	8	9	10	12	14	16
400	2	2	3	4	4	5	6	6	7	8	9	10	12	14	17	21

[a] A zero lane length indicates that a left-turn lane is not warrented. See ref. [1].
[b] For practical purposes, the lane length should be at least two vehicle lengths.

from a computer simulation of the queueing process. A simulation program of the intersection-queueing process (called TSIM) developed by the University of Delaware was used. TSIM was also used to validate Kikuchi and Chakroborty's (*1*) model on left-turn lane warrants at unsignalized intersections. NETSIM was not used because it does not provide adequate simulation of turning conditions at an isolated unsignalized intersection, nor can it capture the lane overflow condition. For the set of input values used in Table 4 and the corresponding recommended lane lengths, the simulation model was executed and the frequencies of queue lengths were observed. From this, the minimum lane length that would result in a probability of overflow less than the threshold value (0.015) was

TABLE 3 Adequate Lane Length at Unsignalized Intersections (in Number of Vehicles), Critical Gap = 5.5 sec, Threshold Probability = 0.015

Left-Turn	Opposing Volume (in vph)															
Volume (vph)	100	160	220	280	340	400	460	520	580	640	700	760	820	880	940	1000
40	0[a]	0[a]	0[a]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	2	2	2	2	2
80	0[a]	1[b]	1[b]	1[b]	1[b]	1[b]	2	2	2	2	3	3	3	3	3	4
120	1[b]	1[b]	1[b]	2	2	2	2	3	3	3	3	4	4	5	5	5
160	1[b]	1[b]	2	2	2	3	3	3	4	4	4	5	5	6	6	7
200	1[b]	1[b]	2	2	3	3	4	4	4	5	5	6	7	7	8	9
240	1[b]	2	2	3	3	4	4	5	5	6	6	7	8	9	10	12
280	1[b]	2	3	3	4	4	5	5	6	7	8	9	10	11	13	16
320	2	2	3	3	4	5	5	6	7	8	9	10	12	14	17	21
360	2	2	3	4	5	5	6	7	8	9	10	12	15	18	23	-
400	2	3	3	4	5	6	7	8	9	10	12	15	18	23	-	-

[a] A zero lane length indicates that a left-turn lane is not warrented. See ref. [1].
[b] For practical purposes, the lane length should be at least two vehicle lengths.

TABLE 4 Adequate Lane Length at Unsignalized Intersections (in Number of Vehicles), Critical Gap = 6.0 sec, Threshold Probability = 0.015

Left-Turn	Opposing Volume (in vph)															
Volume (vph)	100	160	220	280	340	400	460	520	580	640	700	760	820	880	940	1000
40	0[a]	0[a]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	2	2	2	2	2	2	3
80	0[a]	1[b]	1[b]	1[b]	1[b]	2	2	2	2	3	3	3	4	4	4	5
120	1[b]	1[b]	1[b]	2	2	2	3	3	3	4	4	5	5	5	6	7
160	1[b]	1[b]	2	2	3	3	3	4	4	5	5	6	7	7	8	9
200	1[b]	2	2	3	3	4	4	5	5	6	7	7	8	9	11	13
240	1[b]	2	3	3	4	4	5	6	6	7	8	9	11	12	15	18
280	2	2	3	4	4	5	6	6	7	8	10	11	13	16	21	-
320	2	3	3	4	5	6	6	7	9	10	12	14	18	23	-	-
360	2	3	4	4	5	6	7	8	10	12	14	18	24	-	-	-
400	2	3	4	5	6	7	8	10	11	14	18	23	-	-	-	-

[a] A zero lane length indicates that a left-turn lane is not warrented. See ref. [1].
[b] For practical purposes, the lane length should be at least two vehicle lengths.

TABLE 5 Adequate Lane Length at Unsignalized Intersections (in Number of Vehicles), Critical Gap = 6.5 sec, Threshold Probability = 0.015

Left-Turn Volume (vph)	Opposing Volume (in vph)															
	100	160	220	280	340	400	460	520	580	640	700	760	820	880	940	1000
40	0[a]	0[a]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	2	2	2	2	2	3	3	3
80	1[b]	1[b]	1[b]	1[b]	2	2	2	3	3	3	3	4	4	5	5	5
120	1[b]	1[b]	2	2	2	3	3	3	4	4	5	5	6	7	7	8
160	1[b]	2	2	3	3	3	4	4	5	6	6	7	8	9	11	13
200	1[b]	2	2	3	4	4	5	5	6	7	8	9	11	13	16	20
240	2	2	3	4	4	5	6	7	8	9	10	12	15	18	25	-
280	2	3	3	4	5	6	7	8	9	11	13	16	21	-	-	-
320	2	3	4	5	6	7	8	9	11	13	16	22	-	-	-	-
360	3	3	4	5	6	7	9	11	13	16	22	-	-	-	-	-
400	3	4	5	6	7	8	10	12	16	21	-	-	-	-	-	-

[a] A zero lane length indicates that a left-turn lane is not warrented. See ref. [1].

[b] For practical purposes, the lane length should be at least two vehicle lengths.

found. Table 7 compares the simulation and the proposed model's results for different combinations of λ_l and λ_O. The value of T_c used was 6.0 sec.

Table 7 suggests that the two cases are very similar with a maximum difference of two car spaces (for some of the higher-volume combinations considered). The lane lengths derived from the simulation are equal to or shorter than those calculated by the model. This difference is due to the use of Chebyshev's inequality, which models a worst-case scenario, making the results somewhat conservative.

DETERMINATION OF ADEQUATE LANE LENGTH IN UNITS OF DISTANCE

So far the adequate lane length has been considered (in Equation 14 and Tables 2 through 6) in numbers of vehicles. For application to geometric design, however, the length should be provided in units of distance using the following steps:

1. Establish the average space per passenger car when it is waiting in the left-turn lane. This space includes the buffer between two adjacent cars as well as the vehicle length.
2. Analyze the effect of larger vehicles on space requirement and derive passenger car equivalency factors for non-passenger cars.
3. Determine the lane length in units of distance after considering the vehicle mix.

Step 1: Space Requirement of a Standing Passenger Car

The space requirement for a standing passenger car was determined through field observations at several intersections in Newark, Delaware. The number of passenger cars in the queue and the corresponding space required was measured. One hundred twenty-four such queues (containing 383 passenger cars) were measured. The queues sampled in this analysis contained only passenger cars. Figure 2 provides the observations and the least squares regression line obtained for the data.

The relationship between the space requirement y in meters and the number of passenger cars in the queue x is obtained as

$$y = 7.66x - 2.92 \qquad R^2 = 0.989 \tag{15}$$

Equation 15 indicates that the space required per passenger car is approximately 7.7 m (25 ft) including a buffer zone between cars. However, the required space for the first vehicle in the queue is only (approximately) 4.6 m (15 ft), because no buffer zone is needed between the first car and the stop line. This accounts for the non-zero intercept in the calculated regression line.

TABLE 6 Adequate Lane Length at Unsignalized Intersections (in Number of Vehicles), Critical Gap = 7.0 sec, Threshold Probability = 0.015

Left-Turn Volume (vph)	Opposing Volume (in vph)															
	100	160	220	280	340	400	460	520	580	640	700	760	820	880	940	1000
40	0[a]	1[b]	1[b]	1[b]	1[b]	1[b]	1[b]	2	2	2	2	3	3	3	3	4
80	1[b]	1[b]	1[b]	2	2	2	3	3	3	4	4	4	5	5	6	7
120	1[b]	1[b]	2	2	3	3	4	4	5	5	6	6	7	8	9	11
160	1[b]	2	2	3	3	4	5	5	6	7	8	9	10	12	15	19
200	2	2	3	3	4	5	6	6	7	9	10	12	15	19	26	-
240	2	3	3	4	5	6	7	8	9	11	13	17	23	-	-	-
280	2	3	4	5	6	7	8	9	11	14	18	25	-	-	-	-
320	2	4	4	5	6	8	9	11	14	18	26	-	-	-	-	-
360	3	4	5	6	7	9	11	14	18	25	-	-	-	-	-	-
400	3	5	5	7	8	10	13	16	23	-	-	-	-	-	-	-

[a] A zero lane length indicates that a left-turn lane is not warrented. See ref. [1].

[b] For practical purposes, the lane length should be at least two vehicle lengths.

TABLE 7 Comparison of Length Requirements (in Number of Vehicles): Proposed Model and Simulation

Left-turning Vol.(vph)	Opposing Volume (vph)											
	100		160		220		280		340		400	
	S	M	S	M	S	M	S	M	S	M	S	M
120	1	1	1	1	1	1	1	2	2	2	2	2
160	1	1	1	1	1	2	1	2	2	3	2	3
200	1	1	1	2	2	2	2	3	2	3	2	4
240	1	1	1	2	2	3	2	3	2	4	2	4
Left-turning Vol.(vph)	Opposing Volume (vph)											
	460		520		580		640		700		760	
	S	M	S	M	S	M	S	M	S	M	S	M
120	2	3	2	3	3	3	3	4	3	4	4	5
160	2	3	3	4	3	4	4	5	4	5	4	5
200	3	4	3	5	4	5	5	6	6	7	7	7
240	3	5	4	6	5	6	5	7	6	8	7	9

S: Derived from simulation
M: Derived from the proposed model
Threshold probability = 0.015
Critical gap = 6.0 seconds

Step 2: Effects of Large Vehicles on Space Requirement

Large vehicles affect the adequate lane length in two ways: (*a*) they require a longer space, and (*b*) their lower acceleration capability and maneuverability result in a larger critical gap size.

The first point is addressed by assuming passenger car equivalencies, which account for the difference in sizes of large vehicles relative to the passenger car. The equivalency factors are computed from AASHTO's standard on vehicle lengths [Table II-1 of AASHTO Green Book (*3*)] and are provided in Table 8.

The factor of critical gap size in relation to vehicle size requires further research. When large vehicles form a substantial percentage of the total left-turning volume, data should be collected on their gap acceptance characteristics. A critical gap size that reasonably represents the characteristics of the entire traffic stream may be chosen. However, since the analysis presented represents a conservative scenario (by use of Chebyshev's inequality), the lane length computed from the model should be acceptable as long as the percentage of large vehicles is small.

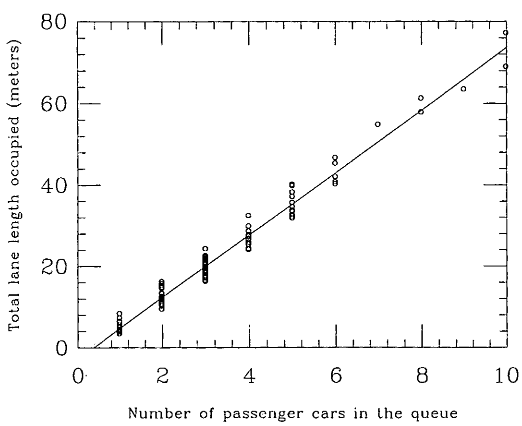


FIGURE 2 Distance occupied versus number of passenger cars.

TABLE 8 Passenger Car Equivalency Factors Based on Vehicle Length

Vehicle Type	Symbol	Equivalency Factor
Passenger Car	E_{PC}	1.0
Bus	E_B	2.1
Truck (WB40-WB60)	E_T	2.6 - 3.4
Recreational Vehicle (MH - MH/B)	E_{RV}	1.6 - 2.8

Note: Computed based on vehicle lengths from AASHTO [3], Table II-1

Step 3: Lane Length in Units of Distance

When the vehicle mix is given, determining the lane length in units of distance follows the method presented by Kikuchi et al (2). In this method it is assumed that the percentage of larger vehicles in the queue equals the percentage of larger vehicles in the left-turning volume.

For a given value of IN^* the required lane length in meters is computed as

$$L = (7.66\, IN^* - 2.92)\,\xi \qquad (16)$$

where the expression in parentheses represents the space occupied by IN^* passenger cars (see Equation 15) and ξ is a conversion factor obtained from the following equation:

$$\xi = 1 + (E_B - 1)P_B + (E_T - 1)P_T + (E_{RV} - 1)P_{RV} \qquad (17)$$

where P_T, P_B, and P_{RV} are the proportion of buses, trucks, and recreational vehicles in the left-turning volume, and E_T, E_B, and E_{RV} are passenger car equivalency factors given in Table 8, which is based on AASHTO's (*3*) standard on vehicle length.

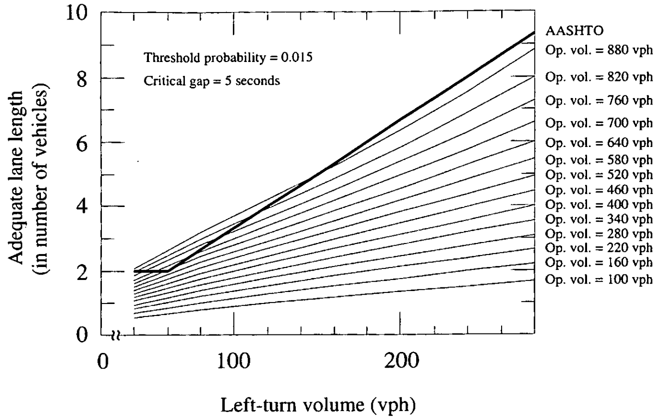
DISCUSSION OF RESULTS

In the following sections the suggested lane lengths obtained from the model are compared with the guides provided by AASHTO, and the selection of the value of the threshold probability is discussed.

Comparison with AASHTO Guidelines

The results obtained from the proposed model are compared with AASHTO's guidelines. Figure 3 shows the adequate lane length for the two cases as a function of left-turn volume. The bold line represents AASHTO's guideline, and the lighter lines represent the results from the proposed model for a threshold probability of 0.015. AASHTO does not incorporate the opposing volume in its guideline, hence, only one line corresponds to AASHTO's guideline (which is used for any opposing volume).

Figure 3 shows that the AASHTO guideline is a conservative estimate for left-turn volume greater than 150 vph; in particular, when the opposing volume is low, the AASHTO values result in overdesign. However, for left-turn volume less than 150 vph, AASHTO suggests shorter lane lengths than our estimate only when the opposing volume is fairly large (more than 700 vph).



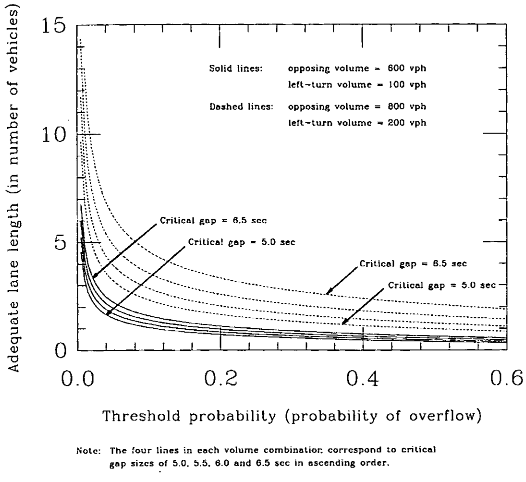
Note: The light lines represent the results of the proposed model. For practical applications, it is recommended to use a minimum of two vehicle lengths.

FIGURE 3 Comparison of AASHTO and proposed model lane lengths.

Choice of Thresholxd Probability

Figure 4 shows how the adequate lane length, N^*, varies with the threshold probability, τ. It is plotted for left-turn volumes of 100 and 200 vph under different combinations of opposing volume (600 and 800 vph) and critical gap (5.0, 5.5, 6.0, and 6.5 sec). The figure confirms that as τ increases, N^* decreases; in other words, shorter lane lengths are justified as more chances of vehicle overflow are allowed. N^*, on the other hand, increases as τ decreases. However, the data suggest some important trade-off considerations when choosing the value of threshold probability.

For a value of τ greater than approximately 0.1, N^* is not only small but also insensitive to changes in τ. AASHTO suggests a minimum lane length of two cars; therefore, the selection of a large τ value will not affect the lane length. However, for large values of τ, the frequency of lane overflow increases, and as a result, the delay to the through movement due to lane blockage also increases.



Note: The four lines in each volume combination correspond to critical gap sizes of 5.0, 5.5, 6.0 and 6.5 sec in ascending order.

FIGURE 4 Adequate lane lengths versus threshold probability.

For a value of τ smaller than approximately 0.05, N^* increases rapidly. This suggests that a small change in τ has a large effect on construction cost while having very little effect on the delay of through movement.

In addition, the selection of the threshold probability must consider the volume of through vehicles (traveling in the same direction as the left-turning vehicles, not the opposing traffic). For a higher volume of through vehicles, the threshold probability should be small in order to minimize the delay caused by the overflowing turning vehicles that are blocking the lane. For smaller volumes of through vehicles, the threshold probability can be kept higher. The authors consider that the threshold probability is a parameter that must be chosen based on site-specific conditions.

Unfortunately, none of the traffic engineering manuals, such as the AASHTO Green Book (*3*), HCM (*4*), and MUTCD (*10*) provide any guidelines on the value of the threshold probability. However, the values of the threshold probability used in related problems in the past range from 0.01 to 0.02. For example, this range was used in studying the warrant conditions for left-turn lanes at unsignalized intersections by Kikuchi and Chakroborty (*1*). AASHTO's (*3*) left-turn lane warrant adopts Harmelink's (*5*) derivation, which is based on the value of 0.015.

CONCLUSIONS

A mathematical model for determining the adequate left-turn lane length at an unsignalized intersection is presented. This subject has not been systematically addressed in the literature, and no unified method has been practiced; in particular, the effect of opposing volume on the turning lane length has not been addressed. The model simulates the arrival, waiting, and turning of the left-turning vehicles (the queueing process). The formulation of the model is complicated by the difficulty in deriving the service time distribution. In the model, the wait of the first vehicle in the queue when searching for a necessary gap in the opposing flow is considered the service time; the Pollazek-Kintchine formula and Chebyshev's inequality are used to derive the adequate lane length. Determining adequate left-turn lane length requires keeping the probability of left-turn lane overflow less than a threshold value. After the model derived the length in terms of the number of vehicles, the values were converted to the actual distance, taking into account the space required for different types of vehicles. For this, a series of surveys were conducted to determine the necessary space per vehicle.

The model results were validated by computer simulation. Using the model, a set of tables for recommended left-turn lane lengths were prepared for different combinations of representative values for left-turning volume, opposing volume, critical gap, and for a threshold probability of 0.015. The results were also compared with existing AASHTO guidelines, and the effect of the opposing volume on the recommended model, which the proposed model considers but AASHTO does not, is discussed.

This study provides a model and a formula to compute adequate left-turn lane length based not only on the left-turning volume but also on critical gap, opposing volume, and vehicle mix. While further studies on the determination of the threshold probability of acceptable overflow and critical gap size for large vehicles are important, the proposed formulation provides a more comprehensive and systematic procedure for determining the adequate left-turn lane length at isolated unsignalized intersections than the existing procedures.

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Publication of this paper sponsored by Committee on Operational Effects of Geometrics.