Lengths of Double or Dual Left-Turn Lanes

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Double (or dual) left-turn lanes (DLTLs) are a relatively new geometric feature, and the literature on their design parameters is limited. The effectiveness of the DLTL in improving the operation of an intersection depends on several design parameters; among them, the most critical is the length of the DLTL. A procedure for determining the length of the DLTL was developed. First, the procedure surveys how drivers choose a lane of the DLTL in the real world and analyzes the relationship between lane use and the volume of left-turn vehicles. Second, the procedure formulates the probability that all arriving left-turn vehicles during the red phase can enter the left-turn lanes; this means no overflow of left-turn vehicles from the DLTL and no blockage of the entrance of the DLTL by the queue of through vehicles. This probability is presented as a function of the length of the DLTL and the arrival rates of left-turn and through vehicles. The adequate lane length is derived such that the probability of the vehicles entering the DLTL is greater than a threshold value. Third, the adequate length is expressed in number of vehicles; later, this value is converted to the actual distance required on the basis of the vehicle mix and preference between the two lanes. Recommended lengths are presented as a function of left-turn and through volumes for practical application. The proposed approach is unique in that it avoids lane overflow and blockage of lane entrance.

The capacity and safety of a signalized intersection are greatly affected by the volume of left-turning movements and its treatment. In most cases, adding a left-turn lane helps to improve the efficiency of the intersection. When the left-turn volume becomes large, the queue length becomes very long in the case of the single left-turn lane (SLTL), which makes the duration of the left-turn signal phase very long. Consequently, this increases the cycle length and lowers the efficiency of the intersection. In such conditions, a second left-turn lane, or the double (or dual) left-turn lane (DLTL) is warranted. DLTL refers to two contiguous lanes on an intersection approach that are assigned solely for left-turning movements and that are protected from the opposing and cross traffic by a separate signal phase. A typical DLTL layout and the patterns of vehicle arrivals are shown in Figure 1. DLTLs are a relatively new geometric feature, and no specific guidelines for geometric design exist in the literature, including the AASHTO Green Book (*1*). In particular, the analytical procedure for determining the lane length is not available except as a general guide. This paper develops a procedure to determine the appropriate lengths of DLTL and presents them for different combinations of left-turn and through volumes for practical application.

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PROBLEM AND APPROACH

The purpose of DLTLs is, in essence, to increase the capacity of left-turning movement by providing two service channels. Compared with an SLTL, the DLTL can increase processing rate of the left-turn vehicles per unit time; as a result, it reduces the delay to the left-turn vehicles and the length of the left-turn signal phase. This, in turn, reduces the signal cycle. Consequently, the delay to the vehicles on all approaches is reduced, and the level of service is improved. Although these general benefits have been recognized, the procedure to determine the lengths of DLTLs has not been established.

The problem addressed in this paper is determining the lengths of DLTLs based on two general considerations: (*a*) minimizing the chance of the overflow of left-turn vehicles onto the adjacent through lane and (*b*) minimizing the chance of the queue of through vehicles blocking the entrance to the DLTL. In other words, the length of DLTLs is determined such that the chance of all left-turn vehicles that arrive during the red signal phase enter the DLTL is maximal. The conditions of lane overflow and lane blocking are illustrated in Figures 1*b* and 1*c*.

The approach taken in this paper is the following: First, a series of surveys were conducted at DLTL sites in Delaware to collect data on how drivers choose one of the two lanes at a DLTL intersection. Second, the factors that affect the adequate lane length of the DLTL were examined. Third, an expression of the probability that all left-turn vehicles enter the DLTL was developed when the arriving rates and the length of the DLTL were given. Fourth, the adequate length of the DLTL was determined to make the probability greater than a threshold value. The final product is a set of graphs and tables that shows the adequate length of DLTL for practical use.

The analytical challenge was to develop an expression that computes the probability that all left-turn vehicles enter the DLTL. Using this expression, the adequate lane length in number of vehicles was determined. This value was converted to the actual distance considering lane use preference and vehicle mix.

LITERATURE REVIEW

Compared with the literature on SLTLs, little specific work has been done on the lengths of DLTLs. The following paragraphs present literature on SLTLs, which has some bearings on the design of DLTL.

The work on SLTLs is classified into two issues: one on the warrant of SLTLs and the other on the length of SLTLs. Regarding the warrant of SLTLs, Agent (*2*), the *Highway Capacity Manual* (HCM) (*3*), and Neuman (*4*) presented the condition in which a left-turning lane on a signalized intersection would be justified. The general agreement for justifying SLTL is to limit the chances that the left-turn

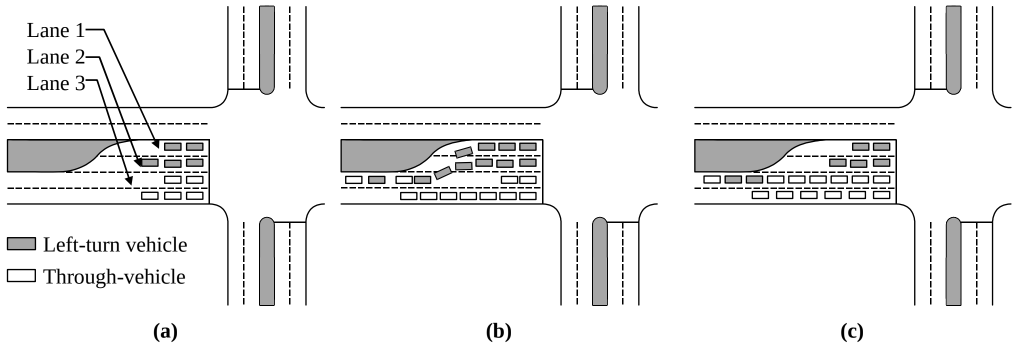

FIGURE 1 DLTL layout and pattern of vehicle arrivals: (*a*) typical DLTL and arrival patterns, (*b*) left-turn vehicles overflowing DLTL, and (*c*) through vehicles blocking entrance of DLTL.

vehicles interfere with the through movement. In the case of DLTLs, the basis for the warrant should take into account the more complicated issue of the effects of DLTLs on the efficiency of the intersection operation as well as the effects of DLTLs on the approach in question. Spring and Thomas (*5*) stated that the performance of DLTLs depends on both the geometric design and the characteristics of the demand on the basis of many surveys of actual DLTLs. They also cited the lack of technical analysis about the geometric design of DLTLs. *NCHRP Report 375* (*6*) and the *HCM 2000* (*3*) provide a general criterion of 300 left-turn vehicles per hour (vph) as the volume at which to consider using DLTL.

Regarding the latter issue of the length of SLTLs, the *HCM 2000* (*3*), Messer and Fambro (*7*), the AASHTO Green Book (*1*), Marcus et al. (*8*), Koepke and Levinson (*9*), Neuman (*4*), and Kikuchi et al. (*10*) laid out the general principles on the design of the length of a left-turn lane. All suggested the importance of considering lane overflow; some suggested considering lane blockage also.

None of these works, however, presents a comprehensive discussion on lane lengths of DLTLs, except for the conventional rule of thumb; that is, first, compute the necessary lane length assuming that an SLTL is to be installed; second, divide this length by a number representing lane use. Marcus et al. (*8*) suggested equal use between the two lanes. Koepke and Levinson (*9*) recognized the difference in lane use and suggested that the total length of the SLTL be divided by 1.8 to account for uneven distribution of vehicles between the two lanes.

This approach of dividing the design length of an SLTL by a constant value, such as 2 or 1.8, has two problems. First, use between the two lanes varies not only from site to site but also with the approach volume and vehicle mix for the same site. Second, and more critical, such an approach disregards the possibility that the entrance of the DLTL is blocked by the queued through vehicles in the adjacent through lane (Lane 3 in Figure 1*a*). The latter issue needs serious attention because the possibility that the through vehicles in the adjacent lane block the entrance to the left-turn lane becomes greater in the case of DLTLs than the case of SLTLs. The length of DLTLs is much shorter (about half) than that of the SLTL.

SURVEY RESULTS ON PATTERN OF LANE SELECTION

The arrival patterns of left-turn and through vehicles are important factors because they directly relate to the possibility of the overflow of the DLTL and the blockage of the entrance of the DLTL. To understand how each left-turning vehicle chooses a lane of DLTL, a series of surveys was conducted at seven intersections with DLTLs in Northern New Castle County, Delaware, during 2002–2003. All intersections were four-leg, right-angle intersections, with a separate left-turn signal phase. A total of 193 signal cycles were observed; in each cycle, the number of vehicles using each DLTL was recorded.

Figure 2 shows how the drivers chose between Lane 1 and Lane 2 (see Figure 1). Each point represents the total left-turn vehicles arrived and the proportion of the number of vehicles that chose Lane 1 (see Figure 1) per signal cycle.

When the total left-turn volume is small, the choice of lane is rather random, with each driver choosing the lane that allows him or her the best access to the desired lane downstream. When the total left-turn volume becomes large, the drivers become concerned about the possibility of not being able to clear the intersection in one cycle. Thus, each driver chooses the lane with the shortest queue length. As a result, the queue lengths become nearly equal between the two lanes (equilibrium is reached in a choice situation). The general tendency is shown by the two converging curves (these were added by the authors.). The curves show the tendency that the points are approaching the line of 0.5. The vehicle type is also a factor; with few exceptions, large trucks chose Lane 2 (see Figure 1*a*) because of the availability of a larger turning radius.

The survey also provides the basic data on the left-turn volumes for the analysis; the arrivals of left-turn vehicles vary between 4 and 22 vehicles per red phase. The duration of the green phase varied between 10 to 30 s. The percentage of large trucks was less than 10% for all cases.

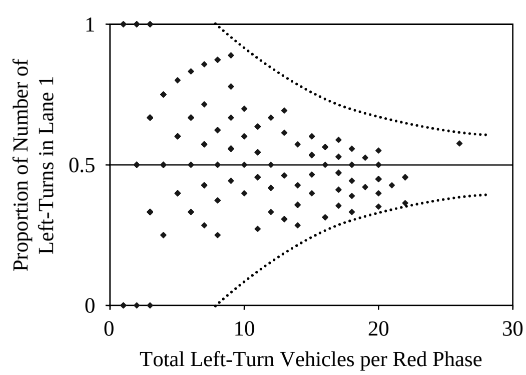

FIGURE 2 Relationship between total left-turn volume and proportion of lane use.

BASIS FOR DETERMINING LENGTH OF DLTLs

Situations That Must Be Avoided

The length of DLTLs should be determined so that the following two conditions can be avoided:

- Overflow of the DLTLs (Figure 1*b*) and
- Blockage of the entrance of the DLTLs by the through vehicles in the adjacent lane. Under this situation, the left-turn vehicles cannot enter the DLTL despite the availability of space (Figure 1*c*).

The left-turn vehicles and the through vehicles are potential adversaries; an overflow of left-turn vehicles onto the through lane could impede the movement of through vehicles, and at the same time, a queue of through vehicles could prevent the left-turn vehicles from entering the DLTL by blocking the entrance. Hence, if the length of the DLTL is long enough so that all the left-turn vehicles can enter the DLTL, then conflict between the two flows is minimized.

Additional reasons why the lane length should be based on the need for all left-turn vehicles to enter the DLTL are as follows: (*a*) the left-turn green phase appears before the through green phase; thus, once all the left-turn vehicles enter DLTL, through vehicles can proceed unimpeded; and (*b*) even if the through vehicles are blocked by the overflow of the left-turn vehicles, the blocked through vehicles still can shift to another through lane (because at most approaches with DLTL, more than one through lane is available) to proceed, but if the left-turn vehicles cannot enter the DLTL because of blockage of the DLTL entrance, then those left-turn vehicles must wait for another signal cycle.

Threshold Probability

A threshold probability refers to the minimum value of probability that all arriving left-turn vehicles enter the DLTL. This situation may be interpreted as the average number of signal cycles, of 100 cycles, for which the arriving left-turn vehicles can enter the DLTL. The threshold probability is determined by the policy of the locality and must be consistent in the region. For reference, Pline (*11,* p. 17) suggests, "The length of storage lane (referring to SLTL) is based on random arrival with a five percent probability of left turn overflow." Another reference is the traditional concept of using the 30th-hour volume for design volume; this can mean that 99.7% [30 h of (24 × 365) hours] of the time the roadway is under capacity. The authors' research suggests a value between 95% and 99%. These values are also consistent with a statement in the AASHTO Green Book (*1,* p. 494), "left-turn demands should be accommodated as near as practical to the point at which the motorist desires to turn left."

Other Factors

Other factors that must be considered are the signal timing and vehicle mix. Because the length of the DLTL is a function of arrivals of left-turn vehicles per signal cycle, the shorter the red phase, the smaller the number of vehicles that accumulates; hence, the length can be shorter. The vehicle mix (proportion of large trucks and buses) is another factor that needs to be considered for actual length. Most large vehicles stay in Lane 2. Ways to account for the vehicle mix when computing the lane length are discussed later in the paper.

STEPS FOR DETERMINING DLTL LENGTH

The following steps are suggested to determine the adequate length of a DLTL:

Step 1. Observe the traffic flow pattern and the characteristics of the intersection. This includes the total volumes of left-turn and through vehicles, vehicle mix, flow pattern after turning left, and the geometry and traffic control schemes. Determine the volume split between the two lanes of the DLTL (e.g., 60/40, based on the anticipated desire of the drivers).

Step 2. Determine the threshold probability—the probability that all arriving left-turn vehicles can enter the DLTL. This value can be between 95% and 99%.

Step 3. Determine the design volumes for the total through and left-turn movements. Accordingly, determine the arrival rate for each movement during the red signal phase, which is denoted as *TH* and *LT* for the through and the left-turn movements, respectively.

Step 4. Assume a DLTL length and compute the probability that all the left-turn vehicles can enter the DLTL lane.

Step 5. Check whether the probability is greater than the threshold probability. If not, increase the lane length and repeat Step 4.

Step 6. Convert the length in number of vehicles to the actual length considering the vehicle mix, lane use, buffer length required between vehicles, and taper.

In these steps, the input is demand (the arriving traffic volume) and signal timing, and the output is the necessary length of the DLTL that meets the threshold probability criterion. Among the steps, the main contribution of this paper is for Step 4, which is the derivation of the probability that the left-turning vehicles can enter the DLTL for a given length of the DLTL.

PROBABILITY THAT ALL LEFT-TURN VEHICLES ENTER DLTL

This section formulates the probability that all left-turn vehicles that arrive during the red phase enter the DLTL. This probability is presented as a function of the length of the DLTL (L) and the average arrival rates of the left-turn vehicles (LT) and the through vehicles (TH).

Assumptions

The system to be modeled is a signalized intersection with significant traffic activity, for which at least one of the approaches requires a DLTL. The two lanes of the DLTL have the same length.

The assumptions are as follows:

1. Arrivals of both the left-turning vehicles and through vehicles follow the Poisson distribution. The probability that k vehicles that wish to enter the DLTL arrive during the red phase is, expressed in Equation 1:

$$\text{Prob}(k) = \frac{(LT)^k e^{LT}}{k!} \tag{1}$$

where LT is the average arrival rate of left-turn vehicles per red phase. Similarly, the probability that j through vehicles arrive during the red phase is expressed in Equation 2:

$$\text{Prob}(j) = \frac{(TH)^j e^{-TH}}{j!} \quad (2)$$

where *TH* is the average number of through vehicles that arrive on the lane adjacent to DLTL (Lane 3 in Figure 1*a*) per red phase of the through movement. Although *TH* and *LT* are the average rates in the respective Poisson distributions, the actual number of vehicles that arrives during each red phase is a random number. It is denoted as random variables *LV* and *TV*, for left-turn and through vehicles, respectively.

2. The system is stable. The average number of left-turning vehicles that arrives during the red phase is less than the maximum number of vehicles that can be discharged during the green phase. As a result, by the end of the green, all left-turn vehicles in the DLTL (those that were waiting and those that arrived during the green phase) clear the intersection. Further, all through vehicles in the adjacent lane (Lane 3 in Figure 1*a*) clear during the through green phase.
3. The number of through lanes is assumed to be one.

Probability Formulation

Let us denote the length of the DLTL as L in number of vehicles. The possible combinations of *LV* and *TV*, the numbers of left-turn vehicles, and through vehicles that arrive per red phase, are the following: $LV \le 2L$, $TV < L$; $LV \le 2L$, $TV \ge L$; $LV > 2L$, $TV < L$; and $LV > 2L$, $TV \ge L$. Among these possible combinations, the following two situations allow for all the left-turn vehicles to enter the DLTL, without left-turn vehicles overflowing or the through vehicles blocking the entrance of the DLTL:

Case 1: $LV \le 2L$ and $TV < L$. The number of left-turn vehicles *LV* that arrives during the red phase is less than $2L$ (or less than twice the length of a single lane), and the number of through vehicles *TV* that arrives during its red phase is also less than L. This means that left-turn vehicles do not overflow and through vehicles do not block the entrance of the DLTL. (The case of Figure 1*a*.)

Case 2: $LV < 2L$, $TV \ge L$, and all left-turn vehicles arrive before the Lth through vehicle arrives. This means that the entrance to DLTL is not blocked by the queue of through vehicles before all the left-turn vehicles arrive, even though $TV \ge L$, and all left-turn vehicles have space in the DLTL.

The expressions for the probabilities that Case 1 or Case 2 occur are

$$\begin{aligned}&\text{Prob (all left-turn vehicles can enter DLTL)}\\ &= \text{Prob}(LV \le 2L, TV < L)\\ &\quad + \text{Prob}(LV \le 2L, TV \ge L, \text{and all left-turn vehicles}\\ &\qquad \text{arrive before the } L\text{th through vehicles}) \quad (3)\end{aligned}$$

Probability of Case 1: Prob (LV ≤ 2L and TV < L)

$\text{Prob}(LV \le 2L, TV < L)$ is computed by the sum of the products of the probabilities of $LV \le 2L$ and $TV < L$, which is obtained through Equations 1 and 2.

$$\text{Prob}(LV \le 2L, TV < L) = \sum_{k=0}^{2L} \sum_{j=0}^{L-1} \frac{(LT)^k e^{-LT}}{k!} \frac{(TH)^j e^{-TH}}{j!} \quad (4)$$

Probability of Case 2: Prob (LV ≤ 2L and All Left Turns Arrive Before Lth Through Vehicle)

This probability is obtained by a sum of the product of Prob (*LV* and *TV*, where $LV \le 2L$, $TV \ge L$) and a conditional probability, Prob (the arrival sequence is such that the all left-turn vehicles arrive before the Lth through vehicle $|LV$ and *TV*). The product is summed over the range of $0 \le LV \le 2L$ and $L \le TV < \infty$; that is,

$$\sum_{k=0}^{2L} \sum_{j=0}^{\infty} [\text{Prob}(LV = k, TV = j) \times \text{Prob(all left-turn vehicles arrive before the } L\text{th through vehicles} \mid LV = k, TV = j)]$$

The probability of the first term in the bracket above is as follows:

$$\text{Prob}(LV = k, TV = j) = \frac{(LT)^k e^{-LT}}{k!} \frac{(TH)^j e^{-TH}}{j!} \quad \text{for } k \le 2L \text{ and } j \ge L \quad (5)$$

The second term, a conditional probability, Prob (all left-turn vehicles arrive before the Lth through vehicles$/LV = k$, $TV = j$), is computed by the proportion of the vehicle arrival sequences that all left-turn vehicles arrive before the $(L - 1)$th through vehicle arrives in the possible number of arrival sequences. It is expressed as follows:

$$\frac{{}_{k+L-1}C_k}{{}_{k+j}C_k} \quad \text{or} \quad \frac{\{(k + L - 1)!/[k! \times (L - 1)!]\}}{(k + j)!/(j! \times k!)} \quad (6)$$

where the denominator represents all possible sequences that k left-turn vehicles ($LV = k$) and $j (\ge L)$ through vehicles ($TV = j$) are present in the arriving vehicles. The numerator is the number of possible sequences that, in the first $k + L - 1$ vehicles, there are k left-turn vehicles and $L - 1$ through vehicles. This condition means that the through vehicles will not block the entrance of the DLTL because the last left-turn vehicles enter the DLTL before the entrance is blocked by the through vehicle (although the total number of through vehicles is greater than L).

The probability of Case 2, hence, is obtained by a sum of the product of Equations 5 and 6,

$$\sum_{k=0}^{2L} \sum_{j=0}^{\infty} [\text{Prob}(LV = k, TV = j) \times \text{Prob(all left-turn vehicles arrive before the } L\text{th through vehicles} \mid LV = k, TV = j)]$$

$$= \sum_{k=0}^{2L} \sum_{j=L}^{\infty} \left[\frac{(LT)^k e^{-LT}}{k!} \frac{(TH)^j e^{-TH}}{j!} \frac{{}_{k+L-1}C_k}{{}_{k+j}C_k} \right] \quad (7)$$

Probability of Case 1 or Case 2: Probability (All Left-Turn Vehicles Enter DLTL)

In summary, the probability that all left-turn vehicles can enter the DLTL when the length of DLTL, L, is given, is obtained by the sum of Equations 4 and 7.

Prob (All arriving left-turn vehicles can enter the DLTL)

$$= \sum_{k=0}^{2L} \sum_{j=0}^{L-1} \frac{(LT)^k e^{-LT}}{k!} \frac{(TH)^j e^{-TH}}{j!} + \sum_{k=0}^{2L} \sum_{j=L}^{\infty} \left[\frac{(LT)^k e^{-LT}}{k!} \frac{(TH)^j e^{-TH}}{j!} \frac{{}_{k+L-1}C_k}{{}_{k+j}C_k} \right] \quad (8)$$

As seen in Equation 8, the factors that affect the probability are the average arrival rates of left-turn and through vehicles (*LT* and *TH*), the length of the DLTL, and *L*.

Our objective is to find the value of *L* for which the probability in Equation 8 is greater than a threshold value, α.

$$\text{Prob (all left-turn vehicles can enter DLTL)} \geq \alpha. \quad (9)$$

Computation of *L* for Given Values of *LT, TH,* and α

The probability shown in Equation 8 is computed for different values of *LT, TH,* and *L*. The following arrival rates of left-turn and through vehicles are used; these volumes are generally consistent with the range of values considered for left-turn and through vehicles in *NCHRP Report 395* (*12*):

- Arrivals of left-turn vehicles = 300, 500, 700, and 900 vph/2 lanes and
- Arrivals of through vehicles = 300, 500, 700, and 900 vph/lane (Lane 3 in Figure 1*a*).

Given this range of values and approximately 100 s of red phase for each movement per cycle, the corresponding values of *LT* and *TH* are 8, 14, 19, and 25 vehicles per red-signal phase. These assume a 20-s green (or 100 s of red in 120-s signal cycle) for the movement.

Figure 3 shows the case of *LT* = 14 and *TH* = 19. The increasing S curve shows the probability that all left-turn vehicles can enter the DLTL increases with *L;* the longer the length of the DLTL is, the greater the chance that all left-turn vehicles will enter the DLTL. In the graph, for the threshold probability of α = 0.95 and α = 0.99, the corresponding *L* is 26 and 30 vehicles, respectively.

Table 1 shows the computed lane length (*L*) for 16 cases of *LT* and *TH* in combination with α = 0.95 and 0.99.

In Table 1, when *TH* is given, except for the case of *TH* = 8, the value of *L* is relatively stable regardless of the value of *LT.* This means when *TH* is small (e.g., *TH* = 8), the length is controlled by the chance of overflow of the DLTL, which is a function of *LT.*

TABLE 1 Computed *L* for 16 Cases of *LT* and *TH* Combinations (α = 0.95/0.99)

		LT per Red Phase			
		8	14	19	25
TH per Red Phase	8	13/15	13/16	14/17	17/19
	14	20/23	21/24	21/24	21/24
	19	25/29	26/30	26/30	27/30
	25	32/36	33/37	33/37	33/37

However, when the value of *TH* increases (e.g., *TH* ≥ 14), the length is controlled by the chances of lane blockage, which is related to the value of *TH* and not *LT.*

DETERMINATION OF LENGTH IN DISTANCE

The adequate lane lengths obtained here, *L**, are expressed in terms of the number of vehicles. Hence, the values must be converted into the actual distance for practical application. This step requires considerations of lane use, vehicle length, vehicle mix, and the additional length required for turn lanes (e.g., deceleration and taper).

Adjustment to Lane Use

Differences in lane use need to be considered in determining the lane length. When the ratio of design volumes between the two DLTLs is *p:q,* then the length must be adjusted to the lane that accommodates the higher volume. Thus, the lane length in number of vehicles, L_C, becomes,

$$L_C = 2L^* \times \max[p/(p+q) \text{ or } q/(p+q)] \quad (10)$$

Suppose that the expected arrival in each lane of the DLTL has a ratio of 60:40; then the lane length is $L_c = 2L^* \times 60/100$. This value is still in terms of the number of vehicles.

Consideration of Vehicle Mix and Vehicle Length

The adequate lane length developed in Equation 10 is converted into the actual length required to store the vehicles in meters (or in feet). This conversion requires information about the vehicle length, the buffer distance between vehicles when stopped, and vehicle mix in each lane.

To calculate the effects of different vehicles (e.g., trucks, buses, recreational vehicles), the concept of passenger car equivalent (PCE)

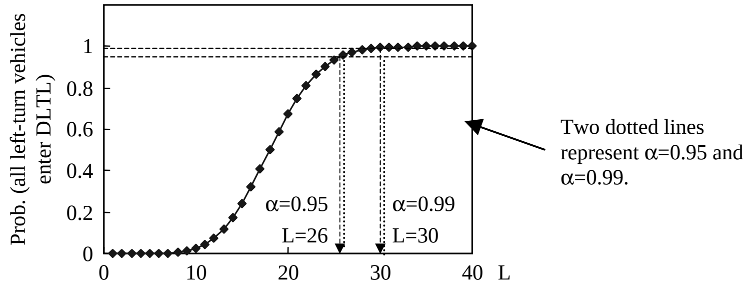

FIGURE 3 Probability (all left turns can enter DLTL) versus length of DLTL (*LT* = 14, *TH* = 19).

was introduced. By multiplying PCE by L_C, as defined in Equation 10, the equivalent number of passenger cars results. This number is then multiplied by the actual distance required for one passenger car to obtain the required lane length.

PCE is the concept used in highway capacity analysis; in this application, it is expressed as follows:

$$\text{PCE} = 1 + (E_B - 1)Prop_B + (E_T - 1)Prop_T \quad (11)$$

where $Prop_B$, and $Prop_T$, are the proportion of buses or recreational vehicles, and trucks, respectively. E_B and E_T are the PCEs of a bus or recreational vehicle and a truck in terms of the vehicle distance required in a turning lane. The approximate values are as follows:

Vehicle Type	*Symbol*	*PCE*
Bus or recreational vehicle	E_B	2.1
Truck	E_T	2.9

The values of E_B and E_T were developed on the basis of the design dimensions of vehicles found in the Green Book (*1*) and a survey done by Kikuchi et al. (*10*), in which the average distance required per stopped "passenger car," including the buffer between the vehicles, is 7 m.

Length of DLTL

The actual length of the DLTL must consider deceleration distance, storage, and taper. What the authors have developed so far has been the storage length. *NCHRP Report 375* (*6*) recommends a 70- to 130-m deceleration length. However, deceleration usually can take place within the lane, and Pline (*11*, p. 17) stated, "It is customary to forgo most of the deceleration length and to provide only the storage length and taper." The assumption that deceleration can take place in taper and the storage lane is perhaps reasonable when the approach speed is low but may not be valid when the approach speed is high. In this paper, the authors followed the *NCHRP Report 375* suggestion; however, the distance required for deceleration could be incorporated easily. The suggested length of taper in *NCHRP Report 375* (*6*) is 30 to 54 m based on an 8:1 to 15:1 taper rate.

For each lane, the adequate lane length, L^{R1} and L^{R2}, is determined by combining Equations 10 and 11 and a taper for the DLTL.

$$\begin{aligned}
&\text{For Lane 1}: L^{R1}(\text{in meters}) = 2L^* \times p/(p+q) \times \text{PCE}_1 \times 7 \\
&\text{For Lane 2}: L^{R2}(\text{in meters}) = 2L^* \times q/(p+q) \times \text{PCE}_2 \times 7 \quad (12)\\
&\text{For through Lane}: L^{RT} = (\text{in meters}) = L^* \times \text{PCE}_T \times 7
\end{aligned}$$

The third line is added to check the effects of heavy vehicles on the through lane, which might become critical in controlling the length of the DLTL. The adequate length for the DLTL, is now determined as

$$LA = \max(L^{R1}, L^{R2}, L^{RT}) + \text{taper} \quad (13)$$

This procedure indicates that the adequate lane length must take into account the volume distribution among the three concerned lanes and vehicle mix.

Example Values

Table 2 shows the DLTL lane length for a set of example values of vehicle mix, vehicle arrival rates, and lane use as defined here.

The given values are

- Threshold probability $\alpha = 0.95$
- Left turn arrival per hour, 300, 500, 700, 900/h or $LT = 8$, 14, 19, and 25 per red phase
- Through vehicle arrival per hour per lane, 300, 500, 700, 900/h or $TH = 8$, 14, 19, and 25 per red phase
- Lane use Lane 1: Lane 2 = 6:5
- Vehicle mix:
  - –Case 1 trucks 5%, buses 5%, passenger cars 90%
  - –Case 2 trucks 10%, buses 5%, passenger cars 85%

Step 1. Calculate the necessary lane length L^* according to Equation 8 in number of cars.

Step 2. Calculate PCE according to the vehicle mix ratio.

Step 3. Calculate each lane length L^{R1}, L^{R2}, L^{RT} using Equation 12.

Step 4. Determine the adequate DLTL length LA using Equation 13.

The values in Table 2 do not include taper length. A taper length of 30 to 54 m is suggested by *NCHRP Report 375* (*6*).

DISCUSSION OF RESULTS

This section details the comparison of the lengths obtained from the proposed procedure with those suggested in the references, which do not consider the blockage of the entrance of DLTL by the through vehicles. The procedure suggested in the references is rather general. Recall that Marcus et al. (*8*) and Koepke and Levinson (*9*) suggest the following: first obtain the length, assuming that it is an SLTL; second, divide this value by 1.8 or 2.0. This is the length solely based on avoiding the lane overflow.

TABLE 2 Actual DLTL Length in Meters (Feet) for Different Arrival Rates and Vehicle Mix Ratio Without Taper

Case 1[1]		Left-turn vol/h			
		300	500	700	900
Through vol/h/ln	300	124 (407)	124 (407)	133 (436)	162 (532)
	500	190 (623)	200 (656)	200 (656)	200 (656)
	700	238 (781)	247 (810)	247 (810)	257 (843)
	900	304 (997)	314 (1030)	314 (1030)	314 (1030)
Case 2[2]		**Left-turn vol/h**			
		300	500	700	900
Through vol/h/ln	300	114 (374)	114 (374)	123 (404)	149 (489)
	500	176 (577)	184 (604)	184 (604)	184 (604)
	700	220 (722)	228 (748)	228 (748)	237 (778)
	900	281 (922)	290 (951)	290 (951)	290 (951)

[1] Trucks 10%, Buses 5%, Pass cars 85%
[2] Trucks 5%, Buses 5%, Pass cars 90%

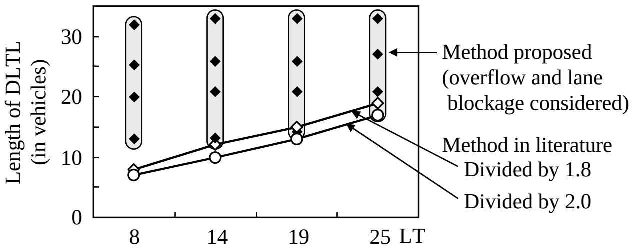

FIGURE 4 With and without consideration of lane blockage by through vehicle.

For the method suggested in the references, the authors first calculated the length of SLTL for which the value of Equation 1 was greater than 0.95 ($\alpha = 0.95$). For the values of $LT = 8$, 14, 19, and 25, the obtained values of SLTL were 13, 20, 26, and 33 (in vehicles), respectively. Each of these values was divided by 1.8 and 2.0. The corresponding lane lengths (in vehicles) were 8, 12, 15, 19 and 7, 10, 13, 17, respectively.

For the proposed approach, according to Table 1, the length of the DLTL for $LT = 8$, 14, 19, and 25 depends on the value of *TH*. For $TH = 8$, 14, 19, and 25, at $\alpha = 0.95$, the corresponding range of DLTL lengths (in vehicles) are 13–32, 13–33, 14–33 and 17–33, respectively (see Table 1). Figure 4 compares the recommended length of the DLTL with the reference.

The upward lines in Figure 4 show the length obtained by the method suggested in the reference. Each of the vertical long ovals indicates the range obtained by the proposed method. The proposed values are much greater than the ones in the references because the authors considered the possibility of lane blockage, which is a function of *TH*. Clearly, the method in the reference underestimates the length because it does not consider the effects of *TH*.

The probability that all left-turn vehicles enter the DLTL is a function of *LT* and *TH;* hence, it is a function of the duration of the red phases for left-turn and through movements. For a given hourly volume, a shorter red left-turn phase will result in a greater probability that all left-turn vehicles enter the DLTL. Thus, if the existing DLTL has a high incidence of lane overflow or blockage, the possibility of shortening the signal cycle or the red phase for the left-turn and through movement is an alternative. This effect also can be analyzed with Equation 8 by changing the values of *LT* and *TH* corresponding to the duration of red phase.

In addition, the number of through lanes affects the necessary DLTL length. With more through lanes, the queue of through vehicles waiting in each lane decreases. As a result, the probability that the through vehicles block the DLTL entrance will decrease. Although this general relationship must exist, the specific relationship between the number of through lanes and the probability of lane blockage cannot be obtained easily because many more variables enter in the equations, including the choice of lane by the through vehicles. The best approach for the multithrough lane case is to derive the arrival rate of the through vehicles for the lane adjacent to DLTL and to use it as *TH* in Equation 8, or if it is not possible, then to divide the total through vehicle arrival by the number of through lanes and use this value as *TH* in Equation 8.

CONCLUSIONS

Length of the lane is perhaps the most important design factor of DLTLs. The length must be sufficiently long so that neither the left-turning vehicles overflow onto the through lane nor the queue of through vehicles blocks the entrance of the DLTL. This paper developed a procedure to determine the lane length in which both the chance of lane blockage and lane overflow were considered. Included in the proposed procedure is a calculation of the probability that all arriving left-turn vehicles enter the DLTL. Example values are presented; however, for application to the real world situation, the authors recommend that the procedure be followed in each case to obtain the most appropriate value for the specific site.

The proposed procedure can be used for designing the lane length for new DLTLs and for evaluating the lane length of existing DLTLs. For the latter, if the existing length is not sufficient, the formula can be used to compute the adequate single red phase period. An important decision issue is how to determine the threshold probability. This issue is fundamental to many design problems in traffic engineering: the question of what level of service should be provided.

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