Theoretical Analysis of Left-turn Waiting Area at Signalized Intersections

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Abstract
In the urban traffic system, the formation of bottlenecks at the intersection is the foremost cause of the reduction in capacity and the wastage of the green signal time. Several conventional and unconventional methods have been introduced to improve the efficiency of left turn lane as it is one of the most important factors that affect the safety and efficiency at the intersections. This research paper analyzes the benefits of a new technique introduced recently in China-the left-turn waiting area. This has an extended left lane that allows the vehicles to wait before the signal turns green. This system is known to have increased the overall capacity at an intersection by about 18%. A mathematical model has been developed to analyze the benefits of a left-turn waiting area.

Keywords: Roadway capacity; Safety; Left turn lane; Benefits; Signal phase

Introduction

In any urban traffic system, congestion is a serious problem at the intersection. Traffic operation at the intersection is a complex process due to the influence of various multi-dimensional random factors, which reduce the capacity at the intersections and increase the delay time. So it is fair to say that intersections have become an underlying source of the traffic congestion in urban road networks. Moreover, the left turning vehicles are one of the important factors of congestion, resulting in the inefficiencies and safety issues at the intersection. A report by the Federal Highway Administration (FHWA) presented a well-designed before-after evaluation method to measure the safety effects of improvements, including installation of added left-turn lanes, added right turn lanes, and extension of the length of existing left or right-turn lanes. This report concluded that the number of intersection-related accidents could be reduced using left-turn lanes [1]. A report of the NCHRP stated that left-turn maneuvers are the main concern of the collisions at unsignalized intersections [2]. The existence of a separate left-turn lane gives the left turning vehicle time to maneuver into the designated lane thus reducing the potential of collision with the through traffic.

In order to cope up with the traffic issues at the intersections some unconventional methods were also developed. One of the unconventional methods followed by the engineers in China is the use of a Left-turn Waiting Area (LWA). Left turn waiting areas are usually set up beyond the stop bar at exclusive left-turn lanes. Such design is intended to allow the left-turning vehicles to enter and wait at the waiting areas after the initiation of the through phase. Left-turn vehicles in the waiting areas will then discharge during a lagging left-turn phase. This is said to improve the overall capacity of the intersection at considerable levels. This research basically introduces this concept and puts forward possible benefits of introducing a similar left-turn waiting area at saturated intersections in the United States.

Studies have been conducted on these left-turn waiting areas in the recent past. Zhao Yang et al. [3] In their study, reported that a left-turn waiting area that accommodates 3 cars can increase the capacity of the left-turn by 17.82%. Shikai You et al. [4] in their paper concluded that a straight waiting area played an important role in reducing the average vehicle delay and also improved the overall safety at an intersection. Gao L et al. [5] in their paper stated that a left-turn waiting area reduces the travel time by about 6% and cuts the delays by up to 8.25%. They also concluded that the average queue length is reduced 36%-74%, depending on the number of vehicles turning left. They also determined that the capacity increased by about 15%.
Left-turn Waiting Areas in Practice

Left-turn waiting areas are already implemented in China. It has been implemented in various parts of many major cities of China. Beijing, Shanghai, Chengdu, Kunming, Nanjing are some of the cities that have implemented the left-turn waiting area in their urban transportation system. These left-turn waiting areas in China have proved to be very helpful to manage the overflowing traffic in the ultra-urbanized major cities of the country [6].

There are two types of left-turn waiting areas that are in use, based on its geometry:

a. A straight waiting area

b. A curved waiting area

Straight waiting area

A straight waiting area is a straight direct extension of the exclusive left-turning lane into the intersection Figures 1 & 2. This type of waiting area gives absolutely no hindrance to the oncoming traffic as it is a direct extension of the exclusive left-turn lane.

Curved waiting area

The other type of left-turn waiting area in use is the curved waiting area (Figures 3 & 4). As the name suggests, this is a curved extension of the exclusive left-turn lane. This is only possible in instances where there is a median separating the two directions of traffic. The advantage with a curved waiting area is that it can accommodate more number of cars in the waiting bay than in a straight waiting area. However, care should be taken that the waiting area when extended into the intersection, does not Studies have been conducted on these waiting areas in China, one particular at the straight waiting area at the intersection of Zhongshan road and Hongqiao road in Shanghai. This was documented in the paper by You et al. [4]. It is stated in this paper that the introduction of these straight waiting areas reduced the west-bound delay by 5.6%.

Probability of blockage formation

Initial assumptions: The length of left turn lane is assumed as N vehicles, i.e. N vehicles can fit into the left turn lane without forming blockage for the through lane at a given point of time. We also assume geometry of the intersection; where through vehicles will block the left turn vehicle from entering the left turn lane.

Also, $n_t = \text{number of left turn vehicles}$

$n_i = \text{number of through vehicles}$

Probability of blockage by a left turn vehicle

During the red signal phase of the lane, we assume that the left turn lane is filled to its full capacity, i.e. there are N vehicles in the left turn lane and the next vehicle arriving at the
intersection is a left turning vehicle. Now, this left turn vehicle tries to enter the lane, but because the lane is filled, it has to wait for the turning and hence results in blocking the through vehicles behind it (Figure 5). To find this probability of blockage of the through lane by the left turning vehicle, we use Binomial distribution. The number of left-turn vehicles follows a binomial distribution, where the arrival of a through vehicle can be considered as an event of success.

![Figure 5: Blockage by a Left turn vehicle (the black cars are left turn vehicles).](image1)

Here, we consider the arrival of the first vehicles irrespective of their turning movements. These vehicles when filled up the intersection are sufficient to form blockage for the remaining vehicles. Hence, Probability density function for is given by,

\[ f(x) = \binom{N+x-1}{x} p^x (1-p)^{N+x-1-x} \]  \hspace{1cm} \text{Equation (2)}

The blockage events due to left turn vehicles include the cases when is greater than N among the vehicles. Hence, the Probability of blockage due to left-turn vehicles can be calculated as,

\[ p_n = \sum_{x=n}^{\infty} f(x) \]  \hspace{1cm} \text{Equation (3)}

\[ \text{Probability of blockage by a through vehicle} \]

![Figure 6: Blockage by a through vehicle (the black cars are left turn vehicles).](image2)

![Figure 6: Blockage by a through vehicle (the black cars are left turn vehicles).](image3)

Figure 6 presents a typical situation where the left turn vehicles are blocked by the through vehicles during the protective left turning signal phase. The probability density function for the blockage of left turn lane by the through vehicle is calculated similarly as,

\[ f(n) = \binom{N+x-1}{n} p^n (1-p)^{N+x-1-n} \]  \hspace{1cm} \text{Equation (3)}

Also, the Probability function is

\[ P_n = \sum_{x=n}^{\infty} f(x) \]  \hspace{1cm} \text{Equation (4)}

Where, \( P_n = \sum_{x=n}^{\infty} f(x) \) where \( P_{(r,t)} = P_{(r,t)} = 1. \)

\[ \text{Average number of vehicles in the bay} \]

When a blockage occurs due to through vehicles, there might be 0 to N vehicles in the left-turn bay as shown in Figure 7 (Where N=3). The average number of vehicles in the left-turn lane is essential for capacity estimations. The occurrence of a blockage by a through vehicle is equivalent to the arrival of the \((N+1)\)th through vehicle. If \( x \) denotes the total number of vehicles on both lanes when a blockage occurs, \( x \) then follows a negative binomial distribution, and the probability density function of \( x \) is given by Equation (5). The negative binomial distribution, also known as the Pascal distribution, gives the probability of \( n \), number of trials necessary to obtain \( k \) successes and \( p \), the probability of success of each independent trial. The probability density function is therefore given by,

\[ f(x) = \binom{x+k-1}{x} p^x (1-p)^k \]  \hspace{1cm} \text{Equation (5)}

Where, \( \binom{n}{k} \) is a binomial coefficient.

Since here, arrival of the \((N+1)\)th vehicle is the success, . Substituting in Equation (5),

\[ f(x) = \binom{x+k-1}{x} p^x (1-p)^{N+1} \]

The expected value of \( x \), \( E(x) \) should be calculated using Equation (7).

\[ E(x) = \sum_{x=n}^{\infty} x f(x) = (N+1)/p \]  \hspace{1cm} \text{Equation (7)}

This general equation can be used to calculate the expected value of \( x \) for a general negative binomial distribution. However, a slight modification on the Equation (7) has to be made in this study, because \( x \) is only allowed to vary \( N+1 \) between \( 2N+1 \) and \( N+1 \).

\[ E(x) = \sum_{x=n}^{\infty} x f(x) \]  \hspace{1cm} \text{Equation (8)}

Where

\[ f(2N+1) = 1 - \sum_{x=n}^{2N} f(x) \]  \hspace{1cm} \text{Equation (9)}

The variance \(\sigma^2 \) (\( \sigma \) is the standard deviation) of \( x \) can then be calculated using Equation (10).

\[ \sigma^2 = \sum_{x=n}^{2N} (x-E(x))^2 f(x) \]  \hspace{1cm} \text{Equation (10)}
The average number of vehicles in the left-turn lane can then be obtained by:

$$E_l(x) = E(x) - (N + 1)$$  

Equation (11)

Similarly, the average number of through vehicles in the short-lane section, when blocked by left-turn vehicles can be obtained.

**Delay Analysis**

For introducing the Left-turn Waiting Zone, the study of the Delay and Capacity changes at a particular intersection is necessary. Figure 7 shows the lane configuration of a typical intersection in our case study.

**Case 1: existing phase conditions**

As per the existing conditions, first green signal is given for the left-turn lane and then for the through lane (Figure 8). In this situation, the worst case scenario where maximum delay occurs is when the $$(N+1)\text{th}$$ vehicles in the through lane completely block the passage of left turn vehicle and the left turn bay is completely empty. This results in the complete wastage of entire green time for the left-turn bay. If we suppose, the intersection has signal timings such that,

For the Left turn lane, Green signal time = $g_l$
Red signal time = $r_l$
Yellow signal time = $y_l$

For the Through lane, Green signal time = $g_t$
Red signal time = $r_t$
Yellow signal time = $y_t$

The total time wasted due to blockage in this case = $4(g_l + r_t + y_l + y_t)$ = One complete cycle.

**Case 2: phase change**

The first solution introduced is reversing the Signal phase. The signal Phase is reversed such that the through vehicles go first and then the left turn vehicles are allowed Figure 9. In this situation, the worst case scenario occurs when the entire left turn bay is filled up and the next vehicle arriving is also a left turn vehicle. Thus the passage of the through vehicles is blocked by the left turning vehicle and the number of vehicles waiting in the through lane at the intersection is zero. This results in the complete wastage of entire green time for the through lane. The total time wasted in this case = $4(g_t + r_t + r_l + y_l)$ = One complete cycle. Hence, from Cases 1 & 2, in both the scenarios the total delay occurred is same and is equal to one complete cycle.

**Case 3: left-turn waiting area**

Another solution to reduce the delay at the intersection due to a blockage is use of a Left-turn Waiting Area. As discussed earlier in the paper, LTWA (Left -turn Waiting Area) is the extension of the left-turn bay into the intersection. This concept is applicable only when the existing signal phase is reversed, i.e. signal first turns green for the through lane and then the left-turn lane. Here as well we assume the first $$(2N+1)$$ vehicles arriving at the intersection. Taking into consideration the worst case scenario of Case 2, maximum delay occurs due to blockage by a left turning vehicle.

Now, when the signal first turns green for the through lane, the left turn vehicles waiting behind the Stop line 1 can cross and enter the left-turn waiting zone. This clears up the left turn bay for the blockage vehicle. Hence the left turn vehicle enters the bay and blockage is prevented. Thus the through vehicles arriving at the intersection can move and cross the intersection and the total green time wastage is prevented.

When the signal turns green for the through lane, the blockage vehicles takes a few seconds to enter the left turn bay and that is the only time wasted at the intersection. Assuming start-up time as $s_t$, Total time wasted = $s_t$. This time is almost negligible compared to the complete signal cycle.

**Capacity Analysis**

The capacity of a signalized approach with a left-turn waiting area can be defined as the maximum flow rate that the approach can service under prevailing geometry, traffic flow, and signal timing conditions. But, to find the capacity of a signalized intersection with a left-turn waiting area, it is necessary to find the capacity of a signalized intersection with a left-turn bay or a short left-turn lane. To obtain the capacity value, the usual assumption is that the traffic demand is infinite. However, for this research, traffic demand is assumed to be high enough for a queue to exist on the approach at the end of the green interval, and therefore, the left-turn lane is always blocked at the start of the green interval. For this research, the model derivation is based on the assumption of a signalized approach with a single through lane and a left-turn bay.
Capacity

In HCM 2010, the capacity condition for an intersection is defined by a composite volume/capacity ratio for the critical lane groups and the adjusted volume and saturation flows for each lane group are combined in the approach analysis [1]. The equation to estimate the lane capacity at a signalized intersection is as follows:

\[ c_i = \frac{s_i \times g_i}{C} \]

- \( c_i \): Capacity of one approach lane (passenger cars per lane per hour)
- \( C \): Cycle length (sec)
- \( s_i \): Prevailing saturation flow of through lane group
- \( g_i \): Effective green time allocated to the lane group

The equation gives us the capacity in passenger cars with a normal headway. To find the approach capacity, add up the lane capacities.

Saturation flow rate

Saturation flow describes the number of passenger car units (pcu) in a dense flow of traffic for a specific intersection lane group. In other words, if an intersection’s approach signal were to stay green for an entire hour and the flow of traffic through this intersection were as dense as could be expected, the saturation flow rate would be the amount of passenger car units that passed through this intersection during that hour [2].

Saturation headway

Headway is the time interval between the passages of successive vehicles moving in the same lane measured from head to head as they pass a point on the road. Saturation headway is defined as the headway of the vehicles in a “stable moving platoon” passing through a green light [3]. A stable moving platoon is a group of vehicles that are all going the same speed. As the number of the saturated flow data is not same in different intersections, related to the signal timing, intersection geometry factors, drainage ways and traffic conflicts, the application of the saturation flow should be measured data as much as possible. If every vehicle requires a time equal to the saturation headway (h), in seconds, to be serviced at a signalized intersection, then the maximum number of vehicles that can be serviced in an hour of green is given by the equation

\[ z = \frac{3600}{h} \]

Where, \( z \) is saturation flow rate, in veh/hr.

Lost time

Lost time is a measure of the wasted time at the beginning and ends of a phase. At the beginning of the green time, actual headway will be relatively longer than saturation headway for the first few vehicles, which includes driver reaction time and the time necessary for acceleration. The sum of the time difference between the saturation headway and the first few unsaturated headways is known as start-up lost time. In addition to start-up lost time there is lost time when the right of way changes, known as clearance lost time. It is the time between the last vehicle entering the intersection and the initiation of green on the next phase.

Therefore, lost time \( (t_f) \)

\[ t_f = t_s + t_c \]

Where, \( t_s \) = Start–up lost time
\( t_c \) = Clearance lost time.

The total lost time for a cycle is the lost time per phase multiplied by the number of phases per cycle.

Cycle length (C)

Cycle length is the amount of time from when a movement first is given the right of way until that movement receives it again.

Effective green time

Actual green time (G), for any movement is defined as the total number of seconds per cycle that the green light is actually displayed for that movement. The effective green time, \( g \), is the equivalent length of time in any cycle that may be utilized at the saturation flow rate. Actual green time is based on the effective green time, and takes into account the lost time and the all-red and yellow time to come up with a value to use in programming the signal. Actual green time is calculated using the equation below.

\[ g = G + Y - t_L \]

Where, \( G \) = Actual green time (sec)
\( Y \) = Yellow and all-red time (sec)
\( t_L \) = Lost time per phase (sec)

As per our previous assumptions, we assume a capacity of \( (2N+1) \) vehicles at the intersection irrespective of turning movements.

a. Case 1: existing phase

The left traffic goes first, and then the through traffic goes. In the worst case scenario, \( (N+1) \) through vehicles arriving first at the intersection, block the passage of Left turn vehicles into the Left turn bay.

Hence, theoretical Capacity wasted during the cycle = \( N \) vehicles.

Total Capacity passing the intersection = \( (2N+1) - (N) = (N+1) \) vehicles.

b. Case 2: reverse phase

The through traffic goes first, and then the left traffic goes. In the worst case scenario, left turn vehicles arriving first at
the intersection, block the passage of through vehicles into the intersection.

Hence, theoretical Capacity wasted during the cycle = N vehicles

\[ \text{Total Capacity passing the intersection} = (2N + 1) - N = (N+1) \text{ vehicles.} \]

**Case 3: use of left turn waiting area**

In this case, the phasing is similar to the earlier case, the left turn vehicles goes first, and then the through vehicles goes. In the worst case scenario, \((N + 1)\) left turn vehicles arriving first at the intersection, block the passage of through vehicles into the intersection. Now, when the signal first turns green for the through vehicles, the vehicles in the left turn bay can move into the left turn waiting area and the blockage is cleared for the through traffic. Hence, theoretically all the \((2N + 1)\) vehicles are able to cross the intersection during the cycle length. No Capacity is wasted during the cycle length.

**Conclusion & Recommendations**

This paper introduces the concept of left-turn waiting area and attempts to perform a theoretical analysis of the benefits of installing such a treatment at signalized intersections in the United States. The theoretical study proved that it is beneficial to utilize such an unconventional treatment. A study conducted to analyze the before and after effects of installing a left-turn waiting area will corroborate the theoretical inferences drawn in this paper. The study should consider germane measures of effectiveness such as delay, travel time and capacity at the study location.

**References**


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