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DEVELOPMENT OF GUIDELINES FOR IMPLEMENTATION OF CONTRAFLOW LEFT-TURN LANES AT SIGNALIZED INTERSECTIONS

Final Report

by

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EXECUTIVE SUMMARY

An innovative intersection design, Contraflow left-turn lane (CLL), designed for increasing the left-turn capacity has been increasingly implemented at the signalized intersections. This study developed a systematic method for determining the length of CLL and the signal timing plan for implementing CLL at signalized intersections. The signal timing and geometric design requirements in the implementation of CLL have been discussed and thoroughly considered in developing the proposed method. First, the development of the signal timing plan has considered both the pre-clearance time required before the start of the pre-signal phase and the clearance time required at the end of the pre-signal phase. As a result, it will reduce the risks associated with the use of CLL, and make CLL a safety solution to mitigate traffic congestion at signalized intersections. Second, the method for estimating the length of CLL is based on the conditions for maximizing the utilization of CLL. As a result, the estimated CLL lengths will allow the CLL intersection to achieve its best operational performance.

A case study was conducted for validating the operational benefits of redesigning a real-world CLL intersection using the signal timing plan and CLL lengths recommended by the proposed method. The traffic simulation results show that the redesigned CLL intersection outperforms the existing CLL intersection in terms of the average traffic delay, average vehicle travel time, and average queue length, and the CLL intersection can achieve its best performance at the recommended CLL lengths. These results verified that the method proposed by this study can provide useful tools and design guidelines to the traffic engineers in the implementation of the CLL intersection design.

Chapter 1. Introduction

1.1 Problem Statement

Recently, an innovative intersection design, contraflow left-turn lane (CLL) has been increasingly implemented at the signalized intersections in China. It was designed for solving the problem that the capacity of the existing conventional left-turn lanes (LTLs) is insufficient for the increasing left-turn demand at a signalized intersection. Figure 1-1 shows the typical geometric layout for a signalized intersection with CLLs installed in four approaches. The basic idea of this design is to provide additional capacity to left-turn vehicles by making use of the opposing lanes dynamically through appropriate traffic signal control. With the CLL design, more existing lanes (i.e. opposing through lanes) can be used for moving left-turn vehicles, thereby increasing the efficiency and capacity of the intersections and reducing the traffic congestion at the intersections. Also, this new design can be easily implemented without modifying the intersection in a way that requires major constructions. Thus, it has the great potential of being a cost-effective solution for mitigating the congestion at the signalized intersections with high left-turn demand.

CLL design was first proposed by a traffic manager in Handan, China, and was then, first implemented in that city in 2014. After that, due to its effectiveness in reducing intersection congestion, it has been widely implemented in over 50 intersections in 21 different cities in China by 2018 (Zhao et al., 2018). However, because it is a new design, a limited amount of studies has been conducted on investigating the operational and design issues in the implementation of CLL at signalized intersections. Most of the previous studies (Wu et al., 2016 and Su et al., 2016) have been conducted on investigating the operational benefits of this innovative intersection design, such as its effectiveness on reducing intersection delay, travel time, and left-turn queue lengths. In this new design, the length of CLL, which is defined as the distance between the upstream median opening and the stop line at the main signal (see L_{CLL} in Figure 1), is one of the key design elements. Appropriate CLL length can maximize the utilization rate of the CLL (Wu et al., 2019). However, the existing method and guidelines have some limitations and this problem needs to be further investigated. Also, there is a lack of systematic and user-friendly guidelines on the signal timing for this innovative intersection design. To fill these gaps, this study is to develop a systematic method for determining the length of CLL and the signal timing plan for implementing CLL at signalized intersections. The developed method can provide useful tools and design guidelines to traffic engineers in converting an existing conventional signalized intersection into a CLL intersection.

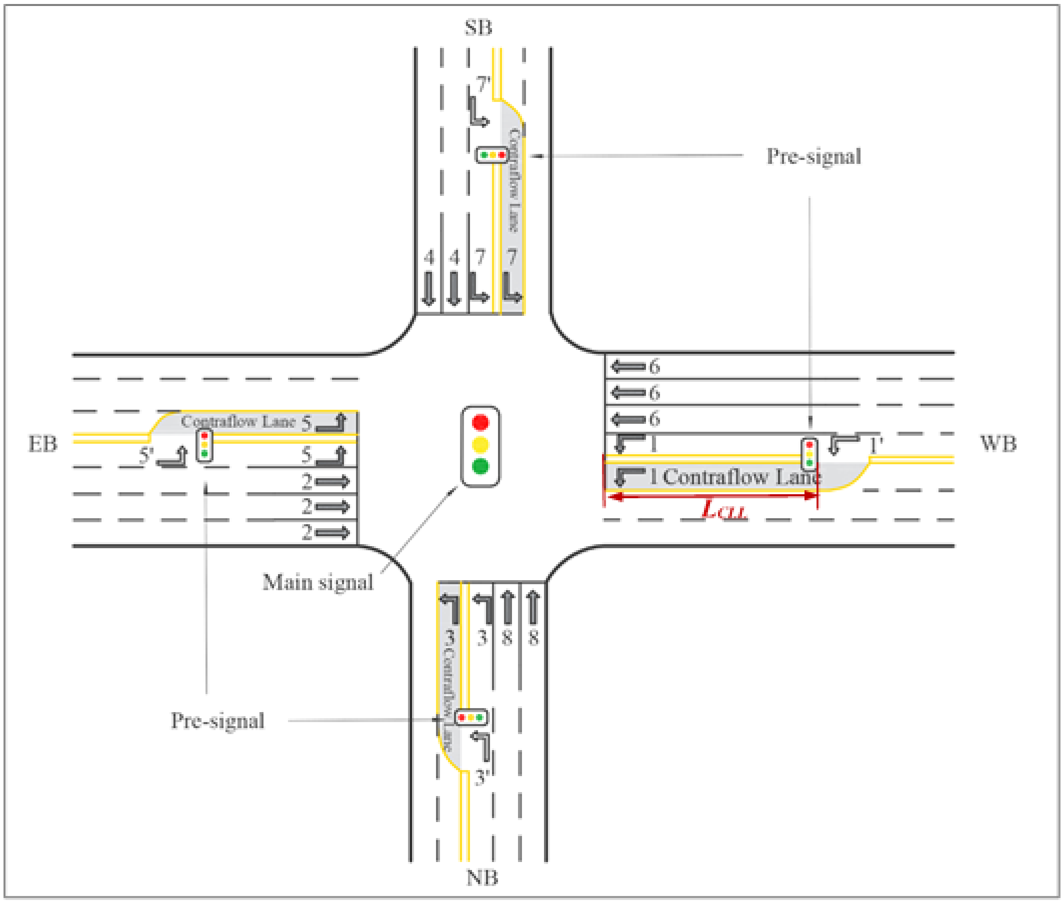


Figure 1-1: Signalized intersection with CLLs

1.2 Objectives

The objective of this report is to develop a systematic method for determining the length of CLL and the signal timing plan for implementing CLL at signalized intersections.

1.3 Report Overview

The remainder of this report is organized as follows: Chapter 2 presents a comprehensive review of previous studies related to the CLL intersections. Chapter 3 introduces the proposed method for determining the length of CLL and the signal timing plan at CLL intersections. Chapter 4 describes a traffic simulation-based case study that is conducted to evaluate the operational benefits of redesigning a real-world CLL intersection using the signal timing plan and CLL lengths recommended by this study. Finally, conclusions and recommendations are provided in Chapter 5.

Chapter 2. Literature Review

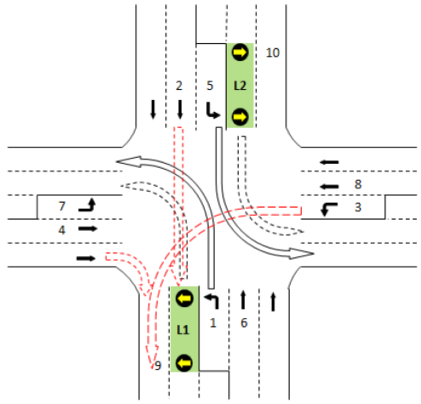
2.1 Introduction

CLL which is also referred to as the exit lanes for left turnings (EFL) or contraflow left-turn pocket lane (CLPL), belongs to the spectrum of dynamic or reversible lane design. Applying the CLLs at intersections is a relatively new design idea. Although it has been implemented in over 50 intersections in China, none are currently implemented in North America. In recent years, a number of studies have been conducted in investigating this new design from different aspects, including its operational and safety performance, geometric design, and traffic signal timing.

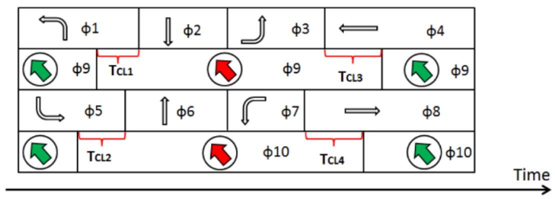
2.2 Operational and safety performance

The operational benefits of using CLL design have been approved by many previous studies. Zhao et al. (2013) found that CLL design increases the capacity of an intersection. In this study, examples show that, by using CLL design, the greatest improvement can be achieved as much as 50%, and the highest reduction of average intersection vehicle delay and queue length can be achieved as much as 49.8% and 72.6% respectively compared with the conventional intersection design. Su et al. (2016) indicated that the CLL treatment can reduce the intersection delay by about 22% at intersections with high left-turn demand. The contraflow treatment will begin to benefit an intersection under the condition that the left-turn V/C ratio is greater than 1.0. Wu et al. (2016) verified that CLL design can improve intersection capacity and reduce traffic delay by comparing the delay experienced by the left-turning and through vehicles at CLL signalized intersections with the conventional left-turn lane and another unconventional left-turn treatment entitled “tandem design”. The results of Zhao et al. (2018) indicate that the CLL treatment can increase a signalized intersection’s throughput by up to 25% and decrease the intersection’s delay by 35% averagely, and at the same time increase the left-turns’ capacity by up to 70% and decrease left-turns’ delay by up to 50%.

Safety is one of the major concerns for this new design because of the potential conflicts between the left-turn vehicles trapped on the CLL and opposing through vehicles (Su et al., 2016). As shown in Figure 2-1, which is illustrated in Su et al. (2016), the northbound (NB) and southbound (SB) approaches have contraflow left-turn treatments, with pocket entrances controlled by phase 9 (NB) and phase 10 (SB). In this study, movements conflicting with NB contraflow left-turn vehicles are illustrated by the red arrows in Figure 1 (a). It is mentioned that, for the NB contraflow left-turn vehicles, their conflicts with westbound (WB) left-turners could be avoided by using pavement markings, routing left-turning vehicles into the right-most lane instead of the contraflow lane, and their conflicts with SB through vehicles must be prevented by terminating the phase 9 green a few seconds before the phase 1 green ends so that all contraflow vehicles can be discharged before SB through vehicles start moving.



a) Geometric Layout



b) Signal Phasing for the Proposed Contraflow Left-Turn Lane

Figure 2-1: Movement Conflicts with NB Contraflow Vehicles
(source: Su et al.,2016)

To assess the safety performance of the CLL design. Zhao et al. (2015) investigated the driver's behavior when approaching CLLs by employing a series of driving simulator experiments. It was found that drivers show a certain amount of confusion and hesitation when encountering a CLL for the first time, however, it is quite easy for drivers to accomplish the left turn task by using the CLL, thus, CLL treatment is not likely to pose any serious safety risk. Zhao et al. (2017) evaluated the potential safety problems of CLL intersections using the field data collected at seven locations in China. Statistical comparison of the safety risk between the CLL intersections and the conventional intersections indicate that the safety problems of CLL intersections mainly lie in red-light violations at the pre-signal, wrong-way violation, and vehicles trapped in the mixed-usage area. As for red-light violations, more information, such as signs and markings, should be provided to the drivers to warn the signal control of the median opening. For wrong-way violation, strong law enforcement and colored lane pavement for the mixed-usage area are recommended. For vehicles trapped in the mixed-usage area, a lower speed value is recommended for the design speed, such as 17.0 km/h.

2.3 The saturation flow rate of exit lanes for CLL intersections

CLL treatment has been demonstrated to be promising for capacity improvement. Although much is known about CLL intersections, the saturation flow rate, which is a key parameter of the intersection design and optimization, is worth attention. Zhao et al. (2019) developed a saturation flow rate adjustment model that can be used for estimating the saturation flow rate of the LTL at both the main intersection and the median openings based on field-collected data at ten signalized intersections. In the development of this model, five influencing factors, namely the median opening blockage, demand starvation, multilane interference, conflict with opposing vehicles, and lane changing, were considered. In this study, a saturation flow rate adjustment model is established as shown in Equation (1) and there are a total of five adjustment factors: the first three factors ($f_{EM1}, f_{EM2}, f_{EM3}$) are used for the saturation flow rate adjustment of the main-stop line, and the last two factors (f_{EP1}, f_{EP2}) are used for the pre-stop line.

$$f_E = f_{EM1} f_{EM2} f_{EM3} f_{EP1} f_{EP2} \qquad \text{Equation (1)}$$

Where, f_E is the estimated adjustment factor for the saturation flow rate, f_{EM1} is the adjustment for the median opening blockage for lanes in the mixed-use area at the main-stop line; f_{EM2} is the adjustment for the demand starvation for lanes in the mixed-use area at the main-stop line; f_{EM3} is the adjustment of left-turn lanes interfere with each other; $f_{EP1}$is the adjustment for conflict with opposing vehicles; and f_{EP2} is the adjustment for the lane changing of the saturation flow rate.

A detailed discussion of these factors can be found in this study. The results of the developed saturation flow rate adjustment model for CLL control and the field survey indicate that the accuracy of the proposed adjustment model is acceptable, the detailed model factors are shown in Table 1, and the group factor is explained in Figure 2-2.

Table 2-1: Comparison of saturation flow rate between model and field survey

Survey location	Group	f_{EM1}	f_{EM2}	f_{EM3}	f_{EP1}	f_{EP2}	Model results	Field survey	Error (%)
1	Group 1	1	1	0.94	—	—	1,610	1,603	0.42
	Group 2–3	0.892	0.844	0.91	—	—	1,173	1,162	0.97
	Group 4	1	1	—	0.956	0.841	1,377	1,339	2.79
2	Group 1	1	1	0.94	—	—	1,610	1,635	−1.53
	Group 2–3	0.892	0.828	0.91	—	—	1,151	1,167	−1.40
	Group 4	1	1	—	0.956	0.841	1,377	1,355	1.60
3	Group 1	1	1	0.94	—	—	1,610	1,552	3.69
	Group 2–3	0.892	0.82	0.91	—	—	1,140	1,139	0.09
	Group 4	1	1	—	0.956	0.841	1,377	1,422	−3.16
4	Group 1	1	1	0.94	—	—	1,610	1,572	2.39
	Group 2–3	0.887	0.853	0.91	—	—	1,179	1,143	3.16
	Group 4	1	1	—	0.98	0.839	1,408	1,387	1.51
5	Group 1	1	1	0.94	—	—	1,610	1,613	−0.23
	Group 2–3	0.887	0.831	0.91	—	—	1,149	1,142	0.60
	Group 4	1	1	—	0.98	0.839	1,408	1,403	0.35
6	Group 1	1	1	0.94	—	—	1,610	1,633	−1.43
	Group 2–3	0.903	0.859	0.93	—	—	1,235	1,190	3.78
	Group 4	1	1	—	0.955	0.851	1,392	1,383	0.63
7	Group 1	1	1	0.94	—	—	1,610	1,666	−3.38
	Group 2–3	0.887	0.842	0.91	—	—	1,164	1,166	−0.23
	Group 4	1	1	—	0.955	0.839	1,372	1,358	1.04

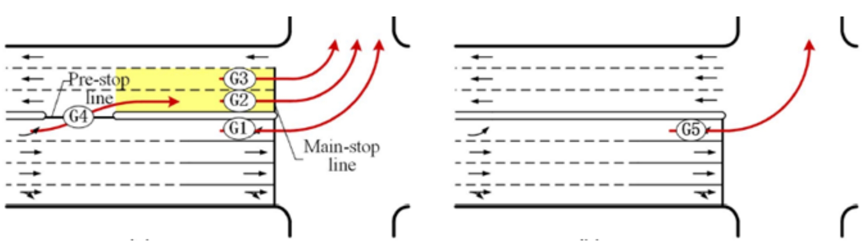


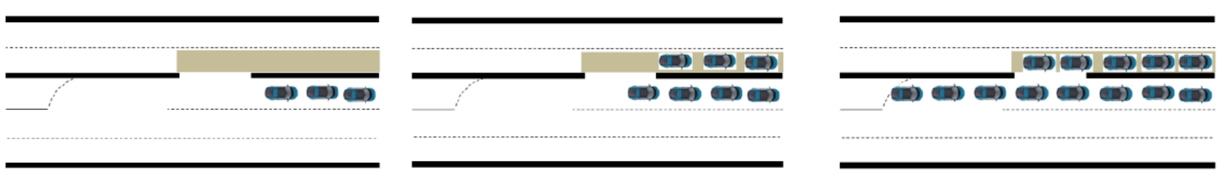
Figure 2-2: Data Grouping
(Source: Zhao et al., 2019)

The results of this model can be used for improving and optimizing the signal timing and geometric design of the CLL design.

2.4 Geometric design and traffic signal timing

The two key design elements for CLL are the length of CLL and the signal timing at CLL intersection. Many previous studies investigated these design elements by establishing optimization models for maximizing the operational benefits of CLL. For example, in Zhao et al. (2013), an optimization problem for CLL control was formulated as a mixed-integer nonlinear program. The objective of this optimization problem is to maximize the reserve capacity of CLL. Twenty-four constraints were set to find the optimum solutions about geometric layout, main signal timing, and pre-signal timing for the CLL intersection design. The results show that the proposed CLL intersection increases the capacity of an intersection, reduces average intersection vehicle delay and queue length compared with the conventional intersection design. In Wu et al. (2016), analytical models were developed for estimating the capacity and delay of intersections associated with the CLL design at first. Then, a procedure was developed to optimize the location of upstream median openings based on the developed capacity model. In the development of these optimization models, some geometric and signal timing constraints for the CLL design were considered, but some constraints related to the pre-signal timing and number of CLLs have not been fully considered.

Some previous studies investigated these design elements by analyzing the operational and safety performance of the CLL design. Su et al. (2016) proposed an experimental design for evaluating signal timing and geometric design elements of CLL intersections. This study examined some key elements in the CLL design, including CLL lengths, access control, and green signal time reallocation. It also analyzes the traffic flows that potentially conflict with the left-turn vehicles on the CLL, and recommends the use of appropriate signal clearing time to avoid such conflicts. It is worth to mention that in this study the design of CLL length is based on assumption that the desired lane utilization ratio between the CLL and standard left-turn pockets 1:1, as shown in Figure 3, there are three-lane utilization scenarios, the desired one is as shown in Figure 2(b). These scenarios are based on an assumption that drivers prefer using the standard left-turn lane, but will use the contraflow lane if the standard lane is filled.



a) Low Left-Turn Volume b) Medium Left-Turn Volume c) High Left-Turn Volume

Figure 2-3: Contraflow Left-turn Lane Vehicle Assignments
(source: Su et al., 2016)

Zhao et.al (2018) developed a probabilistic model to estimate intersection capacity with CLLs. The impacts of the cycle length, LT demand, and lane selection preference on the capacity estimation of CLL intersection were also investigated. Liu et al. (2019) proposed a shockwave-based model, as shown in Figure 4, for estimating the maximum left-turn queue length of CLL at signalized intersections. In this study, a binary logit model was employed as an estimate of the unique queuing behavior at the pre-signals. A modified shockwave-based method was then proposed for estimating the maximum left-turn queue length for the signalized intersections with the CLL design by considering the unique queuing behavior at the pre-signal. The results suggest that the effective red time duration, the offset between the main and pre-signals, and the queuing behavior of left-turning vehicles at the pre-signals greatly affect the maximum left-turn queue length. The proposed queue-length model was validated with the field data considering varying left-turn traffic demands. However, the interactive relationship between the signal timing and CLL geometric design has not been fully studied.

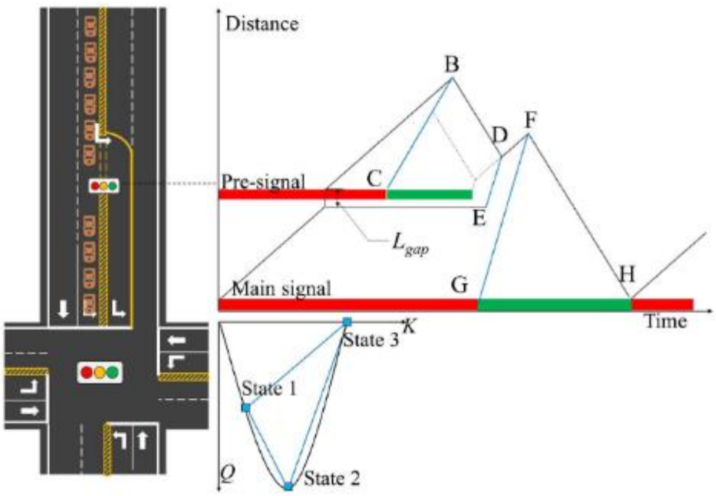
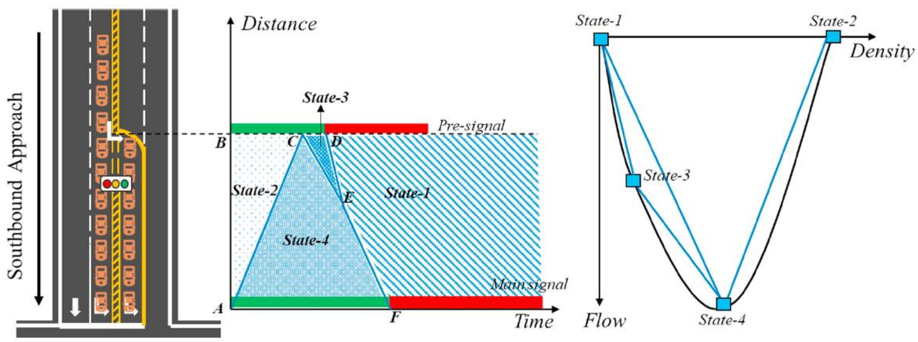
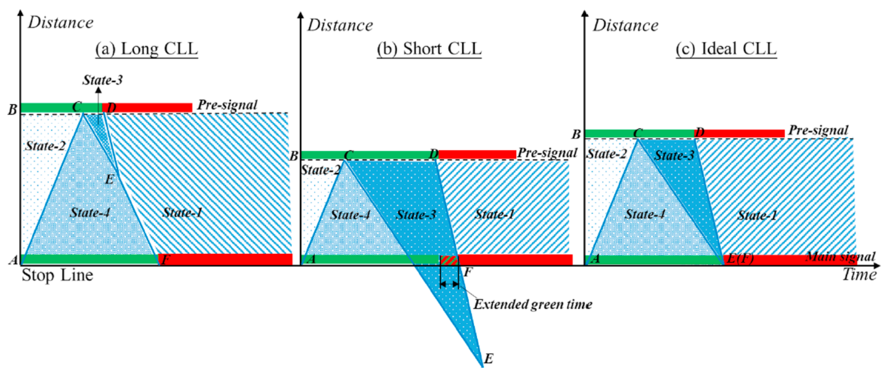


Figure 2-4: Modified Shockwave Diagram for the CLL Design
(source: Liu et al., 2019)

Most recently, Wu et.al (2019) proposed a semi-actuated signal control strategy to improve operations of the CLL design at signalized intersections. It proposed a procedure for optimizing the CLL length for maximizing the discharge rate of the left-turning vehicles and the utilization rate of the CLL. In this study, the interactive relationship between CLL length and traffic signal timing has been considered by using simultaneous equations, and a shock wave-based model was used for estimating the left-turn queue backup length, the ideal CLL length is as shown in Figure 5(b). The limitation for the shock wave-based queuing model is that detailed information about traffic conditions is required to detect the necessary shock waves and such information is difficult to obtain through existing arterial traffic data collection systems (Cheng et al., 2011), which prevent the wide application of the proposed method. In addition, more signal timing requirements need to be considered in their method.



a) Shock wave propagation and fundamental diagram for a typical CLL design.



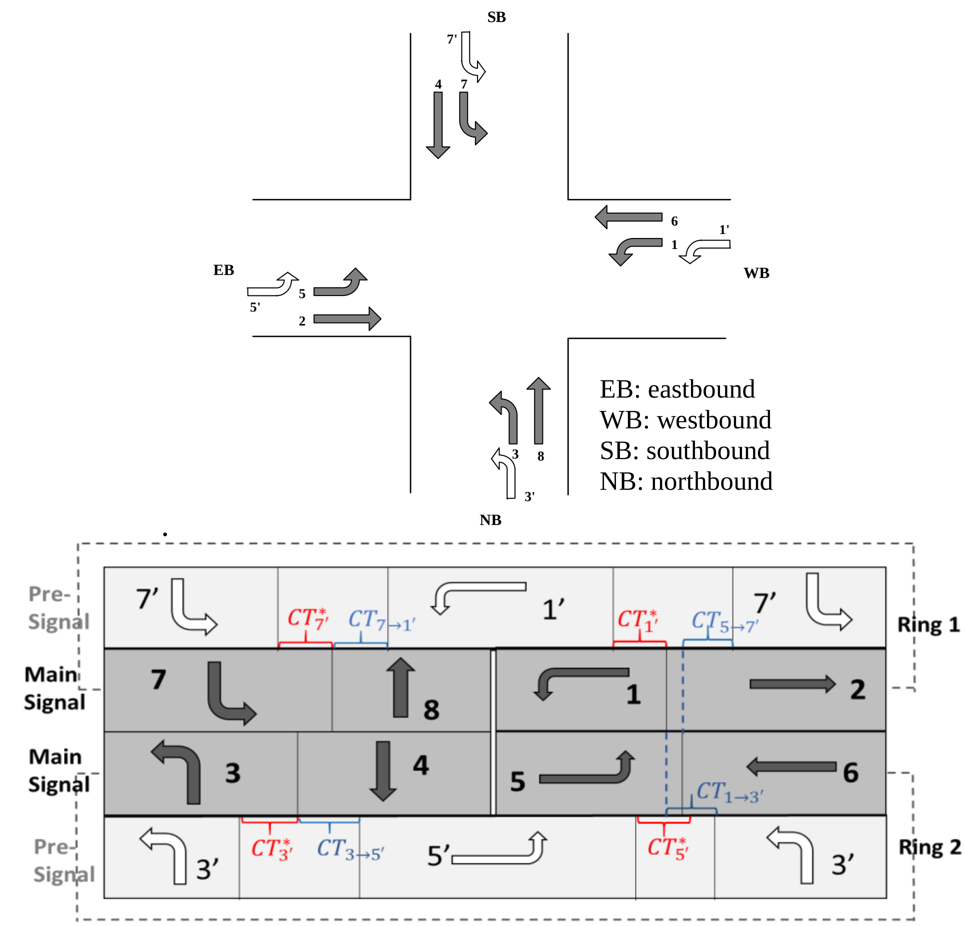
b) The time-space diagrams for long, short, and ideal contraflow lanes.

Figure 2-5: Shock Wave-Based Model for CLL Design
(source: Wu et al., 2019)

According to the above introduction of previous studies, it can be seen that most of the previous studies have indicated that the use of CLLs can improve the operational performance of the intersections. Different sets of geometric and signal timing requirements in the CLL design have been considered by different studies. There is a lack of systematic design guidelines that thoroughly consider the critical requirements associated with the CLL design and incorporated them in a user-friendly procedure for traffic engineers to follow in the implementation of this new intersection design.

Chapter 3. Design Concepts and Critical Requirements

Figure 1-1 shows the design concept of the CLL and Figure 3-1 shown a general signal timing plan used for such design. Generally, the CLL is designed for implementing at the signalized intersections with protected only lead-lead left-turn phases. As illustrated in Figure 1-1 and Figure 3-1, a pre-signal is set at a median opening upstream of the CLL to allow the left-turn vehicles to enter the CLL when the pre-signal is green.



- $*CTi'^{*}$ is the time for clearing the left-turn vehicles on the CLLs that entered the CLLs during the pre-signal phase i
- $CT_{j-i'}$ is the pre-clearance time for clearing the conflicting left-turn movement j from the CLL before starting the pre-signal phase i', sec

Figure 3-1: General signal timing plan for the signalized intersection with CLL design

As shown in Figure 3-1, the signal phases 7', 3', 5' and 1' are pre-signal phases for the left-turn vehicles from different approaches, which correspond to the left-turn phases 1, 3, 5 and

7 at the main signal, respectively. The left-turn vehicles start to enter the CLL in the signal phase for moving the through traffic on the cross street. The entered left-turn vehicles will wait at the CLL until the left-turn signal at the main intersection turns green and then, they will be discharged during the corresponding left-turn phase at the main signal. With the CLL design, more existing lanes (i.e. opposing through lanes) can be used for moving left-turn vehicles, which increase the intersection left-turn capacity. Furthermore, the additional left-turn capacity could allow left-turn phase times to be reduced, such that the saved green time could be reallocated towards other movements at the signal. Therefore, the capacity and operational efficiency of the entire intersections can be improved by using CLLs.

To ensure the safe and efficient operation of CLLs, there are some special geometric and signal timing requirements associated with the CLL design.

3.1 Signal timing requirements for the implementation of CLLs

1. lead-lead protected only left-turn phases

CLL design can only work with the lead-lead protected only phase. It is because, for a lagging left-turn approach, the left-turn vehicles cannot be allowed to enter the CLL during the signal phase that is right before the left-turn phase since this phase is for moving the opposing through vehicles that also need to use CLL. Thus, CLL design can't work with lagging left-turn phase. Also, since both the left-turners and opposing through vehicles need to use the CLL, these two traffic flows need to be strictly separated through proper signal control. Thus, permissive LT phases should be prohibited for the CLL design (Zhao et al., 2018).

2. Sufficient clearance time for clearing the left-turn vehicles on the CLLs at the end of the pre-signal phase.

As we mentioned in the literature review, the major safety concerns of the CLL design is the potential conflicts between the left-turn vehicles trapped on the CLL and opposing through vehicles. To prevent such type of conflicts, sufficient clearance time must be provided for clearing the left-turn vehicles on the CLLs before the left-turn signal at the main intersection turns red. Otherwise, the left-turn vehicle will be trapped on the CLLs and will be exposed to the risks of head-on collisions with the opposing through vehicles. The minimum required time for clearing the left-turn vehicles on CLL can be estimated by the following equation.

$$CT_{i'}^{*} \geq t_{dh} * \frac{L_{CLL_i}}{S_{pc}} + l_s + ar,\ i=1, 3, 5, 7. \qquad (1)$$

Where,

$CT_{i'}^{*}$ is the minimum time required for clearing the left-turn vehicles on the CLLs that entered the CLLs during the pre-signal phase i'

t_{dh} is the saturation discharging headway of left-turn vehicles on CLLs, which can be estimated according to the model developed in Zhao et al. (2019)

l_s is the start-up lost time of the left-turn vehicles, which is assumed to be 2s,
S_{pc} is the average vehicle storage length, which is assumed to be 25ft , and
L_{CLLi} is the length of the CLL at the approach corresponding to signal phase i'.

ar is the "all red" clearance interval for clearing left-turn vehicles from the intersection and it can be estimated according to the method provided in ITE Traffic Engineering Handbook (1992)

Note that, Equation 1 is for estimating the minimum required clearance time. To ensure that all the left-turn vehicles on the CLL can be fully discharged during the left-turn phase, some previous studies (such as Wu et al., 2016) recommended that the whole left-turn phase should be used for clearing the left-turn vehicles on the CLLs. Thus, the maximum clearance time for the left turn vehicles on the CLLs will be the length of the entire left-turn phase. In this case, the pre-signals will turn red before the initiation of the left-turn phase on the major street, and after that, no vehicles can enter the CLLs.

<u>3. Sufficient clearance time for clearing the conflicting left-turn vehicles from the cross street on the right side before starting the pre-signal phase (pre-clearance time)</u>

Besides conflicting with the opposing through traffic, the left-turn vehicles using the CLLs will also conflict with the left-turn vehicles from the cross street on the right side as shown in Figure 3-2. According to Su et al. (2016), appropriate clearing time should be provided for preventing this type of conflict. As shown in Figure 3-1, the pre-signal light for Phase *i*' turns green during the signal phase for the cross street through movement, which is right before its corresponding left-turn signal phase *i*. For example, for the WB left-turn movement, the pre-signal *Phase 1'* turns green during the signal *Phase 8*, which is right before the left-turn Phase *1*. However, the pre-signal *Phase 1'* should start a little later than *Phase 8*. It is because that the SB left-turn traffic (moving during *Phase* 7) needs to be cleared from the CLL before allowing the WB left-turn vehicles to enter the CLL during the pre-signal *Phase 1'*. This type of clearance time, that is for clearing the conflicting left-turn vehicles from the cross street on the right side before starting the pre-signal phase, is referred to as pre-clearance time. As shown in Figure 3, the pre-clearance time is depended on the length of CLL and the vehicle speed, and it can be estimated by the following equation:

$$CT_{j-i'} \geq \frac{L_{CLL_i}}{1.47V_{15\%}} \tag{2}$$

Where,

$CT_{j-i'}$ is the pre-clearance time for clearing the conflicting left-turn movement *j* from the CLL before starting the pre-signal phase *i*', sec
L_{CLL_i} is the length of CLL at the approach corresponding to signal phase *i*, ft
$V_{15\%}$ is the 15th percentile approach speed or speed limit, mi/h.
1.47 is the factor that covert mi/h to feet/sec

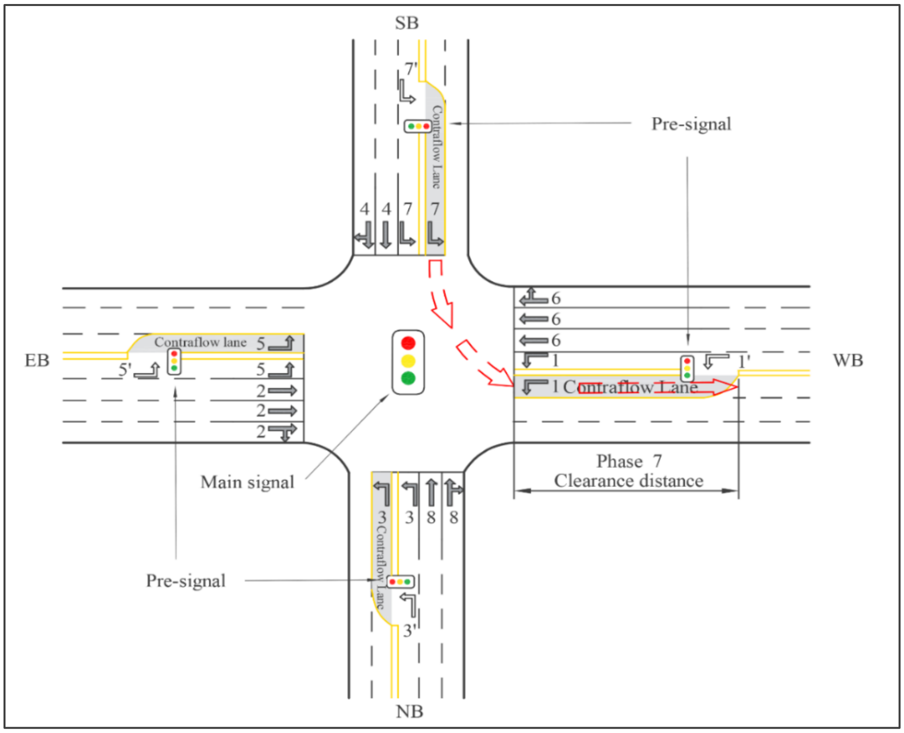


Figure 3-2: Clearance Distance for the Conflicting left-turn Movement

3.2 Geometric Design Requirements for the Implementation of CLLs

Besides the signal timing requirements, there are some special geometric design requirements for the implementation of CLLs.

1. Enough received lanes

Enough received lanes should be provided for left-turn traffic from both conventional LTL and CLL. Therefore, as recommended by Su et al. (2016) and Zhao et al. (2018), to implement the CLL at an intersection, a minimum number of two through lanes on the cross-streets are required and these two through lanes will serve as the receiving lanes for both conventional LTL and CLL as shown in Figure 3-3.a.

2. Pavement channelization markings for Right turners

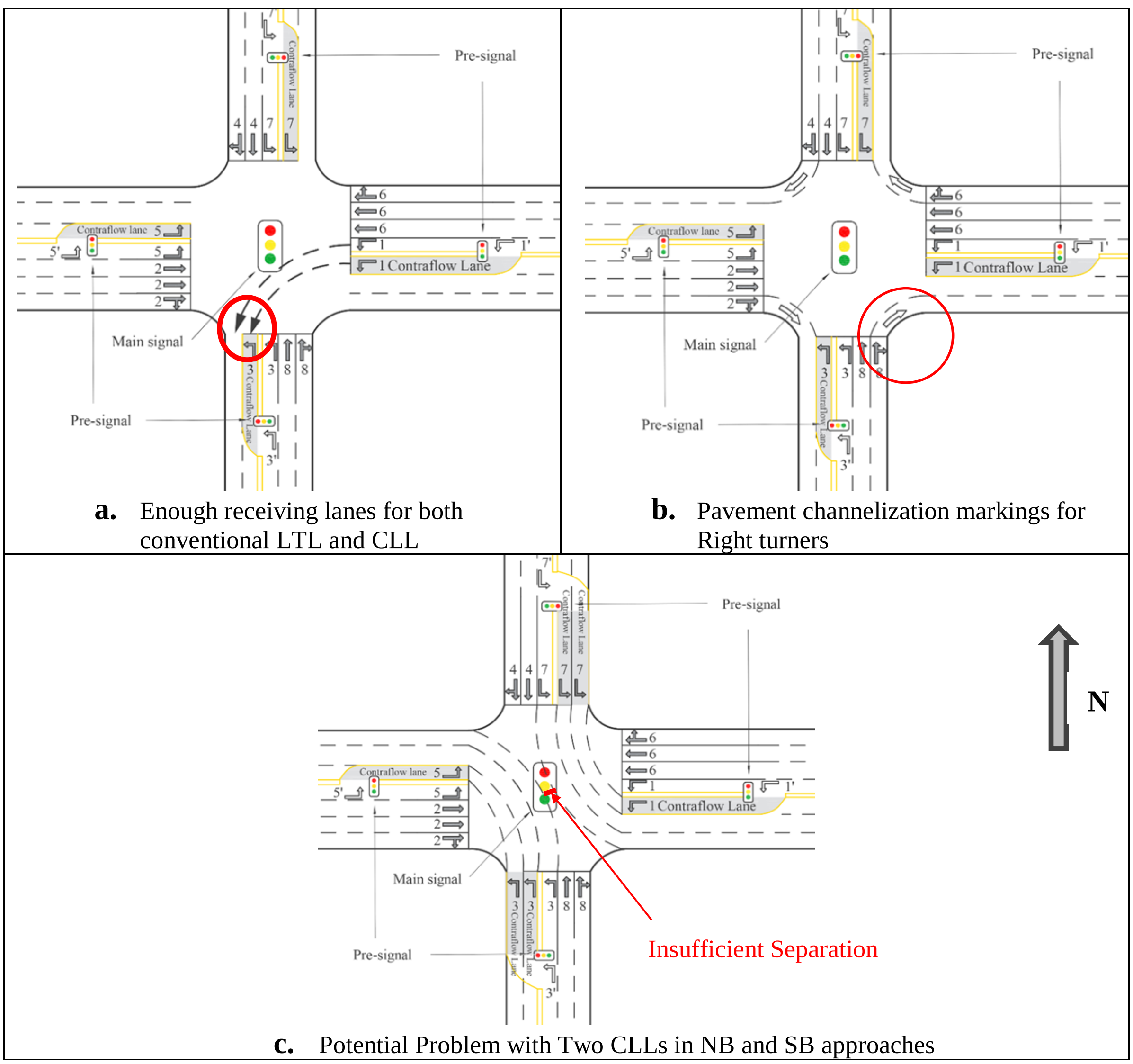
Left-turns will enter the CLLs during the signal phase for moving the through and right-turn traffic on the crossing street. Thus, the right turners from the cross-streets should be funneled away from CLLs to avoid conflicts with the queueing traffic on CLLs (Zhao et al., 2018). For this purpose, appropriate pavement channelization markings should be provided for the right turns as shown in Figure 3-3.b.

3. Number of CLLs per approach

Although, more than one CLLs could be used if there are enough receiving lanes on the crossing street. However, extra caution is required when more than one CLLs are used per approach. It because, if more than one CLLs are used, there will be at least three LTLs from each direction, which may cause the following safety problems:

a) According to Ackeret (1994), concurrent opposing left turns should have at least 10 ft separation. For the CLL design, since there are at least three LTLs in both directions, it may be difficult to maintain sufficient separation and the turning paths may even overlap, as shown in Figure 3-3.c.

b) It may not be safe to allow three vehicles turning abreast, especially for the intersections with a high percentage of large size vehicles (Cooner et al., 2011)



a. Enough receiving lanes for both conventional LTL and CLL

b. Pavement channelization markings for Right turners

c. Potential Problem with Two CLLs in NB and SB approaches

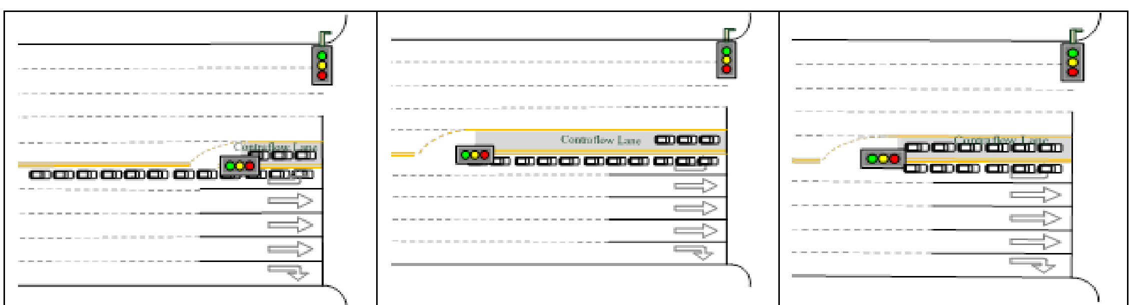
Figure 3-3: Illustration of Some Geometric Design Requirements for CLL Design

4. The appropriate length of the CLL

CLL cannot be either too long or too short. If it is too short, it will be quickly filled up and most of the left-turn vehicles have to line up in the conventional LTL, as shown in Figure 3-4.a. As a result, the capacity increase that is caused by using CLL will be very limited. If it too long, the left-turn vehicles that arrive when the pre-signal is red have to line up in the conventional LTL and missed the opportunity that they can use the CLL, as shown in Figure 3-4.b. Since the pre-signal phase turns green during a relatively short period, only a small portion of the left-turn vehicles can use the CLL and the operational benefits of CLL design cannot be fully achieved. Note that, since drivers will always choose the shortest queue to join when they arrive at the intersection and there is no barrier to prevent the left-turn vehicles to use the conventional LTL, the situation that longer queues in CLL and shorter queue in conventional LTL will never occur. Therefore, the maximum utilization of CLL will be achieved when the queue length on the CLL and conventional LT are balanced, as shown in Figure 3-4.c. Thus, according to the above discussion, the appropriate length of CLL, i.e. L_{CLL}, should be the average queue length of all LTLs, which can be calculated by the following equation:

$$L_{CLL} = \frac{Q_{LT}}{N_{CLL}+N_{RLT}} * S_{pc} \tag{3}$$

Where Q_{LT} is the total queue backup length (in the number of vehicles) and it can be calculated according to the method provided in HCM 2010, Section 31-4. N_{RLT} is the number of conventional LTLs and N_{CLL} is the number of CLLs; and S_{pc} is the average vehicle storage length, which is assumed to be 25ft.



a. *Too short*	***b.*** *Too long*	***c.*** *Appropriate length*

Figure 3-4: Impacts of CLL length on the left-turn queue distribution

3.3 Technology-based Recommendations

As we mentioned before, Safety is one of the major concerns for this new design because of the potential conflicts between the left-turn vehicles trapped on the CLL and opposing through vehicles (Su et al., 2016). To ensure the safe operation of CLL, advanced vehicle detection and wireless communication technologies could be applied to make sure that all left-turn vehicles can be cleared from CLLs before the end of the left-turn phase.

Wireless Sensor Networks (WSNs) have gained increasing attention in detecting traffic information to avoid congestion, ensure priority for emergency vehicles, and improve safety. WSNs can be used for vehicular traffic detection to know real-time traffic information and help the drivers to make several decisions to optimize arrival time and to avoid queues (Collotta, et al. 2014). A significant of studies have proposed traffic light control algorithms that adjust the sequence or length of traffic lights in accordance with the real-time traffic detected (Zhou et al. 2011). To ensure the safe operation of CLL lane, wireless vehicle detectors, such as magnetic sensors can be installed on the CLL to detect the presence of vehicles on the CLL lane, the information collected by the sensors can be wirelessly sent to the roadside units (RSUs) through dedicated, short-range communication (DSRC). Then, the information will be forwarded to the traffic signal controller and an advanced signal control algorithm can be developed and used to provide sufficient clearance time for clearing the detected vehicles on the CLLs.

In addition, drivers of left-turn vehicles may be distracted and not pay attention to the change of traffic signal, vehicle to infrastructure (V2I) communication technologies can be used to provide a warning to the left-turn drivers that are going to be traped on the CLLs. These technologies based countermeasures for improving the safety of CLLs are presented in Figure 3-5.

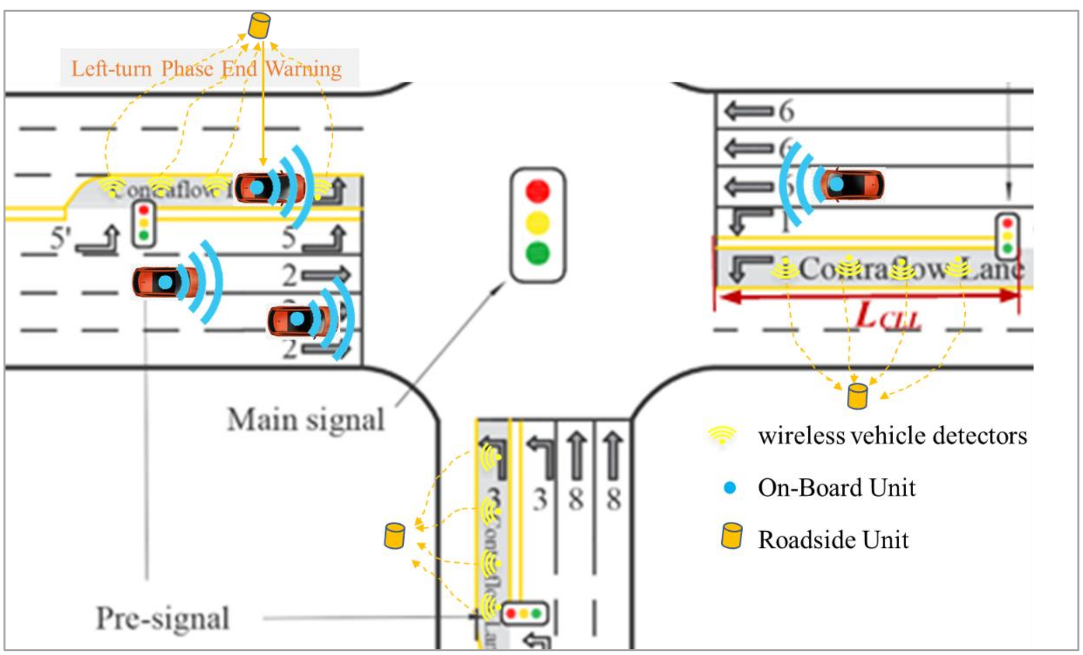


Figure 3-5: Technologies Based Countermeasures for Improving the Safety of CLLs

Chapter 4. Design Procedure

According to the design concepts and the critical signal timing and geometric requirements introduced above, it can be seen that there is an interactive relationship between the signal timing and the CLL length. On the one hand, the signal timing determines the left-turn queue length, thereby determining the appropriate length of the CLL. On the other hand, the length of the CLL also determines the utilization rate of CLL and the required clearance times, thereby affecting the signal timing for both the main signal and pre-signals. In other words, there is a feedback loop between these two key elements in the design of CLL and they should be determined together in one procedure. According to this idea, a step by step procedure for developing the signal timing plan and determining the CLL length was developed as follows.

STEP 1: Develop the initial signal timing plan for the main signal.

First, an initial signal time plan will be developed for the main signal by treating the CLL as a conventional LTL. If the signal cycle length is not fixed, both cycle length and signal phase splits will be calculated based on the traffic volume condition and intersection geometric layout. If the cycle length is fixed (for example, for signal coordination purposes), only the signal phase splits need to be determined. Note that, in this step, the CLLs are treated as the conventional LTLs, which assumes that a CLL will carry the same amount of left-turn traffic as a conventional LTL. Under this assumption, the percentage of LT vehicles shifting to CLLs, i.e. $LT\%_{CLL}$, can be estimated by the following equation:

$$LT\%_{CLL}^{int.} = {N_{CLL}}\Big/{(N_{CLL} + N_{RLT})} * 100\% \quad (4)$$

Where N_{RLT} is the number of conventional LTLs.

STEP 2: Estimate the length of CLL.

According to the discussions in the “Geometric Design Requirements” section, the appropriate length for the CLL can be estimated by using Equation (3). In this equation, the total queue backup length, i.e. Q_{LT}, can be calculated according to the method given in HCM 2010 based on the intersection traffic volume and the left-turn phase time estimated in Step 1. Note that, the minimum storage length for a left-turn bay is 100 feet (TxDOT Roadway Design Manual, 2018). Thus, if the estimated length of the CLL is less than 100 feet, the minimum length of 100 feet will be used.

STEP 3: Develop the initial signal timing plan for the pre-signals.

According to the initial signal timing plan for the main intersection signal and the signal timing diagram presented in Figure 3-1, the signal timing plan for the pre-signal lights can be determined. Specifically, according to Figure 3-1, the length of the pre-signal phase *i'* is equal to the length of the signal phase for the through movement on the cross street (on its left side) plus its corresponding left-turn phase i', and then subtract the pre-clearance time ($CT_{j-i'}$, as given in Equation 2) and the minimum required CLL clearance time ($CT^*_{i'}$, as given in Equation 1).

Note that, in this step, it also needs to be checked if the left-turn signal phase *i* (derived in Step 1) is greater than the minimum required CLL clearance time $CT^*_{i'}$, which is mainly determined by the CLL length estimated in Step 2. If the minimum required CLL clearance time cannot be provided, the left-turn signal phase should be extended to the minimum required CLL clearance time. Specifically, we need to go back to Step 1, recalculate the main signal splits by setting the length of the left-turn signal phase *i* equal to $CT^*_{i'}$ (given by Equation 1) and reallocating the remaining signal green time to other traffic movements according to the traffic volume condition.

STEP 4: Check the assumption given in Step 1

In Step 1, the CLL is treated as a conventional LTL, which assumes that the percentage of LT vehicles shifting to CLL is equal to $LT\%^{int.}_{CLL} = {N_{CLL}}\Big/_{(N_{CLL} + N_{RLT})}$ 100% . Under this assumption, the average amount of LT vehicles entering the CLL per cycle can be estimated by the following equation:

$$LT\#^{int.}_{i'} = \frac{LT\%^{int.}_{CLL} * V_{LTi}}{CPH}$$

Where

$LT\#^{int.}_{i'}$ is the average number of LT vehicles entering the CLL per cycle for left-turn phase i,
V_{LTi} is the total LT volume (vph) for approach i, and
CPH is the number of signal cycles per hour.

It needs to be checked if the pre-signal is sufficient for allowing this amount of the left-turn vehicles to enter the CLL. The maximum amount of LT vehicles that can enter the CLL during the pre-signal phase can be estimated by the following equation.

$$LT\#^{Max}_{i'} = \frac{(T_{i'} - ls)}{t'_{dh}} \qquad (5)$$

Where
$LT\#^{Max}_{i'}$ is the maximum amount of LT vehicles that can enter the CLLs during the pre-signal phase i'
$T_{i'}$ is the length of the pre-signal phase i', estimated in Step 3
t'_{dh} is the saturation discharging headway of left-turn vehicles at the median opening, which can also be estimated according to the model developed in Zhao et al. (2019)
l_s is the start-up lost time of the left-turn vehicles, which is assumed to be 2s,

If $LT\#^{Max}_{i'} < LT\#^{ideal}_{i'}$, it means that not all the left turners can enter the CLL as we assumed in Step 1. Therefore, we cannot assume that CLL can be used as a full conventional LTL. The maximum amount of left turners can be shifted to the CLL is $LT\#_{i\prime}^{Max}$ per cycle. Then, the actual amount of left-turn volume need to use the conventional LTLs can be estimated by the following equation

$$LTV_i^{RTL} = V_{LTi} - LT\#_{i\prime}^{Max} * CPH \tag{6}$$

Where LTV_i^{RTL} is the left-turn volume using the conventional LTLs for the approach corresponding to the left-turn phase i.

After that, the signal phase splits in Step 1 need to be re-calculated by only considering the conventional LTLs and the estimated actual amount of LT volume using the conventional LTLs. Then, by another run of this procedure, the final signal timing plan for the CLL can be derived. The entire process is represented by the flowchart shown in Figure 4-1.

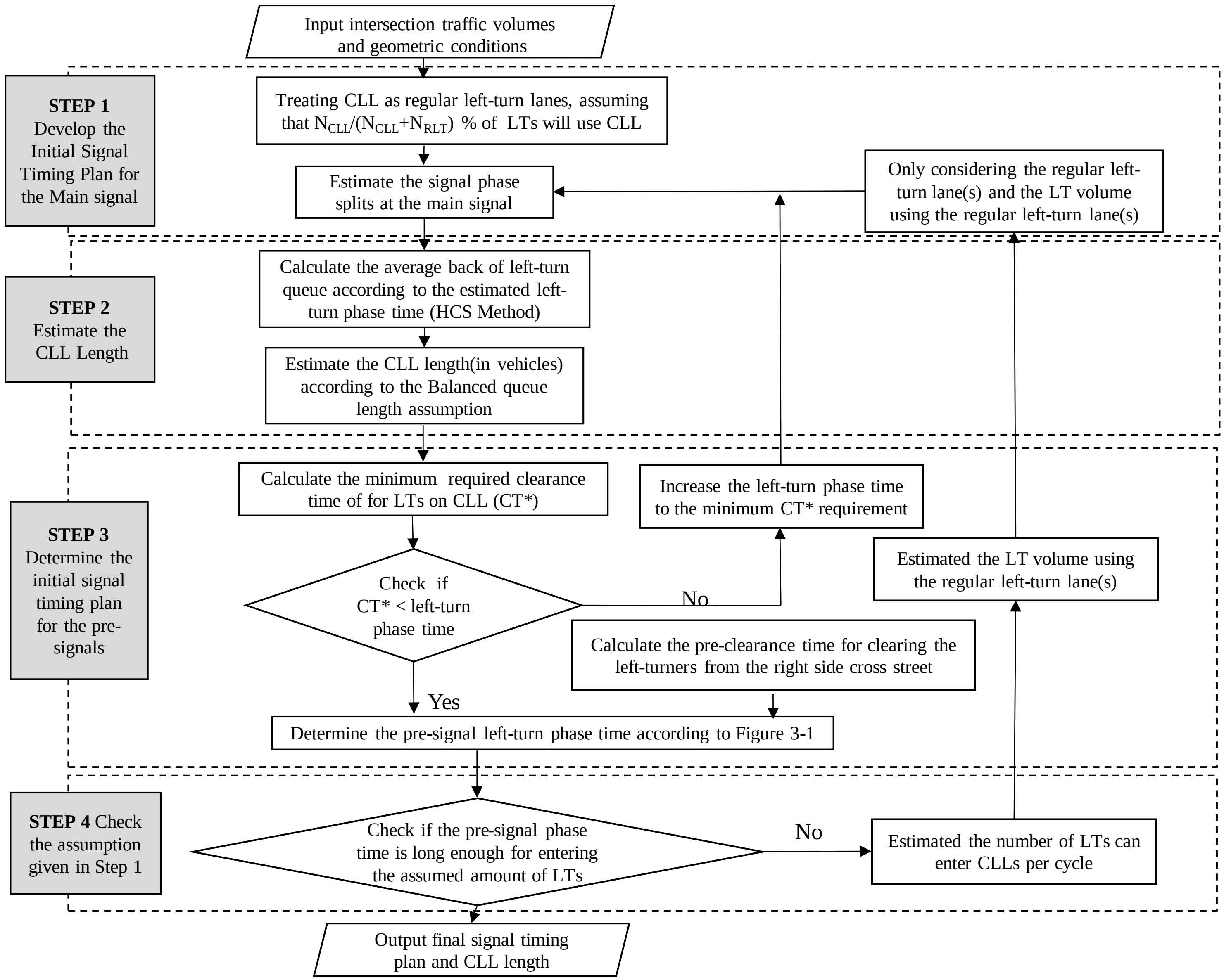


Figure 4-1: Procedure for Determining the CLL intersection Signal Timing Plan and CLL length

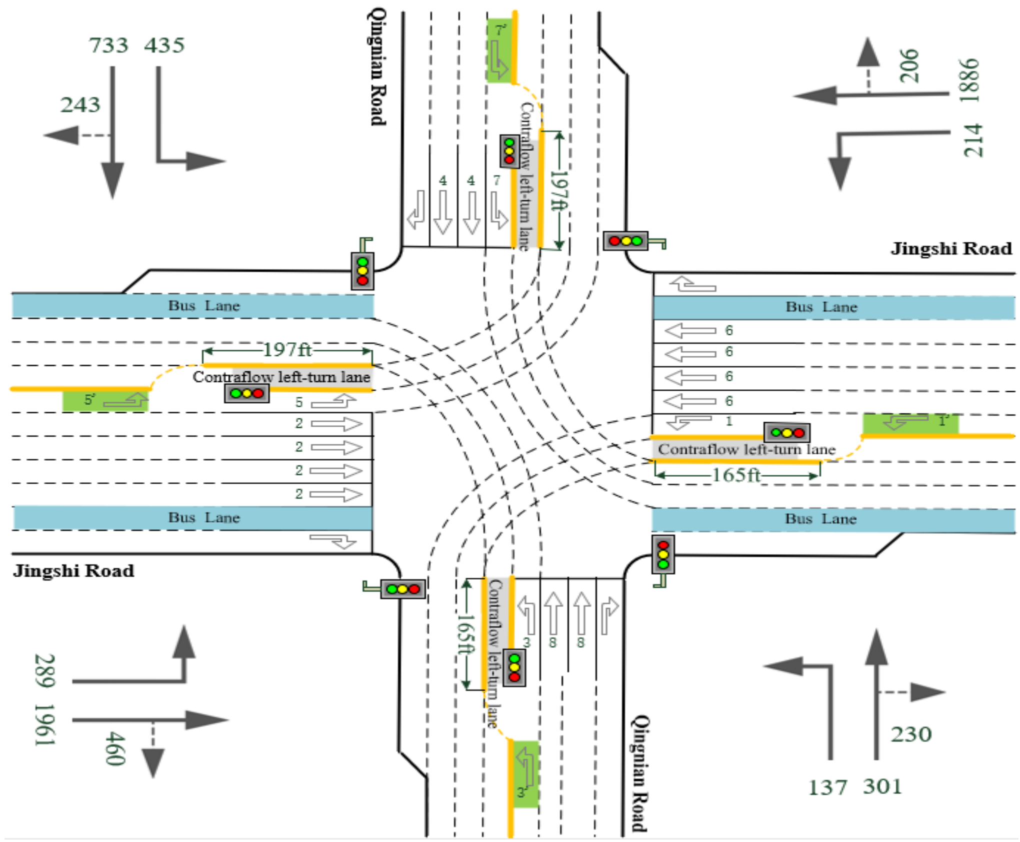
Chapter 5. Case Study

A case study was conducted to evaluate the proposed method for determining the two key design elements: 1) the length of the CLL, and 2) the traffic signal timing plan. A real-world CLL intersection in Jinan City, China was selected for this case study. Field data was collected at this intersection and traffic simulation-based experiments were conducted for analyzing the operational performance of this CLL intersection under different signal timing controls and geometric conditions.

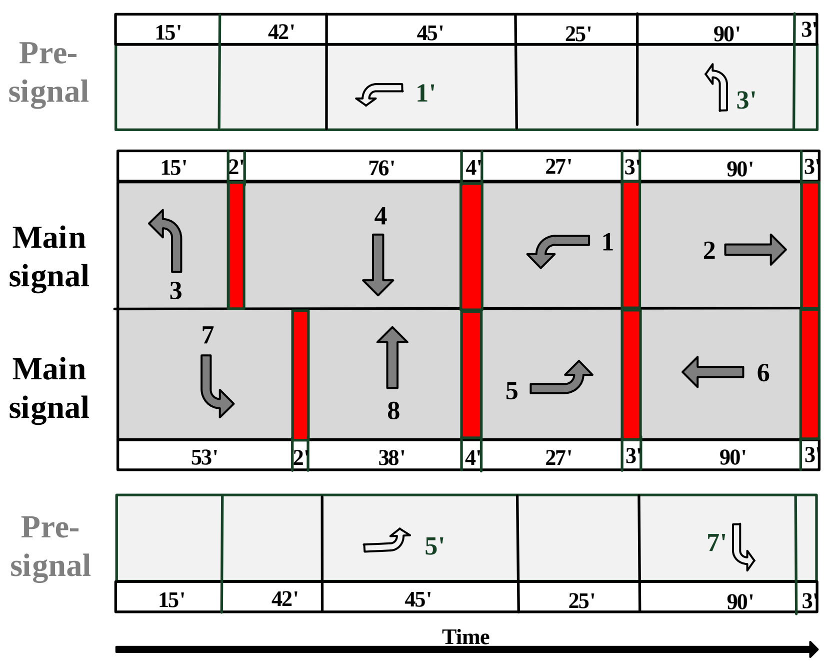
5.1 Study Site and Field Data Collection

The study intersection (Jingshi Road @ Qingnian Road) is one of the busiest intersections in a major arterial, namely Jingshi Road in Jinan City, China. At this intersection, the left-turn demand is very high and CLLs were implemented at the four approaches of this intersection. The existing lane configurations and signal timing plan of this intersection are shown in Figure 5-1. Field data were collected during AM peak hour (7:00 am- 8:00 am) on a typical weekday as follows.

1) Traffic volume was extracted from the traffic videos collected at the study site. The collected data included the through traffic volume, right-turn, and left-turn volume for different types of vehicles from different approaches. Average traffic volumes were presented in Figure 5-1(a).
2) Travel time was collected using a floating-car method. The collected data includes the travel time for the through movements on the major roads from both directions, as shown in Figure 5-3.
3) Intersection geometric conditions, including the number of lanes, the lane width at the main intersection, and the length of CLLs, as shown in Figure 5-1 (a).
4) Intersection signal timing plan, including the cycle length and detailed phase splits for both the main signal and pre-signals, as shown in Figure 5-1 (b).



(a) Intersection layout and traffic volume conditions.



(b) Existing signal timing planning

Figure 5-1: Study Intersection (Jingshi Road @ Qingnian Road)

5.2 Traffic Simulation-Based Analysis

In this study, VISSIM, a microscopic multi-modal traffic flow simulation software, was used for analyzing the operational performance of the CLL intersection. To simulate the operation of CLLs, the bi-directional characteristic of the CLLs is achieved by overlapping CLLs with their opposing through lanes. Figure 5-2 shows the setting of the contraflow LTLs in VISSIM. Then, the dynamic rerouting function is employed to allow left-turn vehicles to choose appropriately between the conventional LTLs and the CLLs. The dynamic rerouting decision is made based on the following attributes: the status of the main signal, the status of the pre-signal, the queuing length on the conventional LTL, and the queuing length on the CLLs.

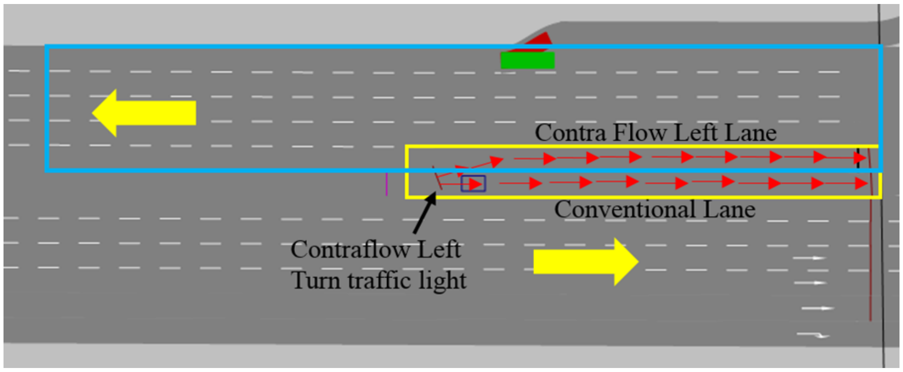
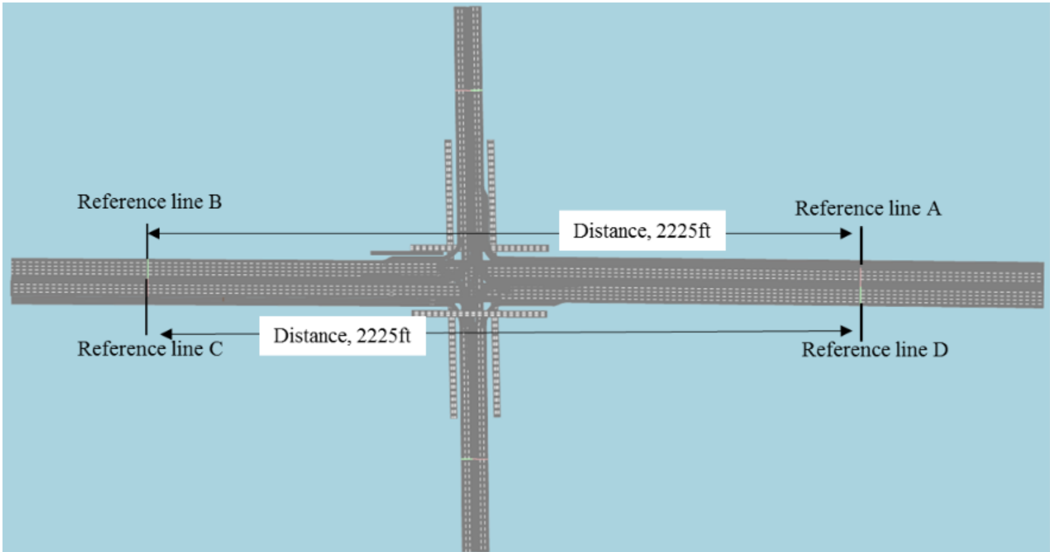


Figure 5-2: Contraflow lane setting up in VISSIM

In this study, for each scenario, a 1-hour traffic simulation was conducted and the first half-hour simulation results were discarded to ensure the simulation analysis starts after the steady-state condition researches. Ten simulation runs were conducted to overcome the randomness in the simulation outputs.

5.2.1 Development of the Base Model

A base model was developed to replicate the existing traffic operation at the studied CLL intersection. The base model was developed according to the lengths of the existing CLLs, the existing signal timing plan, and other existing intersection geometric and traffic conditions as shown in Figure 5-1. The base model was then calibrated based on the major road through travel time. According to the calibration results listed in Figure 5-3, the calibrated model was in good agreement with the actual traffic conditions, showing low relative errors of about 5%. This means that the simulation model can perform reliably in replicating the traffic conditions at the studied CLL intersection.



	Observed (s)	Simulated (s)	Relative error (%)
Travel time from C to D	178.7	171.1	-4.3%
Travel time from A to B	135.2	129.3	-4.4%

Figure 5-3: Calibration of the Base Simulation Model

5.2.2 Simulation Scenario Type A: CLL Intersection with the Proposed Traffic Signal Timing Plan and CLL Lengths

To evaluate the proposed method for determining the traffic signal timing plan and the lengths of CLL, an alternative simulation scenario was created by redesigning the signal timing plan and CLL lengths for the studied CLL intersection according to the procedures given in Figure 4-1:

Step 1: the cycle length was fixed at 220s, and then the initial time split for the main signal was optimized in the Synchro according to the existing roadway geometric designs (treating the CLL as a conventional LTL) and traffic volumes collected from the field study. The new signal timing of the main signal is as shown in Figure 5-4:

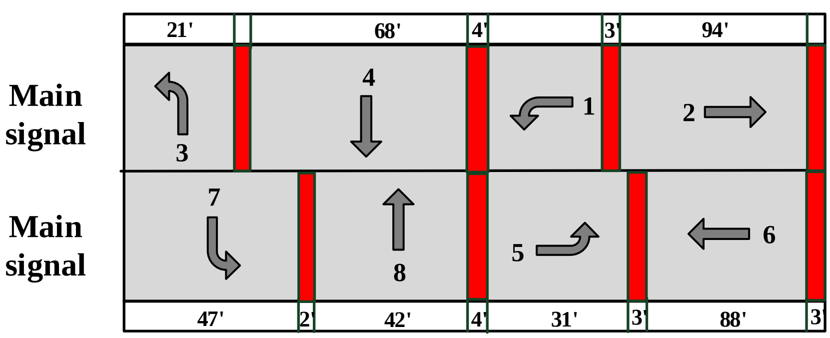


Figure 5-4: Main signal timing using the proposed CLL design procedure

Step 2: Base on the main signal plan, the average queue backup length per cycle were calculated according to Equation (3). The calculated Q Length (in a number of vehicles) is listed as follows:

- EB: 9
- WB: 7
- NB: 5
- SB: 13

Assuming the storage length of a vehicle is 25ft, then the length of CLL is 225ft (EB), 175ft (WB), 125ft (NB), and 325ft (SB).

Step 3: According to the initial signal timing plan for the main intersection signal and the length of CLL, the signal timing plan for the pre-signal lights can be determined. At first, Equation (2) was used to calculate the pre-clearance time, the 15th percentile approach speed is 35mile/hour, and the results was 2.43s for NB, 6.31s for SB,3.4s for WB, and 4.37s for EB. For safety concerns, the length of pre-clearance time is extended to be 4s for NB, 8s for SB, 5s for WB, and 6s for EB. Then, Equation (1) was used to the minimum required CLL clearance time, and the results were 20s for NB, 40s for SB, 26s for WB, and 31s for EB. Thus, the length of pre-signal time were 96s for NB, 91s for SB,43s for WB, and 69s for EB, and the pre-signal is sufficient for allowing this amount of the left-turn vehicles to enter the CLL. The detailed signal timing is shown in Figure 5-5.

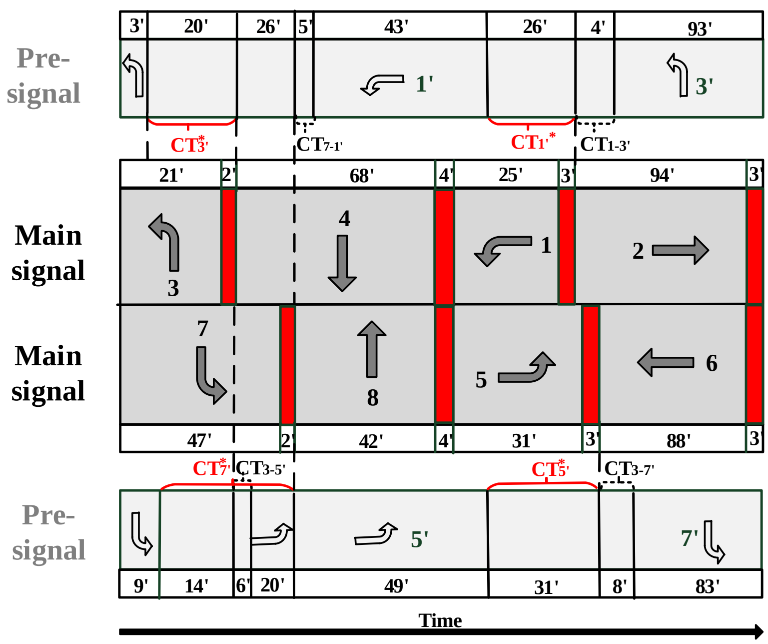


Figure 5-5: Signal timing based on the proposed CLL design procedure

This alternative simulation scenario is referred to as “CLL intersection using proposed traffic signal timing and CLL lengths”.

Based on the simulation results, the operational performance measures, including average traffic delay, average vehicle travel time, and average queue length at the existing CLL intersection (base model) and the redesigned CLL intersection were compared and the results were presented in Figure 10. It can be seen that the intersection with the proposed traffic signal timing and CLL lengths consistently outperform the existing CLL intersection in terms of the average traffic delay, average vehicle travel time, and average queue length.

Table 5-1: Operational performance of the base model and redesigned model

	Base Model	Redesign	Improvement
Average Travel Time(s/veh)	135.5	130.9	3%
Average Delay(s/veh)	68.5	64.8	5%
Average Q Length(ft)	115.5	97.4	16%

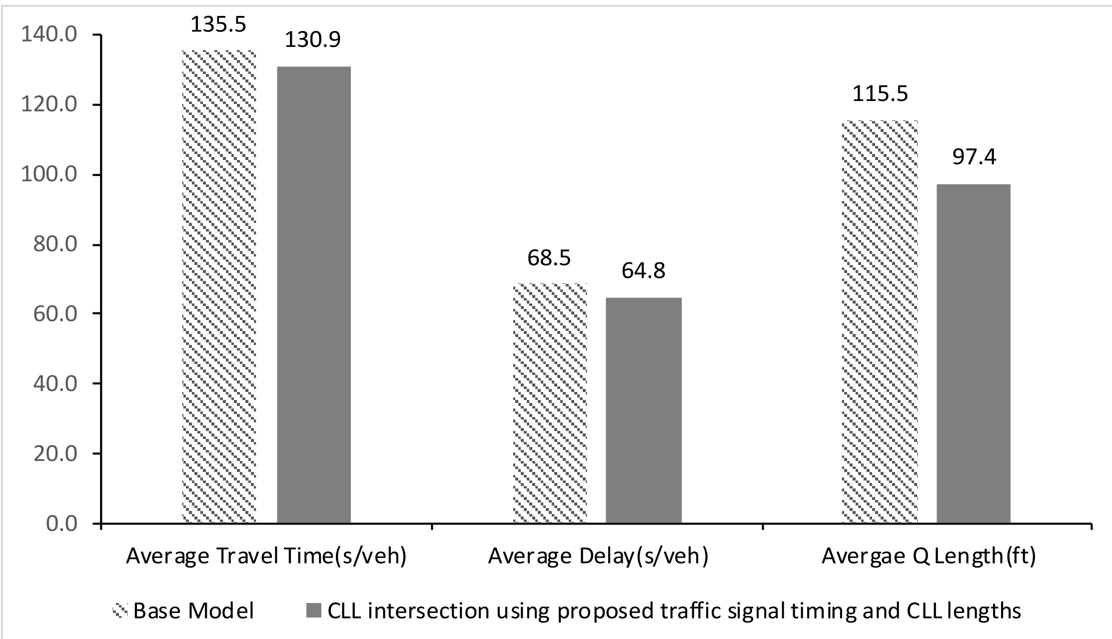


Figure 5-6: Comparison Of Operational Performance of Base Model and Redesigned Model

5.2.3 Simulation Scenario Type B: CLL Intersection with Various CLL lengths

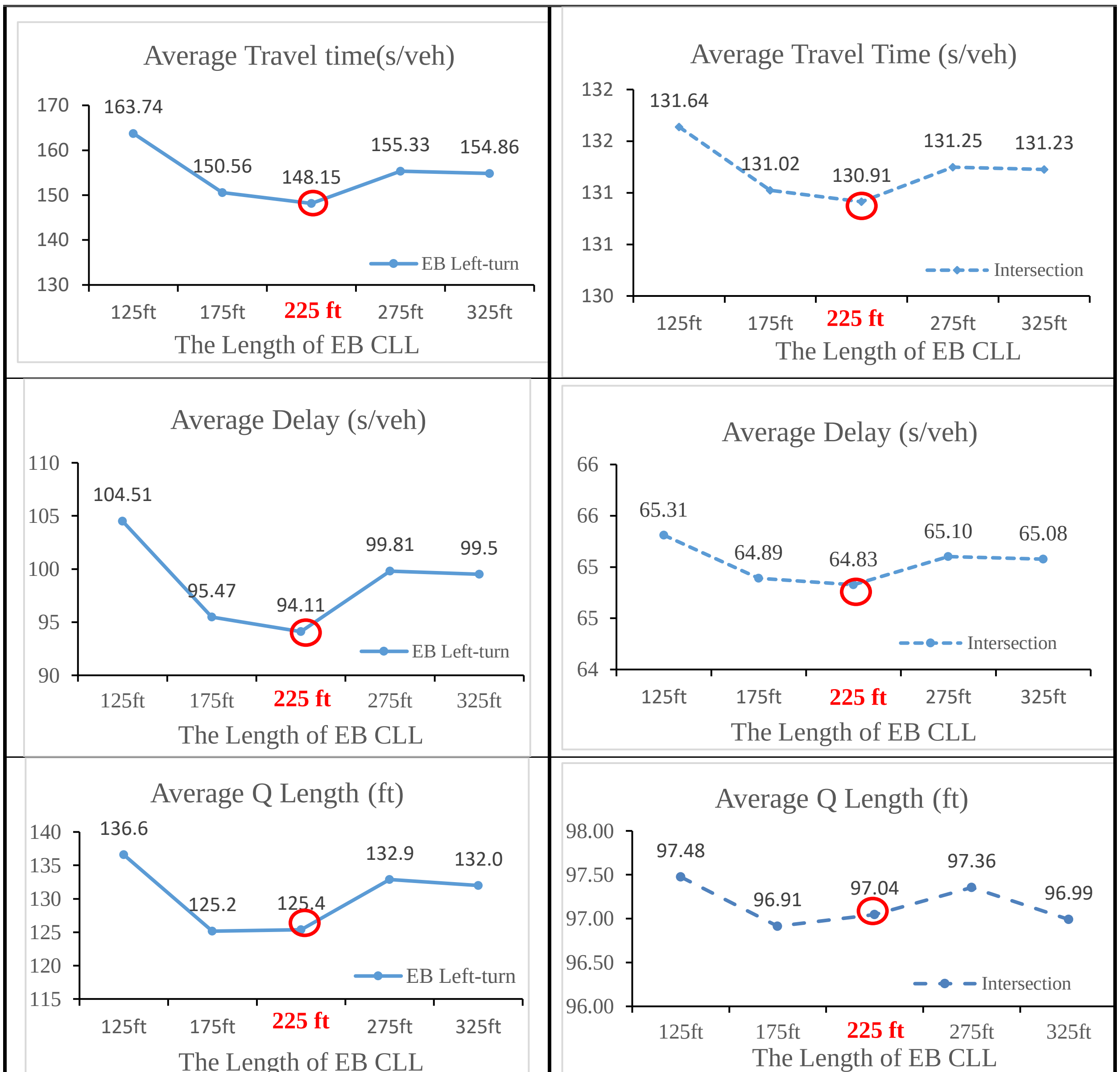
According to the proposed method, the length of CLL is estimated by using Equation (3), which is based on the idea that the maximum utilization of CLL will be achieved when the queue length on the CLL and conventional LTL are balanced. To assess if the CLL length recommended by the proposed method can allow the CLL intersection to achieve its best performance, the operational performance of the interstation with various CLL lengths need to be tested. As aforementioned, the lengths of CLLs at the studied intersection have been estimated according to the procedure given in Figure 4-1. Following are the estimated results:

- Estimated CLL length of WB is 175ft (the exiting length is 165ft)
- Estimated CLL length of EB is 225ft. (the exiting length is 197ft)
- Estimated CLL length of NB is 125ft (the exiting length is 165ft)
- Estimated CLL length of SB is 325ft (the exiting length is 197ft)

Since the estimated CLL lengths for WB and NB are relatively short (less than 200ft) and cannot be further reduced (the minimum required length is 100ft), only the EB and SB approaches are selected for further analysis. Thus, the following two sets of alternative simulation scenarios were created by varying the lengths of EB and SB CLLs around the recommended lengths:

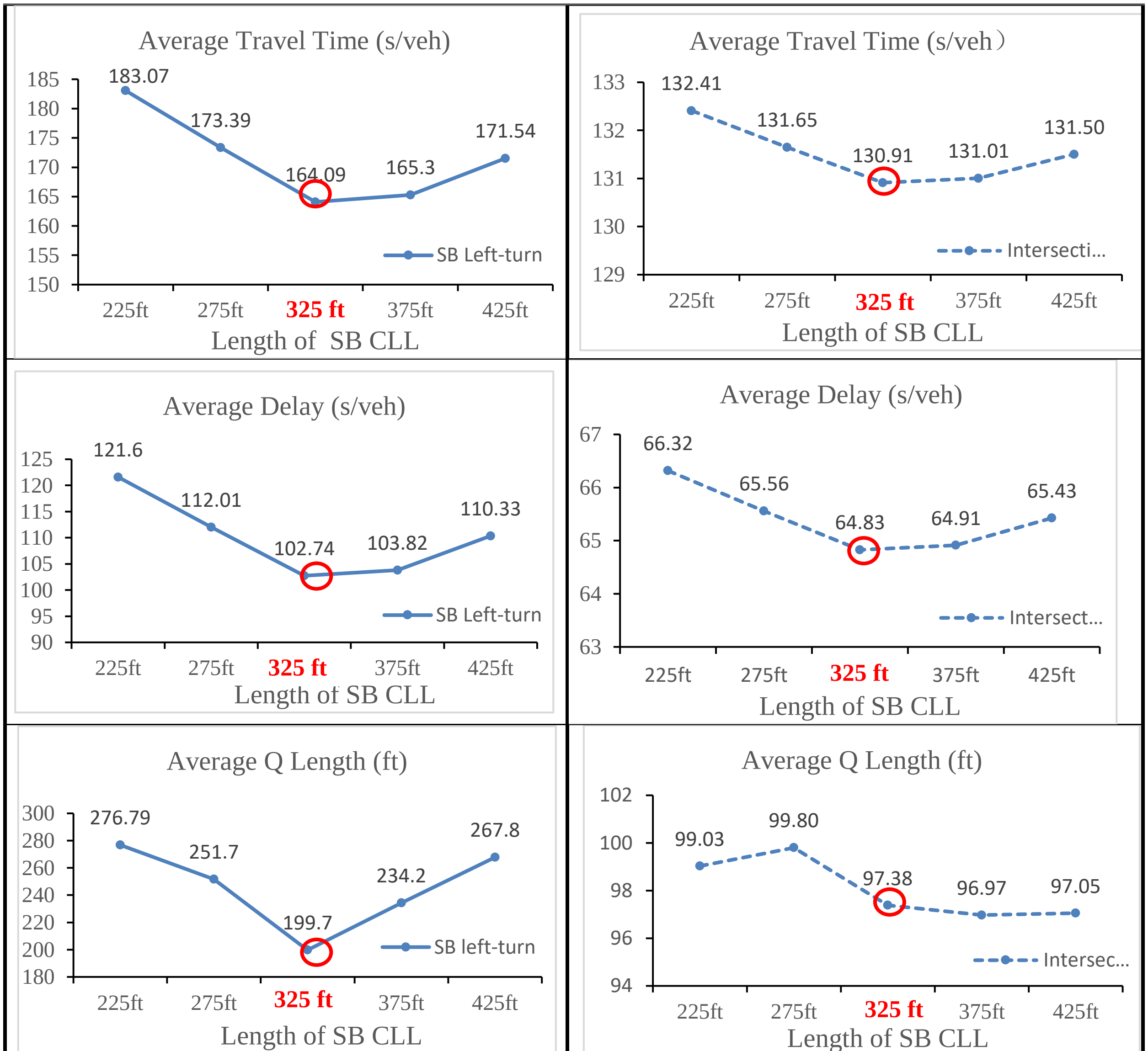
- Increase the length of EB CLL from 125 ft to 325 in 50 ft increments (5 scenarios)
- Increase the length of SB CLL from 225 ft to 425 in 50 ft increments (5 scenarios)

Note that, in these scenarios, except for the CLL length in the subject approach, all other settings keep the same as those in the scenario type A.



(a) Operational Performance for the EB Left-turn | (b) Operational Performance for the Entire Intersection

Figure 5-7: Operational Performance Comparison for Intersection with Various EB CLL lengths



(a) Operational Performance for the EB Left-turn | (b) Operational Performance for the Entire Intersection

Figure 5-8: Operational Performance Comparison for Intersection with Various SB CLL lengths

Based on the simulation results, the operational performance of CLL intersections with various CLL lengths for both the entire intersection and the subject left-turn approach were compared. Figure 5-5 shows the simulation results for the scenarios with various EB CLL lengths and Figure 5-6 shows the simulation results for the scenarios with various SB CLL lengths. From both figures, it can be seen that, for most of the performance measures, the CLL intersection performs best at the estimated CLL length (red cycled). These results verified that the proposed method can provide the appropriate lengths for the CLLs that allow the CLL intersection to achieve its optimal performance.

Chapter 6. Conclusions and Recommendations

This study developed a systematic method for determining the length of CLL and the signal timing plan for implementing CLL at signalized intersections. The signal timing and geometric design requirements in the implementation of CLL have been discussed and thoroughly considered in developing the proposed method. First, the development of the signal timing plan has considered both the pre-clearance times that are required before the start of the pre-signal phase and the clearance time required at the end of the pre-signal phase. As a result, it will reduce the risks associated with the use of CLL, and make CLL a safety solution to mitigate traffic congestion at signalized intersections. Second, the method for estimating the length of CLL is based on the conditions for maximizing the utilization of CLL. As a result, the estimated CLL lengths will allow the CLL intersection to achieve its best operational performance.

A case study was conducted for validating the operational benefits of redesigning a real-world CLL intersection using the signal timing plan and CLL lengths recommended by the proposed method. The traffic simulation results show that the redesigned CLL intersection outperforms the existing CLL intersection in terms of the average traffic delay, average vehicle travel time, and average queue length, and the CLL intersection can achieve its best performance at the recommended CLL lengths.

In addition, to ensure the safe operation of CLL, advanced vehicle detection and wireless communication technologies could be applied to make sure that all left-turn vehicles can be cleared from CLLs before the end of the left-turn phase. The results of this study can help promote this innovative intersection design in the USA. It provides useful tools and design guidelines to the traffic engineers in the implementation of the CLL intersection design in the future.

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