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SIGNAL TIMING STRATEGY FOR DISPLACED LEFT TURN INTERSECTIONS

Final Report

by

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DISCLAIMER

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EXECUTIVE SUMMARY

Conventional intersection design has met the challenges of increasing congestion and traffic delays. To solve this problem, transportation planners and engineers have proposed a variety of innovative intersection designs. Among these innovative intersection designs, displaced left turn (DLT) intersection has been implemented in 12 states in the USA. Since DLT is relatively new and only implemented in a few states, there are few existing guidelines available for designing DLT intersections. One of the critical elements when designing a DLT intersection is the signal timing plan. An appropriate signal timing plan will maximize intersection capacity, reduce congestion, and improve safety. There are very limited existing studies on the signal timing design of DLT and the progression needs of vehicles have not been well considered in these studies.

The purpose of this research is to develop a comprehensive signal timing strategy for DLT intersections. To achieve this purpose, the research team first reviews and summarizes current guidelines and research findings on how to design and optimize signal timing for DLT intersections. Then, a new DLT signal time design methodology is proposed by considering various traffic conditions. The proposed DLT signal timing is evaluated by microscopic simulation. The results are compared with the signal timing provided by an existing signal timing optimization tool named Synchro, and the results show that the developed signal timing outperforms the one generated by Synchro regarding the average delay, travel time, and queue length.

Chapter 1. Introduction

1.1 Background

The displaced left turn (DLT) intersection, also known as the continuous flow intersection (CFI) or crossover intersection (XDL), is one type of innovative intersection designs. It is new and systematic design methods or guidelines are not available although it has been implemented in 12 states. A DLT intersection is designed to increase the mobility of an intersection by relocating its left turn lane (lanes) to the far-left side of the road at the upstream location of the main signalized intersection. The design concept of the DLT intersection and its left turn routes are shown in Figure 1.

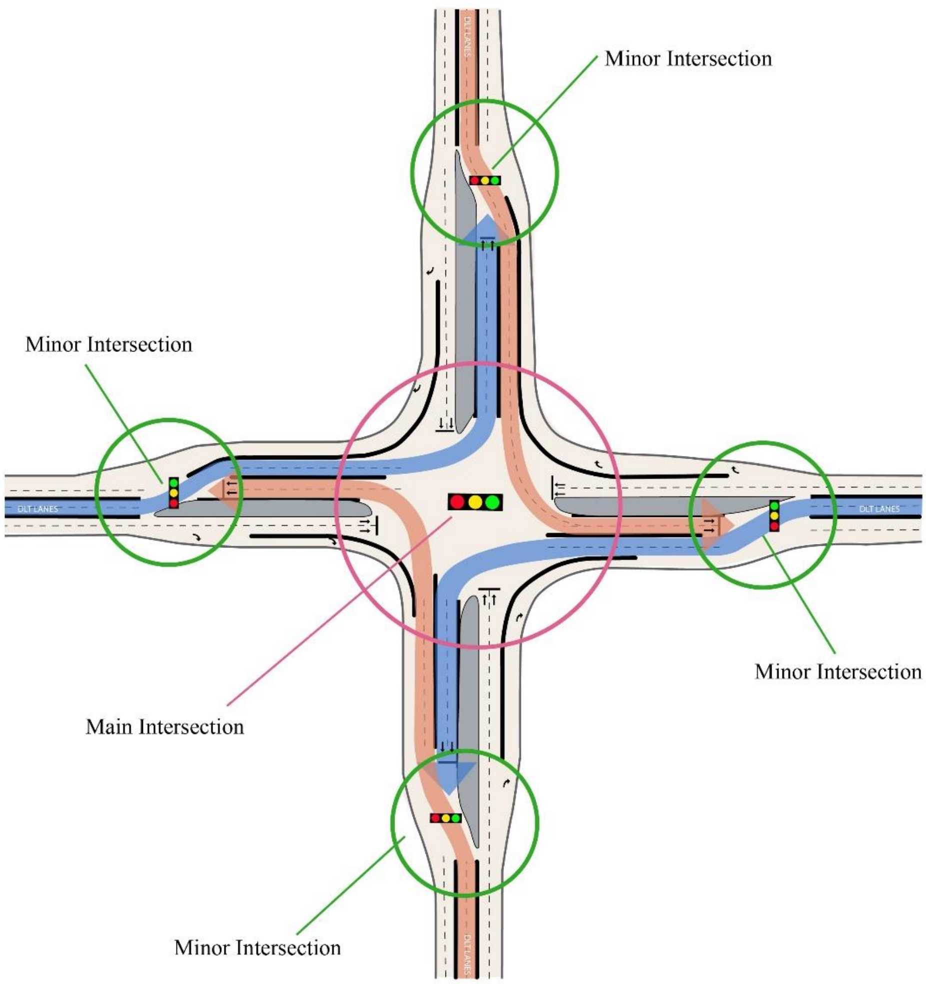


Figure 1: Typical Full Displaced Left Turn Intersection Design with 4 Legs

As indicated in Figure 1, when left-turn traffic reaches a location usually a few hundred feet ahead of the main intersection, it will go through a signalized intersection to move to the far-left side of the road. This intersection is referred to as a minor intersection in this study and is also known as crossover intersections in some other studies (Steyn, Hermanus, et al, 2014). After that, the left-turn traffic will move to the main intersection and will be able to move simultaneously with the through traffic during the same phase. Therefore, in such a design, the traditional four-phase signal control can be replaced by simple two-phase control. As a result, the intersection capacity and operation efficiency can be significantly improved. Furthermore, previous studies (Sarah et.al.2012) also showed that DLT design can improve the safety performance of the intersection by reducing the conflict points.

As shown in Figure 1, the DLT intersection consists of one major intersection and 4 minor intersections. These 5 intersections are closely spaced, and they should be designed and operated as one system. In another word, they should be coordinated with each other to ensure most of the vehicles can go through the whole DLT intersection system smoothly with fewer stops and delays. Therefore, progression should be the most important factor to be considered in the design of traffic signal timing for DLT intersection. It is like a diamond intersection where two proximity signals need to be designed and operated as one system (Chaudhary, N. A., et al., 2000). According to Chaudhary, N. A., et al., the basic idea for the diamond intersection signal timing design is to ensure a good progression of some major traffic movements. Similar design ideas could be applied to the DLT intersection signal design.

However, most of the previous research on DLT signal design focused on optimizing DLT signal timing to minimize control delay or maximize intersection capacity for four-legged DLT intersections (You, et al. 2013). These optimization-based methods have some limitations. First, the intersection traffic delay was estimated by analytic delay models. These delay models are based on many simplification assumptions and have many limitations. For example, in the HCM delay model, traffic progression is considered by using a progression factor, which only has 6 different levels of progression. As a result, the impacts of progression on traffic delay cannot be accurately estimated. More importantly, the delay caused by the turn lane overflow, and the delay caused by queue spillback or starvation have not been well considered in most of the existing delay models. At a DLT intersection, the 5 intersections are closely spaced and the bad progress will very likely cause intersection queue spill back and turn lane overflow. As a result, the traffic delay caused by bad traffic progression will be significantly underestimated. Therefore, these signal optimization-based methods cannot well consider the impacts of the traffic progression on overall DLT performance, which will not yield the truly optimal signal timing design for DLTs. Currently, the signal timing of DLT is usually designed in a trial-and-error way (You, et al. 2013) and there is a lack of comprehensive and user-friendly guidelines on the signal timing design for DLTs. The results of this research will fill this gap by providing step by step guidelines on DLT signal timing design, which will assist traffic engineers in the implementation of DLTs in the future.

1.2 Research Objectives

The primary objective of this research is to develop guidelines on the design of signal timing for DLT intersections based on traffic flow progression. The specific objectives are to:

1. develop procedure and guideline for coordinating the major intersection signal with the minor intersection signals in DLT intersections,
2. develop a guideline for the signal timing for both major intersection and minor intersections in DLT intersections,
3. conduct a case study to evaluate the developed guideline and demonstrate its application.

1.3 Scope

The scope of this research is limited to the displaced left-turn intersection with four minor intersections under the balanced traffic condition. The balanced traffic condition means that the traffic volumes for the pair of opposing directions are close.

1.4 Outline

The rest of the paper is organized in the order as follows. Chapter 2 introduces the existing studies on DLT intersection, including background and application of DLT, operational performance of DLT, the safety performance of DLT, and existing studies on signal timing of DLT. Chapter 3 presents the design of the study, which covers the study approach, methodology illustration, and case study. Chapter 4 provides the results and discussion of the case study. In the end, the conclusion and future work are summarized in Chapter 5.

Chapter 2. Literature Review

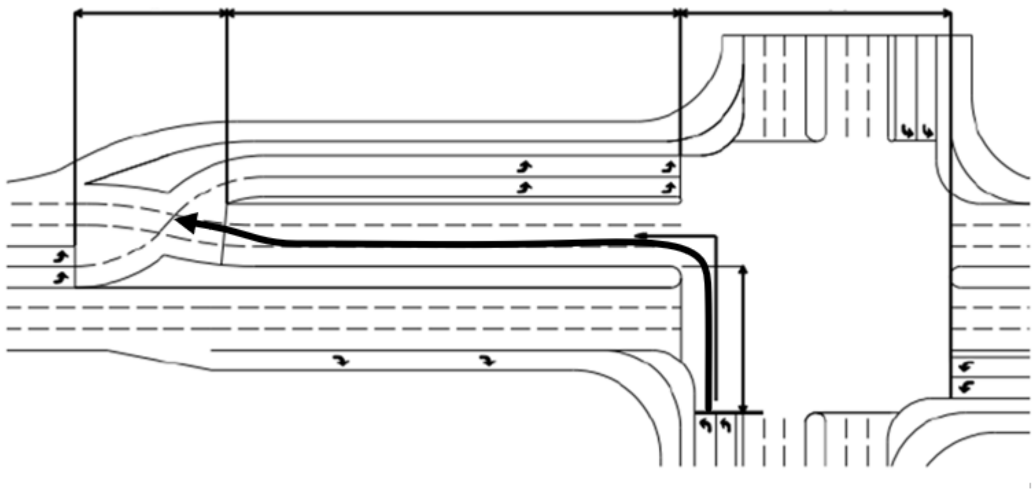
2.1 Introduction

This chapter reviews the existing studies on the DLT intersection and its signal timing design. Most of the existing studies focus on the analysis of the operational performance and safety performance of the DLT intersection and very few of them studied the signal timing design of DLT intersections. The literature review covers the following four topics: 1) typical geometric configurations of the DLT intersection and its applicable conditions, 2) operational performance of the DLT intersection, 3) safety performance of the DLT intersection and 4) existing studies on signal timing design of the DLT intersection.

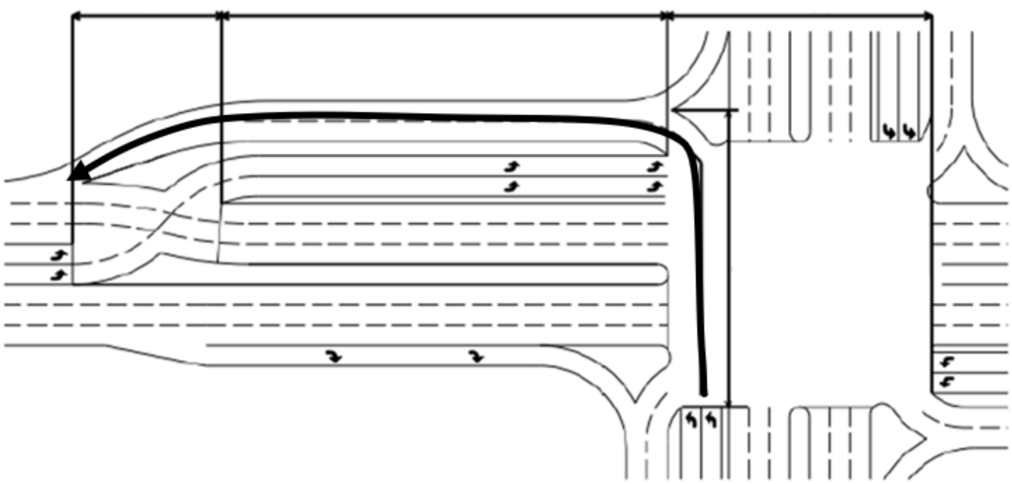
2.2 Typical Geometric Configurations of the DLT Intersection and Its Applicable Conditions

2.2.1 Typical Geometric Configurations

The DLT intersection has two forms of geometric configurations, namely FHWA DLT and Mexican DLT. In the FHWA 4-Legged DLT design, the left turn vehicles make a left turn and enter the crossing street and then travel through the minor intersection at the downstream. In the Mexican DLT design, left turn vehicles would enter the right turn channel in the opposing direction instead of the crossing street. In this way, the left turn vehicles do not need to go through the minor intersection downstream. Please see Figure 2 for the left-turn traffic flow in both configurations (Wu et al., 2017). Figure 3 shows the two-legged DLT intersection and four-legged DLT intersection.

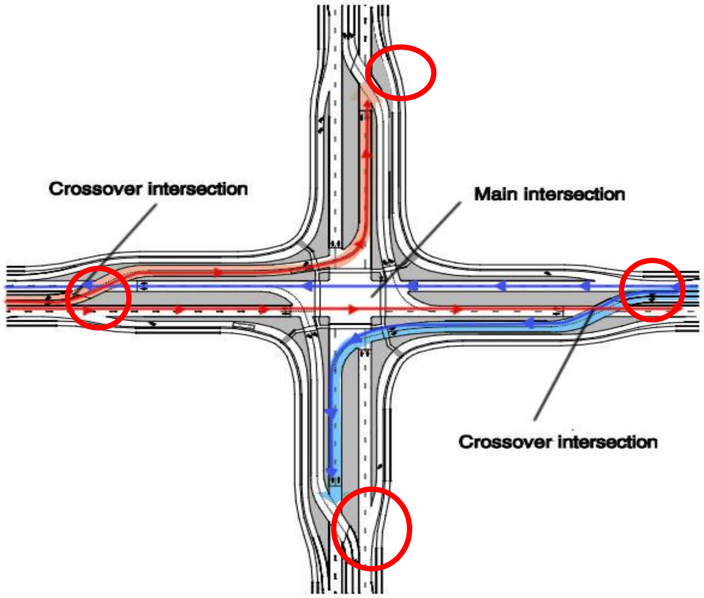


a. FHWA displaced left turn intersection

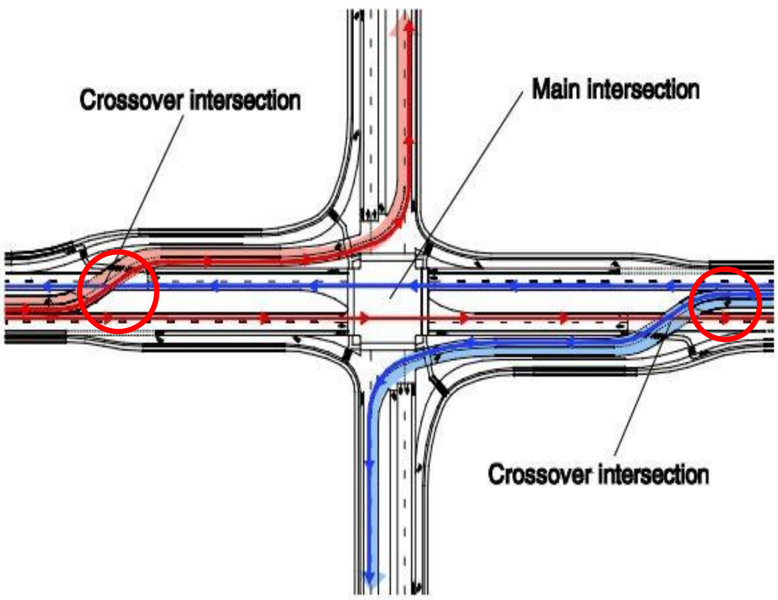


b. Mexican displaced left-turn intersection

Figure 2: FHWA Displaced Left Turn Intersection and Mexican Displaced Left-turn Intersection (Adapted From Wu Et Al., 2017)



(1) 4-legged Full DLT intersection design



(2) 2-legged Partial DLT intersection design

Figure 3: 2-Legged and 4-Legged DLT Intersections

2.2.2 Applicable Conditions

DLT design has been implemented in 12 states in the USA by 2017. Most DLTs were established on the main roads in urban and suburban regions, where high through and left-turn traffic demands present (Qi et al., 2018). Dhatrak et al. investigated the DLT and found a significant improvement in operational performance if traffic flow on opposing approaches is heavy and balanced (Dhatrak et al. 2010). The study conducted by LaDOTD further points out that the greater benefits can be produced by the DLT designs if the left-turn volume percentage is higher (LaDOTD, 2007).

2.3 Operational Performance of the DLT Intersection

Vedagiri et al. (2012) evaluated the DLT intersection under heterogeneous traffic flow conditions by using simulation. The average delay was employed to evaluate the performance of different intersections. The operational performance of the DLT intersection was compared to a Normal Flow Intersection (NFI). The results showed that a DLT intersection is more efficient than an NFI in that a DLT intersection could successfully reduce the average delay by a considerable percentage. Two experiments were conducted by VISSIM, a microscopic simulation software, to simulate the designs because it is not practical to implement the research design in the field test. The traffic volume varying from 500 vehicles per hour to 3,500 per hour was set for the first experiment and 500 to 5,000 vehicles per hour for the second experiment. Different right-turning proportion ranging from 10% to 50% of the total traffic volume was considered. The lane length was 3.5 m, and traffic behavior was set under heterogeneous traffic and random traffic in India. These settings may enable the study to simulate the real traffic accurately. It has been concluded that the DLT intersection is more efficient than NFI especially when traffic volume is more than 2,000 vehicles per hour.

Unlike the authors who use hypothetical volumes to compare the intersection delay and travel time, Reid (2001) conducted a travel time comparison of conventional and seven unconventional designs, namely the quadrant roadway intersection, the median U-turn, the super street median, the bowtie, the jug-handle, the split intersection, and DLT designs by using data from actual intersections. In the research, optimum cycle lengths were used in each intersection design, and several factors were held constant to make the comparison comparable and fair. Different scenarios, off-peak hour, peak hour, and peak-plus-15-percent volume level were analyzed. The simulation results showed that the DLT intersection had the largest number of trips completed and the MOVE-TO – TOTAL-TIME ratio among all of the designs. In cases in which the tested intersection had the largest total volume (ADT was 74,300, 84,800, and 97,200 respectively) and the high volume of turning movements during the peak hour, the DLT intersection outperformed the conventional intersections during peak hours with less travel time.

Goldblatt et al. (1994) evaluated the effectiveness of the DLT concept using the TRAF-NETSIM microscopic simulation model. The results indicated that the DLT intersection has advantages over equivalent standard intersection designs especially when demand approaches or exceeds the capacity of conventional designs and when protected phases are required for large volume left-turn movements. In addition, it was also found that the mean speed of a DLT intersection design nearly doubled that of the conventional design in the approach volume of 1,500, 2,000, and 3,000 vph. Signal efficiency increased by at least 80%. It can be concluded that the operational performance of traffic at the DLT intersection is far superior to that at the conventional intersection.

To provide collective information on the unconventional arterial intersection design (UAID), Kim et al. (2007) conducted research on selected UAIDs in the state of Maryland. The researchers built a knowledge-base-web interface on their research to aid future engineers. The authors conducted 4 case studies on the super street design, the DLT design, the center turn overpass design, and the roundabout design. The study revealed that reductions in accident frequency, accident severity, stopped delay, and queue length can be achieved by the 4 intersection designs. By using average delay as the measure of effectiveness, results from the simulation showed that the DLT intersection could significantly reduce delay for through and left-turn movement on the arterial.

Jagannathan and Bared (2004) used VISSIM to compare the traffic performance of XDL and conventional intersections under different traffic flows. Cases A, B, and C were simulated to represent full DLT, partial DLT on major roads, and one DLT on a T-intersection respectively. The simulation results indicated a great performance improvement in XDL design compared to conventional intersection designs. Total average delay results showed that the XDL intersection decreased significantly with a range of 48% to 85%, 58% to 71%, and 19 to 90% in each case. However, these results considered pedestrian presence. Removing pedestrians caused a lower cycle length, which led to an average intersection delay that ranged from 14s/vehicle to 19s/vehicle for Case A under low to moderate traffic volumes. In the terms of the average number of stops, except for Case 3, in undersaturated traffic flow conditions, the XDL intersection will realize a 15% to 30% reduction and 85% to 95% for saturated traffic flow in each case. As for queue length, the compared reduction rate was 62% to 88%, 66% to 88%, and 34% to 82% for each of the three cases respectively. In addition, the simulation results indicated the capacity increase after the DLT intersection implementation at the rates of 30%, 30%, and 15% for Case A, Case B, and Case C respectively.

Cheong et al. (2008), Dhatrak et al. (2010), El Esawey et al. (2007), Autey et al. (2013), Ladda et al. (2011), Park and Rakha (2010), Zhao et al. (2015), Hildebrand, T. E (2007) also conducted their research, which similarly revealed that the DLT intersection outperformed conventional intersections.

2.4 Safety Performance of the DLT Intersection

Mary Eileen Yahl (2013) investigated the safety effects of a displaced left-turn intersection through observation before and after the study. By using a naïve method, a naïve with traffic factors method, and a comparison group method, the author selected five sites to investigate the safety results of each site and then conducted an overall site analysis. The naïve method can provide a base safety effect, which cannot be corrected for such changes as traffic volumes, historical trends, and seasonality. By using safety performance functions from the Highway Safety Manual and traffic volumes from before and after the installation of a DLT intersection, the naïve method with traffic factors can adjust changing traffic volumes. The comparison group method can select comparison sites near the studied sites, which have similar crash trends to account for historical factors and seasonality. The results from the three methods varied. The Baton Rouge, LA site showed a decrease in the collision in all three types of methods but was the only individual site to do so outside of the margin of error. Generally, the other sites showed increasing collisions after a period for all methods. In the overall site analysis, fatal and injury, rear-end and sideswipe collisions increased while only angle and other collisions decreased.

Zlatkovic (2015) assessed the safety performance of the DLT intersection by developing crash modification factors (CMFs) using the Empirical Bayes (EB) methodology. Eight DLT intersections along Bangerter Highway in Utah were selected to acquire the available before and after crash data and annual average daily traffic (AADT) between 2008 and 2013. Crashes that occurred within 100 feet of each crossover and 250 feet of the main intersection were summed to provide the total crash data for the intersection. According to the EB analysis results, the crash modification factor for the DLT intersection conversion was 0.877, which indicated that the DLT design had the potential to reduce crashes.

2.5 Signal Timing Design of the DLT Intersection

Very few studies have been done on the signal timing design of the DLT intersection. You et al. (2013) developed an optimization model targeting the minimum cycle length, with constraints of fluid progression of left-turn vehicles and through vehicles, capacity, and queue length. The queue length is estimated by the shock wave model. The optimization model is tested in different traffic volume conditions, hypothetically ranging from 0 to 3000 for an approach. Scenarios are grouped by different ratios of left-turn traffic volume and through traffic volume. Capacity, average delay, and minimum cycle length are the measures of effectiveness to evaluate the operational performances of the developed signal timing algorithm. An equivalent conventional intersection is designed to make a comparison with the DLT intersection. The results indicate that the DLT intersection outperforms the conventional intersection in terms of capacity when the traffic volume is high. The significant improvement occurs when the ratio of left-turn traffic volume to through traffic volume increase from 0.3 to 0.4. As for the average delay, a full DLT intersection has a good performance with a less than the 20s' average delay when the volume of a left turn and through is less than 1500 pcu/h. There are two major limitations with this study. First, the minimum cycle length does not necessarily guarantee optimum operational intersection performance, such as minimum intersection delay and maximum intersection capacity. In addition, by comparing the operational performance of a DLT intersection with that of a conventional intersection, it only can approve the advantage of using DLT over the conventional intersection, and it cannot approve that the developed signal timing strategy can provide effective signal timing for DLT intersections.

Wu et al. (2017) developed a signal timing optimization model for DLT of both FHWA and Mexican designs. Instead of targeting the minimum cycle length, this study focuses on minimizing average traffic delay utilizing the average delay estimation model provided by HCM. Constraints and assumptions are similar with You et al. (2013) except for the queue length constraint. In You et al. (2013), the queue length constraint was set by using a shock wave based on the queue length estimation model. In Wu et al. (2017), to ensure the clearance of vehicle queue, queue length constraint requires that the phase split of downstream traffic flow is always larger than its corresponding upstream phase split. A case study is performed based on a real-world Mexican DLT example with its peak and off-peak volume for a typical day. The simulation platform is VISSIM, which is calibrated before the simulation. After the simulation calibration, Mexican DLT and FHWA DLT are both developed by adjusting parameters after calibration. The developed signal timing strategies compared with the synchro optimized signal timing for the same intersections under the same traffic conditions. The results show that the developed signal timing algorithm (Model) can result in less traffic delay and fewer stops than the signal timing provided by Synchro during the PM peak hour. However, during the AM peak hour, Synchro optimized signal timing produces less traffic delay and a fewer number of stops. This mixed result indicates that the developed signal timing algorithm cannot achieve the optimization results under various traffic conditions. Therefore, improved signal timing strategies are needed. In addition, the strategies used for the signal timing design in this study are very complicated, which are considered four different groups and 21 constraints in total. As a result, it is very difficult for transportation practitioners to apply these strategies in the real world.

Overall, there is a lack of user-friendly guidelines on the signal timing design for the DLT intersection and the existing studies did not fully consider the traffic flow progression in the DLT signal timing. Most of the existing signal timing algorithms only consider progression as one of the constraints in their optimization function. Note that, there are many constraints and some of them cannot be met at the same time. As a result, the developed signal timing algorithm cannot ensure ideal progression, which will significantly impact the operation and safety performance of DLT. It is because that the 5 intersections in DLT need to be designed and operated as one system.

Chapter 3. Design of Study

3.1 Introduction

The study is designed to develop guidelines on the design of signal timing for the DLT intersection based on traffic flow progression. The methodology for signal timing design and techniques and tools are introduced in this chapter. Hence two sections are included in this chapter, 1) methodology and 2) techniques and tools.

3.2 Methodology

The basic idea of the proposed signal timing design is to achieve good progressions for the two major conflict traffic flows at the DLT intersection, i.e. left-turn and through traffic flow, as marked in Figure 4a.

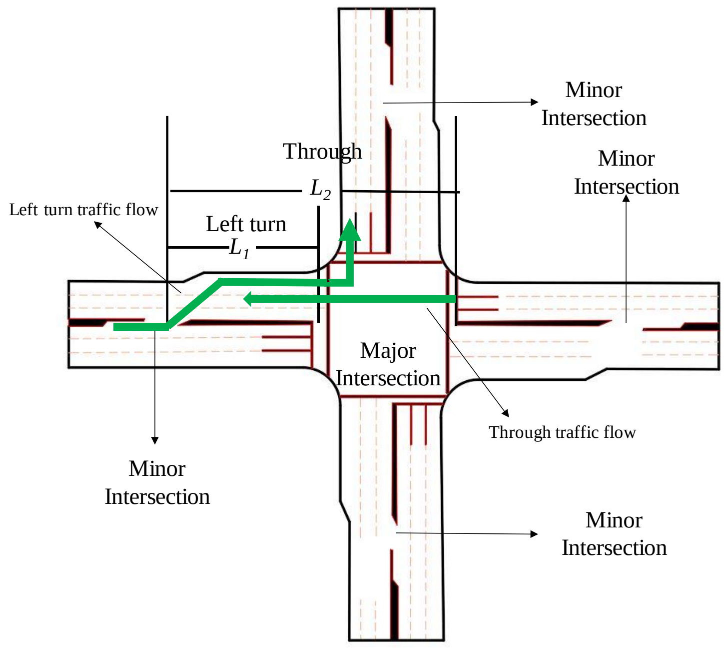
Following is a description of these two major traffic flows.

1) left-turn traffic flow: the left-turn traffic moves across to the most left side lane at the minor intersection and then moves toward the major intersection;

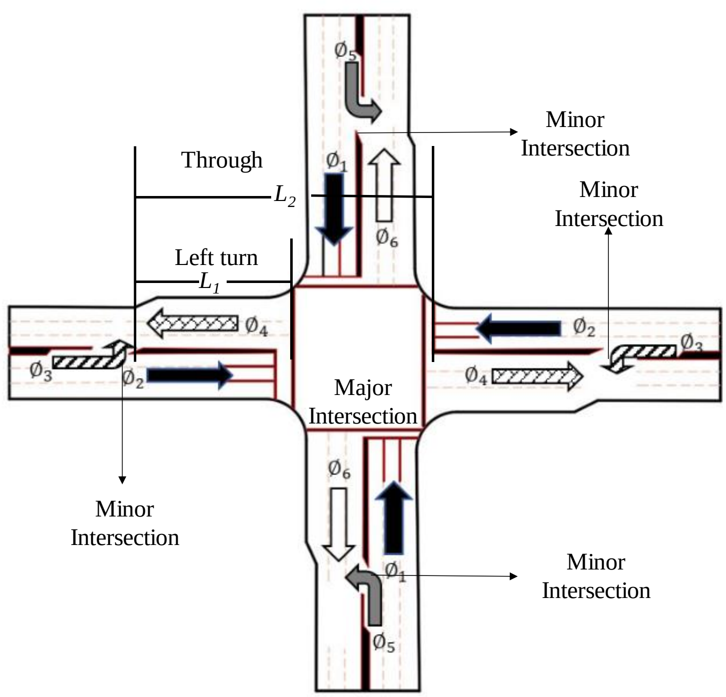
2) through traffic flow: the through traffic moves through the main intersection at first, then moves toward the downstream minor intersection.

The main idea for the DLT signal timing design is to make sure most of the vehicles in these two traffic flows can move continually through both intersections with less delay and fewer stops.

The scope of this research is limited to the DLT intersection under the balanced traffic condition (Assumption 1). The balanced traffic condition means that the volumes of pair equivalent traffic movements at the opposing directions are very similar. This assumption is reasonable because that displaced left-turn intersection has the best performance when balanced and high left-turn volume present (Steve Chery, 2010). Based on this assumption, the pair of equivalent traffic movements in the opposing directions can share the same signal phase. Figure 4b illustrated the signal phase numbering scheme for the different traffic movements at a DLT intersection.



a. Two major traffic flows at a DLT Intersection



b. Signal phases and movements at a DLT Intersection

Figure 4: Two Major Traffic Flows, Signal Phases and Movements at the DLT Intersection

Following are notations used in Figure 4:
C: Cycle length, in seconds

$\emptyset_i$: time for phase *i* (note that there are a pair of movements that move together in each phase *i* without conflicts), in seconds
$\emptyset_1$: phase time for northbound and southbound (NB & SB) through movement and left-turn movement at the major intersection, in seconds
$\emptyset_2$: phase time for eastbound and westbound (EB & WB) through movement and left-turn movement at the major intersection, in seconds
$\emptyset_3$: phase time for EB & WB left-turn movement at the minor intersection, in seconds
$\emptyset_4$: phase time for EB & WB through movement at the minor intersection, in seconds
$\emptyset_5$: phase time for NB & SB left-turn movement at the minor intersection, in seconds.
$\emptyset_6$: phase time for NB & SB through movement at the minor intersection, in seconds
l: total lost time per phase, in seconds
L_1: is the travel distance between the stop bar of minor intersection and the stop bar of major intersection for the left-turn traffic flow
L_2: is the travel distance between the stop bar of the major intersection and the stop bar of the downstream minor intersection for the through traffic flow

A DLT intersection is a system with one major intersection in the center and 4 closely spaced minor intersections. Coordination of these 5 intersections requires that they are operated using the same cycle length (Assumption 2). Thus, the following equations always hold:

$$\emptyset_1 + \emptyset_2 = C \tag{1}$$

$$\emptyset_3 + \emptyset_4 = C \tag{2}$$

$$\emptyset_5 + \emptyset_6 = C \tag{3}$$

The detailed steps of the signal timing design are presented in the following subsections.

Step 1 Determine the signal phase timing at the major intersection based on traffic volume.

At the major intersection, the effective green time is divided according to the ratios between two through traffic volumes and their respective saturation flow rates, which can be mathematically expressed by following equations

$$\emptyset_1 = (C - 2 \times l) \times \frac{\max(y_{1N}, y_{1S}, y_{5N}, y_{5S})}{\max(y_{1N}, y_{1S}, y_{5N}, y_{5S}) + \max(y_{2W}, y_{2E}, y_{3E}, y_{3W})} + l \tag{4}$$

$$\emptyset_2 = (C - 2 \times l) \times \frac{\max(y_{2W}, y_{2E}, y_{3W}, y_{3E})}{\max(y_{1N}, y_{1S}, y_{5N}, y_{5S}) + \max(y_{2W}, y_{2E}, y_{3W}, y_{3E})} + l \tag{5}$$

Where,

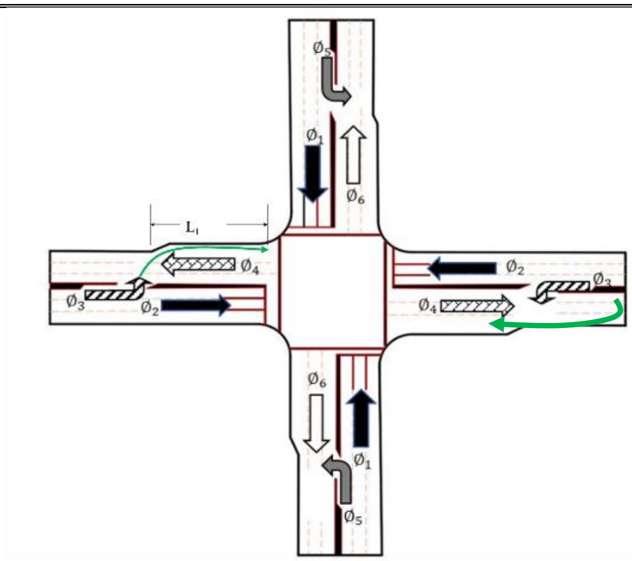
$y_{i\,direction}$: is the ratio of traffic volume and saturation flow rate for a movement during phase i in a given direction (N=North, S=South, E=East, W=West)

Step 2 Determine the signal phase timing at the minor intersections to meet the progression requirements

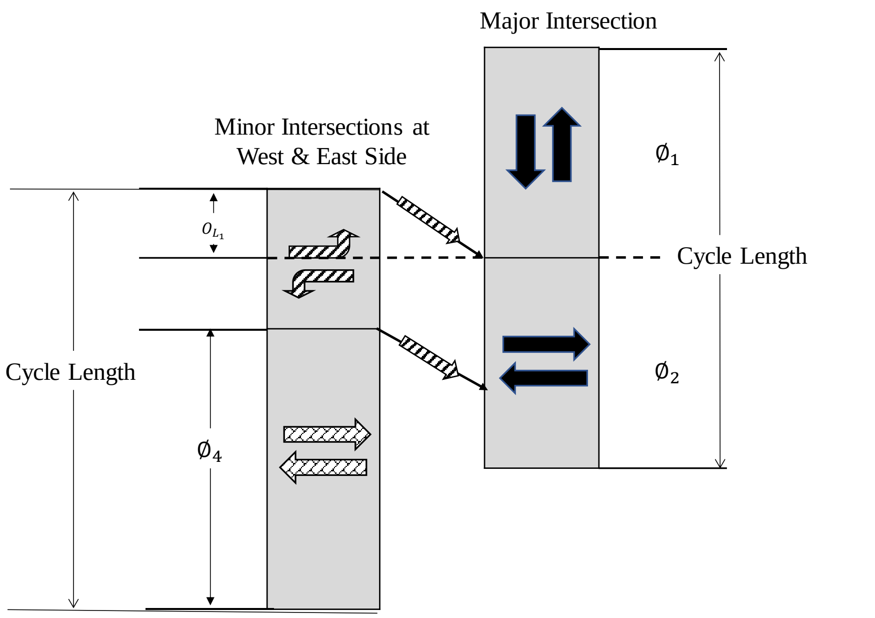
As mentioned before, the proposed methodology is to achieve good progressions for two major traffic flows, i.e. left-turn and through traffic flows. In this study, we use the east and west (EW) side minor interactions as an example to illustrate the design of the signal timing and the signal coordination between the minor and the major intersections at DLTs.

The progression for the left-turn traffic flow

As shown in Figure 5a, for a good progression of left-turn traffic flow, after the EB & WB left-turn vehicles leave the west side minor intersection, drivers expect to meet a green light when they arrive at the major intersection. Hence, the signal for the through movement at the major intersection should turn green O_{L_1} seconds after the left-turn phase at the minor intersection starts. O_{L_1} is the travel time for the left-turn vehicle to travel through distance L_1. Thus, to ensure the good progression of left-turn traffic flow, the offset between the start of the minor intersection left-turn phase and the start of the major intersection through phase should be O_{L_1} (please see Figure 5b for the signal coordination).



a. Left turn traffic flow of EW side at the minor intersection

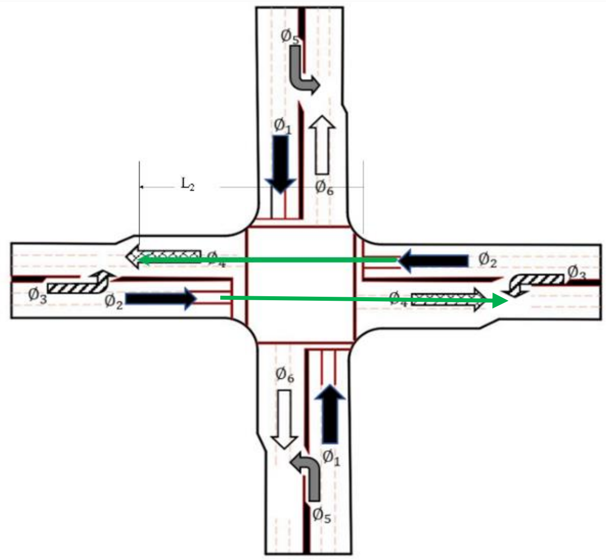


b. Offset for the start of EW side left-turn phase and start of EB & WB through phase at the major intersection

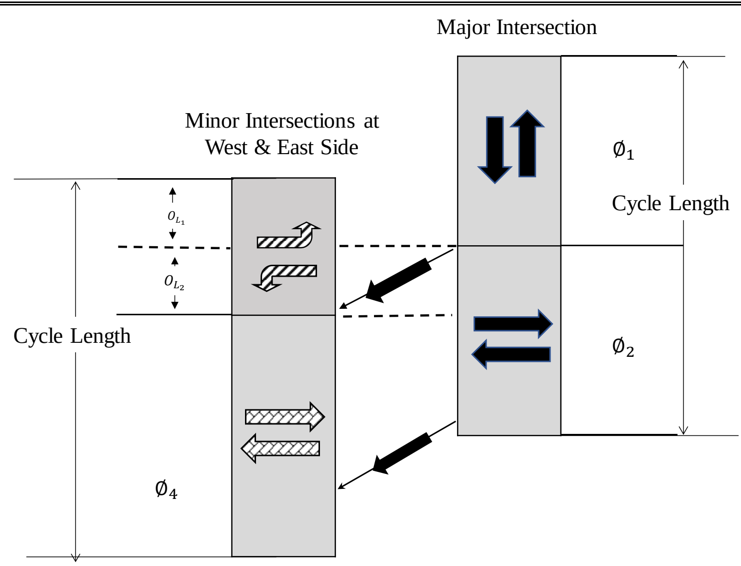
Figure 5: The Progression for Left-Turn Traffic Flow at the DLT Intersection

The progression for the through traffic flow

As shown in Figure 6a, for the through traffic flow from the major intersection, drivers expect to meet a green signal after they drive through a distance of L_2 to arrive at the downstream minor intersection. Hence, the signal for the through movement at the downstream minor intersection should turn green O_{L_2} seconds after the through phase at the major intersection starts, where, O_{L_2} is the travel time for through vehicle to travel through distance L_2. Thus, to ensure the good progression of through traffic flow, the offset between the start of the major intersection through phase and the start of the downstream minor intersection through phase should be O_{L_2} (please see Figure 6b for the signal coordination).



a. Through traffic flow of westbound and eastbound vehicles at the major intersection



b. Offset for the start of EW side through phase at the major intersection and EW side left-turn phase

Figure 6: The Progression for Through Traffic Flow at the DLT Intersection

Combining the required offsets for the good progressions of through and left-turn movements, the ideal length of the left-turn phase ($\emptyset_{ideal\ 3}$) at the minor intersection can be determined as the sum of O_{L_1} and O_{L_2} (see Figure 7).

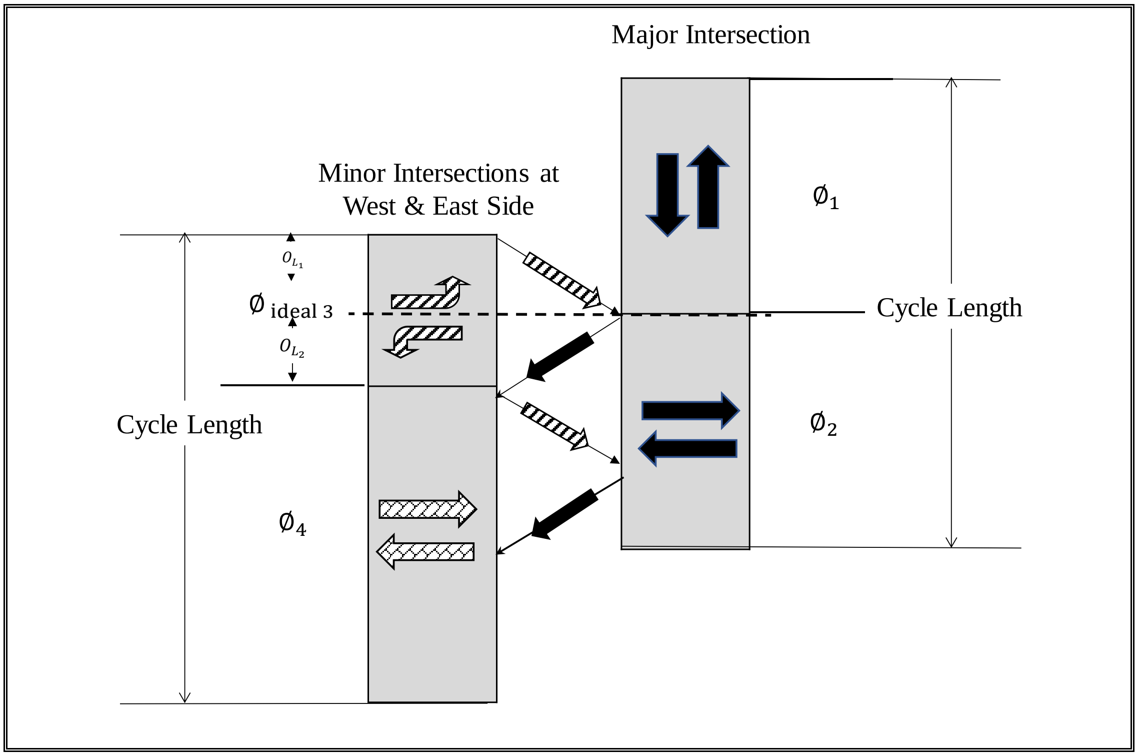


Figure 7: Length Of Left-Turn Phase ∅_(3) for Ideal Progression

In addition, an advanced green time (*Ag*) is proposed to prevent vehicles to make unnecessary slowdowns or stops. Based on a previous study (Chaudhary, 2000), *Ag* here is set as 2s. Therefore, the ideal length of the left-turn phase, $\emptyset_{ideal\ 3}$, can be estimated by the following equation.

$$\emptyset_3 = \emptyset_{ideal\ 3} = \left(O_{L_1} + O_{L_2}\right) - 2 \times Ag + l \tag{6}$$

Where $\emptyset_{ideal\ 3}$ is the ideal phase split length for left-turn vehicles at EW side minor intersections, in seconds. Then, the phase split for through vehicles at the EW side minor intersections, denoted as $\emptyset_4$, can be estimated by the following equation.

$$\emptyset_4 = C - \emptyset_3 \tag{7}$$

Step 3 Check all the constraints

In Step 2, the ideal length of the left-turn phase split is determined based on travel time (O_{L_1} and O_{L_2}) instead of left-turn traffic volume, which raises a concern that $\emptyset_{ideal\ 3}$ might not be sufficient to accommodate the left-turn traffic demand at the minor intersections. In addition, due to that, there are only two phases at the minor intersection, when the left-turn phase is determined, the through phase is also determined, which also raises another concern that a through phase at a minor intersection might not be able to accommodate the through traffic from an upstream major intersection. According to these two concerns, the following two constraints are set.

1) *Constraint 1: the green splits for the $\emptyset_3$ should be sufficient for the left-turn traffic volume at the EW side minor intersection*

The minimum green split required by left-turn traffic volume can be estimated by Equation 8:

$$\emptyset_{min\ 3} = N_3 \times h_{left} + l \qquad (8)$$

Where

h_{left} is left-turn vehicle headway, which is assumed to be 2 seconds

N_3 is average left turn volume per cycle for the EW side minor intersections

Since $\emptyset_3$ should be greater than $\emptyset_{min\ 3}$, according to Equation 6 and Equation 8, Constraint 1 can be mathematically expressed as follows

$$\left(O_{L_1} + O_{L_2}\right) - 2 \times Ag + l > N_3 \times h + l \qquad (9)$$

2) *Constraint 2: the phase for the through movement at a minor intersection must be greater than the phase for the through movement at the upstream major intersection*

To avoid queue spillback at the minor intersection, all the through traffic pass through the major intersection should be able to pass the minor intersection at the downstream. Therefore, the through phase at the downstream minor intersection should be greater than the through phase at the upstream major intersection.

According to this idea, we have the following constraint:

$$\emptyset_4 > \emptyset_2 \qquad (10)$$

Which is equal to:

$$\mathrm{C} - \emptyset_3 > \emptyset_2 \qquad (11)$$

Similar to the definition $\emptyset_{min\ 3}$, $\emptyset_{min\ 2}$ is defined as the minimum required phase time to accommodate the through traffic volumes from eastbound and westbound at the major intersection and $\emptyset_{min\ 4}$ is the minimum required phase time for the through movements at the EW side minor intersections. They can be estimated by Equation 12 and Equation 13 respectively.

$$\emptyset_{min\ 2} = N_2 \times h_{through} + l \qquad (12)$$

$$\emptyset_{min\ 4} = N_4 \times h_{through} + l \qquad (13)$$

Where,

$h_{through}$ is through vehicle headway, assumed as 2 seconds

N_2 is average EB and WB through traffic volume per cycle at the major intersection, veh/s

N_4 is through volume per cycle for the EW side minor intersections, in seconds

It is reasonable to assume that most traffic moves during the through phase $\emptyset_2$ at the major intersection are through traffic instead of right-turn traffic (Assumption 3). Therefore, $\emptyset_{min\,4}$ will be greater than $\emptyset_{min\,2}$ because $\emptyset_{min\,4}$ need to accommodate not only through traffic from a major intersection but also the left-turn traffic and right turn traffic from the crossing road. It is also reasonable to assume that all the intersections at the DLT intersection are not oversaturated (Assumption 4). Since the capacity of the minor intersection is greater than its traffic demand, the following equation stands,

$$\emptyset_{min\,4} + \emptyset_{min\,3} < C \tag{14}$$

Since $\emptyset_{min\,4} > \emptyset_{min\,2}$, Equation 15 also stand.

$$\emptyset_{min\,2} + \emptyset_{min\,3} < C \tag{15}$$

Thus,

$$\emptyset_{min\,2} < C - \emptyset_{min\,3} \tag{16}$$

Equation 16 indicates that by adjusting the length of $\emptyset_2$ and $\emptyset_3$, the Constraint 2 given in Equation 11 can be met.

Step 4 If the constraints are not met, adjust the signal phase timing

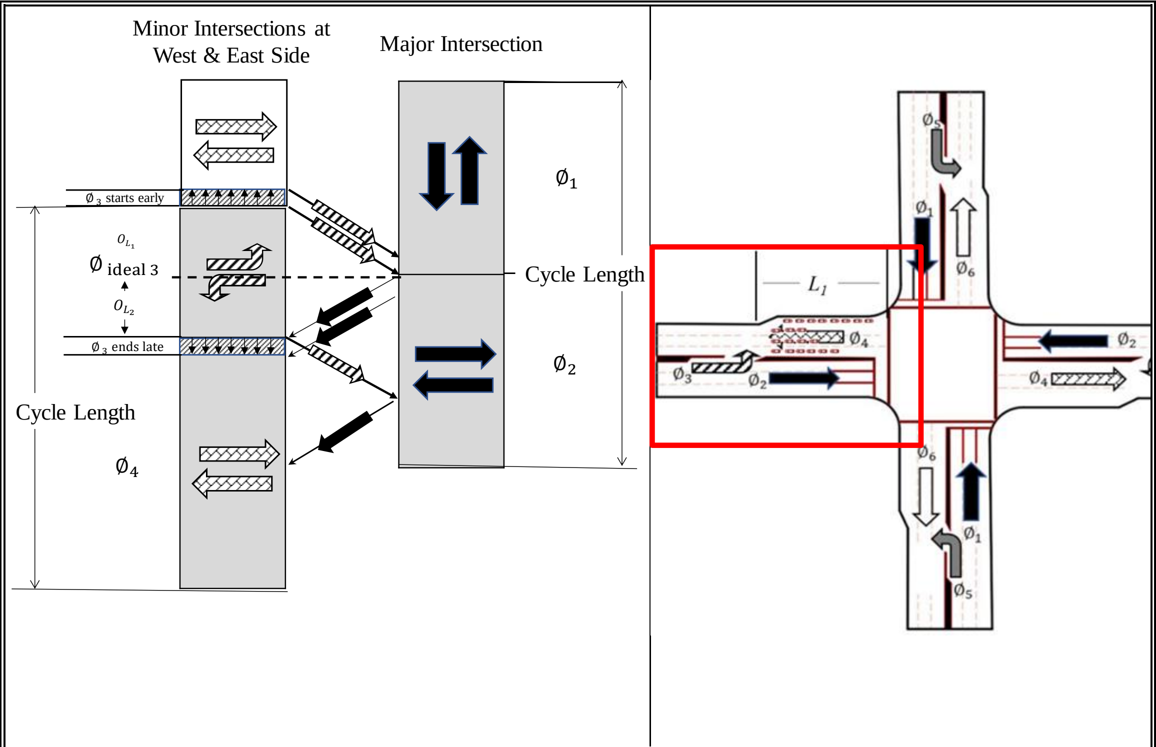
Step 4.1 If Constraint 1 given in Equation 9 is not met, which means the ideal left-turn phase at the minor intersection, i.e. $\emptyset_3$, set according to the progression needs cannot accommodate the left-turn traffic demand at this intersection. To avoid the queue spillback due to insufficient capacity, $\emptyset_3$ should increase to the minimum green split given in Equation 8.

As shown in Figure 8a, the left-turn phase has two boundaries in the signal diagram, upper boundary, and lower boundary. To increase $\emptyset_3$, we can move its boundaries upwards or downwards in the signal diagram as shown in Figure 8a, which means that the left-turn phase should either start earlier or end later. If $\emptyset_3$ starts earlier, left turn vehicles will arrive at the major intersection earlier and wait for a green signal at the major intersection, causing traffic delay, stops, and queue cumulated at the left-turn stop bar at the major intersection. If $\emptyset_3$ ends later, then through vehicles from major intersection to the minor intersection would have to wait for a green signal at the minor intersection, causing traffic delay, stops, and queue cumulated at the through stop bar of minor intersection as well. In both cases, the queue will be accumulated in different lanes as shown in Figure 8a.

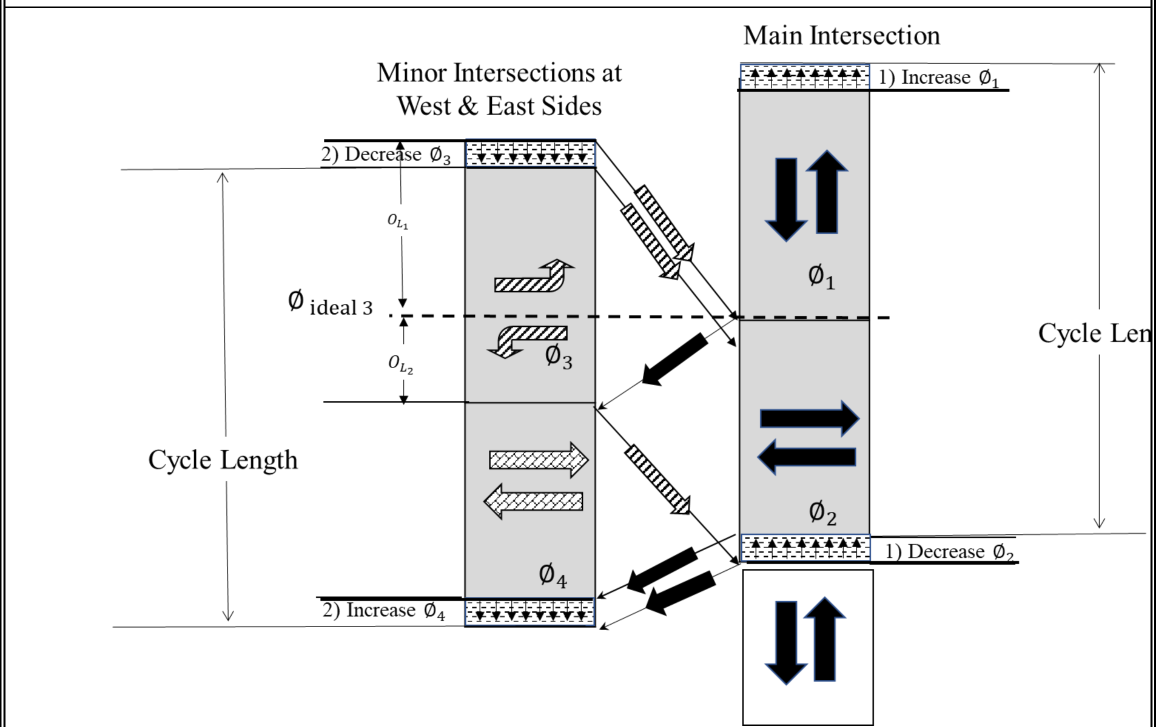
Storage lane length and traffic volume per lane are the two factors that influence how much time a queue can be accumulated before spillback occurs. According to the geometric design of the DLT intersection, it can be observed that the storage length for left-turn vehicles and through vehicles are both close to L_1. Therefore, the more traffic volume per lane is, the more likely the spillback would happen. To avoid the queue spillback, the movement that has more traffic volume per lane should have priority. It means that if the traffic volume per lane for the through movements in phase $\emptyset_1$ is higher than that for phase $\emptyset_3$, then, the upper boundary for $\emptyset_3$ will be pushed up to increase $\emptyset_3$ to the required minimum length given in Equation 8 ($\emptyset_3$ starts early). Otherwise, the lower boundary for $\emptyset_3$ will be pushed down to increase $\emptyset_3$ to the required minimum length ($\emptyset_3$ ends late).

<u>Step 4.2 If Constraint 2 is not met</u>, then the through phase $\emptyset_4$ at the downstream minor intersection is not long enough to accommodate the through traffic from the major intersection. Through vehicles will be queued in front of the minor intersection. As shown in Figure 8b, two viable solutions are (1) to decrease the length of the phase $\emptyset_2$, which is for the through traffic movement at the major intersection, or (2) to increase the length of the phase $\emptyset_4$, which is for the through traffic flow at the minor intersection until Constraint 2 is met. Since the sum of $\emptyset_4$ and $\emptyset_3$ is equal to *C*, it will reduce the length of $\emptyset_3$, which will compromise the progression of the left-turn and through traffic flows (according to the discussion in Step 2). Therefore, it is recommended to decrease the length of the phase $\emptyset_2$ at first. If Constraint 2 is still not met even if $\emptyset_2$ reaches its minimum required length given in Equation 12, then we can increase the length of the phase $\emptyset_4$ until it is longer than $\emptyset_2$.

In this study, if both Constrains 1 and 2 are met, then the DLT intersection is under ideal progression condition.



a. Signal adjustment illustration when constraint 1 is not met



b. Signal adjustment illustration when constraint 2 is not met

Figure 8: Illustration for Signal Adjustment when Constraints Are Not Met

By now, we have developed strategies for determining the signal timing for the EW side minor intersections. Same strategies can be applied to determining the signal timing for the NS side minor intersections. Then, the overall signal timing plan can be developed for the whole DLT intersection. The overall signal timing diagram for a DLT intersection where the ideal progression condition is met is presented in Figure 9.

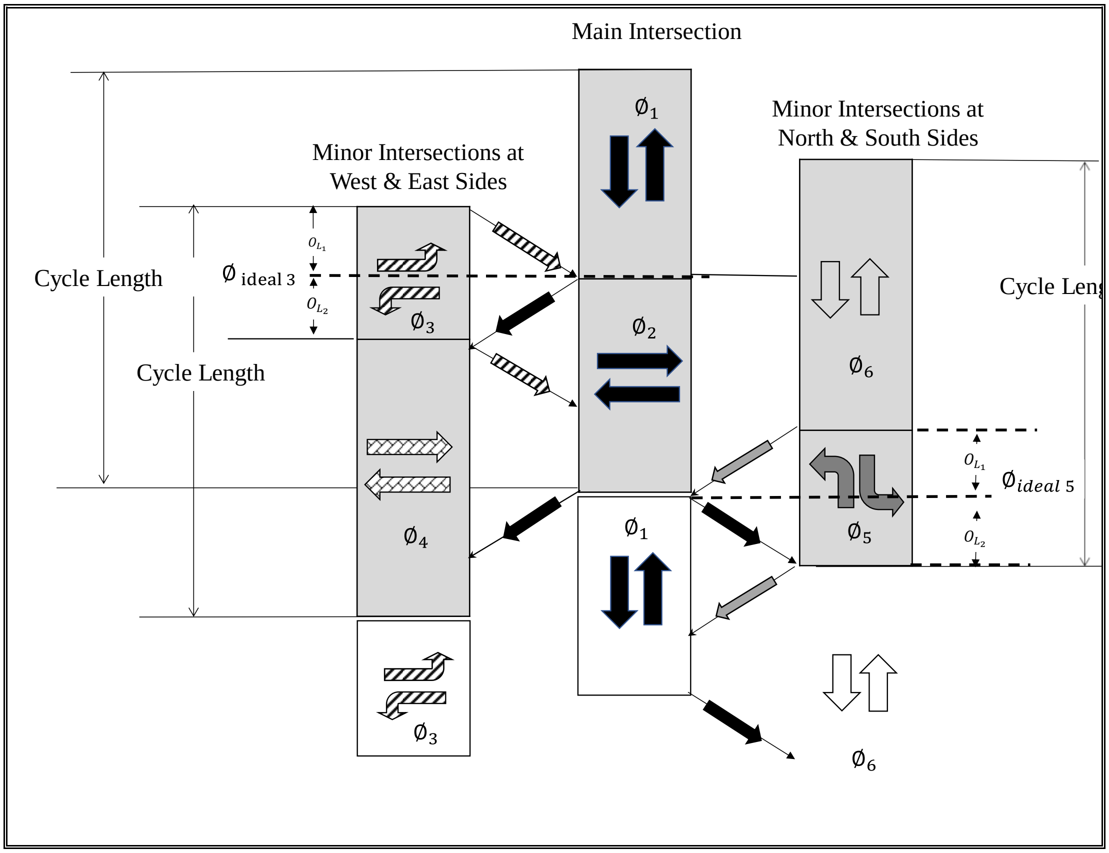


Figure 9: Overall Signal Timing Diagram for A DLT Intersection where the Ideal Progression Condition Is Met

Chapter 4. Results and Discussions

4.1 Introduction

A case study was conducted to evaluate the performance of the developed signal timing strategies at a hypothesized DLT intersection provided by Synchro, a signal design and timing software developed by Trafficware Company. In this case study, traffic simulation-based experiments were conducted to assess the operational performances of a DLT intersection with the developed signal timing, the default signal timing provided by Synchro, and the Synchro optimized signal timing. Different traffic simulation scenarios are established by varying the left-turn traffic volumes and the through traffic volumes proportionally at the studied intersection. VISSIM simulation results for developed signal timing and Synchro provided signal timing are presented and evaluated in this chapter. This chapter is divided into four sections: 1) case study and scenario design, 2) baseline scenarios, 3) alternative scenarios, and 4) discussion of results application.

4.2 Case Study and Scenario Design

To demonstrate the application of the developed signal timing strategy and evaluate its performance, a case study is conducted.

4.2.1 Geometric Design and Traffic Volume Features of the Studied DLT Intersection

A hypothesized DLT intersection provided by Synchro was selected for conducting the case study. Synchro is a signal design and timing software developed based on Trafficware. It allows transportation planners and engineers to model a signalized intersection in a computer-based environment. At first, the intersection signal timing parameters, geometric design features, and traffic volumes are inputted into Synchro to analyze the intersection operational performances and then, the signal timing can also be optimized. For DLT, Synchro provides an example of DLT, which is a four-legged DLT. Figure 10 is the Synchro screenshot for this DLT, which shows the geometric and traffic volume conditions at this intersection.

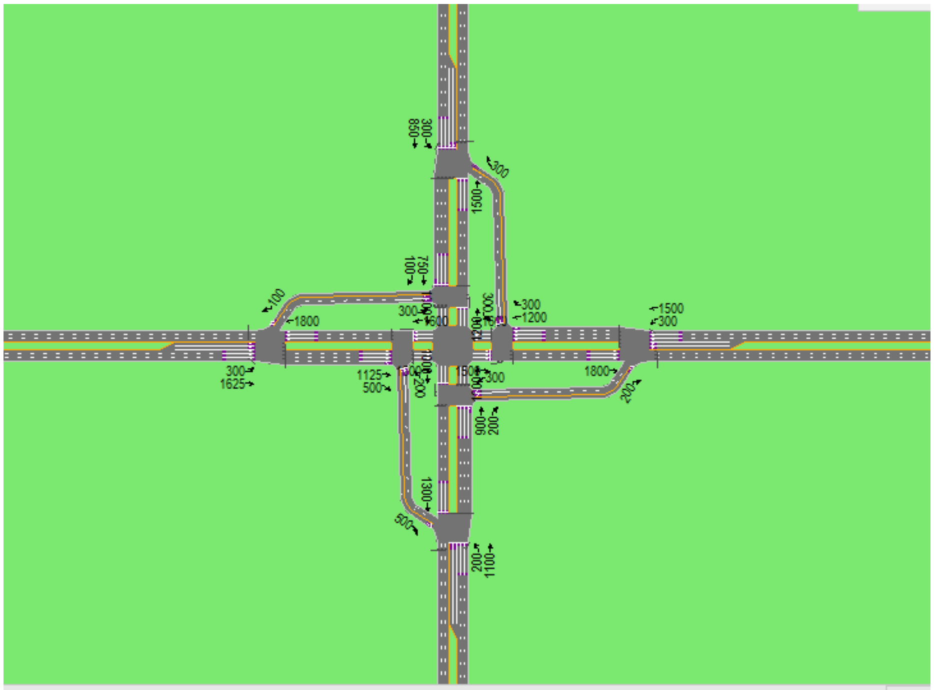


Figure 10: Synchro Screenshot for the Studied DLT Intersection

At this intersection. There are two left-turn lanes, one channelized right turn lane, and three through lanes provided in each approach. The traffic volumes of each approach are shown in Table 1. The distance between the major intersection and the minor intersections is 450 ft.

Table 1: Traffic Volume at the Studies DLT Intersection

EB (*vph*)			WB (*vph*)			NB (*vph*)			SB (*vph*)		
Left	Through	Right	Left	Through	Right	Left	Through	Right	Left	Through	Right
300	1500	500	300	1600	300	200	1200	200	300	1000	100
2300			2200			1600			1400		

4.2.2 Synchro Default and Optimized Signal Timing

As a Synchro example for DLT intersection, the signal timing of this studied DLT is pre-configured, and it can work properly at this intersection with acceptable traffic delay and congestion level. However, this default signal timing has not been optimized according to the traffic volume and geometric conditions at this DLT. Therefore, optimization of cycle length and signal phase splits was conducted in the Synchro to derive the optimized signal timing. The derived optimized cycle length and phase splits are the ones that produce the minimum average vehicle delay based on an analytic delay estimation method (Percentile Delay Method, Trafficware, 2017). A cycle length would be automatically selected during the Synchro optimization process. To make scenarios comparable, developed signal timing should employ the same cycle length as the one used in Synchro optimized signal timing

4.2.3 VISSIM Traffic Simulation and Scenario Design

VISSIM is a microscopic multi-modal traffic flow simulation software package developed by PTV Planung Transport Verkehr AG in Karlsruhe, Germany. It will be used to do operational analysis. The hypothesized DLT intersection provided by Synchro is exported to VISSIM (a microscopic traffic simulation model) for simulating the traffic operations at this DLT with different signal timing plans under different traffic volume conditions. The baseline model is established according to the Synchro DLT example. The geometric design and traffic volume features are replicated in VISSIM as shown in Figure 11.

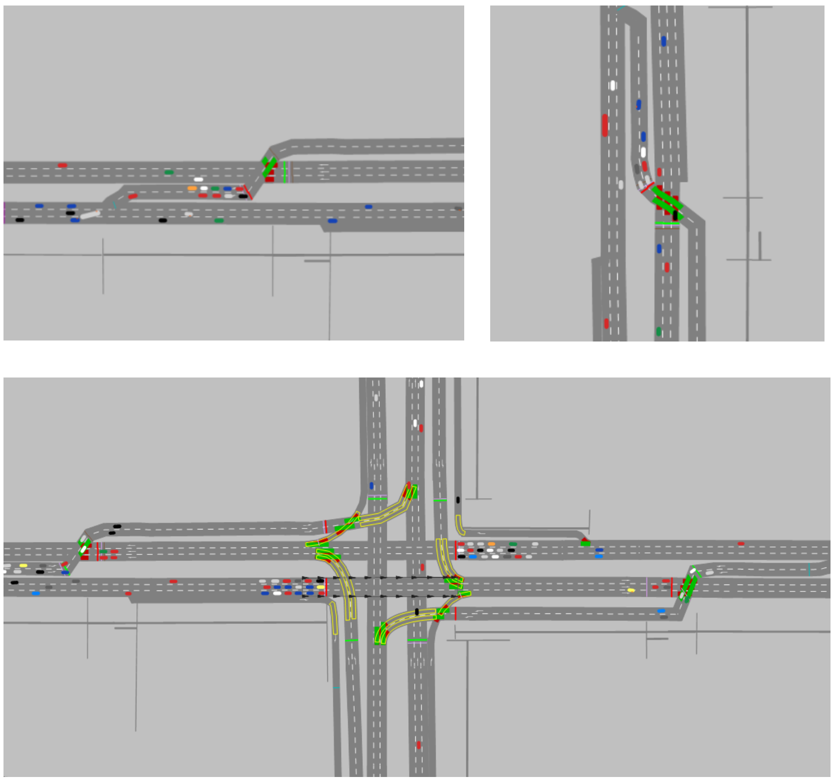


Figure 11: Screenshots of Studied DLT Intersection in VISSIM

1) Baseline scenarios

First, to assess the operational performance of the DLT intersection with different signal timing plans, three different simulation scenarios were designed for the baseline DLT intersection with three different signal timing plans, namely Synchro default signal timing, Synchro optimized signal timing, and developed signal timing. Therefore, there are the following three baseline scenarios:

A.1) DLT intersection with original traffic volume and Synchro default signal timing (default cycle length of the 90s)
A.2) DLT intersection with original traffic volume and Synchro optimized signal timing (optimized cycle length of the 80s)
A.3) DLT intersection with original traffic volume and developed signal timing (cycle length of the 80s)

For the baseline scenarios, traffic simulation was conducted, and based on the simulation results, operational performance measures, including average traffic delay, average vehicle travel time, and average queue length were obtained and compared.

2) Alternative scenarios

To investigate the operational performances of the DLT intersection under different traffic volume conditions, different alternative simulation scenarios were created by varying left turn traffic volume and through traffic volume proportionally according to the original assumed traffic volume at this intersection. To be specific, the following 20 scenarios was designed:

B.1) DLT intersection with 50% original left-turn traffic volume and Synchro optimized signal timing
B.2) DLT intersection with 75% original left-turn traffic volume and Synchro optimized signal timing
B.3) DLT intersection with 100% original left-turn traffic volume and Synchro optimized signal timing (which is same as baseline scenario A.2)
B.4) DLT intersection with 125% original left-turn traffic volume and Synchro optimized signal timing
B.5) DLT intersection with 150% original left-turn traffic volume and Synchro optimized signal timing

C.1) DLT intersection with 50% original left-turn traffic volume and developed signal timing
C.2) DLT intersection with 75% original left-turn traffic volume and developed signal timing
C.3) DLT intersection with 100% original left-turn traffic volume and developed signal timing (which is same as baseline scenario A3)
C.4) DLT intersection with 125% original left-turn traffic volume and developed signal timing
C.5) DLT intersection with 150% original left-turn traffic volume and developed signal timing

D.1) DLT intersection with 50% original through traffic volume and Synchro optimized signal timing
D.2) DLT intersection with 75% original through traffic volume and Synchro optimized signal timing
D.3) DLT intersection with 100% original through traffic volume and Synchro optimized signal timing (which is the same as baseline scenario A2)
D.4) DLT intersection with 125% original through traffic volume and Synchro optimized signal timing
D.5) DLT intersection with 150% original through traffic volume and Synchro optimized signal timing

E.1) DLT intersection with 50% original through traffic volume and developed signal timing

E.2) DLT intersection with 75% original through traffic volume and developed signal timing
E.3) DLT intersection with 100% original through traffic volume and developed signal timing (which is same as baseline scenario A3)
E.4) DLT intersection with 125% original through traffic volume and developed signal timing
E.5) DLT intersection with 150% original through traffic volume and developed signal timing

To make the scenarios comparable, the cycle length of developed signal timing and Synchro optimized signal timing are set equal in the same scenario. A cycle length would be selected in the Synchro optimization process and developed signal timing would employ the same cycle length. The cycle lengths for each scenario are shown in Table 2.

Table 2: Cycle Lengths for Different Scenarios

	Left Turn Traffic Volume Percentages					**Through Traffic Volume Percentages**				
Percentages	50%	75%	100%	125%	150%	50%	75%	100%	125%	150%
Cycle Lengths	80s	80s	80s	80s	90s	90s	90s	80s	80s	90s

VISSIM Version 9-10 was used to model and analyze the experimental scenarios. Since VISSIM uses stochastic (random) models, there may be minor differences in the results depending on the random number seed. To address this issue, multiple runs were used. For each run, the simulation time was set to 4,800 seconds, and the warm-up time was 1,200 seconds for each scenario. 10 runs with different random seeds were performed for each volume of scenarios. The results presented in later sections are the averages for the ten runs. Measures of performance, average delay, and travel time were collected for further evaluation.

4.3 Baseline Scenarios

Operational performance simulation results for baseline scenarios are presented and discussed in this section. Overall, for the baseline scenario, developed signal timing outperforms Synchro default signal timing and Synchro optimized signal timing by all three measures of effectiveness, namely average traffic delay, average vehicle travel time, and average queue length.

Figure 12 shows the results of the average traffic delay. According to Figure 12, the DLT intersection with developed signal timing produces an average traffic delay of 18.64 seconds, which is the lowest. The DLT intersection with Synchro optimized signal timing produces the second-lowest average traffic delay, which is 24.6 seconds. Last, the DLT intersection with Synchro default signal timing produces the highest average traffic delay of 26.16 seconds.

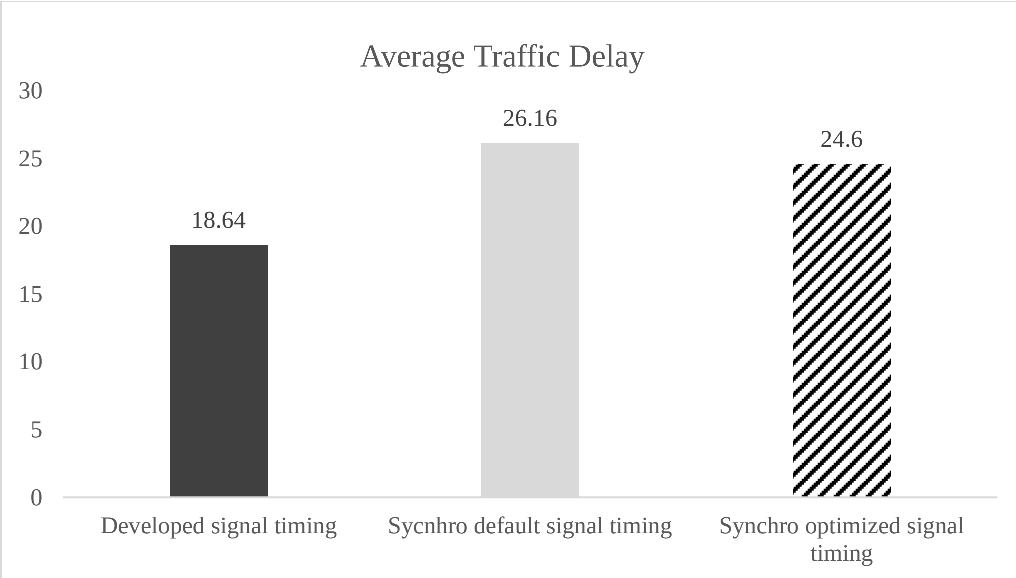


Figure 12: Average Traffic Delay Result for Baseline Scenario

Therefore, regarding average traffic delay, developed signal timing has the best performance over Synchro optimized and default signal timings. Developed signal timing strategy can reduce average traffic delay by 24% compared with Synchro optimized signal timing, and 29% compared with Synchro default signal timing.

Figure 13 shows the average vehicle travel time results. According to Figure 13, the DLT intersection with developed signal timing has produced the lowest average vehicle travel time, which is 64.5 seconds. While the DLT intersection with Synchro optimized signal timing has produced the second-lowest average vehicle travel time, which is 70.5 seconds. Lastly, the DLT intersection with Synchro default signal timing has the highest average vehicle travel time, which is 72 seconds.

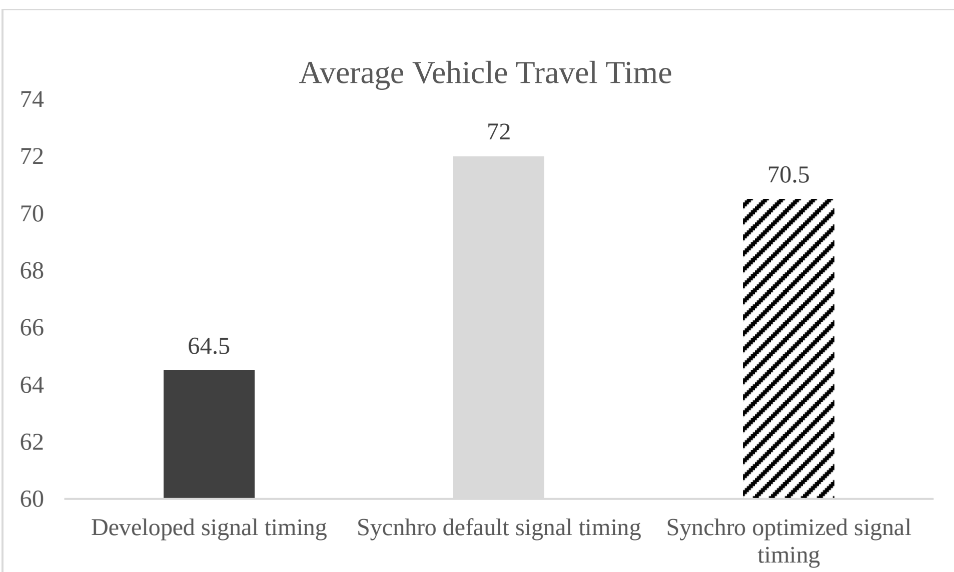


Figure 13: Average Vehicle Travel Time Results for Baseline Scenarios

Developed signal timing has the best performance regarding average vehicle travel time among three different signal timings. Developed signal timing can reduce average vehicle travel time by 9% compared with Synchro optimized signal timing, and 10% compared with Synchro optimized signal timing;

Figure 14 shows the results of the average queue length. Developed signal timing yields the shortest average queue length with 13.65 ft. Synchro optimized signal timing has the second shortest average queue length with 19.16. Synchro default signal timing produces the largest average queue length compared with the other two signal timings.

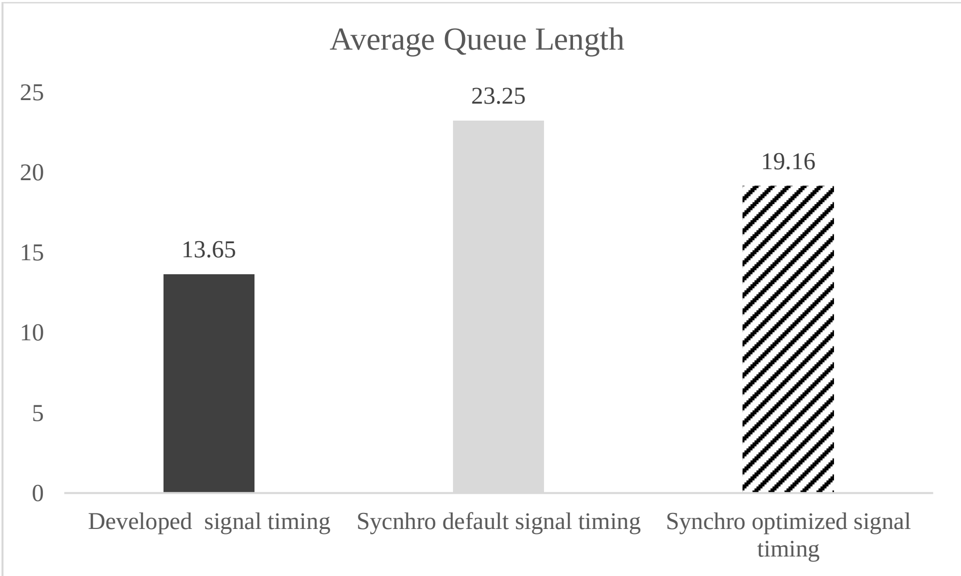


Figure 14: Average Queue Length for Baseline Scenarios

Developed signal timing can reduce average queue length by 28% compared with Synchro optimized signal timing, and 41% compared with Synchro optimized signal timing.

In summary, for the baseline scenario, DLT with developed signal timing can yield the best operational performance regarding average queue length, average vehicle travel time, and average traffic delay compared with Synchro default and optimized signal timings.

4.4 Alternative Scenarios

4.4.1 Average Traffic Delay

Alternative scenarios are designed to test the operational performances of developed signal timing and Synchro optimized signal timings with different traffic volume conditions. 20 scenarios are designed including baseline scenarios. In this section, VISSIM simulation results for alternative scenarios are presented and discussed.

The average traffic delay results for all 20 scenarios are presented in Figure 15. Scenarios of different left-turn traffic volumes and through traffic volume are presented in two separate figures. According to Figure 15, either for different left-turn traffic volume conditions or for different through traffic volume conditions, the scenarios of developed signal timing can consistently produce less traffic delay compared with that of Synchro optimized signal timing in all 20 scenarios.

For scenarios of different through traffic volume percentages, average traffic delay stays stable when through traffic volume increase from 50% to 100% (original) for both signal timings. Nevertheless, when traffic volume increases from 100% to 150%, the average traffic delay of scenarios with Synchro optimized signal timing spikes significantly, while in the scenarios of developed signal timing, the average traffic delay stays stable.

For scenarios of different left-turn traffic volumes, average traffic delays produced under two signal timings slowly increase as the left-turn traffic volume increase from 50% to 125%. When left turn traffic volume increases to 150%, the average traffic delay spikes for Synchro optimized signal timing, while stays stable for developed signal timing.

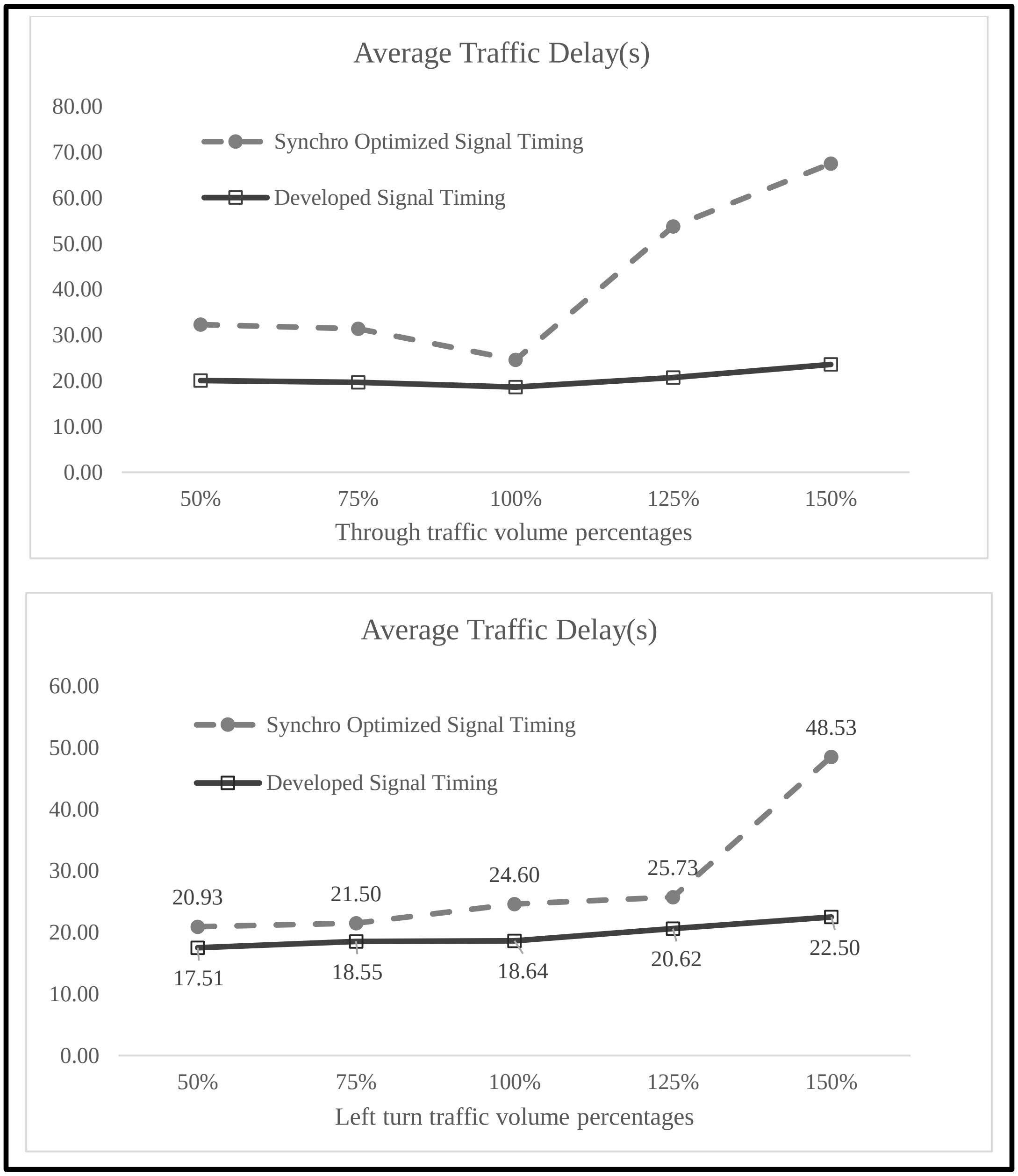


Figure 15: Average Traffic Delay for All 20 Scenarios

Either for through traffic volume percentages or for left-turn traffic volume, when traffic volume varies from 50% to 150%, scenarios of developed signal timing constantly produce low-level traffic delays, while scenarios of Synchro optimized signal timing produce increasing traffic delays. The developed signal timing has a better performance compared with Synchro optimized signal timing especially when traffic volume is high. The developed signal timing outperforms Synchro optimized signal timing by 24% to 68% when through traffic volume varied from 50% to 150%, and 14% to 54% when left-turn traffic volume varies from 50% to 150%.

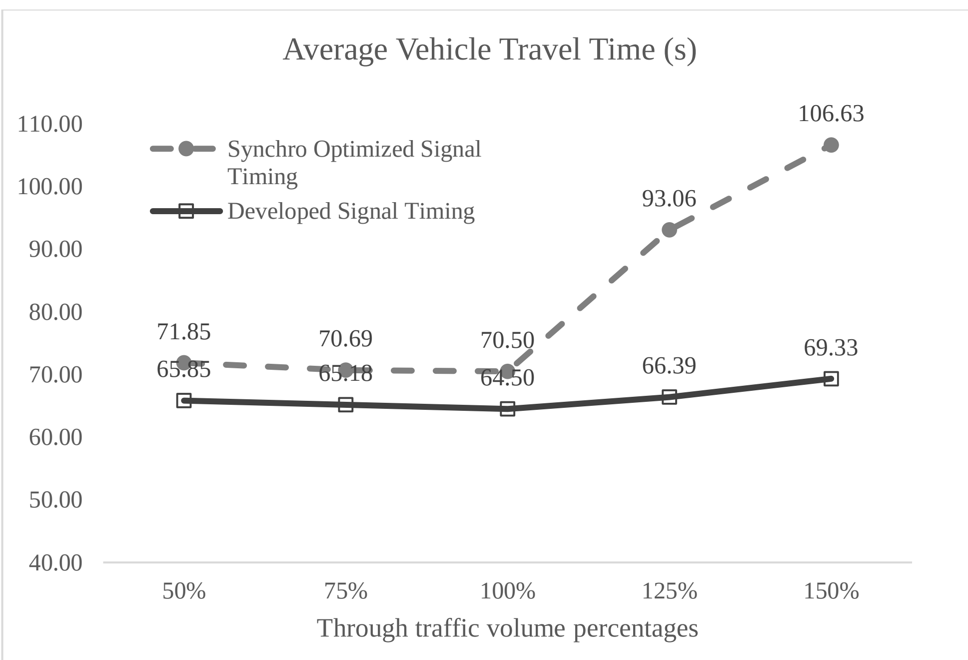
Note that, although in Synchro, the signal optimization is based on minimizing the average delay, the developed signal timing still outperforms the Synchro optimized signal timing in terms of average traffic delay. It is because the delay in Synchro is estimated using an analytic delay estimation model, which is based on many simplification assumptions. In addition, it also has many limitations. For example, the model did not consider the delay caused by the turn lane overflow situation. In other words, the delay caused by vehicles spilling out of a turn lane was not included in the estimated delay. Since, at DLT, the five intersections are closely spaced, bad progression will very likely cause left-turn lane overflow. In this case, the delay caused by bad progression will be significantly underestimated by the Synchro delay estimation model. As a result, the derived signal timing is not a truly optimal solution for this DLT intersection.

4.4.2 Average Travel Time

Figure 16 shows the average vehicle travel time results of developed signal timing and Synchro optimized signal timing. Like average traffic delay, average vehicle travel time is less in scenarios of developed signal timing compared with those of Synchro optimized signal timing overall.

For scenarios of different through traffic volume percentages, developed signal timing outperforms Synchro optimized signal timing for all different traffic volume conditions, especially when through traffic percentage increase to 150%.

For scenarios of different left-turn traffic volume percentages, developed signal timing outperforms Synchro optimized signal timing for all different traffic volume conditions. As the left-turn traffic volume increases, the advantage of developed signal timing becomes more and more significant.



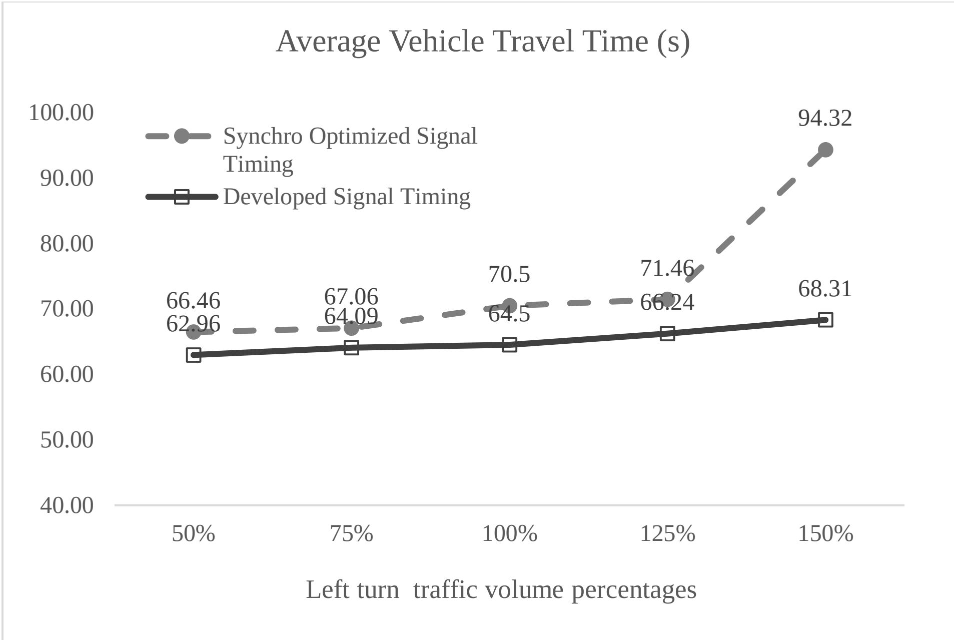


Figure 16: Average Vehicle Travel Time for All 20 Scenarios

For scenarios of different through traffic volume percentages, developed signal timing outperforms the Synchro optimized signal timing from 8% to 38%. For scenarios of different left-turn traffic volume percentages, developed signal timing outperforms that Synchro optimized signal timing from 4% to 28%.

As mentioned before, Synchro optimization-based signal timing model failed to take into account of progression factor and spill back in the turn lane, thus Synchro optimization did not produce the optimal signal timing for displaced left turn intersection regarding average traffic delay. If the average traffic delay is greater, the average travel time is also greater. Thus, the results are reasonable.

4.4.3 Average Queue Length

Figure 17 shows the simulation results of the average queue length for developed signal timing and Synchro optimized signal timing. For DLT intersections with different signal timings, the simulation results of average queue length are consistent with those of average vehicle travel time and average queue length. Either for scenarios of different through traffic volume percentages or for scenarios of different left-turn volume percentages, the developed signal timing strategy can consistently outperform the Synchro optimized signal timing strategy.

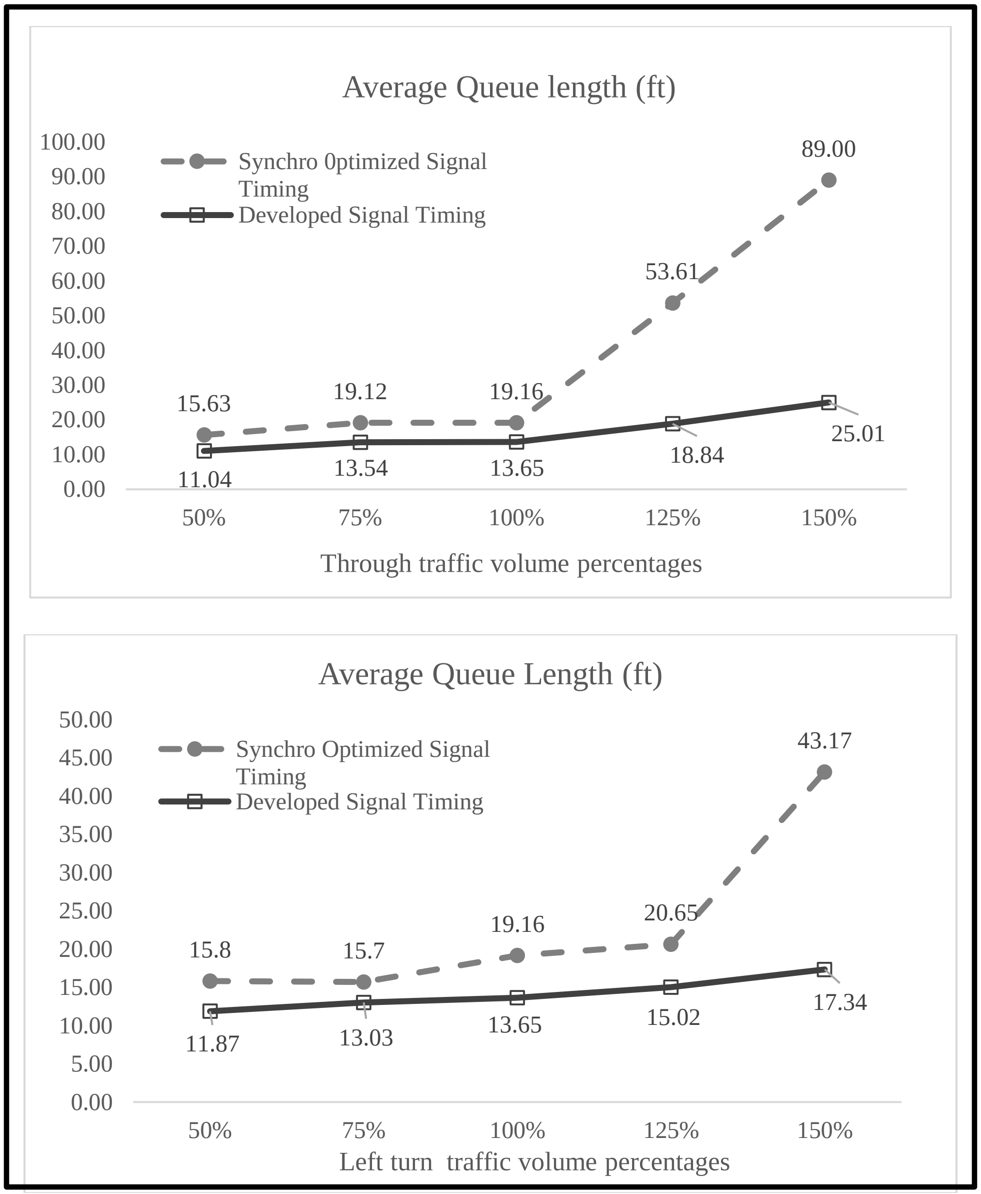


Figure 17: Average Queue Length for All 20 Scenarios

Regarding average queue length, the developed signal timing outperforms Synchro optimizes signal timing by 29% to 72% for through traffic volume percentage variations, and 17% to 60% for left-turn traffic volume percentage variations.

The developed signal timing can produce the shortest average queue length because the signal timing is set to achieve the progression for all the vehicles at best while Synchro optimization model only aims at theoretical average traffic delay, without proper consideration of long queue even spillback that can be caused due to bad progression. Therefore, the Synchro optimization model failed to produce the shortest queue compared with developed signal timing.

In summary, the developed signal timing outperforms the Synchro optimized signal timing in all scenarios, especially when through traffic volume and left-turn traffic volume increase to 150%. The simulation results also show that developed signal timing is less sensitive to the increase of left-turn traffic volume and through traffic volume compared with Synchro optimized signal timing.

4.4.4 Results and Discussions for the Scenarios without Ideal Progression

In the last section, the results are presented for scenarios with the left-turn and through traffic volumes ranging from 50% to 150% of their original traffic volumes. All of these scenarios satisfy constraints for a DLT intersection to achieve an ideal progression. To examine the proposed signal timing strategy under the non-ideal progression scenario, a scenario is established with left-turn traffic volume increasing to 300%. In this scenario, the ideal length of the left-turn phase, which is determined by travel time, is not sufficient for the left turn traffic demand. This means constraint 1) is not met. The ideal left turn phase would extend its length upwards and the progression of left-turn traffic flow would be compromised. Figure 18 shows which steps are conducted and a signal diagram illustration of adjustments.

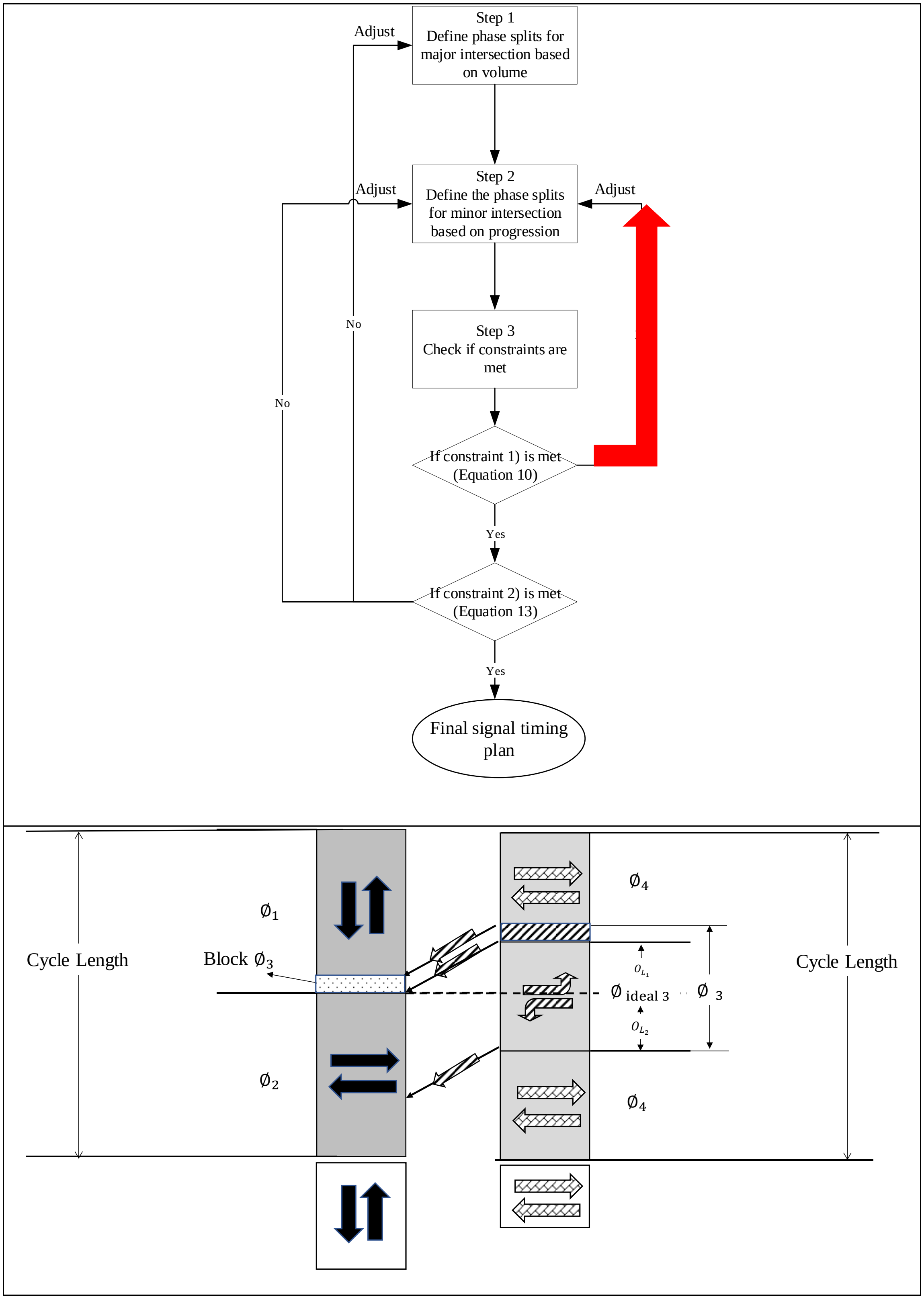


Figure 18: Adjustment for Constraint 1

The simulation results are presented in Figure 19. From Figure 19, it can be observed that developed signal timing is still superior to the Synchro optimized signal timing regarding all three measures of effectiveness.

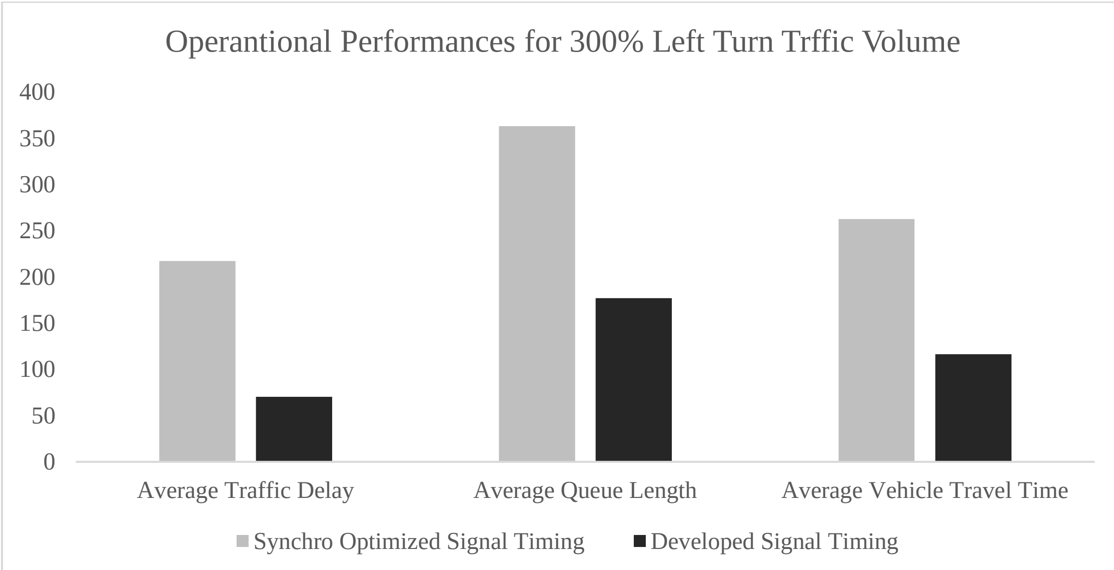


Figure 19: Operational Performances for 300% Left Turn Traffic Volume

4.5 Discussion of Results Application

The results of this study not only provide the signal timing design strategies for DLT intersections but also provide guidance for the geomatic design of a new DLT construction. A critical design element in the DLT intersection is the distance between the minor intersection and major intersection. When constructing a new DLT intersection, the distance between the minor and major intersection, i.e. L_1 in Figure 4, can be determined according to the requirements for ideal progression given in Equation 10.

According to Equation 10, the distance L_1 should meet the following requirement:

$$\frac{L_2}{S_{vehicle}} + \frac{L_1}{S_{vehicle}} - 2 > N_3 \times h + l_1 + l_2 \qquad (20)$$

Where,

W is the intersection footprint in ft,

$S_{vehicle}$ is the vehicle speed, in ft/s,

L_1 is the distance between the minor intersection and major intersection, in ft.

L_2 is the sum of the distance between the minor intersection and major intersection and width of intersection in ft.

N3: average traffic demand per cycle for left-turn vehicles in phase 3

l_1: start-up lost time

l_2: clearance lost time

Since $L_2 = L_1 + W$, then

$$\frac{L_1+W}{S_{vehicle}} + \frac{L_1}{S_{vehicle}} - 2 > N_3 \times h + l_1 + l_2$$
(21)

Thus, it could be derived that

$$L > \frac{(N_3 \times h + l_1 + l_2 + 2) \times S_{vehicle} - W}{2} = L_{min\,1}$$

Where, $L_{min\,1}$ is the minimum required distance between the minor intersection and major intersection for achieving ideal progression in ft.

Chapter 5. Conclusions

To provide a user-friendly guideline of signal timing for the DLT intersection, this study proposed a systematic signal timing methodology with consideration of intersection progression. VISSIM simulation is conducted to evaluate the operational performances of the DLT intersection with signal timing provided by the developed signal timing strategy. the simulation results of developed signal timing are compared with that of signal timings provided by Synchro. Based on the results of this study, the following key findings were obtained:

For the baseline scenario of the original traffic volume condition, the developed signal timing outperformed Synchro default signal timing and Synchro optimized signal timing with regard to average traffic delay, average vehicle travel time, and average queue length. To be specific,

1) For average traffic delay, developed signal timing outperforms Synchro optimized signal timing by 24% and Synchro default signal timing by 29%;

2) For average vehicle travel time, developed signal timing outperforms Synchro optimized signal timing by 9% and Synchro default signal timing by 10% ;

3) For average queue length, developed signal timing outperforms Synchro optimized signal timing by 28% and Synchro default signal timing by 41%.

For the alternative scenarios, the developed signal timing outperformed Synchro optimized signal timing in all left turn and through traffic volume conditions, especially when the traffic volume is at a high level. To be specific:

1) Regarding average traffic delay, the developed signal timing outperforms Synchro optimizes signal timing by 24% to 68% for through traffic volume percentage scenarios, and 14% to 54% for left-turn traffic volume percentage scenarios.

2) Regarding average vehicle travel time, developed signal timing outperforms the Synchro optimized signal timing by 8% to 38% for different through traffic volume percentage scenarios and 4% to 28% for different left-turn traffic volume percentage scenarios.

3) Regarding average queue length, the developed signal timing outperforms Synchro optimizes signal timing by 29% to 72% for through traffic volume percentage variations, and 17% to 60% for left-turn traffic volume percentage variations.

This research also points out the importance of considering the DLT intersection as one system during signal design and timing. Existing studies developed the signal timing models based on inaccurate queuing delay assumption, which failed to provide enough consideration on re-acceleration and deceleration of vehicles when they meet multiple traffic lights.

Besides, this research also provides an important reference for the geometric design of the DLT intersection. To ensure the ideal progression, the distance between the minor intersection and major intersection should be long enough so that travel-time based signal timing can accommodate for left-turn traffic demand.

Future studies can be conducted on the DLT intersection with unbalanced traffic volumes. A field study in the real-world should also be conducted to evaluate the operational performance of developed signal timing.

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Appendix: Notations

C: cycle length for minor intersection and major intersection

$\emptyset_i$: phase split for movement *i*,

$\emptyset_1$: phase split for through vehicles of northbound and southbound at the major intersection

$\emptyset_2$: phase split for through vehicles of eastbound and westbound at the major intersection

$\emptyset_3$: phase split for left-turn vehicles of eastbound and westbound at the minor intersection

$\emptyset_4$: phase split for through vehicles on eastbound and westbound at the minor intersection

$\emptyset_5$: phase split for left-turn vehicles on northbound and southbound at the minor intersection

$\emptyset_6$: phase split for through vehicles on northbound and southbound at the minor intersection

$y_{i\ direction}$: is the ratio of traffic volume and saturation flow rate for movement *during phase i for the given direction*

Ag *:* advanced green time, defined as 2s

h: headway

l : lost time, start-up lost time and clearance lost time

l_1: start-up lost time

l_2: clearance lost time

N_i : traffic volume per cycle for movements in phase *i*

O_{L_1}: travel time for left-turn vehicles go through L_1

O_{L_2}: travel time for through vehicles go through L_2

$\emptyset_{min\ i}$: minimum phase split required by movement *i*

$\emptyset_{ideal\ 3}$: left turn phase split the length in ideal signal coordination

$\Delta\emptyset$: required phase time adjustment on phase split

$\Delta\emptyset^1_{max}$: maximum adjustment on the first boundary of the left-turn phase

$\Delta\emptyset^2$: required phase time adjustment on the second boundary of the left-turn phase

$L_{min\ 1}$: is the minimum required distance between the minor intersection and major intersection for ideal progression