ASSESSMENT OF THE OPERATIONAL IMPACTS OF COMPREHENSIVE WAITING AREAS AT SIGNALIZED INTERSECTIONS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2015

Major Subject: Civil Engineering

ABSTRACT

Urban intersections are becoming increasingly congested when limited land use for transportation cannot fully serve the growing traffic demand in metropolitan areas. A new concept—Comprehensive Waiting Areas (CWAs) — has been proposed recently to increase the capacity of signalized intersections without flaring up the approaches. CWAs use part of approach lanes as left-turn and through waiting areas to fully utilize space resources. The practice of implementing CWAs in Guangzhou and Shanghai, China, shows its superiority in decreasing approach delay under heavy traffic demand. Despite the promising future of CWAs, there are few studies into CWA design and operation. To assess the operational performance of CWAs at intersections, a local intersection was selected in this study for CWA design adoption. Key issues concerning CWA length design and signal timing plans are then discussed, along with comparisons between operation of intersections, with and without CWAs. PTV VISSIM is utilized to simulate intersections with and without CWAs. The results confirm the potential benefits of CWAs and show CWAs work best in heavy traffic demand, especially when the turning percentage is high. However, the benefits of CWAs may be limited when traffic demand is significantly imbalanced.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Zhang, and my committee members, Dr. Hawkins, Dr. Cline, for their guidance and support throughout the course of this research.

NOMENCLATURE

CWA	Comprehensive Waiting Areas
CFI	Continuous Flow Intersection
NB	Northbound
SB	Southbound
EB	Eastbound
WB	Westbound

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CHAPTER I

INTRODUCTION

The increasing congestion in urban intersections, resulting from limited space and time resources at intersections, combined with heavy traffic demands in peak hours, has long challenged transportation engineers. A congested intersection may substantially slow down the traffic, sabotaging the surrounding traffic system at the network level. What may make crowded intersections even worse is the high left-turn percentage. An exclusive left-turn phase to serve a high left-turn demand will drastically reduce the time that could be allocated for through traffic. Normally, through traffic occupy more lanes and better utilize the intersection space than left-turn movements. The exclusive left-turn phase stops through movement and may decrease the intersection efficiency and increase the delay. Increasing capacity and decreasing delay at signalized intersections have been an area of intense investigation.

A new concept—Comprehensive Waiting Areas (CWAs) — has been proposed recently as a solution to increase the capacity of the signalized intersection without flaring up the approaches. CWAs set waiting areas for both left-turn and through vehicles on the same approach, allowing vehicles to fully utilize approach lanes.

The main objective of this study is to assess the operational influence of CWAs under different traffic demand. The results of average travel times and intersection capacity are compared with those from the conventional intersections.

Problem Statement

Although CWAs have been put into practice in several cities in China and decreased approach delays at some intersections in these cities which suffer from intersection space shortages, there are few forays into the operational impact of implementing CWAs. With limited land in cities devoted to traffic, CWAs can be a method to increase the intersection capacity. However, an understanding of when and where the concept of CWAs is desirable is important for its application. More studies are needed to quantitatively assess the impacts of CWAs on the intersection capacity and travel times, so a clearer picture of the effectiveness of CWAs can be obtained. This research was designed to evaluate the performance of CWAs under different traffic demands.

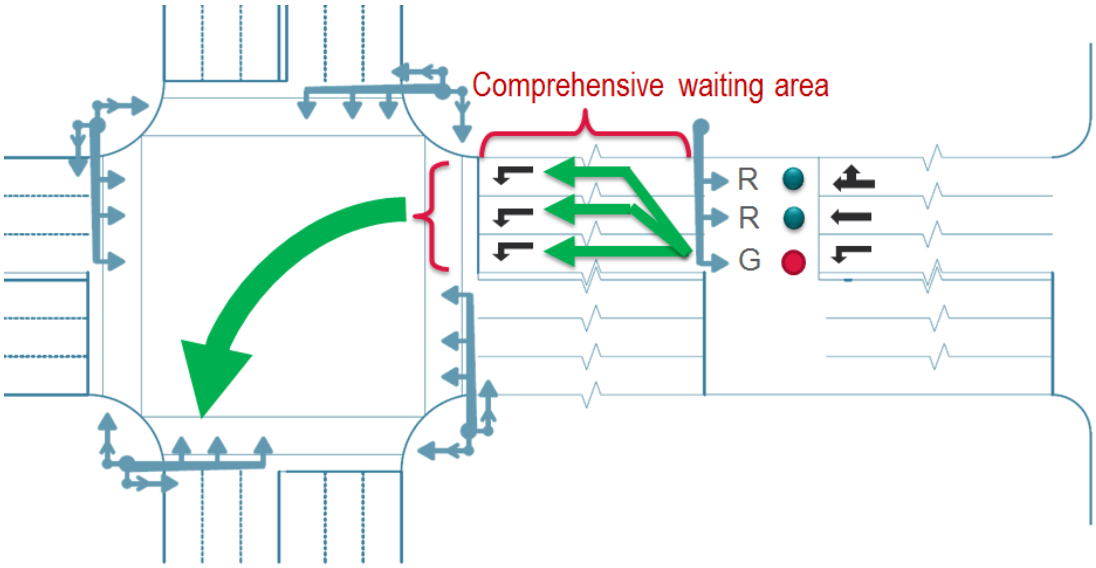
Concept of CWAs

The basic design element of CWAs is the waiting area before the stop bar for both left-turn vehicles and through vehicles. The waiting area is for vehicles to utilize all the available lanes on the approach to clear the intersection, i.e., all available approach lanes can be used as through lanes or left-turn lanes. The typical layout and traffic operation of the intersection with CWAs are shown in Figure 1. Right turns are not shown and are considered to be combined with the through traffic.

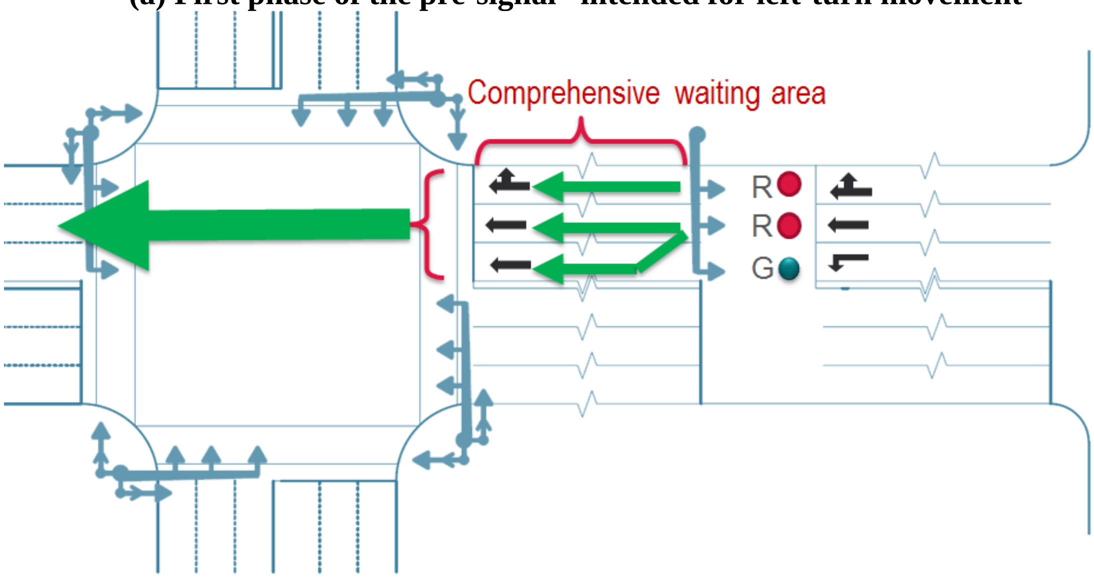
Two stop lines are installed on the intersection approach with the first one located at the front of CWAs (the usual stop line location of the intersection) and the second stop line downstream at the end of CWAs. Two-phase pre-signal control is used at the upstream stop line. As shown in Figure 1(a), Phase 1 is for left-turn movement.

During this phase, the upstream pre-signal provides green indication for the left-turn lane. Left-turn vehicles proceed downstream distributing to all available lanes. The downstream signal at the main intersection, afterwards, provides a left-turn green arrow for all available lanes. During this phase, through and right-turn vehicles are held upstream by the pre-signal for those lanes. Phase 2 (Figure 1(b)) is for through and right-turn movements. Left-turn vehicles are held at the pre-signal while through vehicles distribute to all available lanes with the right-turn vehicles staying in the right lane, where they receive a circular green indication at the downstream signal. Each phase requires an all-red time that is long enough for vehicles to clear CWAs.

Using all approach lanes for CWAs, as illustrated in this case (Figure 1), is ideal for fully utilizing intersection space. However, some considerations may prevent the use of all lanes for CWAs. For example, if there are only two lanes available in the cross road left-turn vehicles enter, only two approach lanes can be used as CWAs for left-turn vehicle to clear the intersection simultaneously. A 'partial-CWA' design can be adopted in such situation.



(a) First phase of the pre-signal– intended for left-turn movement



(b) Second phase of the pre-signal – intended for through/right-turn movements
Figure 1 The Typical Layout and Traffic Operation of the Intersection with CWAs.

For example, only one lane is utilized as CWAs in the partial-CWA design shown in Figure 2. The leftmost lane is an exclusive left-turn lane and the rightmost lane is through/right-turn lane. In this design, only two left-turn movements will be allowed simultaneously. Through/left-turn vehicles can utilize the rightmost lane without waiting for pre-signal indication (permanent green). The same rule applies for left-turn vehicles to use the leftmost lane.

The pre-signal will control the timing for through/right-turn vehicles or left-turn vehicles to enter the middle lane, i.e., CWAs. Though this design cannot fully engage all the approach lanes, it does provide a solution where the available lanes at the downstream of the intersection are limited or intersection space does not allow several simultaneous turning movements.

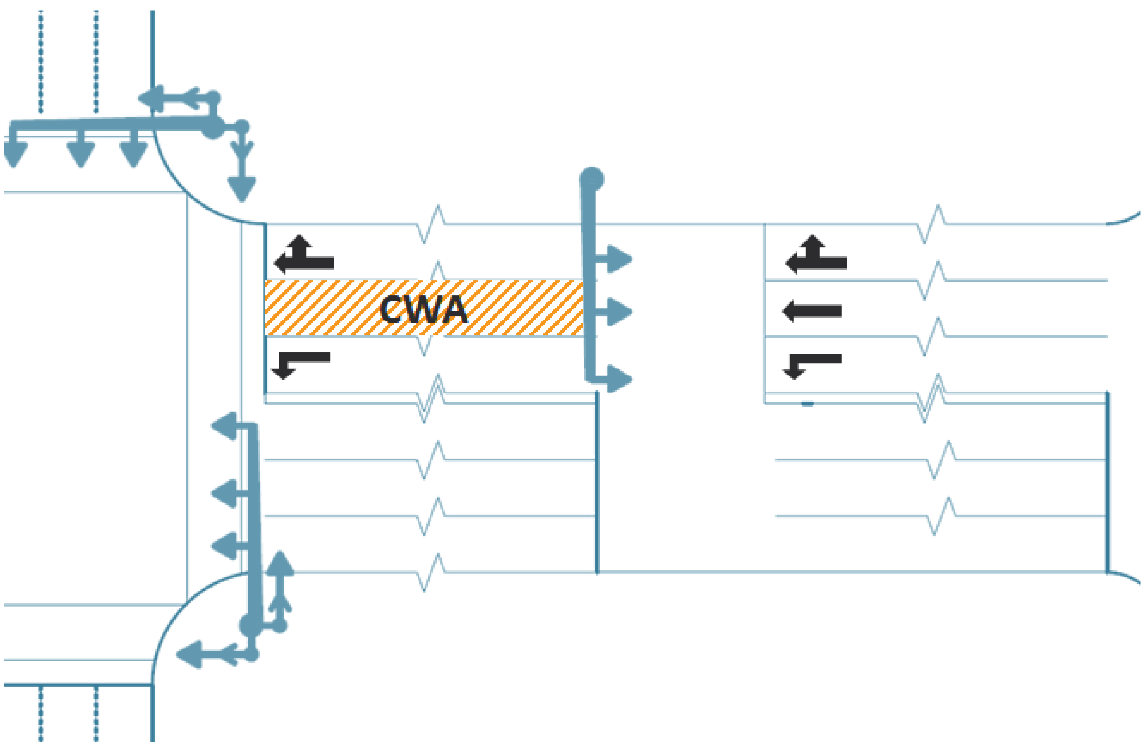


Figure 2 The Typical Layout of Intersection with Partial CWA.

To make a partial-CWA design feasible, CWAs have to be segregated from adjacent general purpose lanes. This is to prevent vehicles from shifting into CWAs in the wrong phase. For example, left-turn vehicles waiting in the leftmost lane cannot shift into CWAs when CWAs are currently serving through/right-turn vehicles.

Objectives

Many factors are implicated in the operation of CWAs, including the geometric characteristics of CWAs and signal timing plans. This research will examine the operational impacts of CWAs at signalized intersections, focusing on comparing the intersection with and without CWAs in different traffic demands. The detailed objectives are presented as follows:

- Develop the signal timing plans and geometric plans of CWAs;
- Identify the potential elements influences the operation of CWAs;
- Analyze the relationship between potential factors and CWA operations based on simulation results; and
- Discuss advantages and limitation of CWAs.

To analyze the operation of CWAs, an intersection in College Station suffering from huge traffic demand in peak hours will be selected for case study. Variation of traffic volume based on the selected intersection will be made for a comprehensive analysis. The following tasks will be performed to accomplish the presented objectives:

- Conduct a comprehensive literature review concerning the operational impact of CWAs;
- Select a local intersection as a study case;

- Collect data of peak-hour traffic, signal timing plans as well as intersection configurations;
- Develop framework of lane assignment and timing plans of CWAs;
- Set up simulation platform using PTV VISSIM;
- Calibrate network model using queue lengths;
- Simulate different scenarios with different traffic demand; and
- Compare the simulation results between the intersections with and without CWAs.

Thesis Organization

This thesis is composed of seven chapters. Chapter I provides the background of this research and the concept of CWAs. Problem statement and research objectives are also illustrated in this chapter. The following chapter summarizes the literature review conducted related to recent and ongoing work on improving urban intersection operation. The third chapter introduces the local intersection selected for analyzing the feasibility of CWA application. Data collection and results of field investigation are also provided in this chapter. Chapter IV explains the methodology this research employed; illustrates the framework of how to operate the intersection with CWAs and walks through the process of experiment design. Before comparing the operation between intersections with and without CWAs, parameters in VISSIM models are calibrated with the collected data. The results are described in Chapter V. This chapter also tests the framework developed in Chapter IV regarding the signal timing plans and CWA length design. The next step is to exercise the calibrated models and carry out a comparative analysis to determine the operational effect of CWAs by varying traffic demands. The results of travel times and capacity of these models under different traffic demands are illustrated and analyzed in the sixth chapter. Lastly, the seventh chapter summarizes the work of this research. This summary also includes discussion on the next steps towards the guidelines of implementation CWAs.

CHAPTER II

LITERATURE REVIEW

The intersection operation lies at the foundation of traffic network. Considerable studies, therefore, have been done as an effort to improve intersection operational efficiency. This literature review explores researches addressing the past and ongoing work related to improving urban intersection operation in peak hours.

Continuous Flow Intersection

Among numerous unconventional intersection designs (quadrant roadway intersection, median U-turn, superstreet median, bowtie, jughandle, split intersection, and continuous flow intersection (CFI)), CFI 'always had the highest move-to-total-time-ratio' and 'probably the smallest right-of-way' (*1*). CFI was co-invented by Mexican-born businessmen, Francisco Mier and Belisario Romo to improve urban intersection operation by reducing the impacts of left-turn movement on the intersection operations. It places the left-turn lane to the left side of the road, allowing left-turn vehicles to cross the opposing traffic a few hundred feet before entering the intersection (Figure 3). CFI, therefore, can eliminate the need for a left-turn phase in the main intersection and save significant amount of time especially when the left-turn demand is intensive (*2*). It is well accepted that CFI could well improve overall intersection capacity compared with conventional counterpart (*3, 4, 5*).

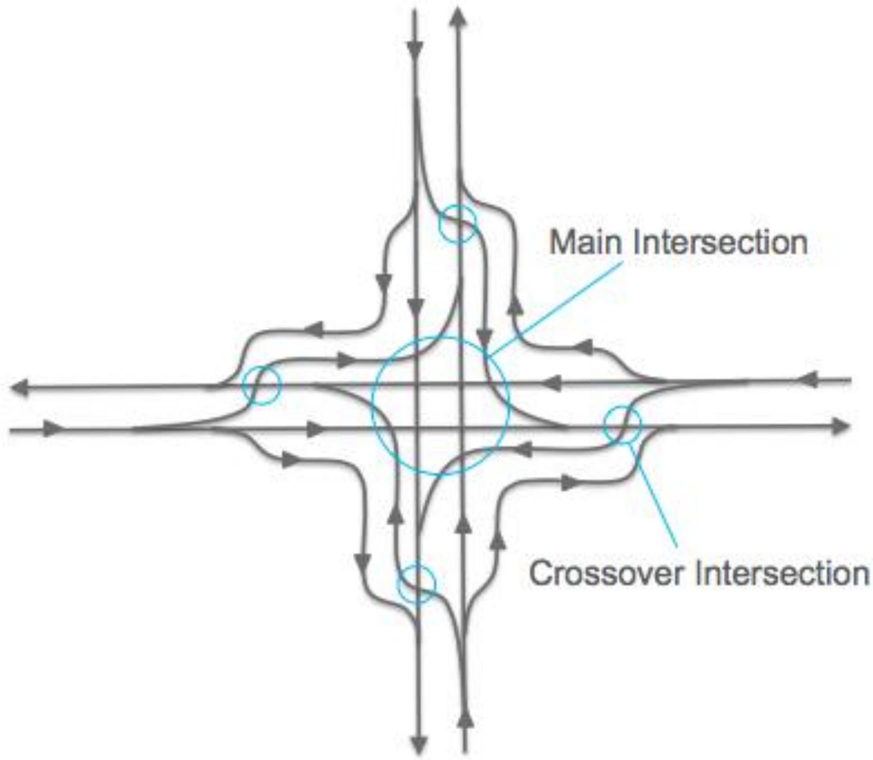


Figure 3 The Layout of Continuous Flow Intersection.

One of the principle drawbacks of CFI is that it requires permanent changes at the intersection layout. It means once CFI is implemented, it will be costly and laborious to restore the intersection to a conventional one. Other main drawbacks include its need for more right-of-way and higher construction cost than the conventional intersection (*2*). The shortage of land availability for transportation in many urban areas makes it difficult to acquire the right-of-way needed to re-construct the intersection for a CFI design.

With limits on the number of lanes that can be provided, increases in traffic demand are more difficult to serve in the peak hour, especially when the percentage of left-turn vehicles is high.

Left-Waiting Areas

Without acquiring additional right-of-way for intersection re-construction, Chinese transportation professionals have started using left-turn waiting areas to better utilize the intersection space. Yang et al. evaluated the operational influence of left-turn waiting areas at signalized intersections in China and found that the left-turn waiting areas increase the capacity of exclusive left-turn lanes. For an intersection with 120-second cycle length and 15-second protected left turn phase, the capacity of the left-turn lane with a left-turn waiting area that can store three passenger cars is 30.3 percent higher compared to a conventional counterpart without a left-turn waiting area (*6*). Study also shows left- waiting areas can reduce delay and better utilize intersection space (*7*).

Additionally, as mentioned above, left-waiting areas do not require permanent intersection layout change, nor is intersection approach flaring needed. However, the storage of a left- waiting area is limited by the size of the intersection. To better utilize the space at the intersection approach, the concept of Comprehensive Waiting Areas (CWAs) has been put into practice in Shanghai as well as Guangzhou in China.

Operation of CWAs

The concept of CWAs was illustrated in Chapter 1. CWAs can better utilize space at the intersection approach and therefore more lanes in that approach can discharge traffic during a certain signal phase. To implement CWAs, a pre-signal before the main intersection shall be employed. Application and operation of pre-signal will be studied in this section as references to develop signal timing plan for intersections with CWAs. Also, drivers' response to CWAs and a similar idea developed by Xuan et al. will also be discussed.

Pre-signal

As with CFI, CWAs also utilize pre-signal to serve left-turn vehicles. Actually the concept of pre-signal, as a control tool for intersections, is not new. It was first documented in the U.K. to achieve bus priority (8). A typical layout of pre-signal for bus priority is shown in Figure 4. The pre-signal sets back general traffic, enabling bus entering the bus advance area without waiting in the queue. At the end of the bus lane (before the pre-signal), a signal control could be utilized to serve the buses. The timing strategy of pre-signal should be coordinated with the main intersection signal so the pre-signal can work well with the main intersection. To set pre-signal times, the studies by Wu et al. and Kejun et al. assumed no loss of intersection capacity and no residual queues at the main signal stop line after green indication. It was also assumed that the discharging flow rate and arrival rate are deterministic (9, 10).

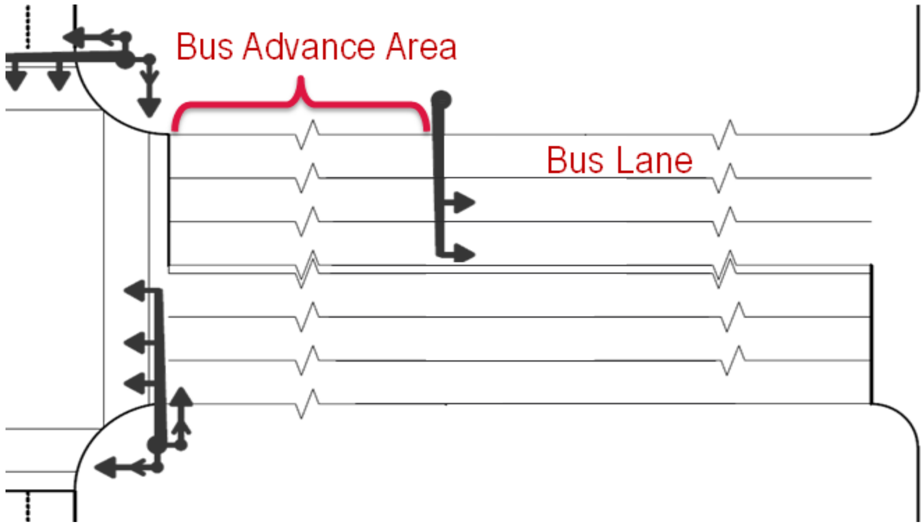


Figure 4 Typical Layout of Pre-Signal for Bus Priority.

Drivers' Response to CWAs

Changeable lane assignment in CWA for different movements is not a common concept for most drivers. It may cause more problems when all the approaches are utilized as CWAs. Some left-turn vehicles will be required to drive in the rightmost lane, which is counterintuitive. When CWAs were applied in an urban intersection in Guangzhou, Xi et al. found some drivers were confused about CWAs and did not utilize the rightmost lane to make the left turn. Then they studied the influence of drivers' familiarity with the idea of CWA signal control strategy on CWA operation. The intersection layout is shown in Figure 5. Three approach lanes were employed as CWAs. A pre-signal was set in the T-intersection upstream of the main intersection. Traffic input and geometric characteristics in Xi's study are gathered from a field survey (*11*).

Figure 5 The Layout of Studied Intersection in Guangzhou (*11*).

Xi et al. simulated the intersection with CWAs under three conditions: (a) all drivers understand the concept of CWAs and fully utilize this control strategy; (b) drivers do not fully understand the concept of CWAs and therefore do not occupy all available lanes in CWAs, and (c) conventional control strategy without CWAs. Simulation software PARAMICS was employed in their research. The volume Q, gathered from the field survey, changed from 0.6Q to 1.4Q for these three conditions in the simulation. The results reveal a significant decrease in link delay with the application of CWAs when traffic demand is bigger than Q, especially when the drivers fully understand how CWAs work (Figure 6). When the volume is lower than Q, intersection with CWAs did not show an advantage over its conventional counterpart (*11*).

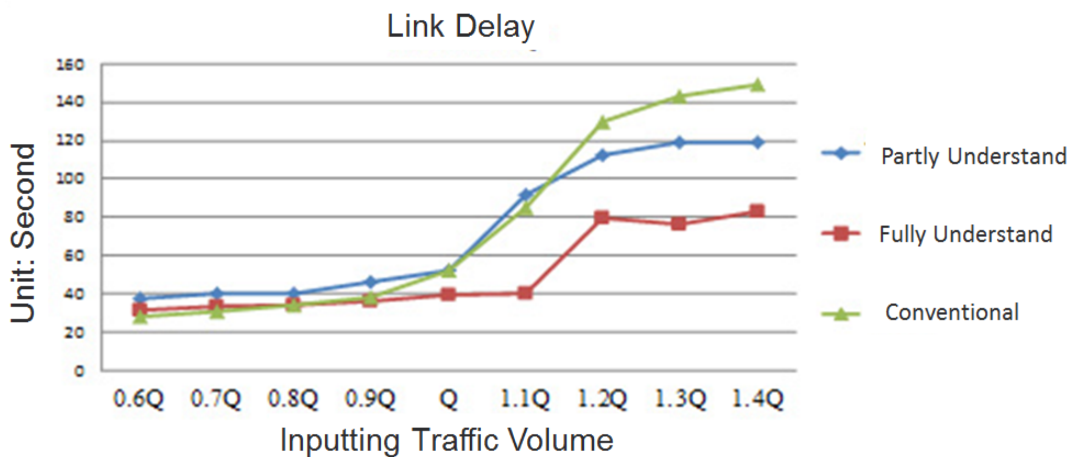


Figure 6 Link Delay under Three conditions in Xi's Study (*11*).

Tandem Intersection

A similar solution with the name of 'Tandem Intersection' was present by Xuan et al. in 2011. The tandem intersection concept was shown in Figure 7. Similar to CWAs, tandem intersections utilize pre-signals in order to further utilize the approach lanes. The space between the pre-signal and the main intersection are called 'sorting areas' instead of CWAs. The main difference of Tandem Intersections from CWAs is that all the vehicles will wait in the sorting area during the same phase in the tandem intersection. As shown in Figure 7, left-turn vehicles wait near the intersection (in the right box), followed by through/right-turn vehicles (in the left box). The sorting area should be long enough to accommodate all the vehicles arriving within one cycle. The study found the capacity is increased compared to conventional intersections based on a simplified calculation (*12*). However, compared to CWAs, tandem intersections need longer road segment to accommodate vehicles in the sorting areas. Also, through/right-turn vehicles cannot clear the intersection by immediately following the left-turn vehicles even though the green indication for the sorting area is on. This counterintuitive control method may cause safety concerns.

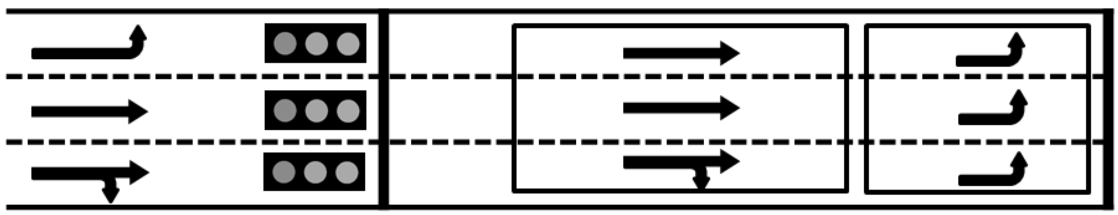


Figure 7 The Concept of Tandem Intersection.

Implementation of CWAs

Since not much researches has been undertaken concerning implementation of CWAs, other documents will be reviewed concerning left-turn lanes and changeable lanes.

Left-Turn Lane Design

The length of the left-turn lane in the signalized intersection consists of three parts: the distance for vehicles to shift into left-turn lane, the distance for vehicles to decelerate and stop, and the storage segment for vehicles to wait for the green indication. The storage lengths are generally determined through three methods. The first one is the Rule of Thumb Method recommended by TxDOT Roadway Design Manual. The storage length for left-turn vehicles is estimated based on the left-turn demand per cycle. This method has been widely employed because of its simplicity. The second one is analytical-based methods based on queuing theory. The accuracy of this method depends on the selected queue models. The last one is simulation-based methods. It requires network coding and calibration to imitate the operation of real-world intersections. This method is generally more practical since the signalized intersections are complicated with numerous influencing factors. However, it will also be costly and time-consuming to develop the models and calibrate with real-world data. (*13*)

One of the famous formulas based on the Rule of Thumb Method is shown below. The storage length is estimated based on the assumption that the average length of a typical passenger car is 25 ft. (*14*)

$$L = \frac{V * k * 25 * (1 + p)}{N_c}$$

Where:
L: the storage length of the left-turn lane(ft); and
V: peak hour flow rate (vph); and
k: the constant in consideration of arrival pattern ; and
N_c: number of cycles per hour; and
p: percentage of truncks and buses.

Changeable Lane

Changeable lanes are considered as a ‘space management’ technique, in addition to ‘time management’ technique—traffic signals (*15*). Changeable lanes can alter lane use according to the turning demand. For example, a left-turn lane and a though lane can change into double left-turn lanes when demand for turning left increase significantly. Advanced overhead signs are installed to guide the drivers into appropriate lanes. An example is shown in Figure 8.

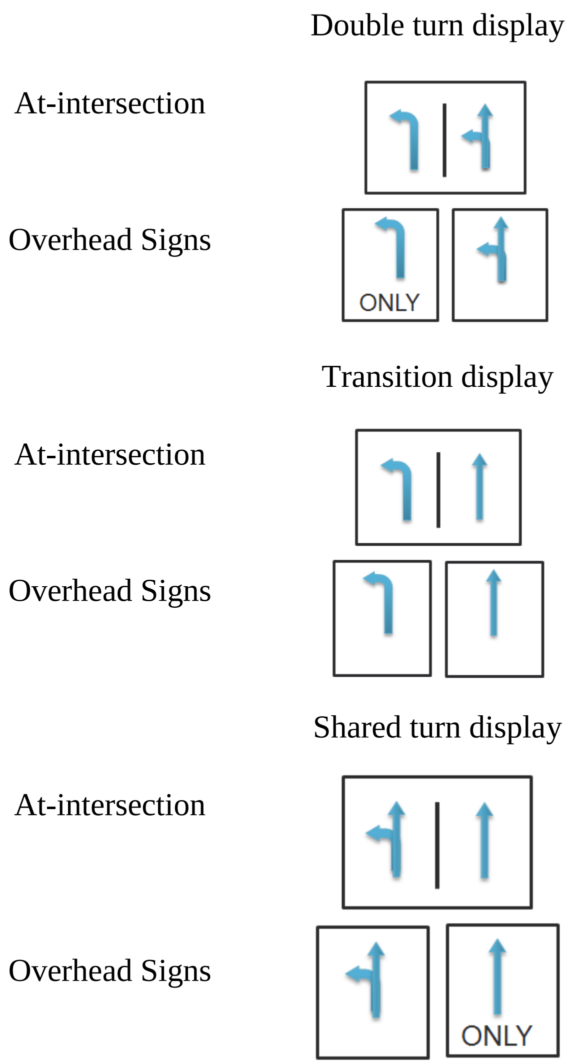


Figure 8 Displays Generated For Changeable Lanes (Double Left Turn Intersection) (*13*).

Reversible Lanes

Reversible lane system can be ‘used for through traffic in alternating directions during different periods of the day (*16*)’. This system can be used to divert traffic temporarily (e.g. construction zone traffic management, emergency traffic management) or control traffic permanently (e.g. peak-period traffic management, event zone traffic management). A study pointed out that it is necessary to perform the safety analysis of reversible lane system (*17*).

Summary

Limited land and increased traffic demand often lead to traffic congestion in urban cities, especially at the intersections. Many main intersections which serve two main roads, suffer from serious congestion during peak hours. The situation may get worse when both left-turn volume and through volume are heavy. Extensive work has been done in the area of alleviating intersection congestion.

Banning and re-routing left-turn traffic is one of the principal types of solutions. Among these methods, CFI requires relative less right-of-way and can significantly increase the intersection capacity, especially when left-turn demand is also high. However, it still requires intersection approach flaring and permanent changes in the intersection layout.

To overcome the shortcoming of CFI, left-waiting areas are widely applied in China. Left-waiting areas only need additional marking inside the intersection. With less construction, left-waiting areas still can increase the left-turn capacity of intersections to a certain degree. Since we can set a waiting area for left-turn vehicles, we can also set waiting areas for both left-turn and through vehicles to fully utilize intersection space. CWAs were then proposed and applied in China.

CWAs can engage as many as lanes in the approach to provide more lanes for left-turn vehicles or even through vehicles to clear the intersection. However, the factors that govern the operation of CWAs have yet to be fully understood.

CHAPTER III

DATA COLLECTION

Due to limited lane use and increased traffic demand, transportation engineers are looking for new solutions to intersection congestion during peak hours. CWAs, which better utilize all the available lanes at the intersection approach, can help increase the intersection capacity. However, design of CWAs and its feasibility are not fully examined. To explore the potential of transforming a conventional intersection to a nonconventional with CWAs, a congested intersection in the City of College Station is selected in this study as the study subject. The intersection layout, traffic demand and signal timing plans will be altered based on the selected intersection to study how these elements will affect CWA operation.

Intersection Selection

Since CWAs require longer approach and aim to improve traffic conditions in peak hours, two criteria were adopted during the intersection selection:

- The approach of the intersection is long enough for implementing CWA; and
- This intersection suffers from serious congestion due to heavy peak hour demand and limited land use.

After field observation, the intersection of George Bush Drive and Wellborn Road shown in Figure 9 was selected for the following reasons:

- In the afternoon peak, there are many vehicles from the southbound approach with a significant turning demand, leading to serve congestion and long queue backing up on the southbound approach;
- There is a railway line parallel to the Wellborn Road. When the train comes, the west side of the intersection will be blocked. During this period, no vehicle from the eastbound approach can clear the intersection and no vehicle from other three approaches can head west. It may increase the congestion in this intersection;
- Because of the existence of the railway line, the intersection cannot be expanded or it will encroach on the adjacent land required by the railway; and
- The nearest upstream driveway in the southbound approach is about 1380 ft away, leaving enough room for setting up CWAs.

After the intersection is selected, data of traffic volumes and intersection configuration were gathered for analysis.

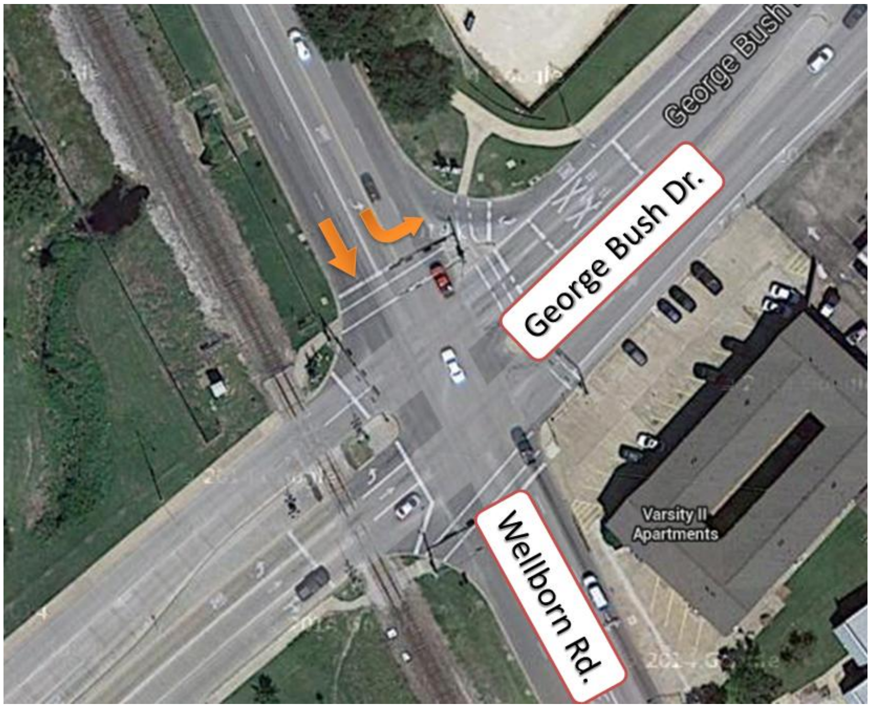
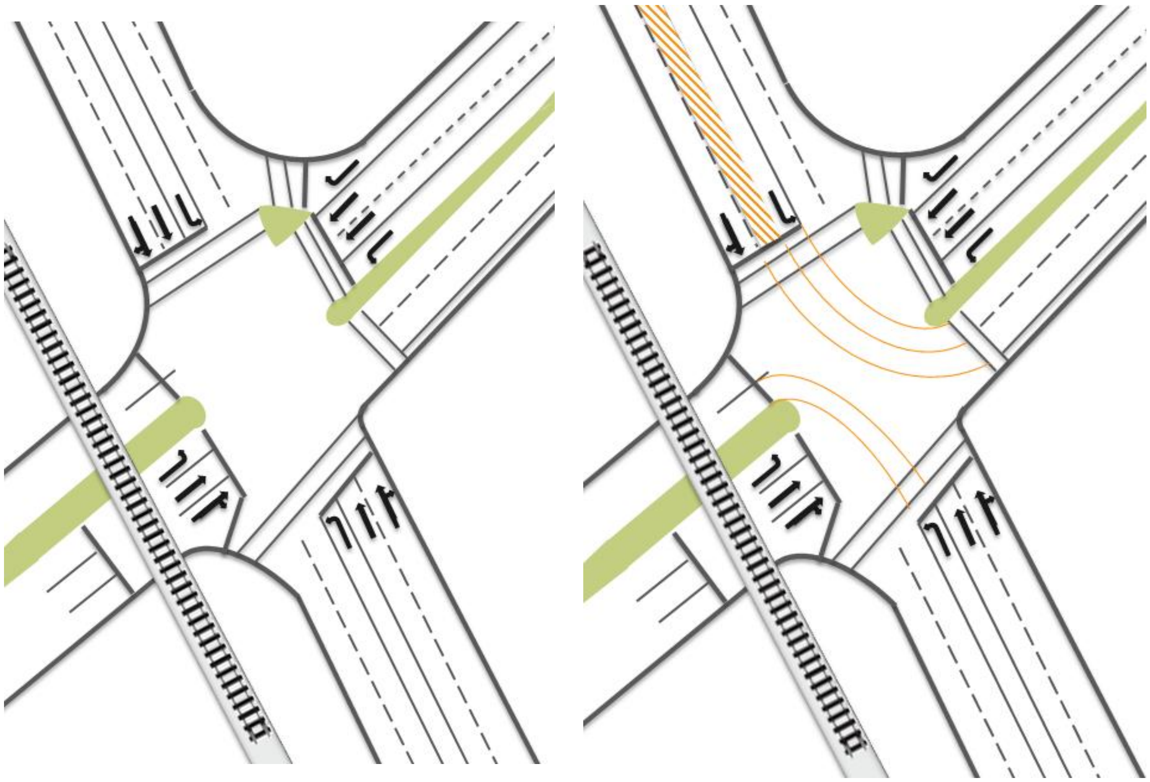


Figure 9 The Studied Intersection to Implement CWAs.
(Source： Google Map)

Intersection Layout

The layout of the studied intersection is shown in Figure 10. The intersection has four legs with five lanes per leg except the westbound approach. There is one left-turn lane, one through lane and one through/right-turn lane on each leg and an exclusive right-turn lane on the westbound approach.

Based on the geometric configuration of the intersection, only two left-turn movements can be allowed simultaneously for one approach. Therefore, the through lane in the middle (the shaded area in Figure 10(b)) can be adapted into CWAs. A pre-signal will be set to make CWAs work, allowing through or left-turn traffic to enter CWAs based on the timing plans.



(a) (b)

Figure 10 The Configuration of Studies Intersection of Wellborn Rd. at George Bush Drive.

Traffic Demand

During several days of observation, the queue in the southbound approach was found to reach its peak around 17:15 to 17:45 on weekdays. Data collection was conducted from 17:15 to 17:45 on Feb 10th, 2015. Information about traffic volumes, signal timings and queue length were gathered in this data collection.

It was observed that, from around 17:00, the green time for southbound approach is not long enough to serve all the waiting vehicles in the approach in a certain signal cycle. Discharging volumes at the intersection, therefore, cannot represent the real demand from southbound approach. The amount of vehicles entering the southbound approach was also counted in the field study. Since there is no driveway between the location collecting entering volume and the stop bar at the intersection, the entered vehicles are exactly those which will clear the intersection through the southbound approach. The entering volume is divided into left-turn, through and right-turn volumes on the southbound approach based on the discharging volumes collected at the intersection.

The traffic volumes are shown in Table 1. Discharging volumes are those collected at the selected intersection. Volumes are adjusted based on the upstream volume to reflect the real demand in the field. The table shows there are more traffic from southbound approach than from three other approaches during afternoon peak hour.

Table 1 Volume for each movement

	Northbound			Southbound		
	L[1]	T[2]	R[3]	L	T	R
Discharging Volume	260	598	224	348	874	110
Adjusted Volume	260	598	224	402	1010	127
Percentage of total volume from one approach (%)	24	55	21	26	66	8
	Eastbound			Westbound		
	L	T	R	L	T	R
Discharging Volume	96	740	110	182	874	290
Adjusted Volume	96	740	110	182	874	290
Percentage of total volume from one approach (%)	9	73	110	13	65	22

Note:
[1] Left-turn movement
[2] Through movement
[3] Right-turn movement

It was observed that significant queue waiting for turning left backed up to the upstream. In the southbound approach, the maximum queue is about 750 ft long and the average queue is about 300 ft for left-turn lane. For the through/right-turn vehicles, the maximum is queue is about 980 ft long and the average queue is about 425 ft. CWAs on southbound approach may help lower the delay and increase the left-turn capacity.

Signal Timing Plan

As shown in Figure 11, an eight-phase dual-ring NEMA controller is employed in the studied intersection.

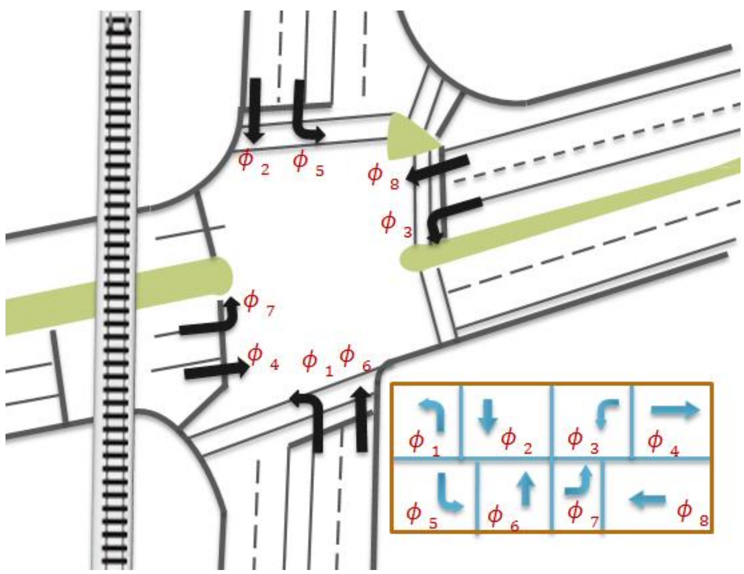


Figure 11 Ring-and-Barrier Diagram of the Studied Intersection.

The signal is actuated control. During the peak hours, however, the signal acts like pretimed control due to high traffic demand. The cycle reaches it maximum length (180 seconds) in every cycle. The signal interval durations are shown in Table 2.

Table 2 The Phase Split of the Studied Intersection During Afternoon Peak.

	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8
Display Green Time (s)	28	52	31	45	34	46	17	59
Yellow (s)	4	4	4	4	4	4	4	4
All red (s)	2	2	2	2	2	2	2	2

Summary

This research aims at exploring the potential advantages and possible problems with the implementation of CWAs. The studied intersection has a high through and left-turn demand from the SB approach in peak hours. So the queue backs up upstream for hundreds of feet in the SB approach. In view of this situation, the southbound approach can be adopted into CWAs. Based on the intersection layout, traffic demand and signal timing plan of the current intersection, a simulation model of the conventional intersection model is set up. The following chapter will illustrate the calibration of this model.

A corresponding unconventional model of the current studied intersection is proposed with CWAs installed in the SB approach. This basic scenario will help us understand how CWAs work and further explore the proper signal timings and length of CWAs with this as a foundation. The methodology will be illustrated in the following chapter.

CHAPTER IV

METHODOLOGY

To alleviate congestion in urban intersections during peak hours, the concept of CWAs was proposed as a nonconventional approach. Studying the potential of CWAs is an important first step in possible adoption by more local transportation agencies. This chapter walks through the study design in this research. First, the framework of developing the CWA length and signal timing plans is proposed. Then, intersections with CWAs are modeled based on the results of calibration of the selected conventional intersection. The framework of developing proper CWA length design and timing plans is applied and verified in the simulation.

Based on the verified framework, timing plans and CWA lengths are determined for intersections with CWAs under different traffic. With proper modelling, scenarios of intersections with and without CWAs are simulated and compared. These results can then be used to examine the factors influencing the operation of CWAs.

Intersection Layout with Accommodation of CWAs

CWA design is complicated since it is related to traffic demands, signal timings and intersection layouts. Two critical questions in the design of CWAs are:

- How long should CWAs be?
- How many lanes in the approach should CWAs utilize?

These two questions are addressed in this section.

The Length of CWAs

From The Point of Demand

The length of CWAs is critical in CWA design. In Chapter II, the literature concerning the length of left-turn lanes is reviewed. Similar to left-turn lanes, CWAs store vehicles and then discharge them during green time; so a length formula should be determined. The Rule of Thumb Method (*13*) can be referred to to estimate CWA length. The formula for estimating CWA length is shown below.

$$L_{CWA} = V * k * S/(N_c * N_l)$$

Where:
L_{CWA}: storage length of CWAs(ft);
V: peak hour flow rate (vph);
k: the constant in consideration of other factors ;
S: average queue storage length per vehicle;
N_c: number of cycles per hour; and
N_l: number of lanes in CWAs.

This equation can be applied to both left-turn movements as well as through and right-turn movements (labeled as L_{LT}, L_T respectively). The average queue storage length per vehicle (S) depends on the percentage of trucks in the queue, which can be determined using Table 3.

Table 3 Average Queue Storage Length per Vehicle Based on Percentage of Trucks (*18*)

Percentage of Trucks (%)	S (ft)
<5	25
5-9	30
10-14	35
15-19	40

For a partial-CWA design, the number of lanes for through vehicles before and after pre-signals is the same. Therefore, the length of CWAs will not influence through vehicles. The theoretic length of CWAs is therefore equal to L_{LT}. For a full CWA design, both types of movements can occupy the approach lanes. The length of CWAs should accommodate both types of traffic. In summary, the theoretical length of CWAs (L_0) can be calculated as:

$$L_0 = \begin{cases} L_{LT}, & partial\ CWA\ designs \\ \max(L_T, L_{LT}), & full\ CWA\ design \end{cases}$$

When traffic demands, signal timings and the number of lanes in CWAs are determined, k is the only factor to be adjusted. k can be optimized in the simulation so the intersection system can achieve its peak performance, i.e., the intersection has higher capacity and lower delays. However, if there is a unique, optimal k to a corresponding traffic demand, it means the CWA length should be changed according to the intersection traffic demand. Changing the CWA length means changing the location of traffic signs and pre-signals, which would requires construction and funding. This study will evaluate the influence of k on the performance of CWAs.

From the Point of Land Use

Traffic is not the only consideration when it comes to determining CWA length. One CWA application in Guangzhou mentioned in the literature review made full use of a driveway and set up the pre-signal right at the driveway; a signalized T-intersection, therefore, takes the place of a pre-signal.

The Approach Segment before Pre-Signals

Not only should CWA length be considered in CWA design, but also the remaining segment of the approach before the pre-signal. Take the studied intersection as an example. The SB approach of the studied intersection is divided into two parts as shown in Figure 12. Segment a in Figure 12 is CWAs, before which a pre-signal is set up to indicate the vehicles in segment b. Segment b has the same number of lanes as in the CWAs, providing waiting areas for vehicles to enter CWAs. A left-turn bay is provided in segment b so that left-turn vehicles can move forward into CWAs without being blocked by through vehicles.

(a) is the comprehensive waiting area
(b) is a segment before pre-signals where vehicles wait before entering CWAs
Figure 12 The Studied Intersection with a CWA on the southbound Approach.

Numbers of Lanes in CWAs

In the view of operation, CWAs shall utilize all available lanes at the intersection approach; however, the analysis of the number of lanes in CWAs must take into account the downstream receiving lanes, the intersection size and safety. The following section will discuss these factors.

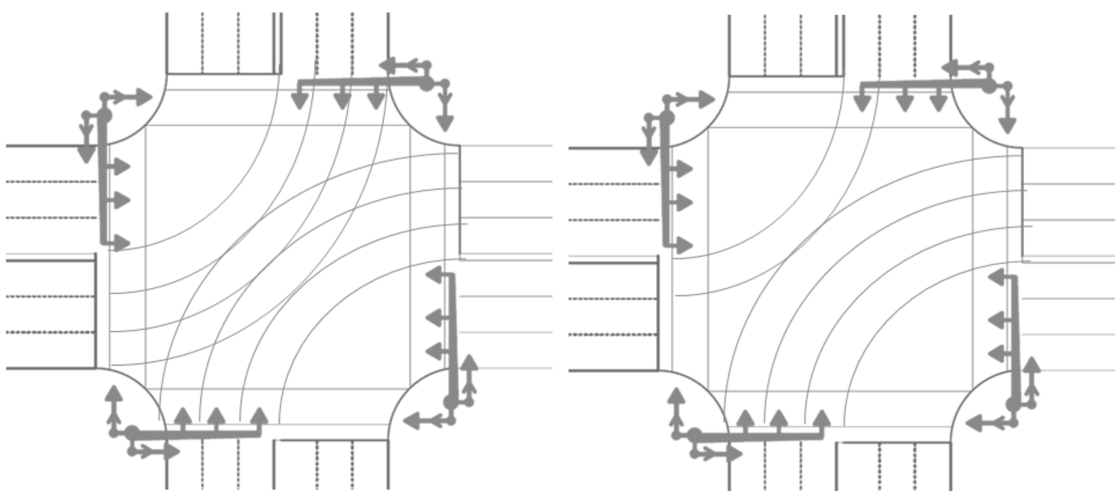
Continuous Downstream Receiving Lanes

It is straightforward that the downstream road receiving left-turn vehicles should have at least the same number of lanes as there are upstream left turn lanes. Take the studied intersection as an example. There are only two lanes on the downstream EB cross road. This means only two SB lanes are allowed to discharge left-turn traffic simultaneously; it is important to avoid a lane drop so the intersection can operate smoothly.

Intersection Size

Available space in the intersection will have a huge influence on the number of available lanes in CWAs. To check whether the swept paths of two turning movements overlap, it is required to plot the swept paths of the selected design vehicles using its corresponding turning radii. For example, Florida's DOT requires 'a minimum of a Single Unit Truck and two Passenger Cars turning simultaneously with a minimum 4 feet separation between the swept paths of the vehicles' for triple left-turn lanes (*19*). Taking the theoretical intersection shown in Figure 13 as an example, the swept paths of three left-turn vehicles from both EB and WB approaches will overlap. The limited space at this intersection will not allow bi-directional operation of CWAs (Figure 13 (a)). Only one-directional (Figure 13 (b)) operation is feasible in this situation.

Turn angles may also have effects on lane performance. When angles are equal to or greater than 90 degrees, performance seems to be more traffic-related, not geometry-related. If angles are less than 90 degrees, the performances of different turning lanes will be influenced by angles. (*20*) Therefore, further studies are required if the crossing roads are not perpendicular to each other.



(a) **(b)**

(a) The intersection with bi-direction CWAs
(b) The intersection with one-direction CWAs
Figure 13 Left-Turn Paths at the Intersection with CWAs.

Safety Concern

Safety always plays the most important role in traffic design. Since more than one lane is used as a left-turn lane in CWAs, additional attention should be paid to details in the design. Researchers suggest triple left-turn lanes can provide substantial operational benefits but might also increase crash rates (*19*). Additional safety analysis will be necessary if more than two lanes are used in CWAs.

Signal Phasing and Timing of Intersections with CWAs

Before developing a specific signal timing plan for the studied intersection, a more general framework is desirable. The general framework should be flexible enough so that it can be adjusted and applied during general applications of CWAs.

Since CWAs aim to ease congestion at intersections where traffic demand is high, adaptive control does not have many advantages over fixed-time controls. An intersection with CWAs can be operated by two pre-timed signal controllers: one for the pre-signals on the approach with CWAs and the other for the main intersection.

Signal Timing Development

The signal timing plan can be divided into two sub-plans which are integrated. One is the plan for the main intersection signals, and the other is for the pre-signals. These two signal timing plans share an identical cycle length, so an intersection with CWAs can be operated continuously.

Two phases are employed for pre-signals with the first phase for left-turn vehicles and the second for through/right-turn vehicles (Figure 14(b)).The signal timing strategies for the main intersection is illustrated in Figure 14(a). Left-turn indication for NB and SB approaches (ϕ_2) follows a through indication for WB and EB approaches (ϕ_1). Then the left-turn indication for WB and EB approaches (ϕ_3) takes its place and the through indication for NB and SB (ϕ_4) is shown last. The reason for separating the phases for left-turn movements and through/right movements from the same approach, i.e. their phases not being next to each other, is to leave more time for vehicles to enter CWAs. For example, the left-turn movement from the SB approach can utilize the phase for the through movement from the EB and WB approaches (ϕ_1).

The HCM method (*21*), which aims to equalize the degree of saturation, is employed to calculate signal timings. The lanes in CWAs are considered as both left-turn lanes and through lanes when calculating the degree of saturation. Take the studied intersection as an example. When CWA method is adopted, the middle lane on the SB approach will function as CWAs. Since there is a left-turn lane on the left of CWAs and a through/right-turn lane on the right of CWAs, two left-turn lanes and two through lanes will be considered when calculating the degree of saturation.

Lane-Clearance Time

Residual vehicles in CWAs pose potential safety concerns. If there is a left-turn vehicle left in CWAs when the left-turn indication ends, it will be hard for this vehicle to turn left when the through indication begins. This left-turn vehicle has to stop, wait for the next left indication in the next cycle and therefore block the entire lane for the duration of the cycle, during which CWAs cannot serve other vehicles behind this left-turn vehicle. A similar situation will happen for a through vehicle if this vehicle cannot clear CWAs in time.

To avoid residual vehicles, it is crucial to have lane-clearing time: t_{clear}. t_{clear} is the red indication of the pre-signal in Figure 14(b) for the SB approach, meaning the green indication of the pre-signal should end earlier than the corresponding indication of the main intersection signal. It discourages residual vehicles in CWAs when the corresponding indication in the main intersection ends. The pre-signal will hold vehicles and enable those vehicles that have entered CWAs to clear the intersection. For example, the pre-signal indication for a left-turn movement shall end earlier than the left-turn indication in the main intersection to prevent residual vehicles in CWAs. Similar to the overlap of the TTI-4 phase strategy (*22*) in the diamond interchange, t_{clear} in CWA design also represents travel time of a vehicle from start to clearing one road segment. Unlike the overlap in the TTI-4 phase strategy, which guarantees through progression for most vehicles, t_{clear} considers the expected minimum speed of the vehicle instead of using design speed so that the slowest vehicle can still clear CWAs. An acceleration rate of 4.44 feet/sec^2 is used for calculating the travel time and the calculated values are shown in Table 4. Half of the speed limit is chosen as the expected minimum speed for the selected intersection. Chapter V will further verify this strategy based on whether there are any vehicles stuck in CWAs.

Table 4 The Amount of Time that Vehicles Needed to Clear Main intersection (t_{clear}) (*22*)

Speed (mph)	CWA length (ft)										
	200	250	300	350	400	450	500	550	600	650	700
20	9 s	10 s	12 s	14 s	16 s	17 s	19 s	21 s	22 s	24 s	26 s
25	8 s	9 s	11 s	12 s	13 s	15 s	16 s	18 s	19 s	20 s	22 s
30	8 s	9 s	10 s	11 s	13 s	14 s	15 s	16 s	17 s	18 s	19 s
35	8 s	9 s	10 s	11 s	12 s	13 s	14 s	15 s	16 s	17 s	18 s
40	8 s	9 s	10 s	11 s	12 s	13 s	14 s	14 s	15 s	16 s	17 s
45	8 s	9 s	10 s	11 s	12 s	13 s	14 s	14 s	15 s	16 s	17 s

Although the lane-clearing time aims to prevent residual vehicles from blocking the approach lanes and limiting the capacity of CWAs, some inattentive drivers (e.g. driving while texting, unfamiliar with the area) may still get stuck in CWAs without clearing the intersection because of low driving speeds. Even in a partial-CWA design, residual vehicles cannot stay in adjacent lanes beside CWAs since partial-CWAs are segregated laterally from adjacent conventional lanes to ensure vehicles from adjacent lanes will not shift into CWAs inappropriately and interrupt CWA operation.

Without space for residual vehicles to pause, warning signs with flashing beacons may help. The standard for setting up warning signs and flashing beacons may refer to Section 2B.26 (Reversible Lane Control Signs) of the Manual on Uniform Traffic Control Devices (*16*).

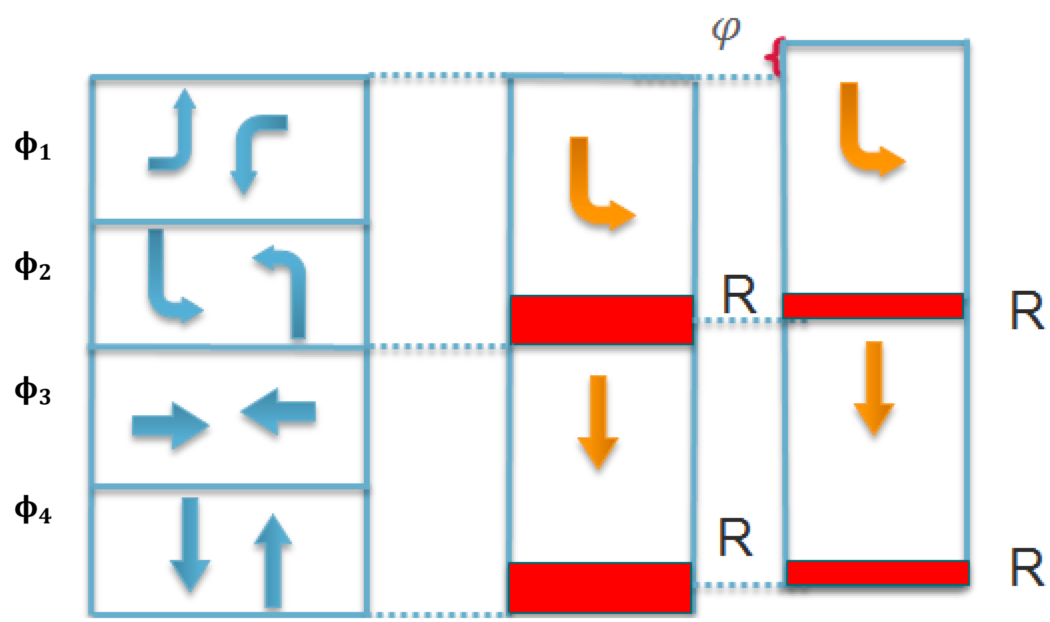
Also, adaptive controls with sensors can be employed to detect vehicles left in CWAs for additional safety.

Offset

To make better use of lane-clearing time, part of t_{clear} can be used as green time for the next indication. Therefore, an offset (φ) can be adopted between the main intersection signals and the pre-signal to increase intersection efficiency (Figure 14 (c)).

However, a longer offset may also increase the potential for safety issues. For example, a left-turn vehicle may move forward into CWAs when the green indication for CWAs is still for through vehicles due to the offset. That vehicle may speed up in order to clear the intersection and potentially run into the opposite through vehicle.

How long the offset should be depends on engineering judgment. This study selects the time a vehicle takes to cover half of the CWA length with the speed of the speed limit based on Table 4. Chapter V will further verify this based on if there are any vehicles running the red.



(a) timing plan for the main intersection

(b) timing plan of the pre-signal before setting offset

(c) timing plan of the pre-signal after setting offset

Figure 14 the signal timing plan of the intersection with CWA.

Pedestrians and Bicycles

The U.S. Department of Transportation encouraged transportation agencies to go beyond minimum design standards when designing walking and bicycling facilities. Instead of following the minimum standards, the design of pedestrian and bicycling facilities is expected to meet the future demand of bicyclists and pedestrians (*23*). In urban areas, where CWAs have a potential market, it is important to accommodate pedestrians and bicycles. Pedestrians and bicyclists are more vulnerable than vehicle drivers and need special facilities provided for them to separate them from motor vehicles.

Sidewalks are preferred for pedestrians in urban environments. Pedestrians crossing intersections with sidewalks on the roadsides should use crosswalks and follow the guidance of provided pedestrian signals. The operation of CWAs will have little influence on intersection crosswalks as long as the pedestrian signals are coordinated with the vehicular traffic signals.

Different types of on-road bicycle facilities exist in urban areas: shared lanes, bicycle lanes, bicycle tracks, etc. When bicycle demand is low, bicycles can 'share a travel lane with motorized vehicular traffic (21***Error! Reference source not found.***) '. If bicycle activities increase, bicycle lanes-'a portion of roadway that has been designated by striping, signage, and pavement markings for the preferential or exclusive use of bicyclist (*24*) '-may be a solution.

When bicycles share the roadway with non-motorized vehicular traffic near an intersection with CWAs, they should clear the intersection in accordance with pedestrians: using the intersection crosswalks. If bicycle lanes are provided, bicycles should operate as vehicles; this requires special marking and space provided for bicycles. The Urban Bikeway Design Guide published by the National Association of City Transportation Officials (NACTO) may be referred to for intersections with CWAs when it comes to bike lane design.

Existence of driveways

Commonly, driveways are not desirable near intersections; even when allowed, right-in-right-out driveways are preferred. The limitation of the presence of driveways may get stricter when it comes to CWAs since vehicles coming from driveways will interrupt CWA operation. A driveway may be allowed together with the pre-signal of CWAs. If so, the pre-signal may operate as a T-intersection signal.

A theoretical timing plan will be developed under the framework illustrated above for the studied intersection based on the traffic data collected. This timing plan will be tested based on the simulation results.

Simulation Platform and Scenarios

PTV VISSIM 7 is a microscopic and time-based traffic simulation program. It is employed in this research because of its ability to model unconventional lane uses and signal timing plans. Each simulation scenario is run with 10 random seeds. In each run, data of the measurements are collected for a duration of 30 min (corresponding to 17:15-17:45) with a start-up time of 15 min (corresponding to 17:00-17:15).

In Chapter V, the model of the studied intersection will be developed and calibrated with queue lengths. The calibrated parameters will also apply in the unconventional intersection models in VISSIM. The corresponding unconventional intersection with CWAs will be designed using the aforementioned frameworks concerning intersection layout, signal phasing and timings. The CWA length and signal timing plan will be tested and evaluated in the simulation.

In Chapter VI, the performance of the signalized intersection with and without CWAs under different traffic demands will be examined. These different scenarios will help understand the advantages and limitations of the CWA concept. Though the volumes will be altered in the different scenarios, geometric and traffic variables are controlled with the aim of comparing the operational performance of two types of intersections in the similar conditions. The results of travel times and entered volumes from the simulation are used as measures in the comparison.

CHAPTER V

CWA LENGTH AND SIGNAL TIMINGS

In this chapter, CWA length and signal timing plans calculated based on the methods in Chapter IV are evaluated based on simulation results. Before the evaluation, the parameters in the models are calibrated using the collected data of the selected intersection.

Model Calibration

To ensure the model built is an approximation of how the real intersection system operates, the parameters in the VISSIM platform are calibrated based on four performance measures: the maximum queue length and average queue length of left-turn movement and through/right-turn movement on the SB approach.

Calibration parameters are then identified. Traffic demand, signal timing and intersection layout are all set according to collected data. Headways in the VISSIM platform default setting are close to the observed ones and will not be calibrated in this study. Therefore, the desired speed distribution and maximum acceleration are selected for calibration as controllable parameters. ‘The Desired Speed Distribution’ in the VISSIM platform for this study has a range of four values: 30 km/h (19mph), 40 km/h (25mph) , 50 km/h (31mph) and 60 km/h (37.5 mph). The maximum acceleration has a range of 9 values: 11.5 ft/s^2,11 ft/s^2,10.5 ft/s^2,10 ft/s^2,9.5 ft/s^2,9 ft/s^2,8.5 ft/s^2, 8 ft/s^{2,} 7.5 ft/s^2. Thirty six combinations are run in the VISSIM platforms with 10 runs per combination. The average performance measures are recorded.

The results show that four performance measures are most close to real queue lengths when the desired speed distribution is 25 mph and maximum acceleration is 8 ft/s^2. The corresponding values of average queue length and maximum queue length for SB approach are shown in Table 5.

Table 5 The Values of Performance Measures for The Optimal Combination

	Average Queue Length (ft)			Maximum Queue Length (ft)		
	Field Study	VISSIM	Difference	Field Study	VISSIM	Difference
Through/right-turn movements	700	623	-11.07%	1250	1256	0.49%
Left-turn movement	540	537	-0.57%	1050	1001	-4.67%

The Base Version of CWA Model

As illustrated in the previous Chapter, a four-phase signal plan is adopted for the main intersection with CWAs. Since few pedestrians and bicyclists were observed during the data collection, these occasional pedestrians and bicyclists can utilize crosswalks and will not impact traffic signal operation. For example, pedestrian/bicyclist heading east or west can cross the intersection during ϕ_3 of the main intersection. Therefore, the pedestrian and bicycle demands are not considered in this study for simplicity. Also, railways are not considered in simulations for the simplicity of experiment design.

The signal timing plans are calculated based on HCM methods. The basic timing plans and CWA layout are shown in Table 6. Based on the methodology illustrated in

Chapter IV, the duration of each phase is 24s, 31s, 63s, 62s for ϕ_1, ϕ_2, ϕ_3 and ϕ_4 respectively (green time + lost time) for the main intersection signals. The amber time is 2 seconds and the yellow time is 4 seconds as observed in the field. The yellow time of 3 seconds (based on Traffic Signal Timing Manual (*25*)) is utilized for the pre-signal. The lane-clearance time and offset may influence the efficiency of signal timing plans. The basic model uses 6 seconds as offset and 9 seconds as lane-clearance time based on the methodology illustrated in Chapter IV. Segment b, which is for vehicles to wait before entering CWAs, starts from the first driveway in SB approach, i.e., 1285 ft from the main intersection. The number of lanes ranges from two to three from the start of segment b.

Table 6 Parameters in the Basic CWA Model

Signal Timing Plans	Main intersection Signals	ϕ_1	26
		ϕ_2	34
		ϕ_3	53
		ϕ_4	67
		Yellow	4 s
		All Red	2 s
		Offset	6 s
	Pre-Signals	ϕ_1	60
		ϕ_2	120
		Yellow	3 s
		t_{clear} (Lane-Clearing)	9 s
		Offset	6 s
CWA Layout	Number of Lanes in CWAs		1
	CWA length ($k = 1$)		250 ft

In order to evaluate the simulation results, the average travel times and queue length are gathered after simulation. The list of performance indices is show in Table 7.

Travel times are calculated from the second driveway or intersection upstream to the first driveway or intersection downstream. Another measurement is the queue length before the pre-signals.

Table 7 Performance Indices

Number	Average Travel Time (seconds)	Average Entered Volume (vehicles per 30 minutes)	Start Location	End Location
1	TT_1	V_1	North Side 2270 ft Upstream	South Side 540 ft Downstream
2	TT_2	V_2		East Side 260 ft Downstream
3	TT_3	V_3	South Side 775 ft Upstream	North Side 1285 ft Downstream
4	TT_4	V_4		West Side 340 ft ownstream
5	TT_5	V_5	West Side 700 ft Upstream	East Side 260 ft Downstream
6	TT_6	V_6		North Side 1285 ft Downstream
7	TT_7	V_7	East Side 635 ft Upstream	West Side 340 ft ownstream
8	TT_8	V_8		South Side 540 ft Downstream
9	TT	V	$V=\sum_{k=0}^{8} V_k$ $TT=\sum_{k=0}^{8} \frac{V_k}{V} TT_k$	

Evaluating Design Elements

Lane-Clearance Time

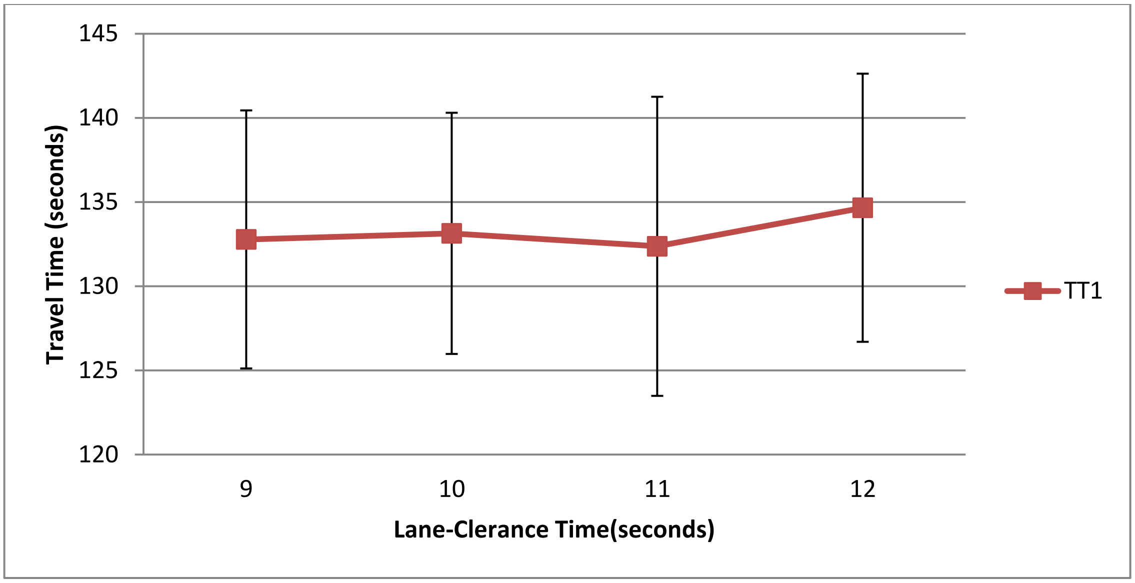
t_{clear} is calculated based on the length of CWAs to prevent vehicles from being left in CWAs when the corresponding phase ends. When the lane-clearance time is not long enough, there may be residual queues in CWAs. Such residual vehicles will block CWAs and may have safety issues. To keep drivers safe, it is important to have adequate lane-clearance time.

Since t_{clear} is not affected by the phases, the suggested value of t_{clear} is changed with offset unchanged (6 seconds) in this section. The simulation scenarios and results are shown in Table 8. Note from the table that inadequate lane-clearance time, 6 seconds, 7 seconds or 8 second, is not feasible. Such t_{clear} result in residual vehicles from time to time during the simulation.

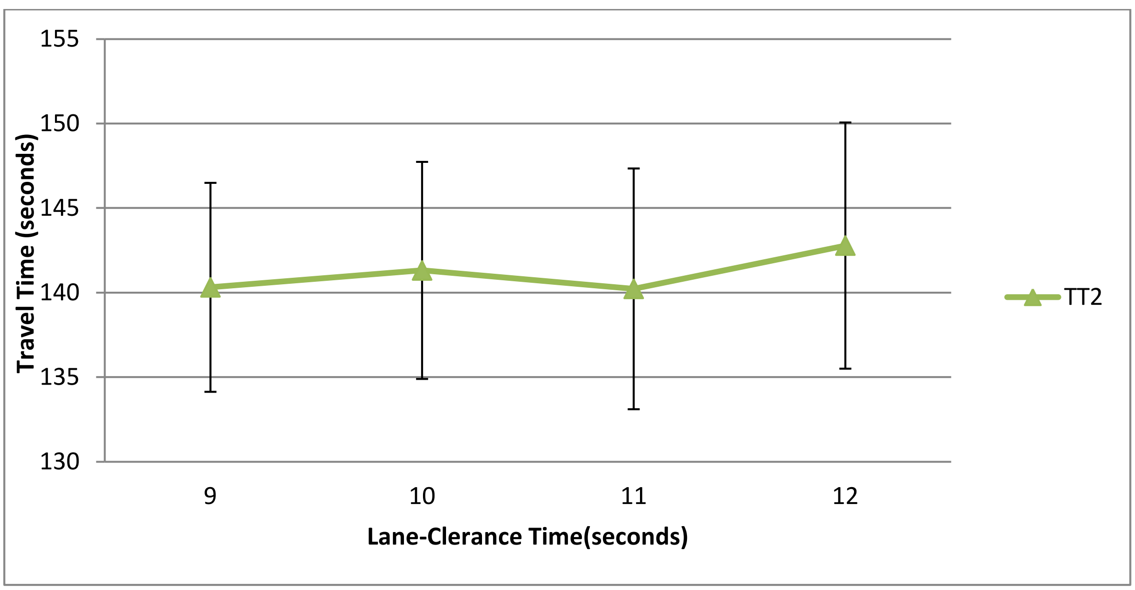
Table 8 Scenarios Modelled to Evaluate Lane-Clearance Time and Corresponding Simulation Results

Scenario Code	t_{clear} (s)	Feasibility	TT_1 (s)		TT_2 (s)		Queue Length before the Pre-Signal (ft)	
			Mean	S.D.	Mean	S.D.	Mean	S.D.
A-1	6	No	--	--	--	--	--	--
A-2	7	No	--	--	--	--	--	--
A-3	8	No	--	--	--	--	--	--
A-4(base)	9	Yes	132.78	3.83	140.31	3.09	451.7	76.21
A-5	10	Yes	133.14	3.58	141.31	3.21	450.57	78.86
A-6	11	Yes	132.37	4.44	140.22	3.56	475.34	109.2
A-7	12	Yes	134.66	3.98	142.78	3.64	462.12	89.72

Figure 15 shows the trend of TT_1 and TT_2. As shown in the figure, the travel times of vehicles from CWAs have an increasing trend when the lane-clearance time increases. It is reasonable since longer lane-clearance time means shorter green indications of pre-signals. If the green indications of pre-signals end earlier, it may cause more vehicles to wait for the next indication and therefore increase the average travel time. However, this trend is not significant. One possible reason is that saturation rate of SB approach is not very high in this experiment. Increasing or decreasing one second from lean-clearance time would not make much difference in the number of vehicles having to wait for the next indication.



(a) The Average Travel Time of Through Vehicles from SB Approach.



(b) The Average Travel Time of Left-turn Vehicles from SB Approach.

Figure 15 Travel Times (+/- 2 S.D.) of Vehicles from SB approach when Lane-Clearance Time Changes.

The trend of maximum queue length before the pre-signals is shown in Figure 16. A trend of more vehicles building up in segment b with a larger variance of the queue length was observed when lane-clearance time increases. This happens for the same reason mentioned above. The earlier ended pre-signal indication may cause more vehicles to wait for the next indication and therefore increase the queue length and fluctuation of it.

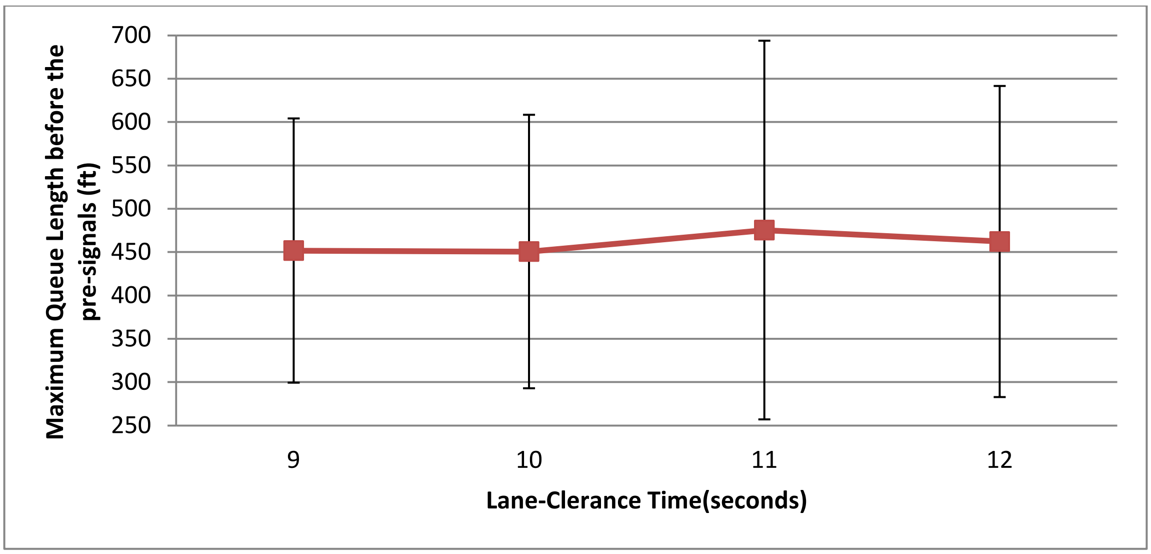
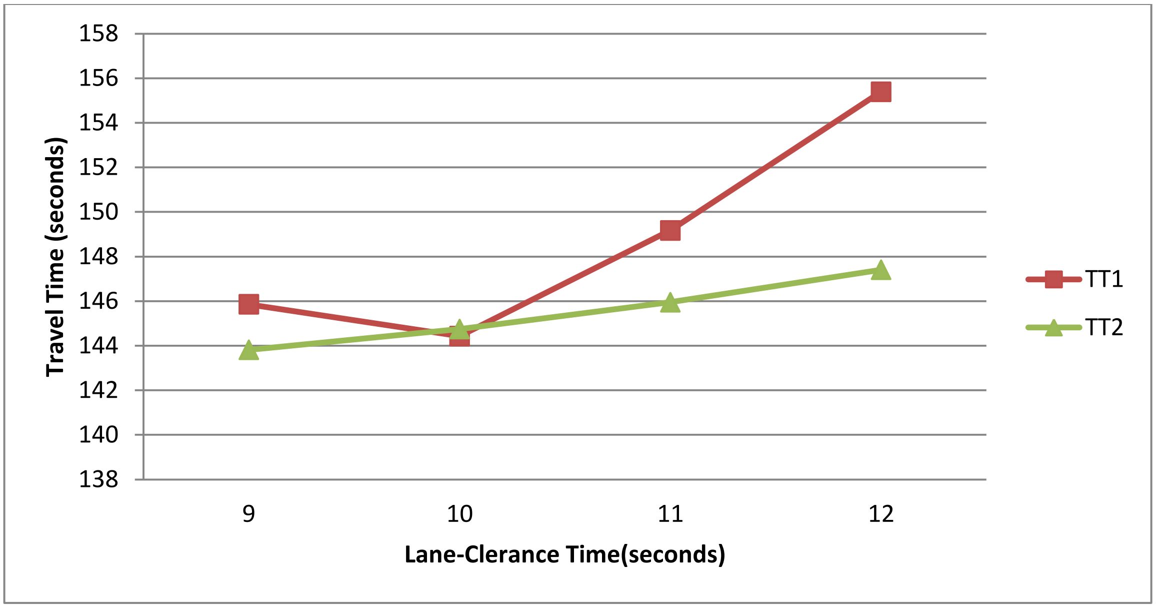
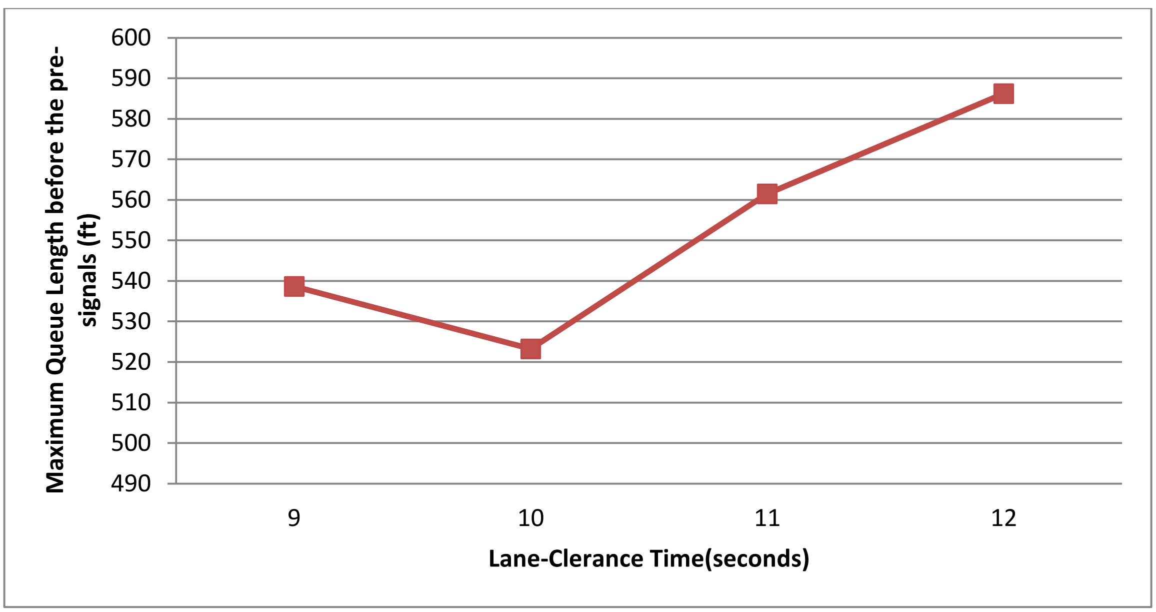


Figure 16 Maximum Queue Length (+/- 2 S.D.) before the Pre-Signals when Lane-Clearance Time Changes.

To evaluate the influence of lane-clearance time when the overall saturation rate is higher, WB exclusive right-turn lane was removed. It will increase the duration of Phase III and decreases the duration of other phases. The results are shown in Figure 17. The trend of increasing is greater in this situation.



(a) Average Travel Times of Vehicles from SB approach.



(b) Maximum Queue Length before the Pre-Signals.

Figure 17 Simulation Results under Different Lane-Clearance Time with WB Exclusive Right-Turn Lane Removed.

Overall, 9 seconds, as calculated based on the methodology, works well in this study. The lane-clearance time calculation in the following simulations will follow the steps in the Chapter IV.

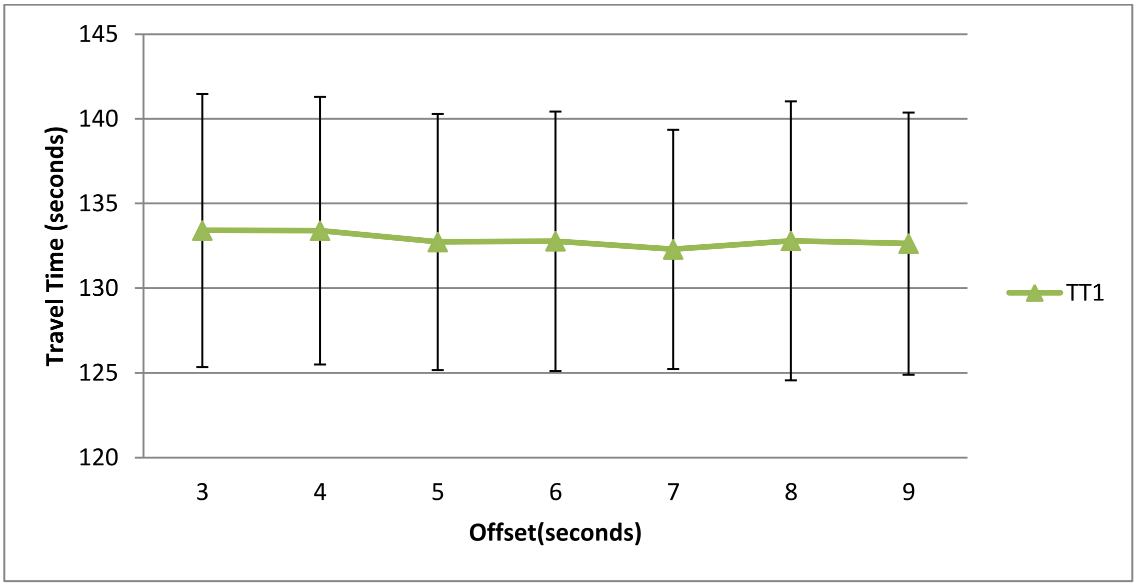
Offset

Offset can help make better use of red time. An early start means more time for vehicles to enter CWAs. In this section, travel time is studied under different offsets as shown in Table 9. t_{clear} remains unchanged (9 seconds).

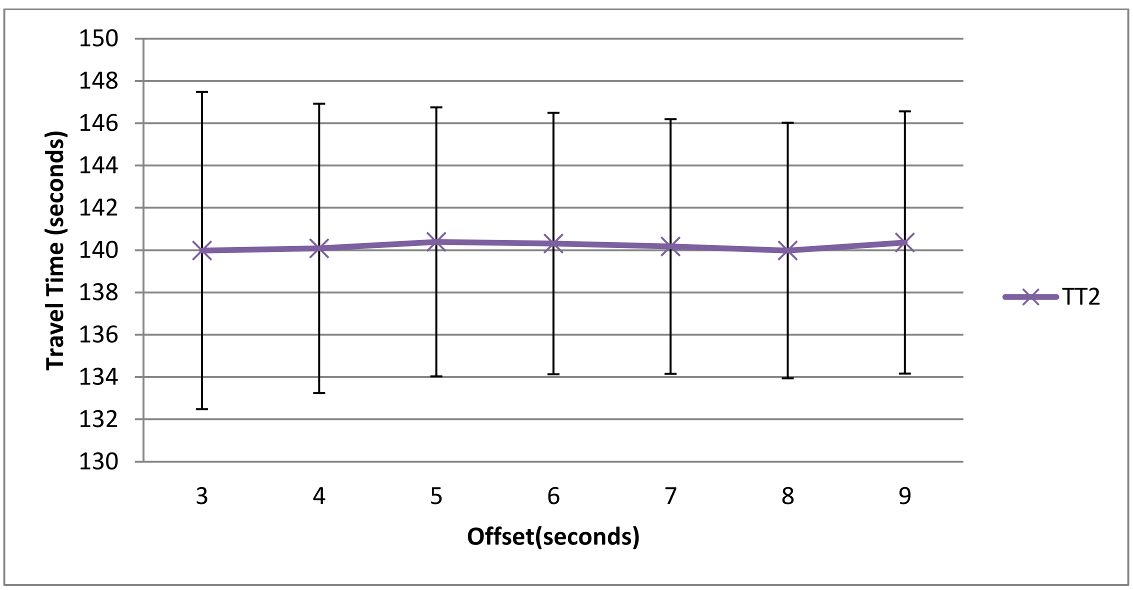
Table 9 Modelled Scenarios to Evaluate the Offset

Scenario Code	Offset (s)	Feasibility	TT_1 (s)		TT_2 (s)		Queue Length before the Pre-Signal (ft)	
			Mean	S.D.	Mean	S.D.	Mean	S.D.
B-1	3	Yes	133.41	4.03	139.98	3.75	452.21	105.22
B-2	4	Yes	133.4	3.95	140.08	3.42	452.58	95.17
B-3	5	Yes	132.73	3.78	140.39	3.18	455.63	83.65
B-4(base)	6	Yes	132.78	3.83	140.31	3.09	451.7	76.21
B-5	7	Yes	132.3	3.53	140.17	3.01	441.18	80.56
B-6	8	Yes	132.8	4.12	139.98	3.02	460.34	92.02
B-7	9	Yes	132.64	3.87	140.36	3.1	453.28	85.79

As shown in Figure 18, the travel times for vehicles form the SB approach do not differ much when offset changes; neither does the queue length before the pre-signal (Figure 19). The simulation results show the number of vehicles entering CWAs remain the same when the offset changes. The possible reason, as mentioned previously, is the saturation rate for SB approach is not every high. It can also explain why travel times and queue lengths do not change significantly.



(a) The Average Travel Time of Through Vehicles from SB Approach.



(b) The Average Travel Time of Left-Turn Vehicles from SB Approach.

Figure 18 Travel Times (+/- 2 S.D.) of Vehicles from SB Approach against Offset.

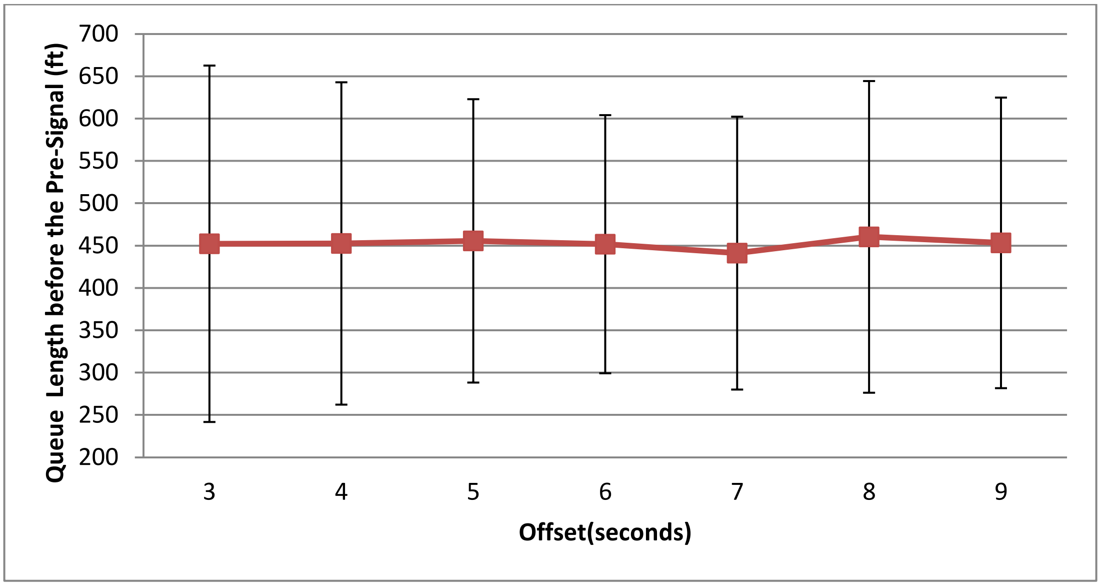


Figure 19 Maximum Queue Length (+/- 2 S.D.) before the Pre-Signals against Offset .

As mentioned before, there are safety risks when a large offset is applied. For example, the first left-turn vehicle can have a significant advance start when the indication for CWAs is still green for through vehicles. If this vehicle move forward with a high speed and tries to clear the intersection before green indication ends, it may run the red and cause severe safety issues. Since such accidents were not observed in the simulations, 6 seconds of offset based on the methodology can be used in this study. The offset calculation for the following simulations will follow the steps in the Chapter IV.

CWA Length

To evaluate if the theoretic CWA length is workable in the field, this section tests operation conditions under different CWA lengths. When examining the applicable CWA length, the timing plan is calculated based on formulas in the methodology illustrated in Chapter IV while the input volume for the approach with CWAs, the length of CWA, and the percentage of left-turn vehicles are changed. Twenty four scenarios are simulated in this section to evaluate the operational influence of CWA length under different volumes and left-turn percentages. The modelled volume, corresponding lane-clearance time and offset time of these scenarios are shown in Table 10.

Table 10 Modelled Scenarios to Evaluate CWA Length

Scenario Code	Modelled Volume (vph)	Theoretic Length (ft)	*k*	Simulated Length (ft)	Lane-Clearance Time (s)	Offset(s)
C-1	1239	200	0.6	120	7	5
C-2			0.8	160	7	5
C-3			1	200	8	6
C-4			1.2	240	9	6
C-5			1.4	280	11	7
C-6	1539	250	0.6	150	7	5
C-7			0.8	200	8	6
C-8			1	250	9	6
C-9			1.2	300	11	7
C-10			1.4	350	12	7
C-11	1839	300	0.6	180	8	6
C-12			0.8	240	9	6
C-13			1	300	11	7
C-14			1.2	360	12	7
C-15			1.4	420	14	8

The theoretic CWA length calculated based on the methods illustrated in Chapter IV is adjusted with *k*, where *k* ranges from 0.6 to 1.4 with step of 0.2. The simulation results are shown in Table 11. The variation of travel times with different CWA length are shown in Figure 20.

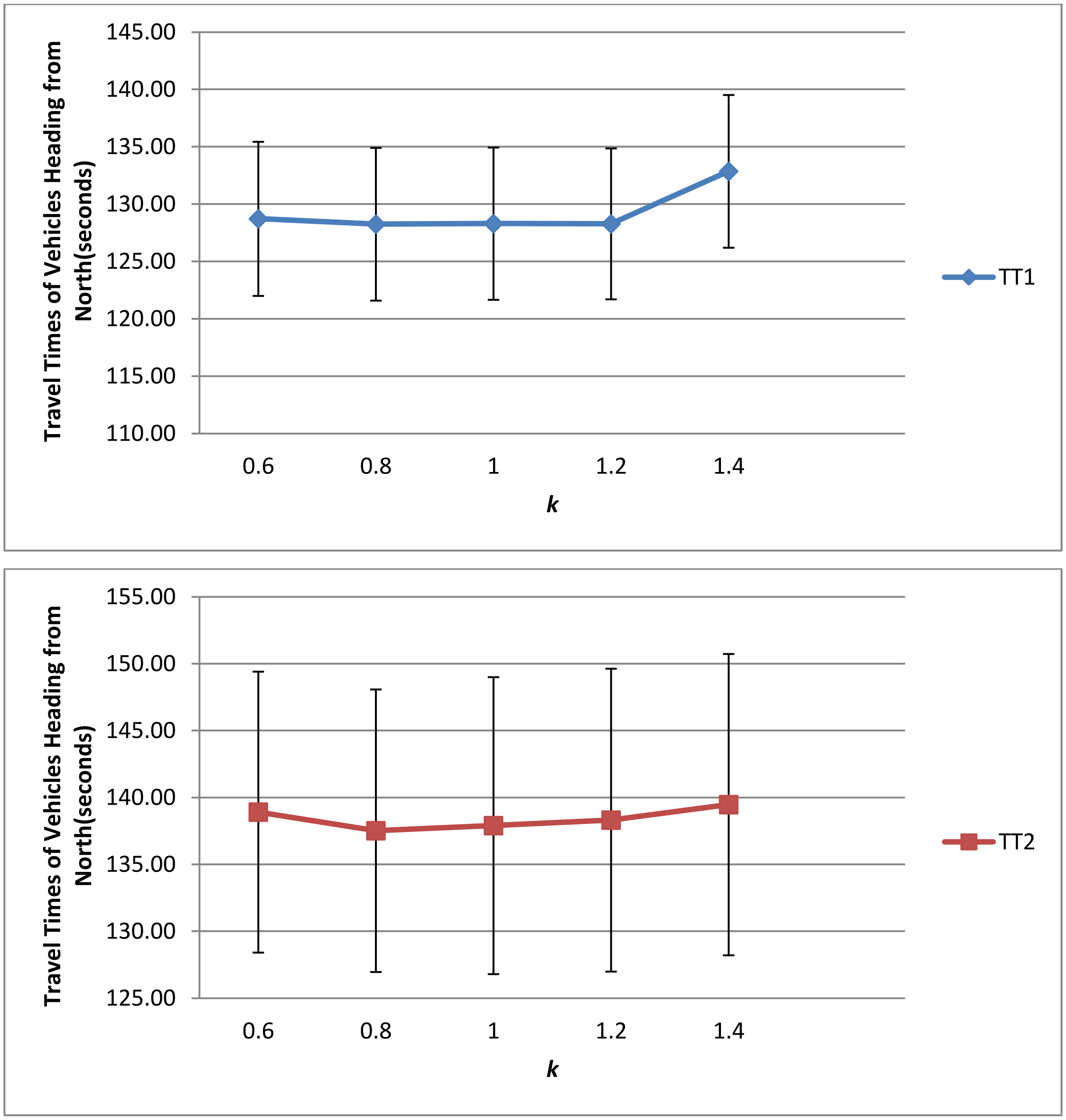
Table 11 Simulation Results of Travel Times and Entered Volumes under Different CWA Length

Scenario Code	TT_1 (seconds)		TT_2 (seconds)		V_1	V_2	V_1+V_2
	Mean	S.D.	Mean	S.D.			
C-1	128.72	3.36	138.91	5.25	402	157	559
C-2	128.25	3.33	137.52	5.28	402	157	559
C-3	128.30	3.32	137.90	5.55	402	158	560
C-4	128.28	3.29	138.31	5.66	402	158	560
C-5	132.86	3.33	139.47	5.63	402	157	559
C-6	133.78	4.90	141.75	3.83	497	198	695
C-7	132.87	3.94	141.01	3.19	497	198	695
C-8	132.63	4.09	140.38	3.13	497	198	695
C-9	132.46	3.81	141.30	2.82	497	198	695
C-10	132.18	3.42	141.26	2.98	498	198	696
C-11	218.23	45.01	167.72	12.76	564	233	797
C-12	213.20	38.31	155.81	11.68	566	236	802
C-13	209.45	46.18	156.02	14.19	567	236	803
C-14	205.64	39.75	155.44	10.68	569	237	806
C-15	197.94	39.10	167.43	9.83	572	238	810

As shown in Figure 20, TT_2 increases when k is too high or too low.

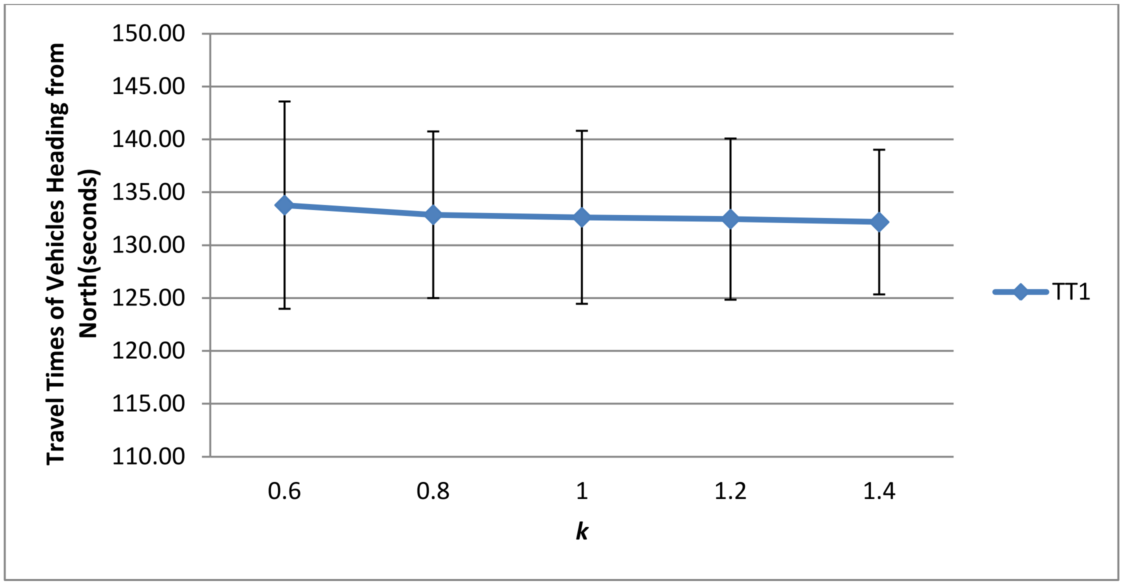
When k < 1, i.e. simulated CWA length is smaller than theoretic CWA length, there is not enough space for left-turn vehicles to form in two lines and be discharged. The left-turn efficiency decreases when there is only one line discharging vehicles during the left-turn phase. TT_2 is therefore increased.

When k > 1, i.e. simulated CWA length is larger than theoretic CWA length, more left-turn vehicles will move forward into the leftmost lane without waiting for the CWA green indication. If so, these vehicles cannot form in two almost even lines and decrease the efficiency of the left-turn phase. Therefore, TT_2 may also increase with k larger than 1.



(a) Modelled Volume =1239 vph

Figure 20 The Results of TT1 and TT2 (+/- 2 S.D.) under Different CWA Length.



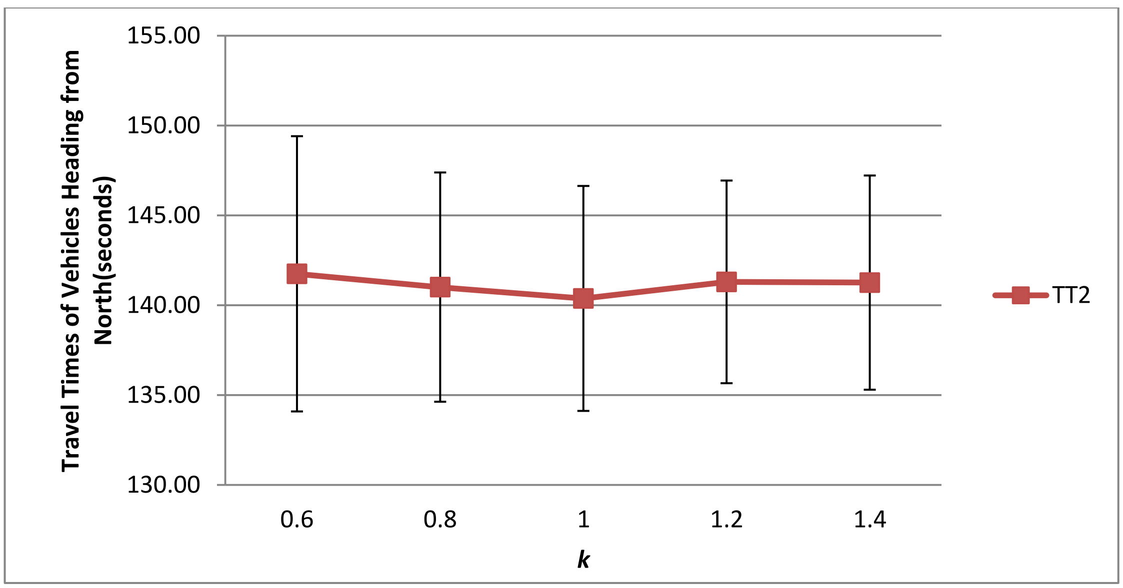


Figure 20 Continued (b) Modelled Volume =1539 vph

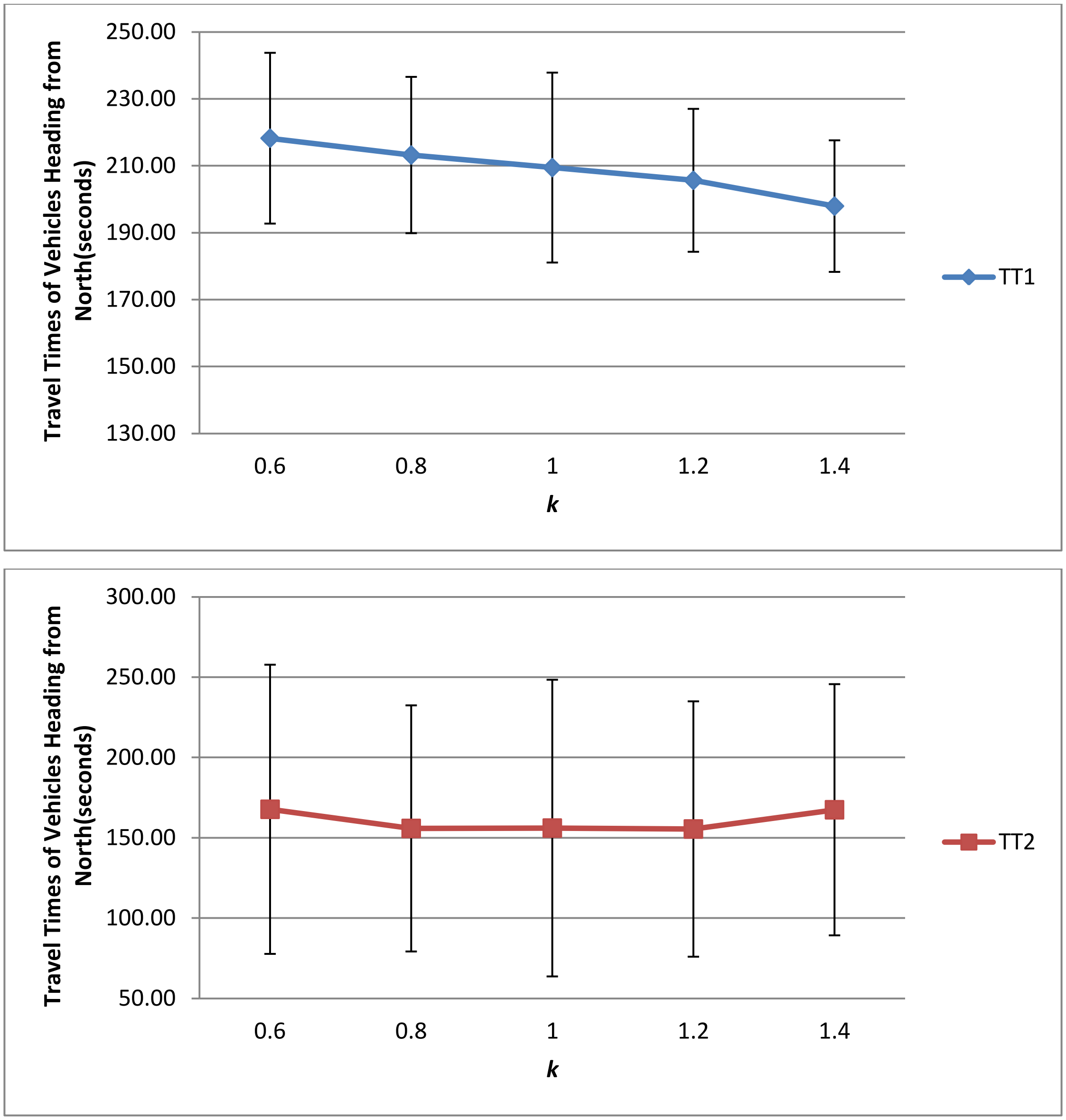


Figure 20 Continued (c) Modelled Volume =1839 vph

The change in CWA length will not influence entering volumes from CWAs when the modelled volume is not high. However, when the demand cannot be served, longer CWAs can increase capacity, though not much.

Figure 21 illustrates the queue accumulating before the pre-signals. Longer CWAs can help decrease the average maximum queue length. When the demand is not high, there is no significant change in the overall length for the queue plus CWAs. However, when the demand is higher, longer CWAs can decrease the overall length.

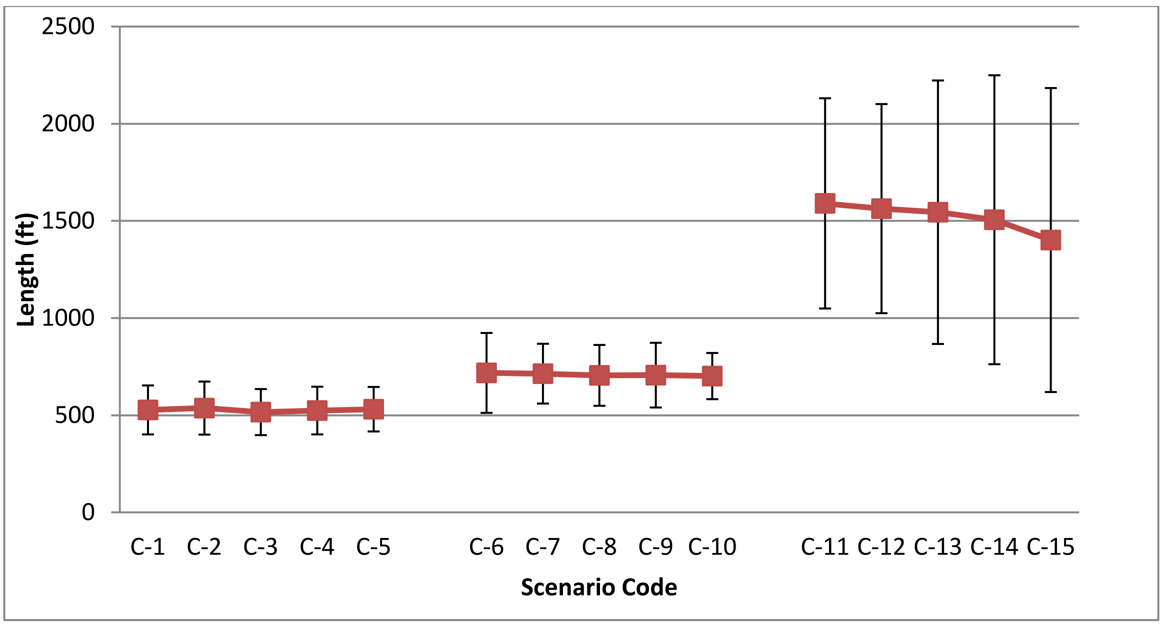


Figure 21 Queue Lengths before the Pre-Signal Plus CWA Lengths under Different CWA Length.

Summary

This chapter explores if the proposed methodology can lead to proper signal timings and CWA lengths. It shows the lane-clearance time and the offset can be calculated based on the formulas in the illustrate methodology in this study.

When calculating CWA length, factor k is used to adjust the value of length. When demand is not very high, travel time of vehicles from CWAs will not differ much with changed k. When the traffic demand is high, vehicles from North to East (turning left from CWAs) have smaller travel times if k is around 1. A bigger k will decrease the travel time of through vehicles from CWAs a little but also increase the travel time of left-turn vehicles from CWAs. Also, longer CWAs can decrease the average maximum queue length before pre-signals and increase the intersection capacity. k is costly to change in field once determined. k of 1 is reasonable in the simulation and will be utilized for calculating CWA length in this study. However, k of 1 is not the optimal option for each scenario, therefore does not generate best possible results of CWAs.

CHAPTER VI

EFFECTS OF VOLUMES AND TURNING PERCENTAGE

To evaluate the performance of CWAs under different volumes and left-turn percentages, the volume and turning percentage are changed in simulation for SB approach (the one with CWAs) in this chapter. Then the traffic demands from other three approaches are altered to study the effects of demand balance from four approaches.

CWA length and signal timings are studied in Chapter V. The simulation models in this chapter are built based on the results from Chapter V. For each scenario, data of the entered volumes and travel times are obtained from two intersections. One is with CWAs and the other is without CWAs. The similar geometric elements are used for intersections with and without CWAs. The results from two intersections will be compared so that an overall understanding of the advantages and limitations of CWAs will be gained.

Effects of Volume and Left-Turn Percentage

Experiment Design

As shown in Table 12, control type, through/left-turn/right-turn percentage and volume for SB approach are changed in this section.

Table 12 Traffic Input to Evaluate Operational Effects of CWA under Different Volumes and Turning Percentages

Variables	Options
Control Type	Conventional
	With CWA
Through/left-turn/right-turn volume Percentage of SB approach	76:16:08
	66:26:08
	56:36:08
SB Volume (vph)	1240
	1540
	1840
	2140

The modelled volume of SB approach, turning percentages and corresponding all red time and offset time of these scenarios are shown in Table 13.

Table 13 Models Scenarios to Evaluate Operational Effects of CWA under Different Volumes and Turning Percentages

Scenario Code	Intersection Type	Modelled Volume	Turning Ratio[1]	CWA Length	Lane-Clearance Time	Offset
D-1	CWA[2]	1240	76:16:08	125	7	5
D-2	CWA		66:26:08	200	8	6
D-3	CWA		56:36:08	280	10	7
D-4	CWA	1540	76:16:08	155	7	5
D-5	CWA		66:26:08	250	9	6
D-6	CWA		56:36:08	345	12	7
D-7	CWA	1840	76:16:08	185	8	6
D-8	CWA		66:26:08	300	11	7
D-9	CWA		56:36:08	415	14	8
D-10	CWA	2140	76:16:08	215	8	6
D-11	CWA		66:26:08	350	12	7
D-12	CWA		56:36:08	480	16	9
D-13	CON[3]	1240	76:16:08	N.A.	N.A.	N.A.
D-14	CON		66:26:08	N.A.	N.A.	N.A.
D-15	CON		56:36:08	N.A.	N.A.	N.A.
D-16	CON	1540	76:16:08	N.A.	N.A.	N.A.
D-17	CON		66:26:08	N.A.	N.A.	N.A.
D-18	CON		56:36:08	N.A.	N.A.	N.A.
D-19	CON	1840	76:16:08	N.A.	N.A.	N.A.
D-20	CON		66:26:08	N.A.	N.A.	N.A.
D-21	CON		56:36:08	N.A.	N.A.	N.A.
D-22	CON	2140	76:16:08	N.A.	N.A.	N.A.
D-23	CON		66:26:08	N.A.	N.A.	N.A.
D-24	CON		56:36:08	N.A.	N.A.	N.A.

Note:
[1]The Ratio of Through/Left-turn/Right-turn Vehicles
[2] Intersections with CWAs
[3] Conventional intersections without CWAs

Simulation Results

The average values of travel times and entered volume for each approach are shown in Table 14 and Table 15.

To compare the operational effects of intersections with and without CWAs under different SB traffic demand, the travel times and entered volumes from two types of intersection are compared. The ratios of travel times and entered volumes for intersections with CWAs to those without CWAs are shown in Table 16 and Table 17.

Note from Table 16 that TT_2, TT_3,TT_5 , $TT_6$and TT_8 are shorter at the intersection with CWAs for almost every scenario. TT_7, unlike other travel times, is longer for almost every scenario in the nonconventional intersections. This happens because intersection with CWAs, unlike conventional CWAs, cannot offer overlapping phase for left-turn and through movements from the same approach. Intersections with CWAs accommodate left-turn and through movement from SB approach in different phase ($\phi_2$and Phase ϕ_4 separately). Since left-turn and through volumes in WB approach are both higher than those in EB approach, movements from EB approaches enjoys longer green time than what their degrees of saturation deserves. Therefore, TT_5 and TT_6 (movements from the EB approach) are generally smaller in nonconventional intersection. For the similar reason, TT_2, TT_3 (travel times of left-turn movement from the SB approach and through movement from the NB approach) are generally smaller when CWAs exist.

Table 14 Travel Times in the Conventional and Nonconventional Intersections under Different Volumes and Turning Percentages

Code	Control Type	Modelled Volume (vph)	Turning Ratio[1]	Travel Times(s)							
				TT_1	TT_2	TT_3	TT_4	TT_5	TT_6	TT_7	TT_8
D-1	CWA[2]	1240	76:16:08	135	136	111	108	91.2	132	118	154
D-2			66:26:08	135	136	115	106	88.7	131	105	139
D-3			56:36:08	134	139	117	104	87.9	130	102	138
D-4		1540	76:16:08	137	140	104	121	102	134	145	180
D-5			66:26:08	133	140	108	110	95.1	131	132	166
D-6			56:36:08	135	143	114	104	92.2	130	118	148
D-7		1840	76:16:08	178	144	97	106	153	160	173	273
D-8			66:26:08	142	148	102	120	107	136	153	203
D-9			56:36:08	144	147	109	100	94.9	133	133	184
D-10		2140	76:16:08	249	190	93	154	170	164	182	278
D-11			66:26:08	187	175	98	121	138	144	170	212
D-12			56:36:08	168	268	169	116	211	281	162	277
D-13	CON[3]	1240	76:16:08	137	144	108	111	91.4	152	94.6	175
D-14			66:26:08	134	146	120	107	91.6	153	91.2	167
D-15			56:36:08	131	149	125	98.2	107	179	106	192
D-16		1540	76:16:08	153	142	108	118	107	179	107	166
D-17			66:26:08	135	150	122	114	98	151	103	188
D-18			56:36:08	128	186	131	104	116	179	127	222
D-19		1840	76:16:08	207	144	108	134	129	207	132	247
D-20			66:26:08	156	162	125	114	112	180	115	216
D-21			56:36:08	141	234	148	108	158	215	148	275
D-22		2140	76:16:08	261	168	110	162	175	221	155	279
D-23			66:26:08	208	183	128	146	142	211	136	245
D-24			56:36:08	168	268	169	116	211	281	162	277

Note:
[1]The Ratio of Through/Left-turn/Right-turn Vehicles
[2] Intersections with CWAs
[3] Conventional intersections without CWAs

Table 15 Entered Volumes in the Conventional and Nonconventional Intersections under Different Volumes and Turning Percentages

Code	Control Type	Modelled Volume (vph)	Turning Ratio[1]	Entered Volumes (vehicles in half an hour)							
				V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8
D-1	CWA[2]	1240	76:16:08	465	96	298	127	372	49	433	88
D-2			66:26:08	404	157	299	127	372	49	439	88
D-3			56:36:08	342	219	300	127	372	49	439	89
D-4		1540	76:16:08	574	121	299	127	372	49	418	85
D-5			66:26:08	499	197	299	127	372	49	426	86
D-6			56:36:08	422	274	299	127	372	49	436	87
D-7		1840	76:16:08	688	146	289	131	369	46	379	92
D-8			66:26:08	596	238	299	127	372	49	410	82
D-9			56:36:08	507	328	299	127	372	49	424	87
D-10		2140	76:16:08	743	161	288	127	360	47	372	89
D-11			66:26:08	672	272	299	127	366	49	387	80
D-12			56:36:08	541	335	292	126	348	44	397	84
D-13	CON[3]	1240	76:16:08	463	99	294	127	375	46	432	94
D-14			66:26:08	399	162	294	128	375	46	434	94
D-15			56:36:08	343	219	294	128	378	47	432	93
D-16		1540	76:16:08	572	118	294	128	378	47	431	94
D-17			66:26:08	499	198	294	127	376	47	432	93
D-18			56:36:08	427	267	294	128	378	47	424	91
D-19		1840	76:16:08	655	142	293	126	376	47	419	89
D-20			66:26:08	593	237	294	127	378	47	429	91
D-21			56:36:08	498	306	294	128	368	47	405	86
D-22		2140	76:16:08	707	152	293	124	362	46	398	84
D-23			66:26:08	663	271	294	125	372	47	420	89
D-24			56:36:08	541	335	292	126	348	44	397	84

Note:
[1]The Ratio of Through/Left-turn/Right-turn Vehicles
[2] Intersections with CWAs
[3] Conventional intersections without CWAs

Table 16 Comparisons of Travel Times between Intersections with/without CWAs

Modelled Volume	Turning Ratio[1]	Ratio of Travel Time (CWA[2]: CON[3])							
		TT_1	TT_2	TT_3	TT_4	TT_5	TT_6	TT_7	TT_8
1240	76:16:08	0.99	0.95	1.00	0.97	1.00	0.87	1.24	0.88
	66:26:08	1.00	0.93	1.00	0.99	0.97	0.86	1.15	0.83
	56:36:08	1.02	0.93	0.90	1.06	0.82	0.73	0.97	0.72
1540	76:16:08	0.89	0.99	1.00	1.02	0.96	0.75	1.35	1.09
	66:26:08	0.98	0.94	0.90	0.96	0.97	0.86	1.28	0.88
	56:36:08	1.06	0.77	0.90	1.00	0.79	0.73	0.92	0.67
1840	76:16:08	0.86	1.00	0.90	0.79	1.19	0.77	1.31	1.11
	66:26:08	0.91	0.91	0.80	1.05	0.95	0.75	1.33	0.94
	56:36:08	1.02	0.63	0.70	0.93	0.6	0.62	0.90	0.67
2140	76:16:08	0.95	1.13	0.80	0.95	0.98	0.74	1.17	0.99
	66:26:08	0.90	0.96	0.80	0.83	0.97	0.68	1.26	0.87
	56:36:08	1.15	0.65	0.60	0.85	0.65	0.49	1.06	0.75

Note:
[1]The Ratio of Through/Left-turn/Right-turn Vehicles
[2] Intersections with CWAs
[3] Conventional intersections without CWAs

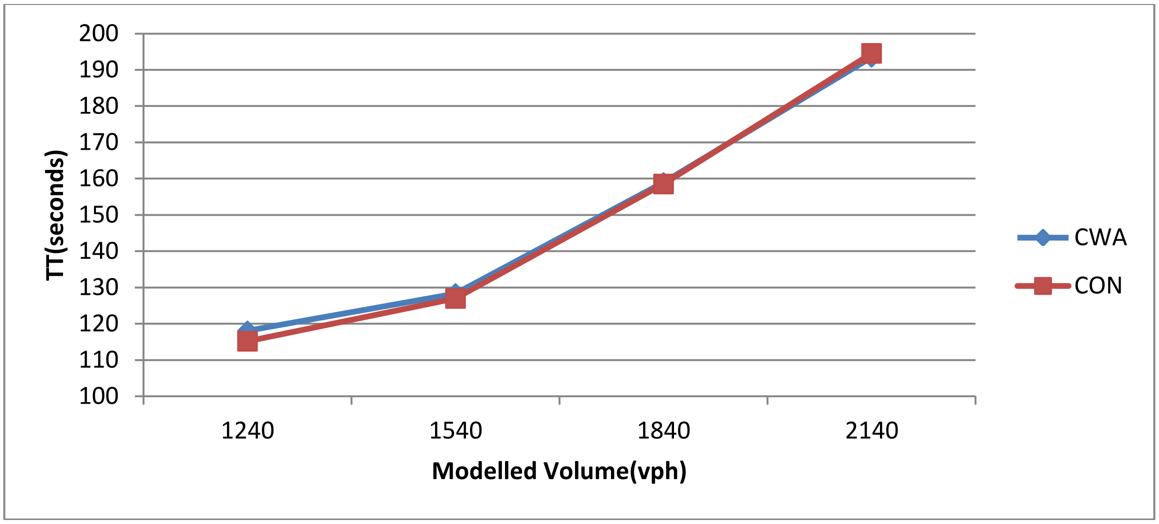
As Table 17 shows, V_1, V_2, V_3 and $V_6$are generally larger in nonconventional intersections. Left-turn movements from the EB approach and through movements from the NB approach have much smaller volumes than those from opposing approaches. For the reason mentioned above, there is no surprise seeing V_3 and V_6 are generally smaller when CWAs exist. The increase of V_1, V_2 for nonconventional intersections may benefit from CWAs.

Table 17 Comparisons of Entered Volume between Intersections with/without CWAs

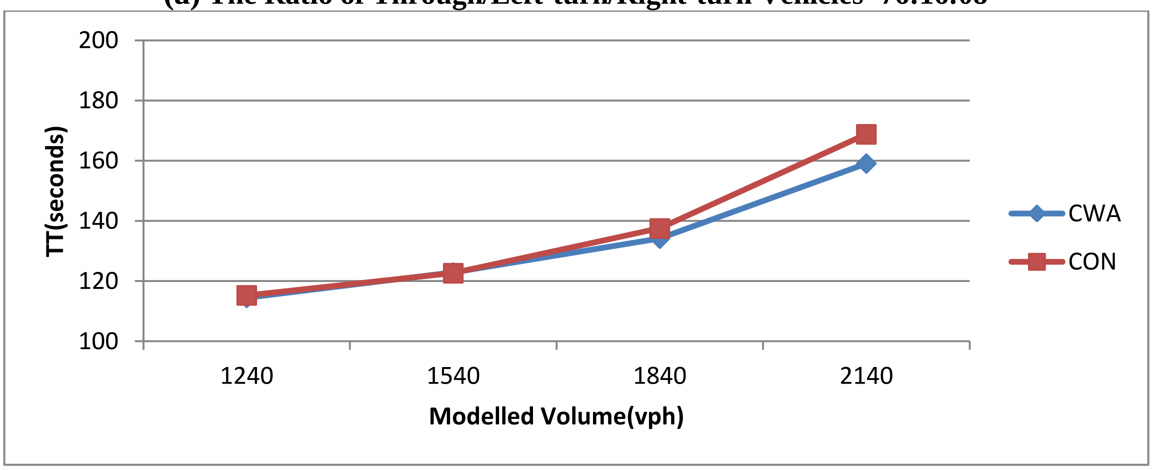
Modelled Volume	Turning Ratio[1]	Ratio of Entered Volume (CWA[2]:CON[3])							
		V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8
1240	76:16:08	1.00	0.97	1.01	1.00	0.99	1.07	1.00	0.94
	66:26:08	1.01	0.97	1.02	0.99	0.99	1.07	1.01	0.94
	56:36:08	1.00	1.00	1.02	0.99	0.98	1.04	1.02	0.96
1540	76:16:08	1.00	1.03	1.02	0.99	0.98	1.04	0.97	0.90
	66:26:08	1.00	0.99	1.02	1.00	0.99	1.04	0.99	0.92
	56:36:08	0.99	1.03	1.02	0.99	0.98	1.04	1.03	0.96
1840	76:16:08	1.05	1.03	0.99	1.04	0.98	0.98	0.90	1.03
	66:26:08	1.01	1.00	1.02	1.00	0.98	1.04	0.96	0.90
	56:36:08	1.02	1.07	1.02	0.99	1.01	1.04	1.05	1.01
2140	76:16:08	1.05	1.06	0.98	1.02	0.99	1.02	0.93	1.06
	66:26:08	1.01	1.00	1.02	1.02	0.98	1.04	0.92	0.90
	56:36:08	1.04	1.12	1.02	1.01	1.06	1.11	0.98	0.95

Note:
[1] The Ratio of Through/Left-turn/Right-turn Vehicles
[2] Intersections with CWAs
[3] Conventional intersections without CWAs

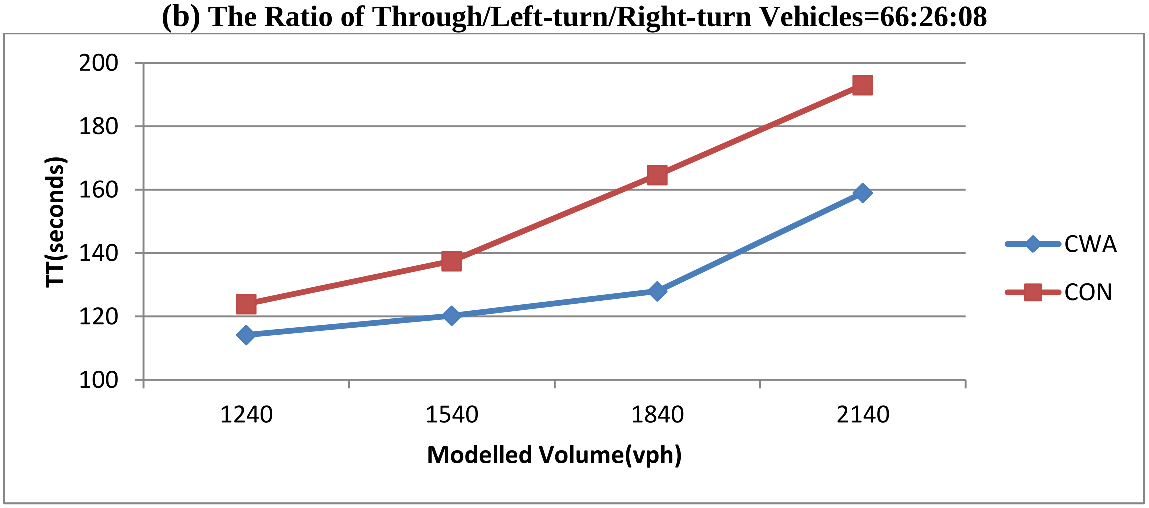
The average travel time (TT) and entered volume (V) are shown in Figure 22 and Figure 23. The average travel time, TT, as the figure shows, does not differ much when the left-turn percentage is not high (16% and 26 %). CWAs decrease TT significantly when the left-turn percentage is 36%. The benefit is greater if the modelled volume for the SB approach is higher. Overall, CWAs can decrease TT when modelled volume is high with heavy left-turn demand.



(a) The Ratio of Through/Left-turn/Right-turn Vehicles=76:16:08

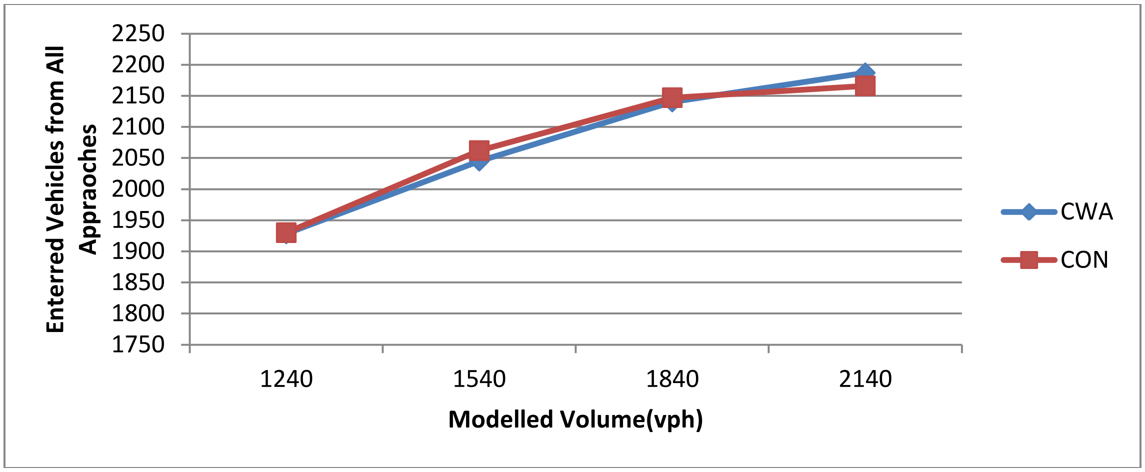


(b) The Ratio of Through/Left-turn/Right-turn Vehicles=66:26:08

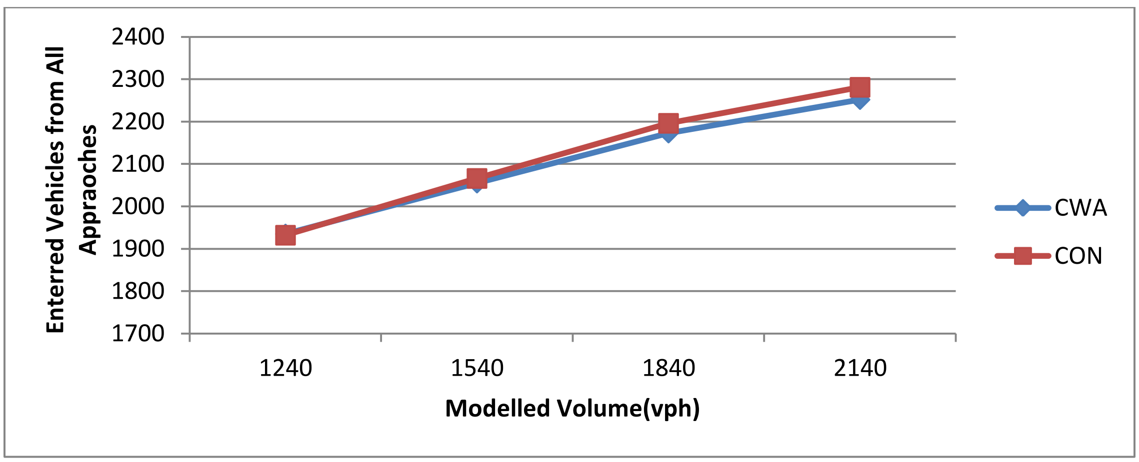


(c) The Ratio of Through/Left-turn/Right-turn Vehicles=56:36:08

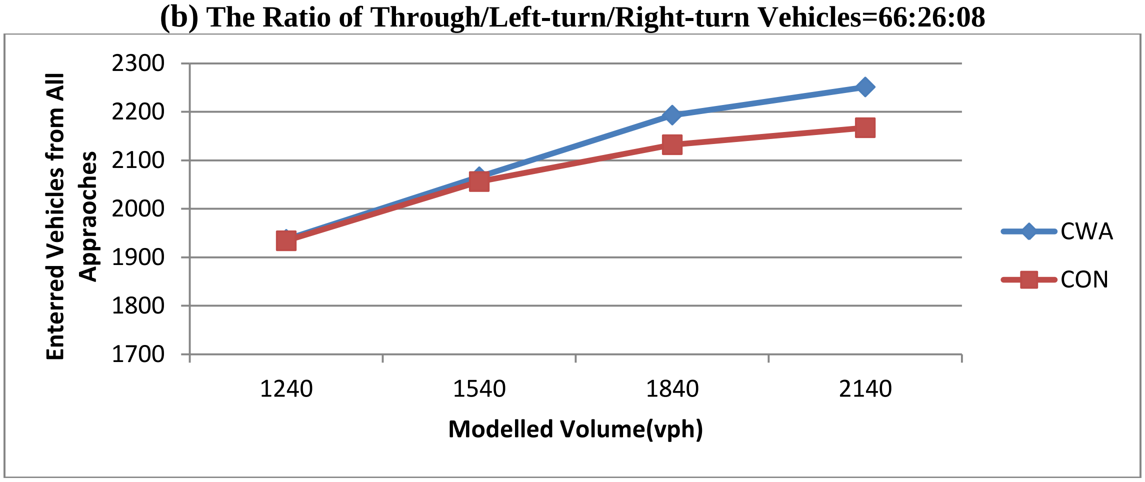
Figure 22 Average Travel Time at the Intersections with/without CWAs under Different Volumes and Turning Percentages.



(a) The Ratio of Through/Left-turn/Right-turn Vehicles=76:16:08



(b) The Ratio of Through/Left-turn/Right-turn Vehicles=66:26:08



(c) The Ratio of Through/Left-turn/Right-turn Vehicles=56:36:08

Figure 23 The Number of Entered Vehicles from All Approaches at the Intersections with/without CWAs under Different Volumes and Turning Percentages.

Figure 23 illustrates the total number of all entered vehicles (V). This number can represent the capacity of the intersection. When the left-turn percentage for the SB approach is 16% or 26%, intersections with/without CWAs produce similar capacity. V is much greater at the intersections with CWAs when the volume for the SB approach is 1840 vph or 2140 vph. Greater benefits in increasing intersection capacity by CWAs are shown when the left-turn percentage of the SB approach is higher.

Effects of Volumes of Other Approaches

Experiment Design

Theoretically, CWAs work best when the movements in the same phase have close flow rate per lane. For example, when the left-turn movements from EB and WB approaches have similar volume waiting in the same cycle, few seconds of $\phi_1$for the main intersection signals will be wasted. Scenario E-1 in Table 18 simulates a balanced situation when movements in the same phase have the same flow rate. In E-1, the traffic demands from SB and EB approaches remain the same as the data collected from the field. Traffic volumes from two other approaches match those of SB and EB approaches.

In scenario E-2 and E-3, the left-turn volume of northbound approach increase and decrease by 20 % respectively. Similarly, the through volume of northbound approach increase by 20 % in scenario E-4 and decrease by 20% in E-5.

Scenario E-6 to E-11 adjust the volumes from westbound and eastbound approaches. In E-6 and E-7 they both increase by 20%. E-8 and E-9 only increase and decrease the left-turn volume of eastbound approach by 20 % respectively. The through volume of eastbound approach increases by 20 % in E-10 and decreases by 20% in E-11.

Since the SB approach demand does not change in this section, the CWA remains 250 ft long with a lane-clearance time of 9 seconds and offset of 6.

Table 18 Models Scenarios to Evaluate the Effects of Demand Balance from Four Approaches

Scenario Code	Modelled Situation	NB Approach Volume		EB Approach Volume		WB Approach Volume	
		Left-turn	Through[1]	Left-turn	Through	Left-turn	Through
E-1/ E-12[2]	Balanced	201	1137	96	850	96	850
E-2/ E-13	Changing NB Left-turn Volume	241	1137	96	850	96	850
E-3/ E-14		161	1137	96	850	96	850
E-4/ E-15	Changing NB Through Volume	201	1364	96	850	96	850
E-5/ E-16		201	910	96	850	96	850
E-6/ E-17	Changing EB/WB Volume	201	1137	115	1020	115	1020
E-7/ E-18		201	1137	77	680	77	680
E-8/ E-19	Changing EB Left-turn Volume	201	1137	115	850	96	850
E-9/ E-20		201	1137	77	850	96	850
E-10/ E-21	Changing EB Through Volume	201	1137	96	1020	96	850
E-11/ E-22		201	1137	96	680	96	850

Note:
[1] Right-turn movement is included if there is no exclusive right-turn vehicles
[2] The left and right codes represent scenarios simulating intersections with and without CWAs separately

Simulation Results

The average travel times and entered volumes for each approach are shown in Table 19 and Table 20.

Table 19 Travel Times in the Conventional and Nonconventional Intersections under Different Demand Balance

Code	Control Type	TT_1	TT_2	TT_3	TT_4	TT_5	TT_6	TT_7	TT_8	TT
E-1	CWA[1]	122	136	104	101	81.9	168	85.9	144	106
E-2		126	141	113	107	89.6	178	97.5	172	114
E-3		122	136	104	97.2	81.8	168	86	144	106
E-4		118	148	116	119	95.3	180	108	179	117
E-5		122	137	97	103	81.8	168	85.6	145	105
E-6		129	148	122	118	91.5	157	116	178	120
E-7		112	128	94	88.6	73	112	72.5	84.8	95
E-8		125	145	109	107	89.3	166	94.3	130	112
E-9		122	136	104	101	83	145	85.9	144	106
E-10		129	147	121	114	88.3	181	83.7	164	113
E-11		122	136	104	101	76.9	166	85.9	144	107
E-12	CON[2]	120	154	146	119	101	203	119	226	129
E-13		124	154	158	125	101	203	120	234	133
E-14		117	154	143	116	101	203	120	231	128
E-15		117	181	167	138	131	280	144	251	149
E-16		123	143	121	110	92	179	103	193	117
E-17		125	181	175	137	139	232	151	281	154
E-18		115	143	120	109	99.3	177	104	193	117
E-19		121	163	150	122	97.6	183	125	233	132
E-20		120	154	146	119	102	157	119	226	128
E-21		124	172	174	137	137	196	101	215	141
E-22		120	154	147	121	89.7	187	117	194	128

Note:
[1] Intersections with CWAs
[2] Conventional intersections without CWAs

Table 20 Entered Volumes in the Conventional and Nonconventional Intersections under Different Demand Balance

Code	Control Type	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V
E-1	CWA[1]	511	193	450	97	366	50	420	44	2131
E-2		500	197	458	121	373	50	426	45	2170
E-3		511	193	448	77	366	50	420	44	2109
E-4		500	197	570	99	373	50	424	45	2258
E-5		511	193	332	98	366	50	420	44	2014
E-6		499	197	454	99	461	57	506	55	2328
E-7		511	201	469	103	278	42	328	36	1968
E-8		485	210	452	108	372	64	424	48	2163
E-9		511	193	450	97	366	38	420	44	2119
E-10		499	197	455	99	460	48	425	45	2228
E-11		511	193	450	97	284	50	420	44	2049
E-13	CON[2]	499	198	449	95	377	47	421	47	2133
E-14		499	198	445	113	377	47	420	47	2146
E-15		499	198	448	78	377	47	421	47	2115
E-16		499	196	519	90	374	46	412	45	2181
E-17		500	197	342	96	375	47	423	48	2028
E-18		499	196	435	93	451	54	467	51	2246
E-19		499	197	455	96	292	37	337	38	1951
E-20		499	197	447	95	378	56	418	47	2137
E-21		499	198	449	95	378	37	422	47	2125
E-22		500	197	434	92	453	45	422	47	2190
E-23		499	198	449	95	292	47	422	48	2050

Note:
[1] Intersections with CWAs
[2] Conventional intersections without CWAs

The results regarding average travel times are shown in Table 21. Note from the table, CWAs decrease average travel times by at least 10 %. Except for TT_1, all other travel times are lower at the intersection with CWAs.

Increasing or decreasing northbound left-turn volume leads to inferior benefits. It appears a balanced traffic pattern in terms of movements in the same phase is crucial to CWAs. Unlike the conventional eight-phase dual-ring controller, the main intersection in CWAs cannot allow overlapping of movements for more efficient operation. Therefore, the conventional intersection has better adaptability to traffic demand. For the same reason, the TT decrease by CWAs is less significant in Scenario E-5, E-8, E-9 and E-11.

Greater decrease in TT is achieved in Scenario E-4, E-6 and E-7. Scenario E-4 increases the NB through volumes by 20%, creating higher demand than increasing left-turn volume by 20%. Since Φ_5 and Φ_6 for the conventional intersection are in the same ring and on the same side of the barrier, the increase in demand for Φ_6 adds more burden on Φ_5 . Φ_5 itself has to serve the high demand of left-turn vehicles from the NB approach. Therefore, phases on the other side of the barrier have even lesser time, significantly increasing TT_5 and TT_6 for the conventional intersection.

Scenario E-5 and E-6, simultaneously changes EB and WB approach volumes without destroying demand balance in E-1. Therefore, intersections with CWAs produce greater benefits in reducing average travel times.

Table 21 Comparisons of Travel Times between Intersections with/without CWAs

Scenario Code	Ratio of Travel Time (CWA[2]: CON[3])								
	1	2	3	4	5	6	7	8	
E-1/ E-12[1]	1.02	0.89	0.71	0.85	0.81	0.83	0.72	0.64	0.82
E-2/ E-13	1.01	0.91	0.72	0.86	0.89	0.88	0.81	0.74	0.86
E-3/ E-14	1.05	0.89	0.73	0.84	0.81	0.83	0.71	0.62	0.83
E-4/ E-15	1.00	0.82	0.70	0.87	0.73	0.64	0.75	0.71	0.78
E-5/ E-16	0.99	0.96	0.80	0.94	0.89	0.94	0.83	0.75	0.90
E-6/ E-17	1.03	0.82	0.69	0.86	0.66	0.68	0.77	0.63	0.78
E-7/ E-18	0.97	0.90	0.78	0.81	0.73	0.63	0.70	0.44	0.81
E-8/ E-19	1.03	0.89	0.72	0.88	0.91	0.91	0.75	0.56	0.85
E-9/ E-20	1.02	0.89	0.71	0.85	0.82	0.92	0.72	0.64	0.82
E-10/ E-21	1.04	0.85	0.69	0.83	0.64	0.92	0.83	0.76	0.80
E-12/ E-22	1.02	0.89	0.71	0.84	0.86	0.89	0.73	0.74	0.83

Note:
[1]The left and right codes represent the scenarios simulating intersections with and without CWAs separately
[2] Intersections with CWAs
[3] Conventional intersections without CWAs

The ratios of the entered volumes for intersections with CWAs to those without CWAs are shown in Table 22. No significant increase in entered volumes is found in this section. One possible reason is that the traffic demand in the simulations is not very high. Both conventional and nonconventional intersections can handle the entered volumes.

Table 22 Comparisons of Entered Volume between Intersections with/without CWAs

Scenario Code	Ratio of Entered Volume (CWA[2]:CON[3])								
	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V
E-1/ E-12[1]	1.02	0.97	1.00	1.02	0.97	1.06	1.00	1.02	1.00
E-2/ E-13	1.00	0.99	1.03	1.07	0.99	1.06	1.01	1.00	1.01
E-3/ E-14	1.02	0.97	1.00	0.99	0.97	1.06	1.00	1.02	1.00
E-4/ E-15	1.00	1.01	1.10	1.10	1.00	1.09	1.03	1.00	1.04
E-5/ E-16	1.02	0.98	0.97	1.02	0.98	1.06	0.99	1.02	0.99
E-6/ E-17	1.00	1.01	1.04	1.06	1.02	1.06	1.08	1.00	1.04
E-7/ E-18	1.02	1.02	1.03	1.07	0.95	1.14	0.97	1.02	1.01
E-8/ E-19	0.97	1.07	1.01	1.14	0.98	1.14	1.01	0.97	1.01
E-9/ E-20	1.02	0.97	1.00	1.02	0.97	1.03	1.00	1.02	1.00
E-10/ E-21	1.00	1.00	1.05	1.08	1.02	1.07	1.01	1.00	1.02
E-11/ E-22	1.02	0.97	1.00	1.02	0.97	1.06	1.00	1.02	1.00

Note:

[1]The left and right codes represent the scenarios simulating intersections with and without CWAs separately

[2] Intersections with CWAs

[3] Conventional intersections without CWAs

CHAPTER VII

CONCLUSION AND FUTURE WORK

Conclusions

Although analysis results apply specifically to the studied intersection evaluated in this paper, the advantages of CWAs still apply to intersections where the geometry and traffic demand are suitable for constructing CWAs. Generally, intersections with CWAs outperform those without CWAs at high traffic volumes. The advantages are even greater when traffic demands from all the approaches are balanced, i.e. the saturation rates of left-turn or through movements is close to that from the opposing approach. The reduction in the saturation rate on the approach with CWAs results in travel time savings as well as intersection capacity increases.

Besides operational performance, CWAs can be built in a more narrow area and require relatively less road re-construction work. If the alternative plan -- CFI or an interchange— is adopted, a longer construction period is needed necessitating a shutdown of the intersection for an extended period of time.

Important findings in this research are summarized as follows:

- To prevent residual vehicles in CWAs, enough lane-clearance time is necessary in signal timing design. The duration of lane-clearance time can be the time a vehicle takes to cover the CWA length with vehicle speed equal to the speed limit in this study;
- To increase the time for vehicles to move forward into CWAs, offsets can be used for pre-signals. The duration can be the time a vehicle takes to

cover half the CWA length with the with vehicle speed equal to the speed limit in this study;

- For partial CWA design, the length of CWAs can be calculated as the queue length of arriving left-turn vehicles during a single cycle in this study. Increasing this length may decrease the through travel time but increase the left-turn travel time at high volumes;
- The CWA concept derives its advantage from better utilization of time space resources at an intersection. One of the main advantages of intersections with CWAs is CWAs increase the intersection capacity and lower the average travel time when volume is high, especially with a high left-turn demand; and
- Acknowledging the limitation of the CWA concept: the signal timing plan with CWAs is not as flexible at the main intersection, which may affect the overall effectiveness of CWA operation. This is evident when traffic demand is very imbalanced - for example, if the necessary green time for a NB approach is much shorter than the SB approach then the main intersection signal can only adopt a longer timing plan for the corresponding phase and waste valuable time for the NB approach.

Overall, CWA installation at conventional intersections is recommended, if conditions allow, when volume is high and not very imbalanced, especially when left-turn volume is high.

Future Work

Full-CWA Design

CWAs can be a cost-effective solution when an intersection faces high demand but limited land use. Theoretically, a full-CWA design should generate greater benefits than a partial-CWA design. An evaluation of full-CWA performance should be considered in the future research.

Sign and Signal Design

Sign and signal design for CWAs are not included in the *MUTCD*. This research does not focus on traffic signal and sign design, but it is necessary to develop and evaluate these designs for CWAs. For example, the signal heads shown in Figure 24 might be adopted for the approach with partial-CWAs in the main intersection. As shown in the figure, the middle lane is used as CWAs. The signal heads for CWAs can indicate direction of travel. When CWAs serve left-turn vehicles, the signal face shall display a left-turn green arrow signal indication. When through vehicles are served in CWAs, the signal face shall display a through green arrow signal indication.

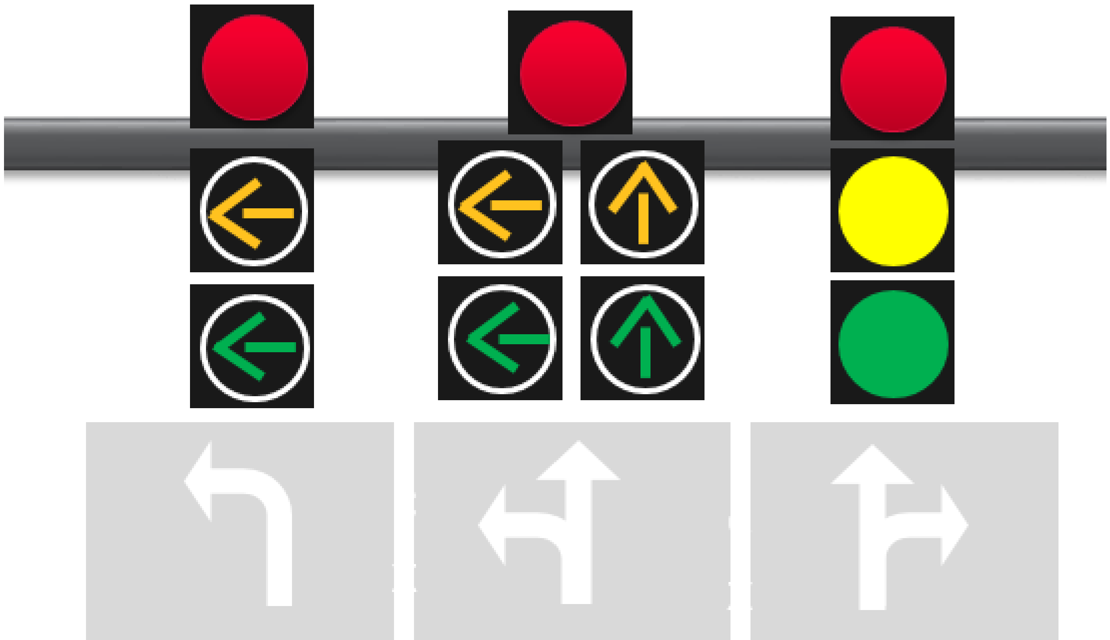


Figure 24 Example of Signal Heads for SB Approach in Main Intersection.

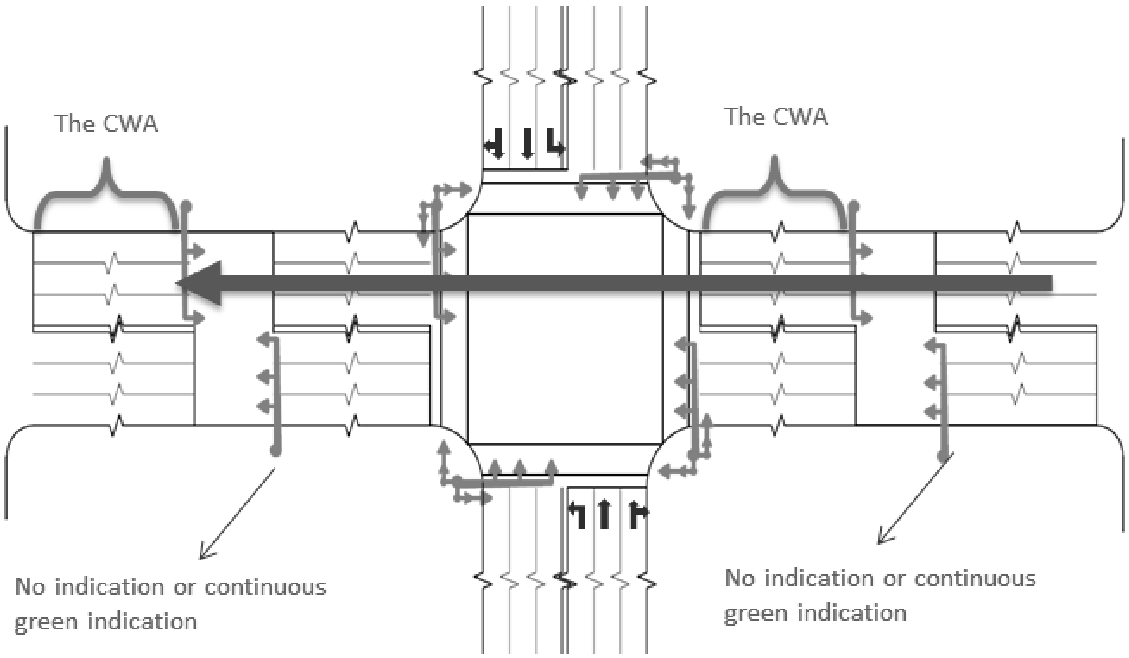
As used in reversible lane systems, Advance Intersection Lane Control Signs may be utilized to indicate the configuration of the approach lanes. Drivers can therefore be prepared for CWAs ahead. (16) Since CWAs can be used for both through vehicle and left-turn vehicles, overhead changeable-message signs are demanded together with the pre-signal to give instructions to drivers about when to enter CWAs and which lanes to occupy. The effectiveness of CWA sign and signal design requires further investigation.

Inactivate CWAs in Certain Time Periods

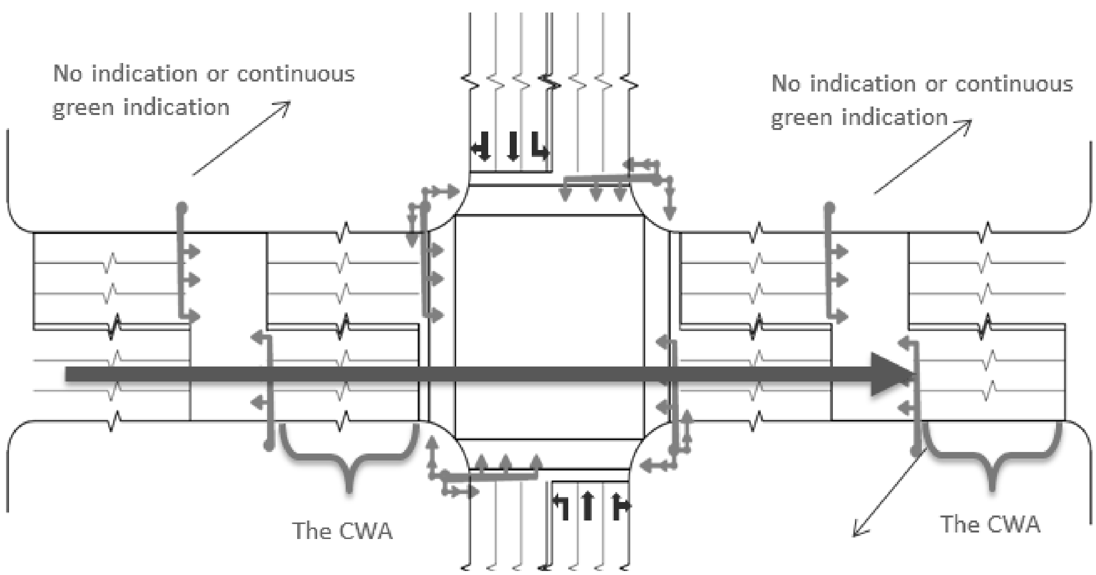
As stated before, one of the advantages of CWAs is that CWAs do not require huge changes to intersection layout. With the help of overhead signals and variable-message signs, an intersection can change its signal control strategies between conventional signal control and CWA signal control. When CWA operation is turned off, pre-signal indication will indicate green constantly. This allows vehicles to move forward into the downstream of the approach and follow the traffic rules of conventional intersections. Transition display is needed to clear CWAs during the control strategies transition. The display design can refer to Figure 8.

Inactivate CWAs in One Direction

CWA strategy can be adopted for one-directional or be bi-directional operation. As shown in Figure 25, CWA design can help serve morning peak and afternoon peak separately. For example, if most commuters are heading west in the morning peak hours, the intersection can operate CWAs only in the WB approach (Figure 25 (a)). And in the afternoon peak hours, only the EB approach utilizes the CWA signal control (Figure 25(b)) to serve commuters heading east. Also, allowing only one approach to operate CWA signal strategy may avoid overlapping of turning paths. The pre-signal indications in the inactive direction will be a continuous green indication. In such a situation, the left-turn vehicles, as usual, will use the left-lane to turn left and the through/right vehicles will use the two right lanes to clear the intersection. CWAs used for only one direction can help serve typical commuting patterns in peak hours, but the effectiveness still needs to be studied further.



(a)The commuter traffic heads west in morning/afternoon peak hours



(b) The commuter traffic heads east in afternoon/morning peak hours
Figure 25 CWAs used for Commuter Traffic.

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