EFFICIENT START FOR LAGGING LEFT-TURN PHASES

A Thesis Presented

by

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Abstract

At signalized intersections with protected left-turn phases, there are four phasing sequences for left-turn movement: leading, lagging, lead-lag, and lag-lead left-turn. Different left-turn phases have been shown to result in different impacts on delay, capacity and safety. Compared to leading left-turn phasing, which best uses slack time, lagging left-turns are frequently objected to be implemented because they are contrary to motorists’ expectancy and they may increase start-up lost time. However, lagging left-turn is the most efficient phasing sequence for traffic operation with coordinated phases along arterials because it can provide better progression and wider green band width and create a safer environment for all users, especially pedestrians and cyclists.

This thesis focuses on the efficient start for lagging left-turn phase for two situations: fully actuated isolated intersections and coordinated-actuated arterials. Intelligent algorithms of efficient start for lagging left-turn phasing were developed for these two specific situations, and the algorithms are tested in VISSIM. Intelligent algorithms applied “trap” logic to provide green durations needed for left-turn phases by counting the number of vehicles in the trap. Intelligent algorithms use “traps” to estimate green duration for the lagging left-turn phase and to predict green end for the concurrent through phase, which has the same green end as the lagging left-turn phase, to establish an efficient start for the lagging left-turn phase. Comparisons were made between intelligent control algorithms and standard control algorithms for different left-turn phasing sequences in terms of performance measures such as cycle length, average traffic delay, average green duration and overflow frequency for the focused movements. The results show that at isolated intersections, compared to standard lagging left-turn phasing, intelligent lagging left-turn phasing results in less overall delay and better uses slack time. For coordinated arterials, compared to standard leading and standard lagging, intelligent lagging left-turn phasing results in smallest overall network delay. It also results in lower overflow frequency because of the prediction logic and green extension logic. As a whole, the intelligent lagging left-turn phasing performs as well as leading left-turn phasing in terms of slack time utilization, while still maintaining its advantages on safety and progression.
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1. Introduction

1.1 Objective

When intelligently designed, traffic signal control can improve operational performance for all road users, including vehicles, pedestrians, or bicyclists. Intelligent traffic signal control allocates time in the most efficient way between conflicting traffic streams so as to maximize capacity, minimize delay and improve safety. With efficient control, the needed footprint of a road can sometimes be reduced, allowing scarce land to be used for other purposes and minimizing the negative impact of traffic on the environment. This thesis addresses one aspect of traffic signal control logic --- deciding when to start and end lagging left-turn phases in a way that minimizes wasted green time, while preserving the safety and progression benefits of lagging, as opposed to leading, left-turn phasing.

At signalized intersections, traffic signal can be controlled in two different ways: fixed (pre-timed) control and actuated control. **Actuated control** operates mainly depending on detector information, ending green phases when moving traffic is no longer detected and starting green phases in response to detecting queued vehicles. Green times and cycle length vary from cycle to cycle depending on actual traffic demand. For the situation in which actual traffic volume is very below capacity (maximum number of vehicles that can pass a certain point on a specific road), green indication terminates if there is a critical gap in traffic (duration that that the corresponding detector is not occupied, typically 2 or 3 seconds). On the other hand, if actual traffic volume is close to capacity, the traffic signal controller works more like the fixed-time control, with maximum green time governing signal operation. Actuated control is mainly applied to isolated intersection. **Fixed-time control** operates with fixed cycle length. Green time for each phase does not change from cycle to cycle. Green times, and cycle length are selected according to historic traffic data; phases then run as scheduled regardless of whether there are vehicles approaching or not. Timing plans may vary for different periods of a day, which are typically AM peak, PM peak, and off-peak. Fixed-time control is preferred for controlling signals along the arterial because it allows them to be coordinated, with fixed offsets that allow through traffic to progress with little delay. With modern arterial control, minor phases are typically actuated, while cycle length and offsets for the arterial phases are fixed.
Whether a signalized intersection uses fixed-time control or actuated control, there are different signal control schemes to accommodate left-turn vehicular movements to improve operational efficiency. The default method is permitted or permissive left-turns, meaning vehicles may turn left when they face a green ball and there is a safe gap in the opposing through movement, which is also facing green ball. Another common signal control schemes protected left-turn control, in which left-turn vehicles may proceed with their movements only when they receive a green arrow, indicating exclusive conflict-free right-of-way for the left-turn movement. The combination of protected and permitted schemes is also applied at many intersections. This thesis deals only with protected left-turns.

Since the protected left-turn phases conflict with the opposite direction through phase, it can either be sequenced so that it precedes the opposing through phase (leading left-turns) or following it (lagging left-turn phase). Different left-turn phasing sequences can result in significant differences in vehicular delay and safety. At both isolated intersections and on arterials, leading left-turns are typically preferred because they make the best use of slack time, as explained in Chapter 3, and thus minimize delay. Standard control for starting and ending lagging left-turn phases usually involves wasting green time, making control less efficient. However, lagging left-turns offer several advantages: improved safety and, on arterial, improved progression.

The objective of this thesis is to develop intelligent logic for starting and ending lagging left-turn phases that minimizes wasted green time and uses slack time more efficiently, so that the safety and progression benefits of lagging left-turns can be gained without the loss in efficiency that typically accompanies lagging left-turns.

1.2 Structure of Thesis

Chapter 2 provides a general background on terminology and assumptions related to traffic signal control. Chapter 3 discusses the advantages of leading versus lagging left-turn phasing. Chapter 4 explains the current standard control and newly developed intelligent algorithms for lagging left-turn control for isolated intersections and for coordinated arterials. Simulation experiments for comparing standard control with intelligent algorithms at isolated intersection and on a coordinated arterial are described in Chapter 5. Chapter 6 presents and analyzes the
simulation results, identifying the advantages of intelligent lagging left-turn control logic over standard control. Chapter 7 offers conclusions and recommendations for future work.
2. Traffic Signal Control Terminology and Assumptions

At a typical four-leg signalized intersection, each approach has one or more traffic streams, which can consist of left, right and through vehicular movement if each movement has its own approach lanes, pedestrians and transit vehicles if they have their own lane, all of which interact with each other. Where movements share approach lanes, a traffic stream can include multiple movements such as through and right movements. Among those different streams, some of them are concurrent, which can run at the same time, such as the through and left turn stream from a same approach, and some of them are conflicting with each other and therefore can only run sequentially, such as a left-turn movement and opposing through movement. A traffic signal timing plan allocates time to the different streams so that all are served in one cycle.

Left-turn movements are a major concern when considering intersection operation in terms of traffic delay and intersection capacity. Typically, left-turn movements may be controlled in three different ways: permitted left-turn phasing, protected left-turn phasing or mixed protected-permitted left-turn phasing. With permitted control, left-turning vehicles receive a green ball and run concurrently with the adjacent through movement, proceeding only when there is a safe gap in the opposing through traffic. With protected control, left-turning vehicles receive a green arrow rather than a green ball, and no conflicting traffic streams are allowed to proceed at the same time. Mixed protected-permitted control includes protected-permitted (leading protected left-turn) and permitted-protected (lagging protected left-turn). During the protected interval, left-turning vehicles receive a green arrow while no other conflicting vehicles are allowed to enter the intersection, and during the permitted interval, the signal indication is a green ball, indicating that drivers can only proceed when there is a safe gap between two successive vehicles in the opposing through traffic.

In terms of traffic lane arrangement at intersection for left-turn phasing, left-turn movements can share a traffic lane with adjacent through movement, or has its dedicated left-turn lane. Layout of a four-leg intersection with exclusive left-turn phase and dedicated left-turn lane is depicted in Figure 1. Two main streams (left-turn and through movement, with which vehicles turning right can run concurrently) are shown for all four approaches, denoted as EB/L (Eastbound), WB/L
(Westbound), SB/L (Southbound), NB/L (Northbound), respectively. The red line in the figure indicates the stop line.

In addition to various control types for left-turn movement, left-turn phasing sequences can lead to significantly different impacts on traffic signal operations. For a given street whose two approaches both have exclusive left-turn phases, left-turn movement may be arranged in four different phasing sequences (leading left-turn phasing, lagging left-turn phasing, lead-lag and lag-lead left-turn phasing), which are shown in Figure 1. Leading and lagging left-turn phasing have their own advantages. Lagging left-turn phasing can lead to lower delay in coordinated signal systems. Assume EB-WB is the main street and EB through is the major direction with coordinated control. To illustrate the four different left-turn phasing sequences, only the half cycle for westbound-eastbound is depicted in a dual ring diagram, which is not scaled. Dual ring diagram identifies that phase may operate one after another and typically, conflicting phases are organized in a particular order. It is a way to show how parallel phases and conflicting phases operate with traffic signal control. In a dual ring diagram, a barrier separates the traffic travelling in the north-south direction from the traffic in the east-west direction. In the figure below, duration of two through movements and two left-turn movements are drawn with equal length, however, their actual durations are not required to be equal in actual operations. In the following figure, lower ring with bold box indicates it being critical ring. Critical ring identifies that sum of green durations of phases in the critical ring is longer than that in the non-critical ring, and therefore, it governs the half cycle length.
In a traffic signal timing plan, each stream should have its own green (G), yellow (Y) and red (R) interval. Summation of green, yellow and red duration yields cycle length. Regardless of which timing plan is applied at specific intersection, yellow time is generally determined based on vehicle speed (speed limit), intersection geometry and local policy. With fixed-time control, the green interval, red interval, and cycle length remain unchanged over different cycles, and are determined depending on the historic traffic demand. However, different signal timing plans can be applied during different periods of a day, such as peak period and off-peak period. With
actuated control, green interval duration varies from cycle to cycle in a range between minimum policy green and maximum allowable green. Using data from an in-road detection system, which can either detect a gap to tell controller to terminate green phase or to extend the green phase until its maximum green is satisfied if there is no gap detected. The first termination strategy is normally called gap-out and second one is called max-out.

The time duration between the barriers (split for a half cycle) is determined by the needs of the critical conflict group. A conflict group is a group of streams that are not compatible with each other, that is, every traffic stream in the group is in conflict with every other. Traffic steams in a conflict group must run sequentially to avoid the conflict, and so the time needed to serve the group is the sum of the time needed to serve each member. The critical conflict group is the conflict group that requires the longest combined splits, i.e., summation of needed green time, yellow time and clearance time for the critical conflict group is longer than that for other conflict groups. In Figure 1, the pairs WB-EBL and EB-WBL are two different conflict groups. The one that requires longer time duration is the critical conflict group, so either WB-EBL or EB-WBL can be the critical conflict group, depending on its actual traffic volume and clearance time requirement.

Based on a dual ring diagram, the ring consisting of critical conflict groups is named the critical ring, and the other one is consequently named as non-critical ring. Because critical ring governs the duration of the half cycle, therefore, there is slack time existing in the non-critical ring. Slack time is the difference between half cycle split and the actual time needed for non-critical ring. Slack time (case with lead-lead left-turn phase) is illustrated in Figure 2. Assume upper ring is the critical ring, and lower ring is the non-critical ring, dashed box is the slack time. Since the critical ring governs half cycle length, let green duration of EBL be 15s, green duration of WBT be 30s, then the half cycle is 45s. However, for the movements in lower ring, WBL needs 12s of green time, and EBT needs 28s of green time, and therefore, there are 5s (15 + 30 – 12 – 28) of slack time existing in the lower ring.
Slack time can be assigned to the through movement or the left-turn movement, or slack time can be allocated to both movements. Then, how to allocate and utilize the slack time becomes an issue for improving the efficiency of intersection operation. Typically, slack time is preferably given to the through movement rather than the left-turn movement because the traffic demand of through movement is usually much greater than that of the left-turn movement, and consequently allocating slack time to the through movement can benefit the intersection operation more by potentially serving more vehicles.

In coordinated signal systems, all intersections along an arterial operate with a common cycle length, which is determined by the critical intersection, which is the one requiring the longest cycle length among all intersections. **Progression (green-wave bandwidth)** is an essential element to the effectiveness of a coordination system. Providing a longer green time to the through phases can lead to wider green bands and improve arterial progression. According to the previous discussion on slack time, allocating the slack time to the coordinated phases, which are commonly the through movements, can improve coordination effect on all intersections along the arterial, i.e., improving progression, maximizing intersection reserved capacity and minimizing average vehicular delay.

**Figure 2 Illustration of Slack Time.**
3. **Advantages of Leading Left-turns Versus Lagging Left-turns**

Chapter 2 showed that left-turns could be sequenced either leading or lagging. The first section of this chapter is an introduction to the flexibility in timing left-turns afforded by dual ring control. The second section describes the general advantages and disadvantages of leading left-turn phasing versus lagging left-turn phasing. The last section is the literature review on left-turn treatments in terms of operational efficiency, coordination and safety.

3.1 **Flexibility of Dual Ring Control**

As stated previously, left-turns can be permitted, protected-only, and a mix of protected and permitted (protected-permitted and permitted-protected). This thesis only takes protected-only left-turn control into consideration. Therefore, all following discussions and analysis are for protected-only left-turns. A particular left-turn movement can be served as either leading or lagging. For the two opposing left-turns on a given street, four options to serve left-turns are lead-lead, lag-lag, lead-lag, and lag-lead. Left-turn phasing can also be separated into two categories, simultaneous (single-ring) left-turn phasing (simultaneous leading and simultaneous lagging left-turn phasing) and non-simultaneous (dual-ring) left-turn phasing [1]. The sequence diagram for simultaneous left-turn phasing and non-simultaneous left-turn phasing is illustrated in Figure 3 and Figure 4.

![Sequence Diagram for Simultaneous Left-turn Phasing](image)

**Figure 3 Single Ring, Simultaneous Left-turn Phasing Sequences.**

With single ring control, simultaneous left-turns start and terminate at the same time and therefore two parallel left-turn movements must operate with same duration. With dual ring control, left-turn phases are allowed to operate with parallel, as well as with the other left-turn, allowing the two left-turn phases to have different durations.
Because the flexibility afforded by dual ring control allows each left-turn phase to have its own duration, tailored to its own demands, it is almost universally preferred.

In the dual ring diagram (Figure 5), assume the upper ring is the critical ring, and assume that each phase uses as little time as is needed to serve its demand. Minimizing phase durations leads to short cycles and therefore shorter red times, which generally minimizes delay. The critical ring governs the length of the half cycle and as a result, there is slack time in the non-critical ring.
Slack time can be assigned to either left-turn movement or through movement, or shared by both phases. With actuated control, the leading movements in the half-cycle terminate as soon as they gap out (subject to minimum green), yielding to the lagging phase in its respective ring. Then, because the two lagging phases must terminate simultaneously (at a “barrier”, followed by the other street’s half-cycle), there will necessarily be some slack time in the non-critical lagging left-turn phase. Therefore, leading left-turn phasing gives slack time to the through movement, while lagging left-turn phasing gives the slack time to the left-turn phase.

### 3.2 Advantages of Leading versus Lagging Left-turn Phasing

According to the previous discussion on the difference between leading and lagging left-turn phasing, each control scheme and phasing sequence has its own advantages over the other from the perspective of traffic delay, coordination and safety.

Leading left-turn has an advantage in slack time utilization. Left-turn movements almost always have lower traffic demand than the opposing through movement. With leading left-turn phasing, slack time goes to a through movement, which, because of its higher demand, can therefore make better use of slack time (i.e., by serving more vehicles that would otherwise have to wait for the next cycle), because left-turn phase terminates immediately if its traffic demand is satisfied. At an intersection applied with protected-permitted left-turn, apart from the slack time utilization, lagging left-turn phase is beneficial to the operational efficiency by legally allowing left-turn “sneakers” (across intersection during all-red period) to complete their movements at the end of phase.

Larry Robinson [1] made a summary on left-turn phasing based on earlier researches completed by Harvey Hawkins in 1963, by Benjamin McKay in 1966 and by Hummer in 1989. This paper summarized the benefits and drawbacks of different left-turn phasing treatments including protected-permitted, exclusive protected left-turn phasing. Each different left-turn plays an advantageous role in certain situation and with specific purpose. Leading left-turn phasing is desirable where there is no left-turn lane and leading left-turn can reduce congestion and blockage at the intersection. Lagging left-turn phasing can improve progression where the intersections are with unequal space and it would not trap left-turn vehicle at the end of the phase.
With protected – permitted left-turns, lagging left-turn results in greater intersection delay and left-turn movements delay at isolated intersection and there is no significant differences in stops, delay or travel time with different operating conditions [2]. Protected – permitted left-turn phasing results in shorter phase duration and therefore shorter cycle length comparing to protected only left-turn phasing. With fixed cycle length and phase duration, permitted-protected phasing results in less delay than protected only left-turn phasing [3]. Because a fraction of left-turning vehicles can be served during the permitted period if protected – permitted left-turn phasing is applied at intersections so that time needed to serve left-turning vehicles is shorter in this case than that in protected only situation. With protected – permitted left-turns, lagging left-turn (protected period comes after the permitted period) can generate excessive delay because there are fewer vehicles can be cleared in the permitted period, caused by heavy demand in the opposing through traffic at start of green so that there is fewer gaps can be detected.

Lag-lag left-turn phasing is commonly used in coordinated systems with closely spaced intersections, and lead-lag left-turn phasing is used to accommodate through movement progression, particularly in the situation that there is protected – permitted left-turn phasing involved [4]. Along an arterial, through traffic might arrive at the downstream intersection earlier or later compared to the green indication display, and then lagging left-turn phasing can benefit through movement by providing the green indication to through traffic when they arrive at the intersection, improving progression. With protected only left-turn phasing, a before and after study (before is a leading left-turn and after is a lagging left-turn) in Tucson, AZ, showed that lagging left-turn phasing allowed improved progression, reduced delay, and lowered overall intersection accidents [5]. Analysis of a pair of intersections showed that lagging left-turn phasing for the downstream signal generates less delay than leading left-turn does no matter which design was used at the upstream. Lagging design at both intersections yields best results in terms of overall intersection delay [6]. Lead-lag left-turn phasing had a significant impact in maximizing progression bandwidth. For a signal system with five or fewer signals, more than 70% of the cases (70 sets of 5-intersections among which there is at least one intersection with lead-lag) used lead-lag phasing to provide a maximum progression bandwidth. When the phase lengths of left-turn were equal, leading and lagging phasing made no difference in terms of
maximizing progression bandwidth. When the lengths were unequal, leading phasing showed some advantages over lagging left-turn phasing [7].

A lagging left-turn has its advantages in safety. With protected – permitted left-turns, lagging left-turn phasing (permitted-protected) results in lower percentage of LTHO (Left-Turn-Head-On) collision comparing to leading left-turn phasing (protected-permitted) [8]. Lagging left-turn phasing results in far less pedestrian – left-turn conflict than leading left-turns, while lagging left-turn also has less conflict with oncoming through traffic [9]. With protected only left-turns, conversion of left-turn phasing from leading arrow to lagging arrow in Arizona has shown great benefits in safety improvement [10]. The mean accident rate for lagging left-turn phasing was found to be slightly lower than the accident rate for leading left-turn phasing [11]. Leading left-turn phasing sequence cause greater vehicle-pedestrian accident risk than lagging left-turn phasing at intersections with heavy pedestrian volume [12]. The mean intersection collision rate was statistically significantly lower for the lagging left arrow. Protected only left-turn had the least collision rate compared to protected-permissive and permissive without dedicated left-turn lane based on third-car actuation (call if there are 3 cars in queue) [13].

3.3 Left-turn Phasing’s Impact on Pedestrian

Generally, lagging left-turn phasing has some advantage (illustrated in Figure 6) over leading left-turn phasing in terms of pedestrian safety at isolated intersection. It offers less opportunity for pedestrians and vehicles turning left to get involved in conflict or crash between them. Along an arterial, traffic demand might arrive early or late compared to the start of its green indication. In cases when through traffic has not arrived when signal is ready to switch to green, it might be beneficial to delay the start of through phase. On the contrary, in cases when through traffic arrives earlier than expected, delaying start of left-turn phase is more beneficial. Therefore, for serial non-ideally spaced intersections, lagging left-turn phases create more benefits than leading left-turn phases by providing better progression and making efficient use of green time, meanwhile safety for motorists, pedestrians and cyclists is improved as well [14].
Generally, pedestrians prefer to proceed with their movements following the conflicting traffic streams, e.g., north-south pedestrian is conflicting with east-west vehicular movement. Take only northbound vehicle and southbound pedestrian as an example and the other conflicting directions work the same way. According to the indication in the figure, when northbound movement is ready to begin, in case where leading left-turn phasing is applied, it is possible that vehicle
turning left meets pedestrian from the opposing direction just at the conflict point, while lagging left-turn phasing can erase this conflict by starting northbound through movement (concurrent with pedestrian from either direction) first.

General advantages of leading left-turn phasing versus lagging left-turn phasing and findings on protected – permitted and protected only lagging left-turn phasing from previous researches are summarized in Table 1 and Table 2, respectively.

Table 1 Advantages of Leading versus Lagging Left-turn Phasing

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leading Left-turn Phasing</strong></td>
<td>• Better slack time utilization, allocating slack time to the following through movement</td>
</tr>
<tr>
<td></td>
<td>• Desirable where left-turn lanes do not exist, avoid blockage to the through traffic</td>
</tr>
<tr>
<td></td>
<td>• Avoid potential blockage on adjacent through movement if left-turn lanes do exist</td>
</tr>
<tr>
<td><strong>Lagging Left-turn Phasing</strong></td>
<td>• Safer for pedestrians and cyclists, reducing conflict opportunities between pedestrians and vehicles</td>
</tr>
<tr>
<td></td>
<td>• Improves progression (reduces delay) in coordinated signal system, by better accommodating left-turn vehicles in the platoon and by giving left-turners less delay at their following intersection</td>
</tr>
<tr>
<td></td>
<td>• Better for coordination for closely spaced intersection (lead-lag or lag-lag phasing)</td>
</tr>
</tbody>
</table>
Table 2 Summary of Findings on Protected + permitted and Protected-only Lagging Left-Turn Phasing

<table>
<thead>
<tr>
<th></th>
<th>Findings from previous research</th>
</tr>
</thead>
</table>
| **Protected + permitted** | • Results in less pedestrian-left-turn conflict and less conflict with oncoming traffic than permitted-protected.  
• Results in less left-turn-head-on conflict than permitted-protected phasing  
• Results in shorter cycle length, shorter phase duration, and lower traffic delay than protected-only phasing.                                                                                                                                 |
| **Protected-only**   | • In coordinated systems, some intersection should have lead-lag to accommodate through movement progression  
• In coordinated systems, lagging left-turn phasing offers better progression, less delay to left-turning traffic  
• Lagging left-turn results in less vehicle-vehicle and pedestrian-vehicle conflict                                                                                                                                 |

Previous research has been used to identify the impact of left-turn phasing sequences on coordination and safety, and to identify the advantages of lagging left-turn phasing versus leading left-turn phasing. However, research has not been conducted focusing on how to start the lagging left-turn phasing efficiently to better utilize the time at individual isolated intersection and to provide better progression and better operation for coordinated-actuated intersections, and how the efficient start of lagging left-turn behaves differently from standard control logic as well as other left-turn phasing sequences. Although lagging left-turn phasing has its advantages on arterial progression and safety, it use slack time more efficiently when comparing to leading left-turn phasing. Therefore, this thesis is to develop more intelligent control algorithms for lagging left-turn phasing so that it can limit slack time given to left-turn movements and give slack time
instead to opposing through movement, and then traffic signals can have the benefits of lagging left-turn phasing without its disadvantages.
4. Intelligent Algorithms for Efficient Start and End of Lagging Left-turn Phasing

Lagging left-turn phasing generates several benefits compared to leading left-turn phasing for individual isolated intersection as well as a series of intersections along arterial from the perspective of safety and coordination. However, a drawback of lagging left-turn phasing is its disadvantageous utilization of slack time compared to leading left-turn phasing.

In this chapter, intelligent algorithms for efficient start and end of lagging left-turn phasing are developed for isolated intersection with full actuation control as well as for coordinated-actuated intersections along an arterial. At intersections with full actuation, if a left is lagging, it gets the slack time, which is not efficient. For this reason, a fixed start time by giving the opposing through movement a long maximum green. That gives slack time to the opposing through movement, but it also lengthens the cycle, hurting the general efficiency of actuated control.

This chapter consists of three sections, which focus on isolated intersection and coordinated arterials, establishing the efficient start for lagging left-turn phasing for individual isolated intersection with full actuation control as well as series of coordinated intersections along an arterial. First, prediction-based green time determination for lagging left-turn phasing is discussed and analyzed, followed by an explanation and analysis on floating force-off of the opposing through movement associated with lagging left-turn phasing. Finally, there is a discussion and comparison of green extension (including the allowable maximum green extension) for lagging left-turn phasing and green extension as a compensation resource.

4.1 Green Time Prediction for Lagging Left-turn Phasing

At intersections where lagging left-turn phasing is applied, an opposing through movement is served before starting the conflicting left-turn movement. There will be slack time existing in the non-critical ring, and allocation of slack time becomes an important issue in terms of effectiveness of time utilization. Question that the through movement in the non-critical ring should be terminated or extended at the moment it gaps out comes out. This question can be easily addressed if the green time requirement of the lagging left-turn phasing is known in advance. In order to make better use of slack time, green time prediction logic is developed for
lagging left-turn phasing. Green time prediction is determined based on “trap” logic. A trap consists of a pair of detectors, predicting green time for lagging left-turn phasing based on a count of the number of vehicles stored between the detectors. Trap configurations are illustrated in Figure 7.

![Figure 7 Illustration of Trap Configuration for Lagging Left-turn Phasing.](image)

There are two types of trap shown in figure, named as main trap and secondary trap, respectively. Entrance detectors are installed at the diverge point (start of the dedicated left-turn lane). The main trap is the space between stop-line and diverge point, and the secondary trap indicates the space between entrance detector (located at the diverge point) and an advanced detector located further upstream. The main trap is mainly used for predicting green time need for the left-turn, while the secondary trap, specifically designed for full actuation situation, is used for green end prediction for the through movement.

Because in coordinated signal systems intersections generally have fixed cycle length and scheduled end point for coordinated phases, the desired start of lagging left-turn phasing can be found by tracing back from the end point for the coordinated phase to give an adequate amount of time to satisfy the left-turn demand detected in the main trap. However, for isolated intersections with fully actuated control, there is no fixed end point for the critical through movement (called the coordinated phase for consistency). Therefore, it is necessary to predict the end of green for this through movement. For these reasons, efficient start of lagging left-turn phasing is discussed separately for isolated fully actuated intersections and for coordinated intersections.
4.1.1 Isolated Intersection with Full Actuation

At intersections where fully actuated control is applied, each phase operates freely and the duration of the green interval is only based on the actual traffic volume. When traffic demand of one movement is satisfied (phase can either gap out or max out), the green indication switches to the following conflicting movement. In this case, slack time in the non-critical ring will be allocated to left-turn movement if lagging left-turn phasing is applied, which is against the desire for efficiency of allocating slack time to the through movement. Thus, in order to establish an efficient start of green for lagging left-turn phasing, two elements should be taken into account: 1) the end point (in time) of the parallel through movement and 2) the green time duration of the lagging left-turn phase or phases. Based on the trap configuration shown in Figure 7, assume $N_1$ is number of vehicles stored in the main trap on left-turn lane, $N_2$ is the number of vehicles stored in the main trap on through lane, and $N_3$ is the number of vehicles stored in the secondary trap. In addition, assume $H_{sat}$ is the saturation headway (typical value is 2s/vehicle).

![Diagram of dual ring intersection](image)

**Figure 8 Dual Ring Diagram for Isolated Intersection.**

Two cases are shown in Figure 8, lead-lag left-turn phasing and lag-lag left-turn phasing. The lower ring is the critical ring (EB + WBL). In the figure above, time point $t = b$ indicates the termination of non-critical through movement, time point $t = a$ indicates the green end for the critical through movement, which is variable for isolated intersections with full actuation. Besides that, $GT_{EBL}$ indicates the green duration of the non-critical left-turn phasing (lagging phase in case with lead-lag left-turn phase), and $GT_{WBL}$ indicates the green duration of the critical left-turn phase.
Based on the previous assumptions and notations, the needed green duration of a lagging left-turn phase can be expressed as:

\[
G_{LLT,\text{needed}} = \frac{(N_1 + p \times N_3) \times H_{sat}}{N_l + L}
\]  
(Equation 1)

Where \( G_{LLT,\text{needed}} \) = green duration needed for lagging left-turn phase;

\( N_1 \) = number of vehicles detected in the main trap (left-turn bay);

\( N_3 \) = number of vehicles detected in the secondary trap;

\( N_l \) = number of traffic lanes (left turn bay), which is one for most left-turn bays;

\( p \) = proportion of left-turn demand to total volume (approach volume);

\( H_{sat} \) = saturation headway (s);

\( L \) = start-up-lost-time, let it be 2s.

Due to the great difference in traffic volume between the through movement and left-turn movements, in some cases the queue length reaches beyond the diverging point of the left-turn lane, so that left-turn vehicles are blocked by through traffic in the secondary trap. Then, it is necessary to consider the potential left-turning vehicles in the secondary trap so as to provide a good and more accurate estimation on the green time duration for lagging left-turn phasing. \( p \) value is supposed to identify the proportion of left-turn vehicles in the secondary trap.

Now that green duration of lagging left-turn phasing has been appropriately predicted based on trap logic, an efficient start of the lagging left-turn phasing with better slack time utilization would be realized if the end of the critical through movement were predicted as well. Green start of the critical through movement follows the critical leading left-turn phase and it can be easily identified, let it be \( t = t_{start} \). Therefore, the predicted green end of the critical through movement is:

\[
t_{end} = t_{start} + \frac{(N_2 + (1 - p) \times N_3) \times H_{sat}}{N_l + L}
\]  
(Equation 2)

Where \( t_{end} \) = green end for the critical through movement;

\( t_{start} \) = green start for the critical through movement;

\( N_2 \) = number of vehicles detected in the main trap (through lane);

\( N_3 \) = number of vehicles detected in the secondary trap;

\( N_l \) = number of traffic lanes, which is two for through movement in this study;
\[ p = \text{proportion of left-turn demand to total volume}; \]
\[ H_{\text{sat}} = \text{saturation headway (s)}; \]
\[ L = \text{start-up-lost-time, let it be 2s}. \]

### 4.1.1.1 Green Start of Lagging Left-Turn (Case: Lead-Lag Phasing)

In the case with lead-lag phasing, the critical left-turn phase terminates immediately once it gaps out and the phase switches to the lagging critical through movement. The lagging left-turn phase should terminate together with the parallel through movement at the barrier. Two key elements, the green duration of the lagging left-turn phasing and green end of the critical through movement, have been identified based on the trap logic. Therefore, the green start of the lagging left-turn in the case with lead-lag phasing yields:

\[
 t_{\text{start}} = t_{\text{end}} - G_{\text{LLT, needed}} \tag{Equation 3}
\]

Where

- \( t_{\text{start}} \) = green start of lagging left-turn;
- \( t_{\text{end}} \) = green end of the critical through movement (parallel to lagging left-turn);
- \( G_{\text{LLT, needed}} \) = needed green duration for lagging left-turn.

### 4.1.1.2 Green Start of Lagging Left-Turn (Case: Lag-Lag Phasing)

It is slightly different to start the left-turn movement in the case with lag-lag left-turn phasing. In this case, both left-turn phases begin after the through parallel through movements, thus, two green durations for EBL and WBL are both estimated so as to define the difference in those two green durations and to provide an efficient start for left-turn phase. Then, it is necessary to check the difference in expected green duration of the two lagging left-turn phases when the first through movement gaps out. Referring to the ring diagram for Case 2 in Figure 8, assume WBT gaps out earlier than EBT. Green end of EB would be at \( t = a \), and WBT gaps out at \( t = b \). Green duration needed for WBL and EBL is \( G_{\text{T WBL}} \) and \( G_{\text{T EBL}} \), respectively. WBT should terminate or extend based on the following conditions:

\[
 WBT \text{ should } \begin{cases} \text{Terminate} & \text{if } a + G_{\text{T WBL}} - G_{\text{T EBL}} < b; \\ \text{Extend} & \text{if } a + G_{\text{T WBL}} - G_{\text{T EBL}} > b; \end{cases}
\]
It is also possible that EBT gaps out earlier than WBT at times. If so, similar logic of determining whether to terminate or to extend EBT works in that situation.

Prediction-based logic for selecting the start of the non-critical lagging left-turn and green end of the critical through movement should improve the operation of lagging left-turn phasing. However, a lagging left-turn phase should be skipped if there is no traffic demand when the conflicting through movement gaps out. Suppose EBL has been skipped and WBT is therefore being extended, and then an EBL vehicle arrives. The phase can still switch if the vehicle arrives early enough. The decision on whether the left-turning vehicle arrives at the intersection early enough for a “late switch” relies on whether the remaining time until the predicted green end of the critical through movement is greater than EBL’s minimum split. If the duration from the left-turn vehicle’s arriving time to the predicted green end of the critical through movement is greater than the sum of EBL’s minimum green duration and change interval, the phase should switch to lagging left-turn; otherwise, the left-turn phase should remain skipped.

Apart from lead-lag and lag-lag left-turn phasing, there is, actually, one additional case, lag-lead left-turn phasing, in which the critical left-turn movement operates as the lagging phasing. Because there is no slack time in the critical ring, there is no issue with slack time utilization in this case.

**4.1.2 Coordinated Intersections**

In a coordinated signal system, the traffic signal timing plan usually aims to provide a green wave for through traffic so that traffic travelling along the arterial can have less vehicular delay and fewer stops. At intersections where coordination-actuation control is applied, traffic streams other than the coordinated phase are actuated, meaning they immediately switch to serve the next conflicting traffic stream when they gap out (or max out). In coordinated systems, all intersections are with a fixed cycle length, and each phase at an intersection gets an assigned time. In this case, for the non-coordinated phases, they might gap out early, and therefore, slack time goes to coordinated phases, letting it start early. Coordinated phase has no gap-out detection, and it always runs until its scheduled termination point. Along the main arterial, the critical through phase is usually selected as coordinated phase. Many signal controllers require that there
be a coordinated phase in both ring, in which case the opposite through phase is also coordinated (meaning it may begin early but always terminates at the scheduled termination point).

Comparing an isolated intersection with fully actuated control, for which phase termination is primarily determined based on actual traffic demand, in coordinated systems, a common cycle length, governed by the critical intersection, is used at all intersections. The critical intersection is the one that has the greater traffic demand and requires more time. Therefore, there is little slack time (for the non-critical movements) at the critical intersection because fixed cycle length limits flexibility, and there is more slack time (for all movements) at non-critical intersections. With coordinated-actuated control, there is a scheduled termination point for the coordinated phases, and so it is unnecessary to predict the green end of the coordinated phase. Consequently, for coordinated intersections, the only element to establish the efficient start for lagging left-turn phasing is to estimate green duration of lagging left-turn phase with the prediction-based trap logic.

Again, referring to the trap configuration in Figure 7, the main trap on left-turn lane is used to determine the number of left turning vehicles that are waiting to be served in the left-turn bay, and the secondary trap is used to estimate the number of potential left turning vehicles upstream of the diverge point (entrance to the left-turn bay). The same logic for predicting the green duration of lagging left-turn phasing, developed for isolated intersections, can also be used in a coordinated system.

4.2 Floating Force-off for Opposing Through Movement (Intelligent)

In a coordinated system, a common cycle length is set up for all intersections and there is a scheduled termination point for all coordinated phases. According to these two fundamental features, establishing an efficient start for lagging left-turn phasing can be equivalently treated as determining an effective termination point for the opposing conflicting through traffic in terms of slack time utilization. For standard lagging left-turn phases in a coordinated system, fixed green time is assigned to the lagging left-turn phases, which is not efficient due to the traffic demand variation over the time, which leads to a changing requirement of green duration. Aiming to better use slack time, intelligent algorithms are developed to provide green time to left turning
vehicles according to the predication-based logic, which allows lagging left-turn phasing to operate with various green time durations.

Based on the fixed cycle length, the scheduled termination point of coordinated phase in the critical ring, and the variable green durations of lagging left-turn phase, the associated opposing through movement terminates with a **floating force-off**. When the through movement in the non-critical ring has a floating force-off, it terminates at different point in each cycle rather than at a fixed-point, which is the case in standard control. With a floating force-off for the leading through movement in the non-critical ring, the through phase will not terminate until a calculated switching point, which is calculated so that slack time, if available, is utilized by the through movement. Seen in Figure 9, since the green duration for EBL is estimated based on the trap logic in each cycle, it varies over the time. With a scheduled termination point for EBT, the termination point of WBT, \( t = b \), is also changing over the time rather than a fixed termination point.

![Figure 9 Illustration of Floating Force-Off.](image)

Two situations are described below, for both of which the critical conflict group is EBT & WBL. Coordinated phases are EBT and WBT. In Figure 10, time point \( b \) indicates the termination of the non-critical through movement (WBT); time point \( a \) indicates the scheduled termination point of the critical coordinated phase (EBT). Time duration \( GT_{EBL} \) and \( GT_{WBL} \) indicate the estimated green duration for two left-turn phases, EBL and WBL, respectively. Two green durations are determined based on the trap logic, by counting vehicles in the left-turn bay and
potential left-turn vehicles from upstream of the intersection. In addition, \( Y \) indicates yellow interval and \( AR \) indicates all-red period, where applicable.

Figure 10 Ring Diagram for Mixed Left-turn Phasing.
4.2.1 Lead-Lag Left-Turn Phasing

At intersections with lead-lag left-turn phasing, the leading left-turn phase terminates immediately once its traffic demand is satisfied, and then switches to the following conflicting through movement, a coordinated phase, which continues until its scheduled termination point and ends at the barrier together with the lagging left-turn phase. Seen in Figure 10 (case 1), WBL operates as a leading left phase, and terminates once it gaps out (or maxes out) and then switches to EBT. In the non-critical ring, EBL operates as a lagging left phase, and it is proposed to choose its start time based on its scheduled termination point, which is \( t = a \), and its predicted green duration need, which is \( GT_{EBL} \).

Therefore, in the non-critical ring, the termination point, \( t = b \) for WBT in the situation of lead-lag left-turn phasing is \( a - GT_{EBL} - Y - AR \). Since the needed green duration of EBL changes from cycle to cycle according to the actual traffic demand, the termination point for WBT will be a floating point, not a fixed point.

4.2.2 Lag-Lag Left-turn Phasing

At intersections where both left-turn movements operate as lagging, the green duration needed for the two left-turn phases are estimated based on the trap logic. Given the scheduled termination point of the critical through movement, the termination point of the non-critical through movement is established based on the difference in two estimated green durations between those two lagging left-turn phases. Since the needed green duration of two lagging left-turn phases varies from cycle to cycle, the termination point of the non-critical through movement can be regarded as a floating termination. Two lagging left-turn phases terminate together at the barrier after both have either gapped out or maxed out.

Normally, traffic demand of the critical through movement (EBT) is greater than that of the non-critical through movement (WBT), so that WBT gaps out earlier than the scheduled termination point for EBT. Then, whether to extend the WBT or to terminate WBT is a question of better utilizing the slack time while leaving enough time to serve the lagging left-turn. In Figure 10, green duration for two lagging left-turn phases is denoted as \( GT_{EBL} \) (EBL) and \( GT_{WBL} \) (WBL), respectively. In addition, termination point for two through movements is \( t = a \) (EBT) and \( t = b \)
If the non-critical lagging left-turn (EBL) requires a longer green duration than the critical lagging left-turn (WBL), as shown in Figure 10 (case 2), the termination point of WBT will be prior to scheduled termination point a, at time $t = a + GT_{WBL} - GT_{EBL}$. In this case, based on the prediction for the green end for critical through movement, $t = a$, and the two lagging left-turn phases’ green duration, slack time can be assigned to the through movement in the non-critical ring, thus, improving the efficiency.

On the other hand, the non-critical lagging left-turn (EBL) might require a shorter green duration than the critical lagging left-turn (WBL), as shown in Figure 10 (case 3). Then the termination point of WBT would be after scheduled termination point a, again at time $t = a + GT_{WBL} - GT_{EBL}$.

### 4.3 Green Extension for Lagging Left-turn and Green Extension Recovery

Previous discussion on green duration prediction for lagging left-turn phases is based on trap logic, which estimates needed green time for left turning vehicles according to the traffic counts. In this case, the lagging left-turn phase will terminate at the barrier together with the adjacent through traffic. However, when considering randomness in vehicle arrivals, it is possible that additional turning vehicles will arrive late at the left-turn bay, so that the lagging left-turn phase will not have gapped out yet at the scheduled termination point of the coordinated phase. In this case, there will be overflow if the scheduled termination point is kept. Another tactic is to extend the termination point until left-turn traffic demand is satisfied.

Since a common cycle length is set up for all intersections along the arterial, extending the coordinated phase’s green means that current cycle length will be longer than the common cycle length. In order to guarantee coordination effect over time and make the average cycle length at an intersection to be the same as the common cycle length, the “borrowed” time, the extension part, should be recovered in the next cycle. For example, assume the scheduled termination point in the current cycle is $t = a$, and therefore the scheduled termination point in the following cycle should be $t' = a + C$ ($C$ is cycle length). However, the actual termination point in the current cycle is $t_1 = a + G_{extend}$ ($G_{extend}$ is the green extension), and therefore, in order to guarantee cycle length to be fixed as the common cycle length, the scheduled termination point of the critical coordinated phase will be $t_1' = t_1 + C - G_{extend}$. The “borrowed” time from the next cycle is illustrated in Figure 11.
4.3.1 Green Extension for Lagging Left-turn Phasing

When the degree of saturation of an intersection (demand to capacity ratio) is low or moderate, (e.g., in tests for this thesis, use 0.85 as a cutoff), traffic demand of the lagging left-turn phasing can usually be satisfied prior to the scheduled termination point of the adjacent coordinated phase. When the degree of saturation is high (e.g., > 0.90) or close to 1, in most cycles, some vehicles might not be served till or even after the scheduled termination point. At times, due to the randomness in vehicle arrivals, lagging left turning vehicles might arrive late in cycle so that the left-turn phase has not gapped out when time reaches the scheduled termination point. In these situations, it would occur additional delay onto left turning vehicles by forcing them to wait for a whole cycle to be served if the green interval was not extended. On the contrary, it can greatly benefit the lagging left turning traffic, specifically for the “last” one or two vehicles, by extending the green interval beyond the scheduled termination point for a few seconds to completely clear the lagging left-turn vehicles before switching control to the cross street. With the green extension scheme to deal with the last arriving left turning vehicles, the traffic delay for left-turn vehicles are reduced, from waiting a whole cycle to near-zero delay for the last vehicles.
Figure 12 Green Extension for Left-turn Phase with Lead-Lag.

As seen in Figure 12, the green extension for lagging left-turn phasing is indicated using dashed boxes. In terms of randomness in vehicle arrival, in order to prevent extending green interval for lagging left-turn phasing too long to generate negative impact on the other conflicting phases, the amount of green interval extension should be constrained to a maximum amount, arbitrarily chosen as 10s.

4.3.2 Green Extension Recovery/Compensation

Since all intersections operate with a common cycle length in a coordinated signal system, the current cycle length would be lengthened if green duration were extended beyond the scheduled termination point for the coordinated phase due to the demands from lagging left-turning vehicles. Therefore, the amount of green extension occurring in one cycle has to be recovered in the following cycle to guarantee that average cycle length (average of current cycle length and next cycle length) be consistent with the common cycle length set up for the coordination system. The green extension might be recovered in two ways: 1) “borrowing” the extended amount of green time from the cross street phases in the following cycle; and 2) recovering the extended green time by the coordinated phase itself. If the current green duration for the coordinated phase is extended, more cars are served in the current cycle, and therefore, fewer cars are expected to be served in the following cycle. The scheduled termination point for coordinated phase in the following cycle will be the same as that in the normal situation (no green extension occurs) even if the green extension occurs in the previous cycle. In this case, the average cycle length over
two cycles is equal to the common cycle length in coordinated system, and however, cycle length in each specific cycle is not constrained to be equal as the common cycle length.

At coordinated intersections, slack time is intended to be utilized by the coordinated phase so that green duration of the coordinated phase can be lengthened to serve the (usually greater) demand along the arterial. Typically, cross streets are actuated, with all slack time going to the coordinated phase after the traffic demand on the cross street is satisfied. If recovering an extended green duration in the previous cycle by “borrowing” some time from the cross street, it would still occur additional delay onto traffic on the cross streets even if the amount of the extended green time is small. Since phases on the cross streets terminate at their force-off point (unless they gaps our earlier), it could cause excessive delay for cross street traffic to force its green duration to be shortened. It is unreasonable to sacrifice one phase’s green duration to benefit another.

An alternative for recovering green extension of the lagging left-turn phase as well as the adjacent coordinated phase is to revise the scheduled termination points in a way that preserves the cross street splits. Green duration extension in a previous cycle allows extra left turning vehicles and through vehicles (EBL, EBT) to pass. Therefore, fewer vehicles are expected to be served by the through phase in the following cycle. As a result, reducing green duration of the coordinated phase by delaying its starting point, as a way of recovering from green extension in the previous cycle, should generate little negative impact to the coordinated phase.

If the intersection operates with a low degree of saturation, there is less opportunity of needing to extend green duration for the lagging left-turn phasing/coordinated phase. When degree of saturation of intersection becomes higher, green duration might be extended repeatedly. Then, if a maximum of 10s of green extension in one cycle is always recovered in the following cycle, and that results in a stable cycle equivalent to delaying the scheduled termination point for the coordinated phase by 10s.
5. **Comparison and Summary of Standard Control Schemes versus Intelligent Algorithms**

Five different left-turn phasing and control scenarios were simulated to test the proposed intelligent algorithms, including prediction logic for needed green duration for lagging left-turn phase, green extension for the critical coordinated phase, and green extension recovery.

### 5.1 Split for Lagging Left-turn Phasing with Standard Control

For a specific traffic stream at an intersection, its green interval should be long enough to be able to clear the vehicles in the initial queue before the phase switches to the following traffic stream.

With standard control, the required split for a lagging left-turn phase can be determined based on four elements: flow ratio ($v/s$), cycle length, lost time and degree of saturation.

\[
\text{Split} = \frac{v}{s} \times X \times C + L \tag{Equation 4}
\]

Where  
- $v =$ left-turn traffic volume (vph);  
- $s =$ saturation flow rate (default = 1800veh/h/lane);  
- $X =$ target degree of saturation (default = 0.85 or 0.9);  
- $C =$ the cycle length (s);  
- $L =$ lost time (default = 4s).

In a coordinated system with standard control, cycle length is fixed and so split can be determined for left-turn phases.

### 5.2 Standard Control for Left-turn Phasing

In terms of left-turn phasing sequence in standard control, three scenarios are tested in the simulation, which are standard lead-lead left-turn phasing, standard lag-lag left-turn phasing and standard lead-lag left-turn phasing. A fourth option, lag-lead, was not tested because it operates efficiently without need for predicting green time need.

Standard lead-lead left-turn phasing has the left-turn movements in both directions start together prior to the opposing through movements, but not necessarily terminating at the same time.
When a leading left-turn phase meets a gap or reaches its maximum green, it switches to the following through movement. The two through phases terminate together at the barrier. For standard lag-lag left-turn phasing control, vehicles turning left are served after their opposing through traffic has been served. The two through movements start at the same time at the beginning of the half cycle, and the two lagging left-turn phases terminate together at the barrier. For lead-lag phasing, the critical left-turn movement operates as leading phase and the non-critical left-turn movement operates as the lagging phase. The leading/critical left-turn movement starts with its adjacent through movement at the beginning of the half cycle while the lagging/non-critical left-turn movement terminates together with its adjacent through movement at the barrier.

Leading left-turn phasing operates in the same way for both isolated intersection and coordinated intersections, switching the phase to the following through movement once the left-turn phase gaps out or reaches the yielding point (satisfying its maximum green). Lagging left-turn phasing operates differently in these two situations. For an isolated intersection with full actuation, there can be two different options to start the lagging left-turn phasing. The first option is that lagging left-turn phasing starts immediately once the previous through movement gaps out, subject to a minimum green. The second option is to fix the through movement’s green time equal to maximum green. In either case, the minimum green can be arbitrarily determined according to the historical traffic demand and the expected difference in green duration requirements between the two rings. In coordinated systems, green start of lagging left-turn phasing, or green termination of the non-critical through movement, is determined based on a fixed split for the lagging left-turn phase and the scheduled termination point of the critical coordinated phase.
In coordinated systems, for the scenario with lead-lag left-turn phasing, the lagging left-turn phase terminates together with the coordinated phase; it does not terminate until time reaches the scheduled termination point for the coordinated phase. For the scenario with lag-lag left-turn phasing, the critical lagging left-turn phasing does not start until the scheduled termination point of the coordinated phase and the two lagging left-turn phasing terminate together at the barrier.

Regardless of phasing sequence, a left-turn phase can be skipped if there is no vehicle presence at the left-turn bay. When a phase is skipped with lead-lead left-turn phasing, the non-skipped left-turn phase and its adjacent through movement start together at the beginning, and the opposing through movement will be serviced after the leading left-turn phasing. Afterwards, both through movements terminate together at the barrier. For lag-lag left-turn phasing, the non-skipped lagging left-turn phase terminates together at the barrier with the adjacent through movement, which runs a longer green duration than usual. For lead-lag left-turn phasing, two through movements would start together at beginning of the half cycle if the leading left-turn movement were skipped while two through movements would terminate together at the barrier if the lagging left-turn movement were skipped.

5.3 **Intelligent Control for Left-turn Phasing**

Different from the standard control, intelligent control schemes for lagging left-turn phasing address the issue of phase transition and phase termination according to the prediction-based logic, which relies on the “trap” logic, counting the number of vehicles stored in the trap. Since
there is no problem for lead-lead left-turn phasing in terms of slack time utilization, lead-lag and lag-lag left-turn phasing are discussed and tested using the intelligent control scheme.

For isolated intersections with full actuation, the green duration needed is estimated for the lagging left-turn phases and green end is predicted for the critical through movement, and green termination of the non-critical through movement is determined by those two elements. In this case, enough green time is provided to the lagging left-turn phasing to be able to clear all vehicles in the initial queue, and any leftover slack time is assigned to the non-critical through movement. It means that the non-critical through movement can extend, after it has already gapped out, to wait for the call for green start for its following lagging left-turn phase. This results in a more effective utilization of slack time comparing to standard actuated control, in which the non-critical through movement terminates immediately once it gaps out or reaches its yielding point.

For coordinated intersections, the green duration needed for the lagging left-turn is estimated for each cycle, so that green duration varies based on the exact number of left-turning vehicles detected, rather than being given a fixed amount of time based on historical traffic demand. For the scenario with lead-lag left-turn phasing, the critical left-turn movements operates as a leading phasing and non-critical left-turn movement lags. With the variable green duration of the lagging left-turn phase and the scheduled termination point of the coordinated phase, the green interval of the non-critical through movement terminates at different time points, a floating force-off point, while the critical through movement terminates at the scheduled green termination point. For the scenario with lag-lag left-turn phasing (case a in Figure 14), needed green duration is estimated for both lagging left-turn phases, and green termination of the non-critical through movement is determined based on the difference in the two left turn needs for lagging left-turn phasing and the scheduled termination point.

In addition, for the scenario with lead-lag left-turn phasing (case b in Figure 14), since the lagging left-turn phase should terminate together with the coordinated phase at the barrier, the green duration can be extended beyond the scheduled termination point of the coordinated phase if the lagging left-turn phasing does not gap out due to randomness in vehicle arrivals. If green extension beyond the scheduled termination point occurs, in order to keep the average cycle
length the same as the common cycle length for coordinated system, green extension will be recovered in the next cycle by “shortening” the green duration for the coordinated phase, maintaining the scheduled termination point in the following cycle.

![Diagram](image)

**Case a: Lag-lag phasing**

**Case b: Lead-lag phasing**

**Figure 14 Dual Ring Diagram with Intelligent Lead-Lag and Lag-Lag Phasing.**

Time point a, indicates the scheduled termination point of the coordinated phase (critical through movement). Time point b, is the floating termination point for the non-critical through movement. The green duration of the lagging left-turn phases in both cases is estimated based on trap counts. In case b, lead-lag left-turn phasing, the green end of the critical through movement can be beyond the scheduled termination point if necessary.

5.4 **Summary of Standard Lagging versus Intelligent Lagging Left-Turn Phasing**

Lagging left-turn phases include lead-lag, lag-lag, and lag-lead left-turn phases. Lag-lead left-turn phasing operates efficiently by allocating slack time to though movement. Therefore, lead-lag and lag-lag left-turn phases are compared between standard control and intelligent control. Difference in control logic is summarized below.
**Figure 15 Lead-Lag and Lag-Lag Left-Turn Phasing.**

For both cases of lead-lag and lag-lag left-turn phasing in Figure 15, lower ring (EBT + WBL) is the critical ring and therefore there is slack time in the non-critical ring.

**Table 3 Comparison of Standard Lead-Lag and Intelligent Lead-Lag at Isolated Intersection**

<table>
<thead>
<tr>
<th></th>
<th><strong>Standard Lead-Lag</strong></th>
<th><strong>Intelligent Lead-Lag</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Green end of critical through movement, t = a</td>
<td>Gaps out (or maxes out), without green end prediction for EBT</td>
<td>Gaps out (or maxes out), with green end prediction for EBT</td>
</tr>
<tr>
<td>Green end of non-critical through movement, t = b</td>
<td>Gaps out (or maxes out)</td>
<td>Gaps out (or maxes out), with green end prediction for EBT and green estimation for EBL</td>
</tr>
<tr>
<td>Determining needed EBL green duration, GT_{EBL}</td>
<td>-</td>
<td>Using Trap Counts</td>
</tr>
<tr>
<td>Phase termination at the barrier</td>
<td>When both EBT and EBL gap out or max out</td>
<td>When both EBT and EBL gap out or max out</td>
</tr>
</tbody>
</table>

In lead-lag left-turn phasing, the critical left-turn (WBL) is leading and the non-critical left-turn (EBL) lags. If the lagging left-turn is skipped (no left-turning vehicles arrived), non-critical through movement (WBT) will terminate together with critical through movement, at the scheduled either gap out or max out. In standard control, eastbound left follows westbound through movement and it terminates with eastbound through together at the barrier, and therefore green duration of EBL cannot be specifically identified.
### Table 4 Comparison of Standard Lag-Lag and Intelligent Lag-Lag at Isolated Intersection

<table>
<thead>
<tr>
<th></th>
<th>Standard Lag-Lag</th>
<th>Intelligent Lag-Lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green end of critical through movement, t = a</td>
<td>Gaps out (or maxes out)</td>
<td>Gaps out, with green end prediction, and green estimation for EBL and WBL</td>
</tr>
<tr>
<td>Green end of non-critical through movement, t = b</td>
<td>Gaps out</td>
<td>Gaps out, with green end prediction, and green estimation for EBL and WBL</td>
</tr>
<tr>
<td>Determining needed EBL green duration, GT\textsubscript{EBL}</td>
<td>-</td>
<td>Using Trap counts</td>
</tr>
<tr>
<td>Determining needed WBL green duration, GT\textsubscript{WBL}</td>
<td>-</td>
<td>Using Trap counts</td>
</tr>
<tr>
<td>Phase termination at the barrier</td>
<td>When both EBL and WBL Gaps out or maxes out</td>
<td>When both EBL and WBL Gaps out or maxes out</td>
</tr>
</tbody>
</table>

In lag-lag left-turn phasing, both left turns start after the through movements. If one of them is skipped, the non-skipped left-turn phase will terminate together with its concurrent through movements at the barrier. (E.g., EBL skipped, WBT and WBL end together; if WBL is skipped, EBT and EBL end together.) If both are skipped, then two through movements end together at the barrier. In standard control, the two lagging left-turns have no specific green durations, such as pre-determined split, to establish an effective green end for the through movement, i.e., an efficient green start for lagging left-turns.
### Table 5 Comparison of Standard Lead-Lag and Intelligent Lead-Lag along Arterial

<table>
<thead>
<tr>
<th></th>
<th>Standard Lead-Lag</th>
<th>Intelligent Lead-Lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green end of critical through movement, ( t = a )</td>
<td>At the scheduled termination point</td>
<td>Scheduled termination point with possible green extension if EBL hasn’t gapped out</td>
</tr>
<tr>
<td>Green end of non-critical through movement, ( t = b )</td>
<td>At the scheduled termination point minus EBL split</td>
<td>Scheduled termination point minus estimated green need for EBL</td>
</tr>
<tr>
<td>EBL green duration, ( GT_{EBL} )</td>
<td>Pre-determined split based on historical volume and target degree of saturation</td>
<td>Estimated from trap counts</td>
</tr>
<tr>
<td>Phase termination at the barrier</td>
<td>Same as ( t = a )</td>
<td>Same as ( t = a )</td>
</tr>
</tbody>
</table>

### Table 6 Comparison of Standard Lag-Lag and Intelligent Lag-Lag along Arterial

<table>
<thead>
<tr>
<th></th>
<th>Standard Lag-Lag</th>
<th>Intelligent Lag-Lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green end of critical through movement, ( t = a )</td>
<td>At its scheduled termination point</td>
<td>At its scheduled termination point</td>
</tr>
<tr>
<td>Green end of non-critical through movement, ( t = b )</td>
<td>At its scheduled termination, based on pre-determined splits for EBL and WBL</td>
<td>At scheduled termination point plus estimated split for WBL minus estimated split for EBL</td>
</tr>
<tr>
<td>EBL green duration, ( GT_{EBL} )</td>
<td>Using pre-determined split</td>
<td>Using “Trap Logic” to estimate</td>
</tr>
<tr>
<td>WBL green duration, ( GT_{WBL} )</td>
<td>Using pre-determined split</td>
<td>Using “Trap Logic” to estimate</td>
</tr>
<tr>
<td>Phase termination at the barrier</td>
<td>When both EBL and WBL gap out, or at max out</td>
<td>Same</td>
</tr>
</tbody>
</table>
6. **VISSIM Simulation for Different Left-Turn Phasing Scenarios**

VISSIM is a microscopic, time step and behavior-based simulation model developed to model urban traffic and public transport operations [15]. The simulation package VISSIM is developed by PTV Group from Germany. VISSIM version 5.40 is used in this study. Five different control schemes related to left-turn phasing are simulated, analyzed, and compared for both an individual isolated intersection and a seven-intersection arterial from the perspectives of vehicular delay and green wave bandwidth. These five different scenarios are categorized into two levels: standard control and intelligent control (explained in Chapter 4). The standard control scenarios include standard lead-lead left-turn phasing, standard lag-lag left-turn phasing and standard lead-lag left-turn phasing, while intelligent control scenarios include intelligent lead-lag left-turn phasing and intelligent lag-lag left-turn phasing (Standard lead-lead control works efficiently without being “intelligent”).

Isolated intersection and seven-intersection arterial scenarios were developed in order to test the new-developed control schemes for lagging left-turn phasing. Traffic volumes were generated for individual isolated intersection and seven-intersection arterial using the bi-proportional method [17], scaled up to meet the target degree of saturation.

6.1 **Isolated Intersection with Full Actuation**

A typical four-leg eight-phase intersection is used to test the intelligent control scheme (prediction-based logic) and to identify the advantages of the new-developed logic over standard control for different phasing scenarios. At the isolated intersection, all four approaches have a dedicated left-turn lane as well as protected-only left-turn phasing. Two through traffic lanes per direction are on the major street and one through traffic lane is on the cross street. Right turning vehicles share the right-most-traffic lane with the through traffic. Pedestrian phases are not modeled explicitly in this study, but minimum green times for through phases are set long enough to permit pedestrian phases that are either actuated or on recall. Layout of the isolated intersection tested in the simulation is depicted in Figure 16. Arrows indicate traffic direction.
In general, lead-lag left-turn phasing can generate benefits in terms of coordination, particularly in the situation that are not ideally spaced along the arterial. When intersections are ideally spaced, which means that travel time between two adjacent intersections is equal to half of the cycle length, perfect two-way coordination can be realized with either lead-lead or lag-lag phasing.

In this study, a dummy arterial consisting of seven intersections is created as the test bed in VISSIM to identify and to test the effectiveness of intelligent control algorithms for lagging left-turn phasing, comparing to the standard control for coordinated intersections. For coordinated-actuated signal systems, offset (difference in green start time between the reference intersection and target intersection) is determined to be equal to the travel time between two adjacent intersections. In terms of simplicity and consistency, distances between adjacent intersections are alternatively distributed with shorter distance and longer distance compared to ideal distance. Layout of the seven-intersection arterial is shown in Figure 17. Each of seven intersections is labeled with a specific number from 1 to 7. Let $d_{ij}$ denote the distance between intersection $i$ and intersection $j$ and $t_{ij}$ denote the travel time traveling from intersection $i$ to intersection $j$. Then, six
distances between seven intersections consist of two shorter distances \( d_{12} = d_{67} \), two longer distances \( d_{23} = d_{56} \) and two ideal distances \( d_{34} = d_{45} \), where the ideal distance is equal to half time of cycle length multiplying by prevailing speed.

For movements at intersection #2, since the travel distance between intersection #1 and #2 is shorter than the ideal space, EBL is supposed to be leading (WBT movement needs more time to cover a longer distance, and therefore it is served after the opposing left-turn phasing) and therefore WBL should be lagging in order to provide a good progression. Similarly, for movements at intersection #6, EBL should be lagging and WBL should be leading considering progression effect. Therefore, since EB is the dominant direction and WBL is therefore critical, intersection #2 has lag-lead operation, while intersection #6 has lead-lag operation.

In the simulation, a common cycle length is chosen as 100s and a 28mph (42ft/s) prevalent travel speed is used. These two parameters determine that ideal space between two adjacent intersections is around 2100ft, with a travel time of 50s. In addition, difference in distance is arbitrarily chosen to be that offset between intersections with shorter space is 45s and offset between intersections with longer space is 55s. Distance, travel time, and offset from reference intersection, which is intersection #1 in this study, are summarized in Table 7.

![Figure 17 Layout of A Seven-Intersection Arterial.](image-url)
Table 7 Distance, Travel Time and Offset from Reference Intersection (Intersection 1) to other Intersections

<table>
<thead>
<tr>
<th>Intersection #</th>
<th>Distance from Intersection #1 (ft)</th>
<th>Travel Time from Intersection #1 (s)</th>
<th>Offset from Intersection #1 (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1900</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>4200</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>6300</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>8400</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>10,700</td>
<td>255</td>
<td>55</td>
</tr>
<tr>
<td>7</td>
<td>12,600</td>
<td>300</td>
<td>0</td>
</tr>
</tbody>
</table>

Cycle length = 100s; Travel speed = 28mph (42ft/s).

Among the seven intersections, intersection #6 is the critical intersection, whose traffic demand requires a cycle length of 100s and operates as lead-lag left-turn phasing. Traffic demand at intersection #2, #4 and #7 requires a cycle length of at least 90s and these three intersections operate with eight phases and protected-only left-turn phasing. Traffic demand at intersection #1, #3 and #5 require a cycle length of at least 80s and they operate with six phases, without exclusive left-turn lane and left-turn phasing on the cross streets. At intersections with 80s cycle length need, cross street has low traffic and the split on cross street is primarily constrained by the pedestrian need, which is 25s, consisting of 7s of minimum green and 18s of clearance time (crossing five traffic lanes, 60ft, with an average speed of 3.5ft/s).

6.3 Traffic Volume Generation

Traffic data are a fundamental element in traffic study and the essential input to traffic simulation and the following analysis. There are several ways to access to traffic data for intersection analysis. Traffic data can be acquired from the transportation department of city or local government, who usually collects traffic data using detectors located at approaches of an intersection. Local government can also collect traffic data with the application of over-head camera. Traffic data can be gathered based on manual counts on representative days during long time period or over several days. However, data collected through manually counting is not as accurate as the detector or video information due to complexity of real situation at the
intersection, especially during the peak period, or human cognitive errors. Other methods can include plate tracking by analyzing the video information captured on different approaches at intersection or at different intersections.

For this study, there is no direct-resource to acquire traffic data since the intersection/arterial is manually created. Therefore, traffic volume is generated using bi-proportional method with the feature of propensity. According to the traffic demand requiring different cycle length, three sets of traffic volume are generated. Based on the traffic volume distribution that both right-turn and left-turn movement is with propensity of 0.18 and through movement is with propensity of 0.64, traffic volume is generated for the situations with three different degree of saturation (also known as volume to capacity ratio, v/c), denoted as X, (X = 0.85, X = 0.90, X = 0.99).

In this study, traffic traveling to the east is identified as the main direction on east-west street, which is the major street, and traffic traveling to south is the main direction on south-north street, which is the minor street. This thesis selected bi-proportional method to generate traffic volume as the input to the VISSIM simulation. There are five steps for the detailed traffic volume generation process: 1) Set up seed matrix using propensity; 2) Choose preliminary total ins and total outs; 3) Get bi-proportional result; 4) Identify critical movement and calculate critical sums; and 5) Scale volumes to meet target degree of saturation.

1) Set up seed matrix using propensity

In order to get turning movements at an intersection with the model applied in this thesis, a seed matrix with propensity is set up as a base to generate traffic volume to match the target degree of saturation at an intersection. Each fraction in Table 8 indicates the vehicles’ propensity of traveling through, left, and right when approaching an intersection.

By setting propensity as 0.18 for both left-turn and right-turn movement and as 0.64 for through movement, seed matrix for traffic volume generation is shown in Table 8:
Table 8 Seed Matrix (Propensity Matrix) for Traffic Volume Generation

<table>
<thead>
<tr>
<th>Seed matrix (propensity matrix)</th>
<th>N leg</th>
<th>E leg</th>
<th>S leg</th>
<th>W leg</th>
<th>Total In</th>
</tr>
</thead>
<tbody>
<tr>
<td>N leg</td>
<td>0.0</td>
<td>0.18</td>
<td>0.64</td>
<td>0.18</td>
<td>1</td>
</tr>
<tr>
<td>E leg</td>
<td>0.18</td>
<td>0.0</td>
<td>0.18</td>
<td>0.64</td>
<td>1</td>
</tr>
<tr>
<td>S leg</td>
<td>0.64</td>
<td>0.18</td>
<td>0.0</td>
<td>0.18</td>
<td>1</td>
</tr>
<tr>
<td>W leg</td>
<td>0.18</td>
<td>0.64</td>
<td>0.18</td>
<td>0.0</td>
<td>1</td>
</tr>
<tr>
<td>Total Out</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

2) Choose preliminary total ins and total outs

Once a seed matrix is set up, with preliminary total ins and total outs filled, an initial matrix with target volumes (unscaled, before meeting the target degree of saturation) is prepared for a further task of obtaining detailed turning movements.

According to a basic principle in graph theory [16] that amount of flow into a node equals the amount of flow out of the node, which is normally an intersection in traffic area, total traffic volume into the intersection from each approach must be equal to the total traffic volume out from the intersection.

In addition, by choosing a ratio of traffic volume on the main street to that on minor street being 3:1 and ratio of traffic travelling in main direction to that in minor direction being 6:4, an initial array of entry and exit target volumes is generated, shown in Table 9:

Table 9 Initial Matrix for Traffic Volume Generation with Total Ins and Total Outs

<table>
<thead>
<tr>
<th>Initial Entry/Exit Target Volumes</th>
<th>N leg</th>
<th>E leg</th>
<th>S leg</th>
<th>W leg</th>
<th>Total In</th>
</tr>
</thead>
<tbody>
<tr>
<td>in \ out</td>
<td>N leg</td>
<td>E leg</td>
<td>S leg</td>
<td>W leg</td>
<td>Total In</td>
</tr>
<tr>
<td>N leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>E leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>240</td>
</tr>
<tr>
<td>S leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>W leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>360</td>
</tr>
<tr>
<td>Total Out</td>
<td>80</td>
<td>360</td>
<td>120</td>
<td>240</td>
<td>800</td>
</tr>
</tbody>
</table>
3) **Get bi-proportional result**

In this step, with the seed matrix and the initial matrix with total ins and total outs, several iterations are made to get the detailed turning movements, with the respect of arbitrarily chosen tolerance.

The iterative proportional fitting procedure (IPF, also known as *bi-proportional fitting* in statistics) is an iterative algorithm for estimating cell values of a contingency table such that the marginal totals remain fixed and the estimated table decomposes into an outer product [17].

Based on the initial matrix for traffic volume generation, after nine iterations, result matrix satisfies the pre-determined tolerance of 0.2%. The bi-proportional result matrix (not scaled) is shown in Table 10:

<table>
<thead>
<tr>
<th>Result Matrix</th>
<th>N leg</th>
<th>E leg</th>
<th>S leg</th>
<th>W leg</th>
<th>Total In</th>
</tr>
</thead>
<tbody>
<tr>
<td>in \ out</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>N leg</strong></td>
<td>0</td>
<td>36</td>
<td>55</td>
<td>29</td>
<td>120</td>
</tr>
<tr>
<td><strong>E leg</strong></td>
<td>22</td>
<td>0</td>
<td>29</td>
<td>189</td>
<td>240</td>
</tr>
<tr>
<td><strong>S leg</strong></td>
<td>31</td>
<td>27</td>
<td>0</td>
<td>22</td>
<td>80</td>
</tr>
<tr>
<td><strong>W leg</strong></td>
<td>27</td>
<td>297</td>
<td>36</td>
<td>0</td>
<td>360</td>
</tr>
<tr>
<td><strong>Total Out</strong></td>
<td>80</td>
<td>360</td>
<td>120</td>
<td>240</td>
<td>800</td>
</tr>
</tbody>
</table>

4) **Identify critical movement and calculate critical sums**

With detailed turning movements at an intersection, in order to identify the critical conflict group and splits needed in further simulation, critical movement and critical sums (a way to show the critical movements and the critical ring) need to be identified.

Assume NTOR (No Turn On Red) is displayed for all approaches at intersection. In addition, right turning vehicles share the right-most traffic lane with the through traffic. Therefore, right turning vehicles complete their movement only during the green duration for through movement. In order to identify critical movements and to calculate critical sums, right-turn
traffic volume and through traffic volume are combined in analysis to guarantee that green duration is long enough to satisfy the traffic demand of both right-turn movement and through movement.

There are two conflict groups, either of which can be the critical one in terms of the total volume in the conflict group. Since major street and main direction on each street has been identified previously, based on the result matrix (not scaled) came up with bi-proportional methods, movements belonging to critical conflict group are labeled with asterisks in Figure 18.

![Figure 18 Unscaled Turning Movements.](image)

In Figure 18, each number indicates the non-scaled (base input, before scale them to meet the target degree of saturation) traffic volume for each movement from the bi-proportional method. Since right-turning vehicles proceed with their movements only when the signal head is green for through traffic, through movements and right-turn movements are considered as a group, served together in one phase.

There are two through traffic lanes on major street (east-west) and one through traffic lane on minor street (north-south). If exclusive left-turn phasing is designed for specific approach, there is only one dedicated left-turn lane provided. Based on traffic volume per lane, critical sums are calculated in Table 11:
Table 11 Critical Sums for the Assumed Traffic Volume at an Intersection

<table>
<thead>
<tr>
<th>Movement</th>
<th>EBL</th>
<th>WBT</th>
<th>WBL</th>
<th>EBT</th>
<th>NBL</th>
<th>SBT</th>
<th>SBL</th>
<th>NBT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (vph)</td>
<td>27</td>
<td>211</td>
<td>19</td>
<td>333</td>
<td>36</td>
<td>58</td>
<td>22</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td># of lanes</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Volume (vphpl)</td>
<td>27</td>
<td>106</td>
<td>19</td>
<td>167</td>
<td>36</td>
<td>58</td>
<td>22</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>Sum (vph)</td>
<td>133</td>
<td>186</td>
<td>94</td>
<td>106</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical sum (vph)</td>
<td>186</td>
<td>106</td>
<td>292</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Critical movements are WBL & EBT and the critical sum is 292veh/h.

5) Scale volumes to meet target degree of saturation

In order to get traffic volume, input to the VISSIM simulation, with the given lost time, saturation flow rate and target degree of saturation, a base results from bi-proportional method is scaled up to meet the target degree of saturation.

The scale factors and corresponding traffic volumes are found for three levels of target degree of saturation based on a calculation in “dual ring” spreadsheet, seen in Appendix A, which takes cycle length, saturation flow rate (typical capacity of urban roadway, 1800vphpl) and lost time (4s for each phase) into consideration. Based on Highway Capacity Manual [18], needed cycle length is determined as:

\[ C_{\text{needed}} = \sum L / \left( 1 - \sum \frac{v}{s} \times X_{\text{target}} \right) \]  \hspace{1cm} (Equation 5)

Where, \( C_{\text{needed}} \) = cycle length (s);

\[ L = \text{lost time per phase (default = 4s/per phase);} \]

\[ v = \text{traffic volume per lane for each phase (vphpl);} \]

\[ s = \text{saturation flow rate (default = 1800vphpl);} \]

\[ X_{\text{target}} = \text{target degree of saturation;} \]

For isolated intersection tested in this study, needed cycle length is 90s, which requires a critical sum of 1258 vehicles at \( X = 0.85 \), 1332 vehicles at \( X = 0.90 \), and 1466 vehicles at \( X = 0.99 \). Then unscaled turning movement matrix was scaled to match those critical sums,
seen in Appendix B, including traffic volume non-equal critical sum (Case A) and equal critical sum (Case B) for the isolated intersection.

Seven intersections along the arterial are categorized into three types. The first set of intersections consists of intersections #1, #3, and #5, which have six phases with a cycle length need of 80s, little traffic on cross street. There are no exclusive left-turn phases on cross street. The second set of intersections consists of intersections #2, #4, and #7, which have eight phases with a cycle length need of 90s. Protected-only left-turn phases exist on both major street and cross streets. Intersection #6, the critical intersection, has eight phases with a needed cycle length of 100s. Correspondingly, unscaled turning movements are scaled for these three categories of intersection to match the requirements of total traffic volume per lane at two different levels of saturation degree (\(X = 0.85\) and \(X = 0.99\), at \(C = 100s\)). Traffic volume for the whole network with seven intersections is shown in Appendix B (Case C).

Adjustments on traffic volume at each intersection are made to balance traffic volume along the arterial. Based on a target cycle length and degree of saturation, proportions of through traffic and right turn movements are changing at each intersection, while remaining left-turn movements. For example, if the coordinated phase (EBT) at downstream intersection requires higher input, while the through movements from upstream before the adjustments is lower than the requirement, then adjustments are made at upstream intersection by increasing the through movement and reducing the right-turn movements to balance the requirement at downstream intersection.
7. Simulation Analysis

Aiming at identifying the advantages of intelligent control algorithms (prediction-based logic) to establish an efficient start for lagging left-turn phasing over the typical standard control scheme, simulation is conducted to test the new-developed algorithms at an individual isolated intersection and on a seven-intersection arterial. At isolated intersection, average cycle length, green duration for lagging left-turn phasing and the opposing through movement and average vehicular delay are compared between the intelligent control algorithms and standard control scheme. For the seven-intersection arterial, overall delay, average intersection delay, average vehicular delay and average green duration of two movements (EBL and WBT) in the non-critical ring, and overflow frequency of the two left-turn phases on the major street are all compared and analyzed between intelligent control algorithm and standard control scheme.

Basic signal timing parameters used in the simulation for both cases (isolated intersection and seven-intersection arterial) are explained in Table 12.

Table 12 Signal Timing Parameters in Simulation

<table>
<thead>
<tr>
<th>Phase</th>
<th>EBL</th>
<th>WBT</th>
<th>WBL</th>
<th>EBT</th>
<th>SBL</th>
<th>NBT</th>
<th>NBL</th>
<th>SBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Green (s)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Max Green (s)</td>
<td>20</td>
<td>40</td>
<td>20</td>
<td>40</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Critical Gap (s)</td>
<td>2</td>
<td>2.5</td>
<td>2</td>
<td>2.5</td>
<td>2</td>
<td>2.5</td>
<td>2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Note:
Non-simultaneous gap-out at barrier for both major and minor street for all scenarios
(Non-simultaneous gap-out: phases terminate when both phases at the barrier meet a gap but not need to be at the same time)
NTOR at all approaches
No pedestrian interference for right-turning vehicles
Cross street is always with standard lead-lead left-turn phasing, except at intersections 3 and 5 whose cross street has no exclusive left-turn phase
In terms of detector location, for isolated intersection with full actuation, detectors work as three functions. The first function is to detect a gap to terminate a phase. The second function is for “trap logic” to count vehicles arriving on the left-turn bay. The third function is particularly for isolated intersection, which is to predict green end of the through movement on the major street. While for coordinated intersections, there is a scheduled termination for coordinated phases, and therefore, there are no detectors needed with third function.

Detectors with the function of detecting a gap are located based on the gap time and travel speed. Detectors are located 75 ft (although 84 ft is determined based on 2s gap time and 42 ft/s travel speed) upstream of the stop line on left-turn lanes where applicable. This setting can reduce end lost time (part of yellow time can be used to serve the last vehicle). Detectors are located 90 ft (although 105 ft is determined based on 2.5s gap time and 42 ft/s travel time) upstream from the stop on through lanes. Detectors with the function of counting left-turn vehicles are located at the entrance to the left-turn bay. Detectors with the function of predicting green end for through movements are located 520 ft (travel time to stop line is 13s) upstream from stop line.

7.1 Simulation Analysis for Isolated Intersection

Five scenarios are tested for isolated intersection, which are: a) standard lead-lead left-turn phasing, b) standard lag-lag left-turn phasing, c) standard lead-lag left-turn phasing, d) intelligent lead-lag left-turn phasing and e) intelligent lag-lag left-turn phasing. All five scenarios are tested with three target degrees of saturation, $X = 0.85$, $X = 0.90$, and $X = 0.99$ at a 90s cycle. Simulation is run for each scenario with a simulation duration of 4 hours, excluding a warm-up period of 10 minutes.

For the isolated intersection, traffic data in the simulation were scaled so that the target degree of saturation would be achieved with a 90s cycle. This applied for all three different target degrees of saturation, and therefore, there are three sets of traffic data. In addition, two different traffic data sets are tested in the simulation, with non-equal critical sums in two rings and equal critical sums in two rings, respectively.
7.1.1 Case with non-equal critical sums in two rings

When the critical sums in two rings differ substantially (e.g., > 50), a critical ring governs the half-ring split and there is slack time in the non-critical ring. This slack time is supposed to be assigned to the through movement (WBT) with the intelligent control scheme. Each performance measure is compared between the following five different control schemes:

- **Case a**: Standard control with lead-lead left-turn phasing;
- **Case b**: Standard control with lag-lag left-turn phasing;
- **Case c**: Standard control with lead-lag left-turn phasing;
- **Case d**: Intelligent control with lead-lag left-turn phasing;
- **Case e**: Intelligent control with lag-lag left-turn phasing;

With the goal of identifying the advantages of intelligent algorithms over the standard control schemes, two comparisons are made for isolated intersection with full actuation control: a) standard lead-lag left-turn phasing vs. intelligent lead-lag left-turn phasing and b) standard lag-lag left-turn phasing vs. intelligent lag-lag left-turn phasing. In addition, standard lead-lead left-turn phasing, which efficiently allocated slack time to the through phase, is treated as the base case.

7.1.1.1 Degree of saturation, \( X = 0.85 \)

Traffic demand at specific intersection varies from different periods of a day. In cases where intersections operate with low traffic demand (\( X = 0.85 \) with a 90s cycle), each phase frequently meets the critical gap, which is one of the decisions to terminate phase, so that a shorter cycle length can be realized.

According to the result analysis, cycle length for standard lead-lead left-turn phasing is shorter than the other four different scenarios. Average green duration includes the cycles in which a phase was skipped. Average green duration of the non-critical left-turn movement (EBL) is the shortest among the five different scenarios, and correspondingly, average green duration of the non-critical through movement (WBT) is the longest, showing how well standard lead-lead allocates all slack time to the through movement. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, cycle length is reduced from 86.3s to 80.3s, a reduction of 6.95%. Average green duration of the non-critical left-turn movement (EBL) is
reduced from 18.1s to 13.3s, a reduction of 26.5%, while average green duration for the non-critical through movement (WBT) is slightly increased from 26.7s to 28.2s, an increase of 5.6%.

Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, cycle length is reduced from 82.1s to 80.6s. Average green duration for the non-critical left-turn movement (EBL) is reduced from 18.6s to 13.4s, a reduction of 27.9%, while average green duration for the non-critical through movement (WBT) is increased from 22.9s to 28.5s, an increase of 24.5%. Intelligent algorithms use prediction logic to predict the green end of the critical through movement and use trap logic to estimate green need for the lagging left-turn phases. It beats standard lagging left-turn phasing, which assigned slack time to the lagging left-turn phases, by efficiently using the slack time, part of which is assigned to the left-turn phases.

Figure 19 Cycle Length and Average Green Duration for EBL and WBT (Non-equal Critical Sum, X = 0.85 at C = 90s).

Seen in Figure 20, standard lead-lead left-turn phasing results in the smallest overall intersection delay, highest delay for EBL and smallest delay for WBT. Because standard lead-lead makes efficient use of slack time, all of which is allocated to the through movement, shorter cycle results in shorter average delay. Longer green duration for WBT and shorter green duration for EBL lead to shorter average delay for WBT and longer average delay for EBL. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, overall intersection
delay is reduced from 34.6s to 29.9s, a reduction of 13.6%. Average delay for EBL is increased from 29.9s to 33.2s, an increase of 11%, while average delay for WBT is reduced from 31.5s to 24.6s, a reduction of 21.9%. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, overall intersection delay is slightly reduced from 31.4s to 30s, a reduction of 4.5%. Average delay for EBL is increased from 28.8s to 33.3s, an increase of 15.6%, while average delay for WBT is reduced from 33.1s to 23.3s, a reduction of 29.6%. Generally, shorter cycle length leads to smaller average delay. Because intelligent lagging left-turn phasing wisely utilize the slack time, cycle length is closer to that with lead-lead left-turn phasing, which best use the slack time. Although the green duration for the WBT is reduced with intelligent lagging left-turn phasing, it still wins the standard lagging left-turn phasing in terms of overall delay.

![Figure 20 Overall Delay and Average Vehicular Delay for EBL and WBT (Non-equal Critical Sum, X = 0.85 at C = 90s).](image)

Based on the results in above two figures, intelligent algorithms for lagging left-turn phasing result in shorter cycle length and smaller overall intersection delay comparing to standard control schemes. With the intelligent lagging left-turn control algorithms, green duration of the non-critical through movement (WBT) is increased at the expense of the non-critical left-turn movement (EBL), showing that slack time is being better allocated to the through movement. Overall average delay is almost as small as with lead-lead phasing, showing that intelligent
control makes it possible to achieve nearly the full efficient benefits (best slack time utilization) of lead-lead left-turn phasing with the safety benefits of lag-lag left-turn phasing.

7.1.1.2 Degree of saturation, $X = 0.90$

With greater traffic demand ($X = 0.90$ with a 90s cycle length), each phase requires longer green duration. Then, the actual cycle length should be closer to the background cycle length of 90s based on which the traffic volume was generated.

According to result analysis, cycle length for standard lead-lead left-turn phasing is the smallest and all cycle lengths for five scenarios are indeed very close to 90s. For standard lead-lead left-turn phasing, average green duration of the non-critical left-turn movement (EBL) is the shortest among the five different scenarios, and correspondingly, average green duration of the non-critical through movement (WBT) is the longest because of how lead-lead logic assigns all slack time to the through movement. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, cycle length is slightly reduced from 89.9s to 88s. Average green duration of the non-critical left-turn movement (EBL) is reduced from 23.6s to 14.5s, a reduction of 30%, while average green duration for the non-critical through movement (WBT) is increased from 28.2s to 31.7s, an increase of 8.9%. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, cycle length maintains the same (from 88.2s to 88s). Average green duration for the non-critical left-turn movement (EBL) is reduced from 20.7s to 14.9s, with a reduction of 28%, while average green duration for the non-critical through movement (WBT) is increased from 26.2s to 31.1s, an increase of 18.7%.
Figure 21 Cycle Length and Average Green Duration for EBL and WBT (Non-equal Critical Sum, X = 0.90 at C = 90s).

Seen in Figure 22, standard lead-lead left-turn phasing results in the smallest overall intersection delay, highest average delay for EBL and smallest average delay for WBT. For the standard lead-lead, the highest delay for EBL is partly due to the blockage at entry to pocket lane so that a fraction cars have to wait twice. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, overall intersection delay is reduced from 37.8s to 35.6s, a reduction of 5.8%. Average delay for EBL is increased from 31s to 37.9s, an increase of 21.9%, while average delay for WBT is reduced from 31.5s to 25.4s, with a reduction of 19.4%. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, overall intersection delay is reduced from 37.3s to 34.4s, a reduction of 7.8%. Average delay for EBL is increased from 29.8s to 37.9s, an increase of 27.2%, while average delay for WBT is reduced from 33.1s to 23.3s, a reduction of 29.6%.
Figure 22 Overall Delay and Average Vehicular Delay for EBL and WBT (Non-equal Critical Sum, X = 0.90 at C = 90s).

Based on the results in above two figures, intelligent algorithms for lagging left-turn phasing (both lead-lag and lag-lag) result in shorter cycle length and smaller overall intersection delay than standard lagging control schemes do. In addition, green duration of the non-critical through movement (WBT) is increased and average delay is reduced at the expense of the non-critical left-turn movement (EBL), of which green duration is reduced while average traffic delay is increased. The results show that lagging left-turn phasing with intelligent control can also make efficient use of slack time, while not losing its benefits to safety.

7.1.1.3 Degree of Saturation X = 0.99

In cases where intersection is in operation with high traffic demand (X = 0.99 with a 90s cycle), there are few gaps can be detected to terminate the through phase so that each phase might not terminate until satisfying requirement of its maximum green time. Consequently, actual cycle length might be greater than the background cycle length so that adequate numbers of vehicles can be served in each cycle.

According to result analysis, average cycle length of five different scenarios is close to 100s. For standard lead-lead left-turn phasing, cycle length is 97s, 3s shorter than other scenarios. Average
green duration of the non-critical left-turn movement (EBL) is the shortest among the five different scenarios, and correspondingly, average green duration of the non-critical through movement (WBT) is the longest because of all slack time being assigned to the through movement. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, cycle length stays the same. Average green duration of the non-critical left-turn movement (EBL) is reduced from 23.6s to 17.8s, a reduction of 24.6%, while average green duration for the non-critical through movement (WBT) is increased from 31.7s to 37.5s, an increase of 18.3%. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, cycle length stays the same. Average green duration for the non-critical left-turn movement (EBL) is reduced from 24.7s to 16.1s, a reduction of 34.8%, while average green duration for the non-critical through movement (WBT) is increased from 30.9s to 38.9s, an increase of 25.9%.

Figure 23 Cycle Length and Average Green Duration for EBL and WBT (Non-equal Critical Sum, $X = 0.99$ at $C = 90s$).

Seen in Figure 24, standard lead-lead left-turn phasing results in the smallest overall intersection delay, highest average delay for EBL and smallest average delay for WBT. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, overall intersection delay is slightly reduced from 47s to 44.7s, a reduction of 4.9%. Average delay for EBL is increased from 37.3s to 43.3s, an increase of 16.1%, while average delay for WBT is reduced
from 35.5s to 29.4s, a reduction of 17.2%. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, overall intersection delay is reduced from 46.2s to 44.2s, a reduction of 4.3%. Average delay for EBL is increased from 33.7s to 42.8s, an increase of 27.3%, while average delay for WBT is reduced from 36.1s to 27.5s, a reduction of 23.8%.

![Figure 24 Overall Delay and Average Vehicular Delay for EBL and WBT (Non-equal Critical Sum, X = 0.99 at C = 90s).](image)

Base on the results in two above figures, intelligent algorithms have the same cycle length as the standard control when X is 0.99 at a 90s cycle. Average intersection delay for lagging left-turn phasing with intelligent algorithms is lower than that with standard control and is closer to that with standard lead-lead left-turn phasing, showing that lagging left-turn phasing with intelligent control not only owns the benefits in safety but also can efficiently utilize the slack time as lead-lead phasing does.

As a conclusion, for the case with unequal critical sums in two rings, lead-lead left-turn phasing always result in the smallest overall delay, the shortest average green duration with the highest average delay for EBL and the longest average green duration with the smallest average delay for WBT. Shorter cycle length and smaller overall intersection delay is achieved for lagging left-turn phasing with intelligent algorithm, which also results in shorter green duration with higher
delay for EBL, and longer green duration with smaller delay for WBT. The results show that lagging left-turn phasing with intelligent control scheme can efficiently utilize the slack time, while still maintaining its specific advantages on safety.

7.1.2 Case with equal critical sums in two rings

When both rings have equal critical sums, there is no clear critical ring, because both rings require same amount of green duration on average. Due to randomness in traffic, one ring can be critical in one cycle while the other ring is critical in the next. In general, there will be little slack time in the non-critical ring. Though there is no clear indication on which ring is critical when both rings have equal critical sums, in the simulation logic, the ring with EBT and WBL is still treated as the critical ring and therefore, applying intelligent force-off to WBT.

7.1.2.1 Degree of saturation, X = 0.85

In case where intersection operates with low traffic demand (X = 0.85 with a 90s cycle), each phase frequently meets the critical gap, which is one of the decisions to terminate phase, so that shorter cycle length can be acquired. Although lead-lead left-turn phasing is considered as the most efficient sequence in terms of slack time utilization, intelligent algorithms for lagging left-turn phasing shows the benefits over the standard lagging left-turn phasing.

According to Figure 25, standard lead-lead left-turn phasing has the smallest cycle length, while average green duration of the non-critical left-turn movement (EBL) is the shortest among the five different scenarios. However, average green duration of the non-critical through movement (WBT) of five scenarios is closer to each other, varying from 37.4s to 40s. Comparing intelligent control for lead-lag left-turn phasing to standard control for lead-lag left-turn phasing, cycle length is reduced from, 94.3s to 87.9s, a reduction of 6.8%. Average green duration of the non-critical left-turn movement (EBL) is reduced from 16s to 10.3s, a reduction of 35.6%, while average green duration for the non-critical through movement (WBT) is also slightly reduced from 40s to 37.7s. Comparing intelligent algorithms for lag-lag left-turn phasing to standard control for lag-lag left-turn phasing, cycle length is slightly reduced from 91.3s to 89.3s. Average green duration for the non-critical left-turn movement (EBL) is reduced from 13.6s to 11.1s, a
reduction of 18.4%, while average green duration for the non-critical through movement stays almost the same, only a 0.2s difference.

Figure 25 Cycle Length and Average Green Duration for EBL and WBT (Equal Critical Sum, X= 0.85 at C = 90s).

Figure 26 Overall Delay and Average Vehicular Delay for EBL and WBT (Equal Critical Sum, X = 0.85 at C = 90s).
Seen in Figure 26, standard lead-lead left-turn phasing results in the smallest overall intersection delay, highest average delay for EBL and smallest average delay for WBT. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, overall intersection delay is reduced from 35.8s to 31.9s, a reduction of 11.2%. Average delay for EBL is slightly increased from 40.5s to 42.8s, while average delay for WBT is reduced from 27s to 24.6s, a reduction of 8.9%. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, overall delay in reduced from 35.1s to 32.6s, with a reduction of 7.1%. Average delay for EBL stays the same, a 0.8s difference, while average delay for WBT is reduced from 28.3s to 25.2s, a reduction of 10.6%.

Based on the results in above two figures, lead-lead left-turn phasing shows its advantages in using slack time, resulting in smallest overall intersection delay. Intelligent algorithms shows the better operation by resulting smaller overall intersection than the standard control, indicating that lagging left-turn phasing better utilizes the slack time with intelligent control algorithms, while still maintaining its safety benefits.

7.1.2.2 Degree of saturation, X = 0.90

With greater traffic demand (X = 0.90 with a 90s cycle length), each phase requires longer green duration. Then, the actual cycle length should be closer to the background cycle length of 90s based on which the traffic volume was generated.
Figure 27 Cycle Length and Average Green Duration for EBL and WBT (Equal Critical Sum, $X = 0.90$ at $C = 90s$).

According to Figure 27, standard lead-lead left-turn phasing has the shortest cycle length, while average green duration of the non-critical left-turn movement (EBL) is the shortest among the five different scenarios. However, average green duration of the non-critical through movement (WBT) of the five scenarios stays almost the same, varying from 41.6s to 45s. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, cycle length is reduced from 102.5s to 96.7s. Average green duration of the non-critical left-turn movement (EBL) is slightly reduced from 12.9s to 10.9s, while average green duration for the non-critical through movement (WBT) is also slightly reduced from 45s to 42.5s by 2.5s. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, cycle length is slightly reduced from 98.3s to 96.8s. Average green duration for the non-critical left-turn movement (EBL) is reduced from 13.7s to 11.2s, while average green duration for the non-critical through movement (WBT) is slightly increased from 41.6s to 42.8s. Based on this result, intelligent algorithms only results in slightly shorter cycle length than the standard control logic. In terms of average green duration of the non-critical movements, there is no big difference between standard and intelligent control.
Figure 28 Overall Delay and Average Vehicular Delay for EBL and WBT (Equal Critical Sum, $X = 0.90$ at $C = 90s$).

Seen in Figure 28, standard lead-lead left-turn phasing results in the smallest overall intersection delay, highest average delay for EBL and smallest average delay for WBT. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, overall intersection delay is reduced from 40.8s to 38s, a reduction of 6.9%. Average delay for EBL is increased from 43.3s to 44.6s by 1.3s, while average delay for WBT is reduced from 30.6s to 28.4s, a reduction of 7.8%. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, overall intersection delay is reduced from 40.5s to 37.9s, a reduction of 6.5%. Average delay for EBL is increased from 41.9s to 44.9s, an increase of 7.2%, while average delay for WBT is reduced from 32.2s to 28s, a reduction of 13.1%.

Although the green duration of the non-critical movement slightly differs between standard and intelligent control, average delay for the through movement is reduced at an expense of slight increase on average delay for the left-turn movement. The shorter cycle length is, the smaller delay is. With shorter cycle length, intelligent lagging left-turn phasing has smaller overall intersection delay than standard control, which is consistent with the hypothesis that intelligent algorithm better utilizes the slack time, resulting in less overall intersection delay.
7.1.2.3 Degree of Saturation $X = 0.99$

In case where intersection is in operation with high traffic demand ($X = 0.99$), gap between vehicles is hardly met so that each phase might not terminate until satisfying requirement of its maximum green time. Consequently, actual cycle length might be greater than the background cycle length so that adequate numbers of vehicles can be served in each cycle.

According to Figure 29, cycle length of five different scenarios surpasses 100s, varying from 103s to 108s and lead-lead left-turn phasing has the shortest cycle length. For standard lead-lead left-turn phasing, average green duration of the non-critical left-turn movement (EBL) is the shortest among the five different scenarios, and correspondingly, average green duration of the non-critical through movement (WBT) is the longest comparing to other scenarios. For the four scenarios with lagging left-turn phasing, average green duration of the non-critical left-turn movement (EBL) varies from 11.9s to 13.4s, and intelligent lagging left-turn has slightly shorter green duration. Average green duration of the non-critical through movement (WBT) varies from 47.2s to 48.4s. Because this case is with close-saturation, average green duration approaches the maximum green 50s.

![Figure 29 Cycle Length and Average Green Duration for EBL and WBT](image)
Seen in Figure 30, standard lead-lead left-turn phasing results in the smallest overall intersection delay, highest average delay for EBL and lowest average delay for WBT. Comparing intelligent lead-lag left-turn phasing to standard lead-lag left-turn phasing, overall intersection delay is slightly reduced from 48.8s to 47.4s. Average delay for EBL is increased from 48s to 52.2s, while average delay for WBT is reduced from 39.2s to 37.3s. Comparing intelligent lag-lag left-turn phasing to standard lag-lag left-turn phasing, overall intersection delay is reduced from 50s to 47.1s. Average delay for EBL is increased from 47.9s to 49.3s while average delay for WBT is reduced from 42.1s to 37.8s.

As a conclusion, for the case with equal critical sums in two rings, lead-lead left-turn phasing always results in smallest overall intersection delay, shortest green duration with highest average delay for EBL and longest green duration with lowest average delay for WBT. Intelligent algorithms for lagging left-turn phasing results in shorter cycle length and less overall intersection delay, shorter green duration with higher average delay for EBL and longer green duration with lower average delay for WBT, comparing to the standard control for lagging left-turn phasing. The results show that when an intersection operates with equal critical sums in two
rings, lagging left-turn phasing can also better utilize the slack time with intelligent control algorithms, though not as efficient as the lead-lead phasing. Besides, advantage of lagging left-turn phasing in safety can never be ignored.

7.2 Simulation Analysis for Seven-Intersection Arterial

The seven-intersection arterial used in this study was manually created. Seven intersections are categorized into three types. The first sets are intersections #1, #3, and #5, six-phase operation and low traffic demand on the cross street (X = 0.678 with a 100s cycle length, X = 0.850 at critical intersection, #6). The second sets are intersections #2, #4 and #7, eight-phase operation with medium traffic demand (X = 0.827 with a 100s cycle length, X = 0.850 at critical intersection, #6). The last type is intersection #6, critical intersection, eight-phase operation, X = 0.850 with a 100s cycle length. In terms of intersection spacing, intersections #2 and #6 are the only two non-ideally spaced intersections, while the other five intersections are all treated as ideally spaced intersections. Then, in terms of simplicity, call other intersections except #2 and #6 as “ideally spaced” intersections and call intersection #2 and #6 as “non-ideally spaced” intersections.

Three scenarios are tested in this study for the seven-intersection arterial, which are:

a) Standard Leading --- standard lead-lead left-turn phasing at “ideally spaced” intersections, lag-lead left-turn phasing at intersection #2, and standard lead-lag left-turn phasing at intersection #6;

b) Standard Lagging --- standard lag-lag left-turn phasing at “ideally spaced” intersections, lag-lead left-turn phasing at intersection #2, and standard lead-lag left-turn phasing at intersection #6;

c) Intelligent Lagging --- intelligent lag-lag left-turn phasing at “ideally spaced” intersections, lag-lead left-turn phasing at intersection #2, and intelligent lead-lag left-turn phasing at intersection #6;

For all scenarios, use lead-lag at intersection 6 and lag-lead at intersection 2. All scenarios use same cycle length (100s) and same offsets (seen in Table 7) between intersections. In addition, all scenarios use the same minimum green (6s) for all movements and same maximum green (20s for left-turn phases, 40s for through phases on cross street and 50s for through phases on
major street). In standard lag-lag case, fixed splits based on a cycle length and degree of saturation is determined for lagging left-turn phases.

Standard lead-lead left-turn phasing is applied on cross street for all three scenarios. All three scenarios are tested with two degrees of saturation at the critical intersection, \( X = 0.85 \) with a 100s cycle length (low traffic demand) and \( X = 0.99 \) with a 100s cycle length (high traffic demand). Simulation is run for each scenario with a simulation duration of 4 hours, excluding a warm-up period of 20 minutes.

Traffic data used as the input for simulation is based on the result in traffic generation section and the corresponding adjustments in order to match the targeted degree of saturation and to satisfy the requirement that the inflow should be equal to the outflow at certain intersection. In terms of simplicity when analyzing the simulation result, similar intersections are grouped as follows: 1) intersection #1, #3 and #5; 2) intersection #2; 3) intersection #4 and #7; and 4) intersection #6. Performance measures for the seven-intersection arterial are overall delay for each scenario, average intersection delay, average vehicular delay and average green duration of the focused movements (EBL and WBT) and overflow frequency of the focused movements (EBL and WBL).

### 7.2.1 Degree of Saturation, \( X = 0.85 \)

Critical intersection along the arterial governs the common cycle length, with which each intersection operates. When arterial is in operation with low traffic demand (\( X = 0.85 \)), slack time at critical intersection exists in the non-critical ring. For the other intersections, slack time not only exists in the non-critical ring but also exists in the critical ring. Generally, all slack time is preferable given to the coordinated phases so as to provide better progression.

Overall network delay and average intersection delay are shown in Figure 31, intelligent lagging left-turn phasing results in the smallest overall network delay, 19.5s per vehicle comparing to 21.3s per vehicle with standard leading left-turn phasing and 20.6s per vehicle with standard lagging left-turn phasing. In terms of average intersection delay, at all intersections except intersection #2, intelligent lagging left-turn phasing results in smaller average delay than the
other two scenarios do, while average intersection delay is close to each other at intersection #2 for the three scenarios.

Leading left-turn phasing is disadvantageous in providing progression along arterial, and although it can effectively allocate the slack time to the coordinated phases, the excessive delay on left-turning vehicles, which might wait for an entire cycle, made a significant impact on overall intersection delay. Fixed split is based to establish the start for the lagging left-turn phasing (if it is not skipped) in the scenario with standard lagging left-turn phasing, while prediction logic is applied in the scenario with intelligent lagging left-turn phasing. Standard lagging left-turn phasing uses the difference in two fixed splits to establish the green end for the non-critical through movement (or the green start for the non-critical left-turn phase), while intelligent lagging left-turn phasing uses the estimated green durations of the two lagging left-turn phases. Due to the randomness in traffic arrivals, using the fixed splits of lagging left-turn phasing, on one hand, might result in excessive delay for left-turning vehicles when actual green difference is greater than split difference, and on the other hand, green time might be wasted when the actual green difference is smaller than the split difference.

The distance between intersection #1 and #2 is shorter than the ideal intersection space (based on a common cycle length and travel speed), and therefore lag-lead (the critical left-turn phase, WBL, is lagging, while the non-critical left-turn phase, EBL, is leading) left-turn phasing is needed to be applied at intersection #2 to provide a good progression. The average intersection delay from three scenarios makes no difference because lag-lead left-turn phasing has already efficiently utilized the slack time.
Average vehicular delays for the two focused non-critical movements are compared in Figure 32 (average delay for EBL) and Figure 33 (average delay for WBT). At all intersections, standard leading left-turn phasing results in the highest average delay and intelligent lagging left-turn phasing results in the smallest average delay for EBL. Small difference in average delay is seen between intelligent lagging left-turn phasing and standard lagging left-turn phasing. Leading left-turn phasing results in higher average delay due to worse progression. Due to randomness in traffic arrivals, excessive delay is burdened to the lagging left-turn phasing with standard lagging when the actual left-turn traffic demand is greater than the provided green duration. Consequently, slightly higher average delay for EBL is seen for the scenario with standard lagging left-turn phasing. Intelligent lagging left-turn phasing applies the prediction logic to start the lagging left-turn phasing based on the estimated green need of the two lagging left-turn phases rather than based on the split difference, which is used in the standard lagging left-turn phasing, and therefore intelligent algorithms for lagging left-turn phasing benefit the arterial in slack time utilization and good progression.
Figure 32 Average Vehicular Delay for EBL (X = 0.85, at the critical intersection, with a 100s cycle length).

At all intersections other than the critical intersection (intersection #6), three scenarios result in almost the same average delay for WBT, while at intersection #6, intelligent lagging left-turn phasing results in the smallest average delay and standard leading left-turn phasing generates the highest average delay for WBT. At the non-critical intersections, degree of saturation is lower than the target degree of saturation at the critical intersection, and therefore actual traffic demand is less than the reserved capacity. With slack time allocated to the coordinated phases, traffic demand are perfectly satisfied, thus, average delay for WBT is close to each other in the three scenarios. Lagging left-turn phasing is advantageous from the perspective of progression, and intelligent lagging left-turn phasing focuses on better utilization of the slack time. As a result, at the critical intersection, standard lagging left-turn phasing results in less average delay than the standard leading left-turn phasing and intelligent lagging left-turn phasing performs the best in terms of average delay for WBT.
Average green durations of two focused non-critical movements are also compared in Figure 34 (average green duration of EBL) and Figure 35 (average green duration of WBT). In terms of average green duration of EBL, at grouped intersections 1&3&5 and 4&7, average green duration of EBL is the longest with intelligent lagging left-turn phasing, while standard leading left-turn phasing witnesses the shortest green duration of EBL. At intersection 2 and intersection 6, average green duration of EBL is close to each other in the three scenarios. The difference behind is that standard logic has a fixed green duration, while intelligent algorithms vary green duration between shorter and longer as needed. At grouped intersections 1&3&5, and 4&7, leading left-turn phases terminate as soon as it gaps out or reach the yielding point (maximum green). Intersection 2 is with operation of lag-lead left-turn phasing (EBL is a leading left-turn phase), and therefore average green duration of EBL makes no difference in the three scenarios. At intersection 6, average green duration for EBL is close to each other in the three scenarios, which indicates that intelligent lagging left-turn phasing utilizes the slack time as well as the leading left-turn phasing does in addition to the progression benefits of the lagging left-turn phasing.

Figure 33 Average Vehicular Delay for WBT (X = 0.85, at the critical intersection, with a 100s cycle length).
In terms of average green duration of WBT, at grouped intersections 1&3&5 and 4&7, average green duration of WBT with the standard leading left-turn phasing is slightly longer than the other two scenarios, while average green duration of WBT makes no difference with standard lagging left-turn phasing and intelligent lagging left-turn phasing. At intersection 2 and intersection 6, average green duration of WBT is close to each other in the three scenarios. The results related to the average green duration of the two focused non-critical movements show the consistency. Standard leading left-turn phasing results in shortest average green duration of EBL and longest average green duration of WBT. In addition, standard lagging left-turn phasing and intelligent lagging left-turn phasing makes no big difference in terms of average green duration of both movements. At intersection 2, lag-lead left-turn phasing results in almost the same average green duration of WBT, to which all slack time is allocated. At intersection 6, intelligent lagging left-turn results in only slightly longer average green duration than the other two scenarios. This is also consistent with the average green duration of EBL, which has already indicated the better utilization of slack time.
Overflow frequency of the two focused left-turn movements (EBL and WBL) is compared in Table 13. For the scenario with standard leading left-turn phasing, the only overflow occurrence for EBL is at the critical intersection. At intersection 1, 3, 5, 4, and 7, two left-turn phases operate as leading and each of them terminates when it gaps out or reaches the yielding point (maximum green). At intersection 2, EBL is a leading left-turn phasing, and therefore it gaps out or maxes out. WBL is a lagging left-turn phasing, and it gaps out and terminates together with the WBT since there is no scheduled termination point in this case. At intersection 6, due to randomness in traffic arrivals, constrained by the fixed split for EBL and the scheduled termination point for EBT, the lagging left-turn phase (EBL) is indeed overflowed in some cycles. With standard lagging left-turn phasing, intersection 2 is still with lag-lead left-turn phasing, and therefore, there is no overflow occurrence. At intersection 1, 3, 5, 4, and 7, both two left-turn phases operate as lagging, and both through movements (EBT and WBT) have its own scheduled termination point. These two left-turn phases terminates when they gaps out (non-simultaneous) or reaches their yielding points (maximum green). Overflow occurs in some cycles due to such randomness in traffic arrival that maximum green is reached but actual traffic demand has not been satisfied. At intersection 6, EBL operates as a lagging left-turn phasing, and
the reason for overflow occurrence is the same, reaching the maximum green but not gapped out. With intelligent lagging left-turn phasing, EBT has a scheduled termination point, while WBT has a flexible termination point based on the difference in green requirement of two lagging left-turn movements. In this case, less overflow occurrence is seen than standard lagging left-turn phasing. At intersection 6, green extension logic (actual green end can be beyond the scheduled termination point for EBT) is applied, and therefore there is no overflow for the lagging left-turn phasing.

Table 13 Overflow Frequency for EBL and WBL (X = 0.85, at the critical intersection, with a 100s cycle length)

<table>
<thead>
<tr>
<th>Case</th>
<th>1&amp;3&amp;5</th>
<th>2</th>
<th>4&amp;7</th>
<th>6</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EBL</td>
<td>WBL</td>
<td>EBL</td>
<td>WBL</td>
<td>EBL</td>
</tr>
<tr>
<td>Standard Lead</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17/144</td>
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<tr>
<td>Standard Lag</td>
<td>8/432</td>
<td>9/432</td>
<td>0</td>
<td>0</td>
<td>6/288</td>
</tr>
<tr>
<td>Intelligent Lag</td>
<td>4/432</td>
<td>4/432</td>
<td>0</td>
<td>0</td>
<td>4/288</td>
</tr>
</tbody>
</table>

As a conclusion, comparing to standard leading left-turn phasing and standard lagging left-turn phasing, intelligent lagging left-turn phasing results in less overall network delay and less average intersection delay. In addition, intelligent lagging left-turn phasing results in less overflow frequency than standard lagging left-turn phasing. The simulation results indicated that the intelligent algorithms perform better than the standard leading and standard lagging left-turn phasing. It indeed utilizes the slack time as well as leading left-turn phasing does, and possess its own advantages in arterial progression and safety.

7.2.2 Degree of Saturation, X = 0.99

Critical intersection along the arterial governs the common cycle length, with which each intersection operates. When arterial is in operation with high traffic demand (X = 0.99 with a
100s cycle length), there is less slack time at critical intersection existing in the non-critical ring comparing to the case with low traffic demand. For the other intersections, slack time not only exists in the non-critical ring but also exists in the critical ring. In terms of progression effect, all slack time is preferable given to the coordinated phases.

Overall network delay and average intersection delay are shown in Figure 36. Intelligent lagging left-turn phasing results in the smallest overall network delay, 25.3s per vehicle comparing to 27.6s per vehicle with standard leading left-turn phasing and 26.2s per vehicle with standard lagging left-turn phasing. In terms of average intersection delay, at grouped intersection 1&3&5, standard leading left-turn phasing results in the highest average delay and intelligent lagging left-turn phasing generates the highest average delay. At grouped intersection 4&7, and intersection 6, intelligent lagging left-turn phasing results in the smallest average intersection delay, while standard leading left-turn phasing and standard lagging left-turn phasing have almost the same average intersection delay. Intersection #2 has almost the same average delay for the three scenarios.

Again, leading left-turn phasing has its own advantage in utilizing slack time but disadvantages in providing progression along arterial, and although it can effectively allocate the slack time to the coordinated phases, the excessive delay due to worse progression on left-turning vehicle made a big difference on overall intersection delay. Standard lagging left-turn phasing uses split to determine the start of the lagging left-turn phase, while intelligent lagging left-turn phasing applies the prediction logic. Due to randomness in traffic arrivals, providing fixed splits for lagging left-turn phasing, on one hand, might results in excessive delay for left-turning vehicles when actual demand for green time is greater than the split, and one the other hand, green time might be wasted when the actual demand for green time is less than the split. This feature comes to effect at the intersection with lead-lag left-turn phasing, which is applied at the critical intersection in this study.

Intersection 2 and intersection 6 are the two non-ideally spaced intersections. The distance between intersection #1 and #2 is shorter than the ideal intersection space (based on cycle length and travel speed), and therefore lag-lead (the critical left-turn phase, WBL, is lagging, while the non-critical left-turn phase, EBL, is leading) left-turn phasing is applied at this intersection to
provide a good progression. The average intersection delay from three scenarios makes no difference because lag-lead left-turn phasing has already efficiently utilized the slack time. On the contrary, lead-lag left-turn phasing is needed at intersection 6.

Figure 36 Overall Delay and Average Intersection Delay (X = 0.99, at the critical intersection, with a 100s cycle length).

Average vehicular delays for the two focused non-critical movements are compared in Figure 37 (average delay for EBL) and Figure 38 (average delay for WBT). At all intersections except intersection 2, standard leading left-turn phasing results in the highest average delay for EBL and intelligent lagging left-turn phasing results in the smallest average delay. However, slight difference in average delay is seen between intelligent lagging left-turn phasing and standard lagging left-turn phasing. At intersection 2, average delay for EBL is close to each other in the three scenarios because lag-lead left-turn phasing allocates all slack time to the coordinated phase. Leading left-turn phasing results in higher average delay due to worse progression. Intelligent lagging left-turn phasing results in less average delay for EBL than standard lagging left-turn phasing because prediction logic is applied so that green given to the lagging left-turn phase better matches the green time needed in each cycle.
At grouped intersections 1&3&5 and intersection 2, the three scenarios result in almost the same average delay for WBT. At intersection 4&7, intelligent lagging left-turn phasing results in the smallest average delay, while standard leading and standard lagging left-turn phasing performs almost the same in terms of average delay for WBT. At intersection #6, intelligent lagging left-turn phasing results in the smallest average delay and standard leading left-turn phasing generates the highest average delay for WBT. At the grouped intersections 1&3&5, degree of saturation is much lower than the target degree of saturation at the critical intersection, and therefore, actual traffic demand is less than the reserved capacity. With slack time allocated to the coordinated phases, traffic demand are perfectly satisfied, thus, average delay for WBT is close to each other in the three scenarios. Intersection 2 is with lag-lead operation, and therefore all slack time is assigned to the coordinated phases so that the average delay for WBT makes no difference. Lagging left-turn phasing is advantageous from the perspective of progression, and intelligent lagging left-turn phasing focuses on better utilization of the slack time. As a result, at the critical intersection, standard lagging left-turn phasing results in less average delay than the standard leading left-turn phasing and intelligent lagging left-turn phasing performs the best in terms of average delay for WBT.
Figure 38 Average Vehicular Delay for WBT (X = 0.99, at the critical intersection, with a 100s cycle length).

Average green durations of two focused non-critical movements are also compared in Figure 39 (average green duration of EBL) and Figure 40 (average green duration of WBT). In terms of average green duration of EBL, at grouped intersections 1&3&5, average green duration of EBL is the longest with intelligent lagging left-turn phasing, while standard leading left-turn phasing witnesses the shortest green duration of EBL. At intersection 2, average green duration of EBL is close to each other in the three scenarios. At grouped intersections 4&7 and intersection 6, standard leading left-turn phase has the shortest average green duration for EBL, while standard lagging and intelligent lagging left-turn phasing have the same amount of average green duration for EBL. Standard leading left-turn phasing allocates all slack time to the opposing through movement (WBT), while lagging left-turn phasing takes part of the slack time. Intersection 2 is with operation of lag-lead left-turn phasing (EBL is a leading left-turn phase), and therefore average green duration of EBL makes no difference in the three scenarios. At intersection 6, EBL is the lagging left-turn phase, and its start is with a base of the scheduled termination point of EBT. With high traffic demand, like X =0.99 with a 100s cycle length, average green duration of EBL is the same for standard lagging left-turn phasing and intelligent lagging left-turn phasing, showing that there is no difference in performance in terms of average green duration of EBL.
In terms of average green duration of WBT, at grouped intersections 1&3&5, average green duration of WBT with the standard leading left-turn phasing is slightly longer than the other two scenarios. At grouped intersection 4&7 and intersection 2, average green duration of WBT is close to each other in the three scenarios. At intersection 6, intelligent lagging left-turn phasing results in slightly higher average green duration of WBT. At intersection 1&3&5, degree of saturation is much lower comparing to the target degree of saturation at the critical intersection, and therefore, there is extra capacity to serve the through movements, and three scenarios perform equally. At intersection 2, lag-lead left-turn phasing results in almost the same average green duration of WBT, to which all slack time is allocated. At intersection 6, intelligent lagging left-turn results in only slightly longer average green duration than the other two scenarios. This is also consistent with the average green duration of EBL, which has already indicated the better utilization of slack time. In addition, at the intersections with high degree of saturation (close to 1), average green duration of WBT is close to 40s, which is the maximum green for WBT, showing that WBT merely maxes out.
Overflow frequency of the two focused left-turn movements (EBL and WBL) is compared in Table 14. For the scenario with standard leading left-turn phasing, at intersection 1, 3, 5, 4, and 7, two left-turn phases operate as leading and each of them terminates when it gaps out or reaches the yielding point (maximum green). At intersection 2, EBL is a leading left-turn phasing, and therefore it gaps out or maxes out. WBL is a lagging left-turn phasing, and it gaps out and terminates together with the WBT since there is no scheduled termination point in this case. At intersection 6, due to randomness in traffic arrival, constrained by the fixed split and the scheduled termination point for EBT, the lagging left-turn phase (EBL) is indeed overflowed in some cycles. With standard lagging left-turn phasing, intersection 2 is still with lag-lead left-turn phasing, and no overflow occurrence indicates that actual green need is less than the maximum green. At intersection 1, 3, 5, 4, and 7, both two left-turn phases operate as lagging, and both through movements (EBT and WBT) have its own scheduled termination point. These two left-turn phases terminates when they gaps out (non-simultaneous) or reaches their yielding points (maximum green). Overflow occurs in some cycles due to such randomness in traffic arrival that maximum green is reached but actual traffic demand has not satisfied. Intelligent lagging left-turn phasing has lower overflow frequency because it utilizes the slack time more wisely with
the prediction logic. At intersection 6, fixed split is provided for EBL in each cycle so that there is a big opportunity for overflow, and it is. With intelligent lagging left-turn phasing, EBT has a scheduled termination point, while WBT has a flexible termination point based on the difference in green requirement of two lagging left-turn movements. In this case, less overflow occurrence is seen than standard lagging left-turn phasing. At intersection 6, green extension logic (actual green end can be beyond the scheduled termination point) is applied for lagging left-turn phasing, and therefore there is almost no overflow for the lagging left-turn phasing.

### Table 14 Overflow Frequency for EBL and WBL (X = 0.99, at the critical intersection, with a 100s cycle length)

<table>
<thead>
<tr>
<th>Case</th>
<th>1&amp;3&amp;5</th>
<th>2</th>
<th>4&amp;7</th>
<th>6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EBL</td>
<td>WBL</td>
<td>EBL</td>
<td>WBL</td>
<td>EBL</td>
</tr>
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<td>Standard Lead</td>
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<td>0</td>
<td>53/144</td>
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<td>Standard Lag</td>
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<td>10/432</td>
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<tr>
<td>Intelligent Lag</td>
<td>6/432</td>
<td>6/432</td>
<td>0</td>
<td>0</td>
<td>8/288</td>
</tr>
</tbody>
</table>

As a conclusion, comparing to standard leading left-turn phasing and standard lagging left-turn phasing, intelligent lagging left-turn phasing results in less overall network delay and less average intersection delay. In addition, intelligent lagging left-turn phasing results in less overflow frequency than standard lagging left-turn phasing and standard leading left-turn phasing. The simulation results indicated that the intelligent algorithms perform better than the standard leading and standard lagging left-turn phasing. It indeed utilizes the slack time as well as leading left-turn phasing does, and possess its own advantages in progression and safety.
8. Conclusions and Recommendations

Based on the simulation results, conclusions are made for isolated intersection in terms of cycle length, overall delay, average vehicular delay, average green duration of the focused movements, and for seven-intersection arterial in terms of overall delay, average vehicular delay, average green duration and overflow frequency.

8.1 Conclusions for isolated intersection

1) Standard lead-lead left-turn phasing always results in shorter cycle length and less overall delay comparing to other four scenarios, regardless of whether it is with standard lagging or intelligent lagging.

2) Intelligent lagging left-turn phasing results in shorter cycle lengths, and less overall delay than standard lagging left-turn phasing.

3) Intelligent lagging left-turn phasing can utilize the slack time as wisely as leading left-turn phasing. In addition, lagging left-turn phasing possesses its own advantages in progression and safety when compared to standard lagging left-turn phasing control.

4) Intelligent lagging left-turn phasing results in shorter average green durations and higher average delay for the non-critical left-turn phase when compared to standard lagging left-turn phasing control.

5) Intelligent lagging left-turn phasing results in longer average green duration and lower average delay for the non-critical through phase.

8.2 Conclusions for seven-intersection arterial

1) Intelligent lagging left-turn phasing results in lower overall network delay and average intersection delay compared to standard leading left-turn phasing and standard lagging left-turn phasing.

2) Intelligent lagging left-turn phasing results in lower average delay for the non-critical left-turn phase and the non-critical through phase at the critical intersection compared to standard lead and standard lag control.

3) At the non-critical intersections, intelligent lagging left-turn phasing performs as well as standard leading left-turn phasing in terms of slack time utilization.
4) Intelligent lagging left-turn phasing results in lower overflow frequency than standard lagging left-turn phasing, and even lower than standard leading left-turn phasing when the degree of saturation at the critical intersection is close to 1.

This study considered protected-only left-turn phasing and only vehicular movements are involved in the simulation. For future work, algorithms for protected-permitted left-turn phasing should be developed as well as adding pedestrian phase or transit movement. In addition, this study uses a dummy arterial with traffic volume from bi-proportional method. The algorithms can be tested on actual traffic volume in the future.
Reference

10. [http://cms3.tucsonaz.gov/transportation/left-turn-arrows](http://cms3.tucsonaz.gov/transportation/left-turn-arrows)
15. VISSIM 5.40, VISSIM PTV, Germany.
## Appendix A Dual Ring Spreadsheet

### Case A: Cycle length 90s, X = 0.85, Scale Factor = 4.17

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Lost Time per Phase</th>
</tr>
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<td><strong>Chosen C</strong></td>
<td><strong>T</strong></td>
</tr>
<tr>
<td>90</td>
<td>0.25</td>
</tr>
<tr>
<td>Phase</td>
<td>1</td>
</tr>
<tr>
<td>WBL</td>
<td>EBT</td>
</tr>
<tr>
<td><strong>DATA</strong></td>
<td></td>
</tr>
<tr>
<td><strong>v</strong></td>
<td>121</td>
</tr>
<tr>
<td>lanes</td>
<td>1</td>
</tr>
</tbody>
</table>

### FIND CRITICAL STREAMS AND DETERMINE SPLITS

| **s** | 1800 | 3600 | 1800 | 3600 | 1800 | 1800 | 1800 |
| **v/s** | 0.07 | 0.39 | 0.06 | 0.24 | 0.05 | 0.19 | 0.08 | 0.13 |
| conflict pair sum | 0.45 | 0.31 | 0.25 | 0.22 |
| critical? | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| lost time | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Σ critical lost | | | | | | | | 8.0 | 8.0 | 16.0 |
| **X_{target}** | | | | | | | | 0.850 |
| needed split | 11.1 | 44.9 | 10.6 | 29.9 | 9.4 | 24.6 | 12.8 | 18.2 | 56.0 | 34.0 | 90.0 |
| slack | 0.0 | 0.0 | 7.7 | 7.7 | 0.0 | 0.0 | 1.5 | 1.5 | 0.0 | 2.9 |
| split | 11.1 | 44.9 | 18.4 | 37.6 | 9.4 | 24.6 | 14.3 | 19.7 | 56.0 | 34.0 | slack ok |
| g | 7.1 | 40.9 | 14.4 | 33.6 | 5.4 | 20.6 | 10.3 | 15.7 |

### RESULTING DELAY AND LEVEL OF SERVICE

| **phase v/c** | 0.85 | 0.85 | 0.39 | 0.65 | 0.85 | 0.85 | 0.73 | 0.77 |
| **d_1** | 40.9 | 21.8 | 33.9 | 23.4 | 41.9 | 33.2 | 38.5 | 35.4 |
| **d_2** | 45.8 | 5.8 | 4.0 | 2.5 | 52.9 | 19.2 | 20.1 | 16.6 |
| **d** | 86.7 | 37.9 | 25.9 | 94.8 | 52.5 | 58.6 | 52.0 | 37.1 |
| **LOS** | **F** | **C** | **D** | **C** | **F** | **E** | **E** | **E** |

Notes:
1. Possible effect of progression not accounted for in delay estimates
2. Degree of saturation equalized for critical phases
3. Slack time for each half-cycle split equally between non-critical phases
4. Minor addition errors are superficial rounding effects
**Case B: Cycle length 90s, X = 0.90, Scale Factor = 4.42**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Lost Time per Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chosen C</strong></td>
<td><strong>T</strong></td>
</tr>
<tr>
<td>90</td>
<td>0.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>EW</th>
<th>NS</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WBL</td>
<td>EBT</td>
<td>EBL</td>
<td>WBT</td>
<td>NBL</td>
<td>SBT</td>
<td>SBL</td>
<td>NBT</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DATA**

| v | 128 | 1471 | 119 | 932 | 97 | 371 | 159 | 256 |     |     |         |
| lanes | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 1 |     |     |         |

**FIND CRITICAL STREAMS AND DETERMINE SPLITS**

| s   | 1800 | 3600 | 1800 | 3600 | 1800 | 1800 | 1800 |     |     |         |
| v/s | 0.07 | 0.41 | 0.07 | 0.26 | 0.05 | 0.21 | 0.09 | 0.14 |     |     |         |
| conflict pair sum | 0.48 | 0.33 | 0.26 | 0.23 |     |     |     |     |     |     |         |
| critical? | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |     |     |         |
| lost time | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |     |     |         |
| Σ critical lost |     |     |     |     | 8.0 | 8.0 | 16.0 |     |     |     |         |
| X\text{target} |     |     |     |     |     |     |     | 0.900 |     |     |         |
| needed split | 11.1 | 44.9 | 10.6 | 29.9 | 9.4 | 24.6 | 12.8 | 18.2 | 56.0 | 34.0 | 90.0 |
| slack | 0.0 | 0.0 | 7.7 | 7.7 | 0.0 | 0.0 | 1.5 | 1.5 | 0.0 | 2.9 |     |
| split | 11.1 | 44.9 | 18.4 | 37.6 | 9.4 | 24.6 | 14.3 | 19.7 | 56.0 | 34.0 | slack ok |
| g | 7.1 | 40.9 | 14.4 | 33.6 | 5.4 | 20.6 | 10.3 | 15.7 |     |     |         |

**RESULTING DELAY AND LEVEL OF SERVICE**

| phase v/c | 0.90 | 0.90 | 0.42 | 0.69 | 0.90 | 0.90 | 0.77 | 0.82 |     |     |         |
| d₁ | 41.1 | 22.7 | 34.0 | 23.8 | 42.0 | 33.7 | 38.7 | 35.8 |     |     |         |
| d₂ | 52.5 | 8.4 | 4.4 | 3.0 | 62.7 | 25.2 | 23.9 | 20.4 |     |     |         |
| d | 93.6 | 31.0 | 38.4 | 26.8 | 104.7 | 58.9 | 62.6 | 56.1 | 40.5 |     |         |
| LOS | F | C | D | C | F | E | E | E |     |     |         |

**Notes:**
1. Possible effect of progression not accounted for in delay estimates
2. Degree of saturation equalized for critical phases
3. Slack time for each half-cycle split equally between non-critical phases
4. Minor addition errors are superficial rounding effects
**Case C: Cycle length 90s, X = 0.99, Scale Factor = 4.86**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Lost Time per Phase</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chosen C 90</td>
<td>T = 0.25, k = 0.5, I = 1, S_ideal = 1900</td>
<td>EW phases = 4</td>
</tr>
<tr>
<td>Phase 1-8</td>
<td>EW: WBL, EBT, EBL, WBT</td>
<td>NS: NBL, SBT, SBL, NBT</td>
</tr>
<tr>
<td>DATA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>v = 141, 1618, 131, 1025, 107, 408, 175, 282</td>
<td>lanes = 1, 2, 1, 2, 1, 1, 1, 1</td>
<td></td>
</tr>
<tr>
<td>FIND CRITICAL STREAMS AND DETERMINE Splits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s = 1800, 3600, 1800, 3600, 1800, 1800, 1800</td>
<td>v/s = 0.08, 0.45, 0.07, 0.28, 0.06, 0.23, 0.10, 0.16</td>
<td></td>
</tr>
<tr>
<td>conflict pair sum = 0.53, 0.36, 0.29, 0.25</td>
<td>critical? = 1, 1, 0, 0, 1, 1, 0, 0</td>
<td></td>
</tr>
<tr>
<td>lost time = 4, 4, 4, 4, 4, 4, 4, 4</td>
<td>∑critical lost = 8.0, 8.0, 16.0</td>
<td></td>
</tr>
<tr>
<td>X_target = 0.990</td>
<td>needed split = 11.1, 44.9, 10.6, 29.9, 9.4, 24.6, 12.8, 18.2, 56.0, 34.0, 90.0</td>
<td></td>
</tr>
<tr>
<td>slack = 0.0, 0.0, 7.7, 7.7, 0.0, 0.0, 1.5, 1.5, 0.0, 2.9</td>
<td>split = 11.1, 44.9, 18.4, 37.6, 9.4, 24.6, 14.3, 19.7, 56.0, 34.0, slack ok</td>
<td></td>
</tr>
<tr>
<td>g = 7.1, 40.9, 14.4, 33.6, 5.4, 20.6, 10.3, 15.7</td>
<td>RESULTING DELAY AND LEVEL OF SERVICE</td>
<td></td>
</tr>
<tr>
<td>phase v/c = 0.99, 0.46, 0.76, 0.99, 0.99, 0.85, 0.90</td>
<td>d_1 = 41.4, 24.4, 34.3, 24.7, 42.3, 34.6, 39.1, 36.4</td>
<td></td>
</tr>
<tr>
<td>d_2 = 72.8, 20.0, 5.2, 4.1, 84.0, 41.9, 33.0, 30.2</td>
<td>d = 114.2, 44.4, 39.5, 28.8, 126.2, 76.5, 72.1, 66.6, 51.0</td>
<td></td>
</tr>
<tr>
<td>LOS = F, D, C, F, E, E, E, E</td>
<td>Notes:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 Possible effect of progression not accounted for in delay estimates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Degree of saturation equalized for critical phases</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 Slack time for each half-cycle split equally between non-critical phases</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 Minor addition errors are superficial rounding effects</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B Traffic Volume

Case A: Non-Equal Critical Sum in Two Rings at Individual Intersection

Figure 41 Traffic Volume at Individual Intersection, Non-Equal Critical Sums (X=0.85 at a 90s background cycle).

Figure 42 Traffic Volume at Individual Intersection, Non-Equal Critical Sums (X=0.90 at a 90s background cycle).

Figure 43 Traffic Volume at Individual Intersection, Non-Equal Critical Sums (X=0.99 at a 90s background cycle).
Case B: Equal Critical Sum in Two Rings at Individual Intersection

Figure 44 Traffic Volume at Individual Intersection, Equal Critical Sums (X=0.85 at a 90s background cycle).

Figure 45 Traffic Volume at Individual Intersection, Equal Critical Sums (X=0.90 at a 90s background cycle).

Figure 46 Traffic Volume at Individual Intersection, Equal Critical Sums (X=0.99 at a 90s background cycle).
**Case C: Seven-Intersection Arterial**

Figure 47 Traffic Volume at Each Intersection along the Arterial (X=0.85 at the critical intersection with a 100s cycle).

Figure 48 Traffic Volume at Each Intersection along the Arterial (X=0.99 at the critical intersection with a 100s cycle).
Table 15 Actual X with a 100s Cycle and Needed Cycle Length for X = 0.85

<table>
<thead>
<tr>
<th>Intersection</th>
<th>X with 100s cycle</th>
<th>Needed cycle length for X = 0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection 1 (6 phases)</td>
<td>0.678</td>
<td>41</td>
</tr>
<tr>
<td>Intersection 2</td>
<td>0.827</td>
<td>87</td>
</tr>
<tr>
<td>Intersection 3 (6 phases)</td>
<td>0.678</td>
<td>41</td>
</tr>
<tr>
<td>Intersection 4</td>
<td>0.827</td>
<td>87</td>
</tr>
<tr>
<td>Intersection 5 (6 phases)</td>
<td>0.678</td>
<td>41</td>
</tr>
<tr>
<td>Intersection 6 (critical)</td>
<td>0.850</td>
<td>100</td>
</tr>
<tr>
<td>Intersection 7</td>
<td>0.827</td>
<td>87</td>
</tr>
</tbody>
</table>