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An Innovative Signal Timing Strategy for Implementing Contraflow Left-Turn Lanes at Signalized Intersections with Split Phasing

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Abstract: Contraflow Left-Turn Lanes (CLLs) have the potential of being a solution for mitigating congestions at signalized intersections where split phasing is recommended or required. However, the current signal timing strategy for the intersections with CLLs cannot be directly applied at the signalized intersections with split phasing (SIWSP). To address this problem, this study proposed an innovative signal timing strategy, which is referred to as Counterclockwise Split Phasing (CSP) signal timing, for implementing the CLLs at the SIWSPs. A traffic simulation-based case study was conducted and the results indicate that, by using the proposed CSP signal timing plan, CLLs can be implemented at the SIWSP and can significantly reduce the traffic congestions caused by the high left-turn demand at this type of intersection. In addition, since the proposed CSP signal timing design procedure has fully considered the clearance time requirements for the left-turn vehicles on the CLLs, the risk associated with the use of CLLs can be controlled which makes it safe to use this innovative intersection design at SIWSPs.

Keywords: Contraflow Left-Turn Lanes (CLLs); intersection congestion; split phasing

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1. Introduction

Traffic congestion is a critical issue for the sustainability of transportation development. It can cause traffic delays, reduced economic efficiency, and safety and air pollution problems. As traffic congestion increases, the need to maximize the utilization of existing lane configurations, and therefore improving the sustainability of the transportation system, is of great importance. At some intersections, excessive left-turn queue lengths may cause the queue to spill out of the left-turn bay and block the through lanes, which adversely affects the operation and safety of the entire intersection. An innovative intersection design, Contraflow Left-Turn Lane (CLL), is designed for solving the problem where the capacity of the existing regular left-turn lanes is insufficient for the increasing left-turn demand at a signalized intersection. The basic idea of this design is to dynamically use a portion of the opposing through lanes as additional left-turn lanes [1] Wu et al., 2016. Figure 1 shows the design concept of the CLL and Figure 2 shows the signal timing plan used for such a design. Generally, the CLL is designed for use at signalized intersections with lead-lead protected left-turn phases. As illustrated in Figures 1 and 2, a pre-signal and a median opening are set upstream of the CLL to allow the left-turn vehicles to enter the CLL during the signal phases for the crossing-through movements. The entered left-turn vehicles will wait at the CLL until the left-turn signal at the main intersection turns green. Then, they move together with other left-turn vehicles on the adjacent regular left-turn lane(s) during the leading left-turn phase. Note that the pre-signals will turn red before the left-turn signal at the main intersection turns red, and enough clearance time (CT) will be provided to ensure that all the left-turn vehicles on the CLLs can be cleared before the left-turn phase ends. In this way, the conflicts between the left-turn vehicles using CLLs and the opposing through vehicles can be avoided. As shown in Figure 1, the shaded lanes are the CLLs, which can be used by both left turn and opposing through vehicles. With the CLL design, more existing lanes (i.e., opposing through lanes) can be used for moving left-turn vehicles. Thus, the capacity and operational efficiency of the intersections can be improved. In addition, this new design can be easily implemented without modifying the intersection in a way that requires major roadway construction. Therefore, it could be a low-cost solution for mitigating the traffic congestion at the signalized intersections, especially for the intersections with high left-turn demand [2] CLL design was first proposed by a traffic manager in Handan, China, and was first implemented in that city in 2014. After that, due to its effectiveness in reducing intersection congestion, it has been widely implemented in over 50 intersections in 21 different cities in China since 2018 [3].

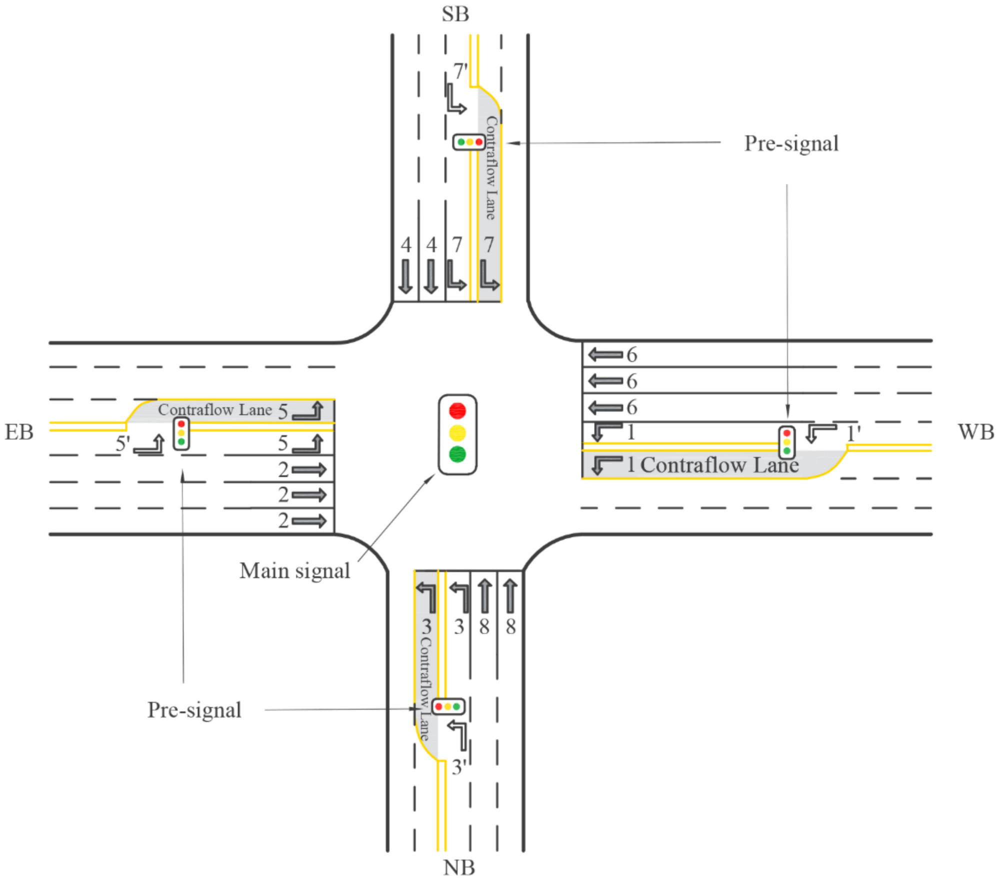
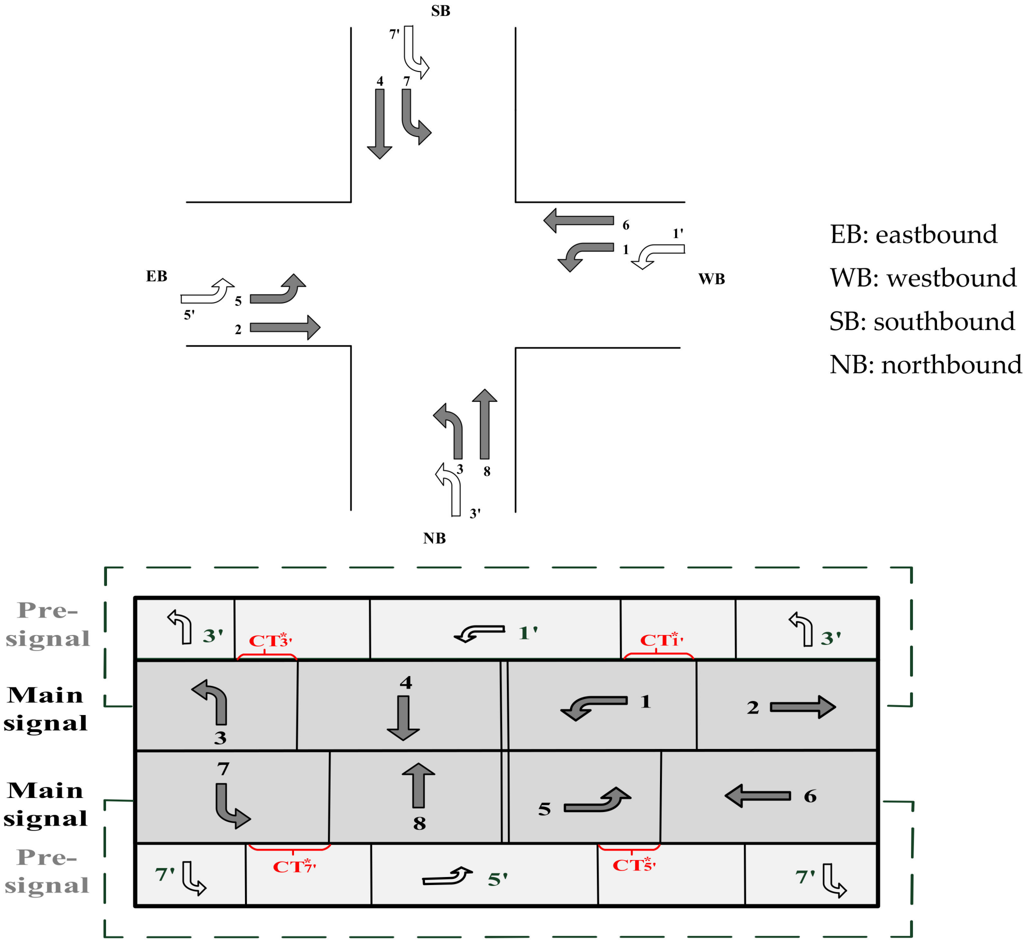
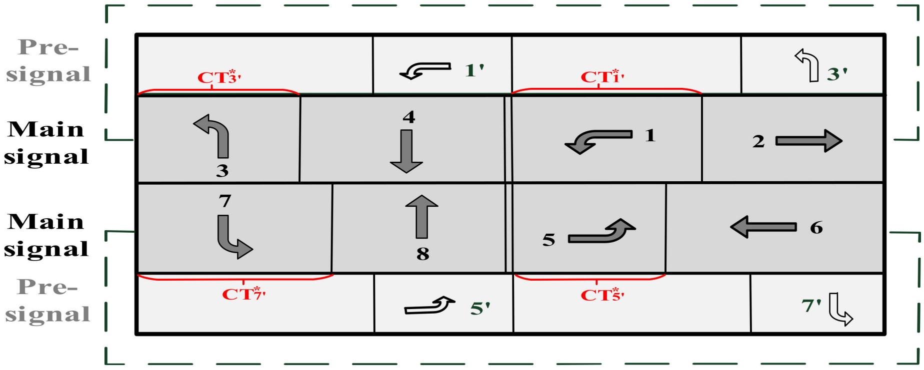


Figure 1. Geometric design for the signalized intersection with CLL design.



(**a**) General signal timing plan



(**b**) Signal timing plan with Maximum

Figure 2. Existing signal timing plan for the signalized intersection with CLL design. (**a**).General signal timing plan; (**b**). Signal timing plan with Maximum. * $CT_{i'}$* is the time for clearing the left-turn vehicles on the CLLs that entered the CLLs during the pre-signal phase i′.

Split phasing represents an assignment of the right-of-way to all movements of a particular approach, followed by all of the movements of the opposing approach [4]. Figure 3 presents a split phasing signal timing plan. According to a FHWA study [5], at the intersections where the left-turn lane volumes on two opposing approaches are approximately equal to the through traffic lane volumes and the total approach volumes are significantly different on the two approaches, split phasing may prove to be more efficient than conventional phasing. In addition, split phasing is necessary under certain intersection geometry conditions, such as when the opposing left-turn paths overlap because of intersection geometry layout [4]. Thus, split phasing, as one important left-turn phase option, has its own advantages under certain intersection traffic and geometric conditions. However, the CLL design cannot be directly used at the intersections with split phasing. This is because one of the requirements for implementing CLL design is that the intersection should use leading protected left-turn phases on both streets [3]. The CLL design cannot work with the lagging left-turn phase because, for the lagging left-turn approach, left-turn vehicles cannot be allowed to enter the CLLs during the signal phase that is right before the left-turn phase since this phase is for moving the opposing through vehicles that also need to use CLLs. However, in split phasing, the left-turn phase in one direction has to be the lagging phase. Therefore, CLL design cannot be directly used at the intersections with split phasing. To solve this problem, in this study an innovative signal timing strategy, which is referred to as Counterclockwise Split Phasing (CSP) signal timing, is proposed for the implementation of CLL at the signalized intersections with split phasing (SIWSP). The proposed signal timing strategy can combine the advantages of the split phasing and the CLL design to achieve more operational and safety benefits at the intersections where split phasing is recommended or required.

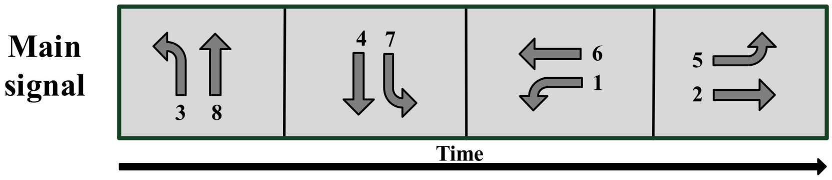


Figure 3. Split phasing signal timing plan.

In this paper, previous studies related to the CLL intersections are reviewed and discussed first, followed by an introduction of the concept design of the proposed signal timing strategy. Then, a traffic simulation-based case study is conducted to demonstrate the application of the new signal timing strategy to a hypothetical CLL intersection, and its mobility benefits under various traffic conditions are assessed based on the simulation results. Finally, conclusions and recommendations are provided.

2. Literature Review

CLLs are also called exit lanes for left turns (EFL) or contraflow left-turn pocket lanes (CLPL), which belong to the category of dynamic or reversible lane design. Applying the CLLs at intersections is a relatively new design idea. Although it has been implemented in over 50 intersections in China, they are not currently implemented in North America. In recent years, several studies have been conducted in investigating the design, operational, and safety performance of the CLLs.

In Zhao et al. [6], CLL was introduced as a left-turn congestion mitigation strategy for signalized intersections. In this study, an optimization problem for CLL control was formulated as a mixed-integer nonlinear program. The objective of this optimization problem is to maximize the reserve capacity of CLL. Twenty-four constraints were set to find the optimum solutions about geometric layout, main signal timing, and pre-signal timing for the CLL intersection design. The results show that the proposed CLL intersection increases the capacity of an intersection and reduces average intersection vehicle delay and queue length compared with the conventional intersection design.

Su et al. [2] proposed an experimental design for evaluating signal timing and geometric design elements of CLL intersections. In this study, case studies were used to illustrate how the design concepts are applied and to examine the key design elements in the CLL, including pocket lengths, access control, and green signal times. In a case study, the operational advantages of intersections with CLL design under different traffic demand levels were evaluated. The results indicated that the CLL treatment can reduce the intersection delay by about 22% at intersections with high left-turn demand.

Wu et al. [1] developed analytical models for estimating the capacity and delay of intersections associated with the CLL design. In addition, a procedure was developed to optimize the location of upstream median openings based on the developed capacity model. The results indicate that the CLL design can improve the intersection capacity and reduce traffic delay compared with the conventional left-turn lane design. It is also pointed out that one of the major concerns of the CLL design is the potential conflicts between the vehicles trapped in the CLL and opposing through vehicles.

Zhao et.al. [3] developed a probabilistic model to estimate intersection capacity with CLLs. The impacts of the cycle length, left-turn demand, and lane selection preference on the capacity estimation of CLL intersection were also investigated. The results of this study indicate that the CLL treatment can increase a signalized intersection's throughput by up to 25% and decrease the intersection's delay by 35% on average.

Zhao et al. [7] developed a saturation flow rate adjustment model that can be used for estimating the saturation flow rate at both the main intersection and the median openings for CLLs based on field-collected data at ten signalized intersections. In the development of this model, five influencing factors, namely the median opening blockage, demand starvation, multilane interference, conflict with opposing vehicles, and lane changing, were considered. The results of this model can be used for improving and optimizing the signal timing and geometric design of the CLL design.

Liu et al. [8] proposed a shockwave-based model for estimating the maximum left-turn queue length of CLL at signalized intersections. In this study, a binary logit model was employed as an estimate of the unique queuing behavior at the pre-signals. To develop such a model, field studies were conducted at five signalized CLL intersections in Handan, China. Based on the field observations, it was found that although the chance of vehicles being accidentally trapped on the CLL is very small, the potential collision risks cannot be ignored.

Most recently, Wu et al. [9] proposed a semi-actuated signal control strategy to improve the operations of the CLL design at signalized intersections. It proposed a procedure for optimizing the CLL length by maximizing the discharge rate of the left-turning vehicles and the utilization rate of the CLL. In this study, the interactive relationship between CLL length and traffic signal timing was considered by using simultaneous equations, and a shock wave-based model was used for estimating the left-turn queue backup length. Wu et al. [10] also analyzed the operational performance of the CLL design by considering the influence of the upstream signalized intersection. It was found that both the intersection traffic arrival pattern and the lengths of the CLLs have significant impacts on the operational performance of the CLL intersection. In this study, an empirical optimization method was proposed for deriving the optimal length of CLLs and the signal offset between adjacent intersections to minimize the intersection control delay.

When implementing innovative intersection designs such as CLLs, driver acceptance is an important issue. Although this issue has not been explicitly discussed in the existing literature, some studies have investigated the driver's behavior associated with the use of CLLs. Zhao et al. [11] investigated driver behavior when approaching CLLs by employing a series of driving simulator experiments. In this study, the effects of different sign and pavement marking designs for CLLs were examined. The results of this study indicate that drivers show a certain amount of confusion and hesitation when encountering a CLL for the first time. However, this problem could be mitigated by public outreach, driver education, or the improvement of traffic signages. To overcome the limitation of the simulator-based study, Zhao et al. [12] studied the driver's behavior at seven real-world intersections with CLLs. Results indicated that the risks of using CLL intersections mainly lie in red-light violations at the pre-signal, wrong-way violation, and vehicles trapped in the mixed-usage area. In this study, countermeasures for preventing these risks were also identified.

Furthermore, to safely and effectively implement the CLL design, driving behavior characteristics related to left turns also need to be considered. For example, Frazier et al. [13] found that drivers do not always select the leftmost lane (Lane 1) as their destination lane when turning left, which brings another risk in the use of CLL. This is because if two left-turn vehicles (one on the CLL and one on the adjacent regular left-turn lane) that are turning abreast choose the same destination lane, a sideswipe crash could occur.

From the literature mentioned above, it can be seen that most of the previous studies have indicated that the use of CLLs can improve the operational performance of the intersections. However, these existing studies are all based on the assumption that the signal timing phase at the main signal is the lead-lead protected left-turn phase. As we mentioned before, the CLL design cannot be directly implemented at signalized intersections with split phasing. Thus, for the intersections where the split phasing is recommended or required, the benefits of using CLL design cannot be achieved. This research aims to find a solution to this problem.

3. Proposed Concept

To understand the proposed signal design strategy for the SIWSP, the existing signal timing strategy for applying CLLs at a regular signalized intersection needs to be introduced first.

3.1. Existing Signal Timing Strategy For Applying CLL at Regular Signalized Intersections

The existing signal timing plan for the signalized intersections with CLLs is presented in Figure 2. Basically, CLL treatment can only work with the protected-only lead-lead left-turn signal phasing. This is because the left-turn vehicles waiting on the CLLs need to be cleared from the intersection before the opposing through vehicles can be released. As shown in Figure 2, the signal phases $7'$, $3'$, $5'$ and $1'$ are the pre-signal phases that control the left-turn vehicles entering the CLLs from different approaches, which correspond to the left-turn movements during the left-turn phases 1, 3, 5 and 7 at the main intersection signal, respectively. The entered left-turn vehicles will wait at the CLL until the left-turn signal at the main intersection turns green and then they will be discharged during the leading left-turn phase. Sufficient clearance time must be provided for clearing the left-turn vehicles on the CLLs before the left-turn signal at the main intersection turns red. Otherwise, the left-turn vehicle will be trapped on the CLLs, which will lead to head-on collisions between the trapped left-turning vehicle and opposing through vehicles during the following through movement phase. The minimum required time for clearing the left-turn vehicles on CLL can be estimated by the following equation.

$$Min\_CT^{*}_{i'} \geq t_{dh} \times \frac{L_{CLL_i}}{S_{pc}} + l_s, i \ = 1,3,5,7 \tag{1}$$

where $Min\_CT^{*}_{i'}$ is the minimum time required for clearing the left-turn vehicles that entered the CLLs during the pre-signal phase i$'$, t_{dh} is the saturation discharging headway of left-turn vehicles, l_s is the start-up lost time of the left-turn vehicles, which is assumed to be 2s, S_{pc} is the average vehicle storage length, which is assumed to be 25 ft, and L_{CLLi} is the length of the CLL at the approach corresponding to signal phase i$'$.

Note that Equation 1 is for estimating the minimum required clearance time. To ensure that all the left-turn vehicles on the CLL can be fully discharged during the left-turn phase, some previous studies (such as [1]) recommended that the whole left-turn phase should be used for clearing the left-turn vehicles on the CLLs. Thus, the maximum clearance time for the left-turn vehicles on the CLLs will be the length of the entire left-turn phase, as shown in Figure 2b. In this case, the pre-signals will turn red before the left-turn signal at the main intersection turns green, and after that no vehicles can enter the CLLs. However, even if the maximum clearance time was provided, which means that the whole left-turn phases are used for clearing the left-turn vehicles on the CLLs, it may still not be safe to use CLLs. This is because the length of the left-turn phase itself usually is not very long, especially for the intersection with CLLs. Note that at CLL intersections, the additional left-turn capacity could allow left-turn phase times to be reduced, such that the saved green time could be reallocated towards other movements at the signal [2]. Therefore, in many cases, the length of the left-turn phase at CLLs is not sufficient or is just about the minimum required clearance time, which may cause safety problems. This is because if any human errors occur (for example, drivers are distracted and fail to realize the initiation of the green signal), the left-turn vehicles will be trapped on the CLLs. According to the field observation in Zhao et al. [12], vehicles trapped on the CLLs is one of the major safety problems of the CLL intersections. Therefore, based on the traffic engineers' judgment, a more conservative headway that is larger than the saturation discharging headway can be used in Equation 1 to provide sufficient time for clearing the left-turn vehicles on the CLLs.

3.2. The Proposed Signal Timing Strategy for Applying CLLs at SIWSP

Since CLL treatment is designed for the intersections with high left-turn volume, it could be beneficial for the intersections where split phasing is used due to high left-turn demand. In this way, more left-turn capacity can be provided to meet the high left-turn demand at these SIWSPs. However, the existing signal timing strategy for the regular CLL intersections cannot be directly applied to SIWSPs. As shown in Figure 3, in the split phasing, all of the movements from a particular approach will move together during a leading phase (this approach is referred to as the leading approach), followed by a lagging phase where all the movements of the opposing approach will move together (this approach is referred to as the lagging approach). For example, in Figure 3, Northbound (NB) and Westbound (WB) are the leading approaches, and Southbound (SB) and Eastbound (EB) are the lagging approaches. For the lagging approaches, left-turn vehicles cannot be allowed to enter the CLLs before the left-turn signal phase of this approach starts because they will conflict with the through vehicles from the leading approaches. Thus, CLLs cannot be directly applied at the SIWSPs. To address this problem, in this study a new signal timing strategy, which is referred to as Counterclockwise Split Phasing (CSP) signal timing, is proposed, as presented in Figure 4.

In this new signal timing strategy, all the traffic from different approaches still move together and they move in turn in a counterclockwise direction. For example, as shown in Figure 4, the NB vehicles will move first, followed by the WB, then the SB and EB vehicles. The basic operation of this signal timing strategy can be described as follows. During the signal phase for moving the vehicles from a particular approach, the left-turn vehicles on the right side of this approach will be allowed to enter the CLL through a pre-signal set at a median opening upstream of the CLL. Then, they will wait on the CLL until the signal for this approach at the main intersection turns green. In this signal timing strategy, the entire signal phase for this approach can be used for clearing the left-turn vehicles on the CLLs. Usually, the signal phases in the split phasing signal timing plan are not very short. Thus, the risk of the left-turn vehicles being trapped on the CLL is relatively low, which makes CLLs relatively safe for the SIWSPs. In the following section, a step-by-step procedure for developing the proposed CSP signal timing plan for a SIWSP with CLLs is introduced.

3.3. Procedure for Developing the CSP Signal Time Plan for a SIWSP with CLLs

3.3.1. Step 1. Develop an Initial Signal Time Plan for the Main Intersection Signal

First, an initial signal time plan will be developed for the main intersection signal by treating the CLLs as the regular left-turn lanes. If the signal cycle length is not fixed, both cycle length and signal phase splits will be calculated based on the peak hour traffic volume and intersection geometric layout. If the cycle length is fixed (for example, for signal coordination purposes), only the signal phase splits need to be calculated.

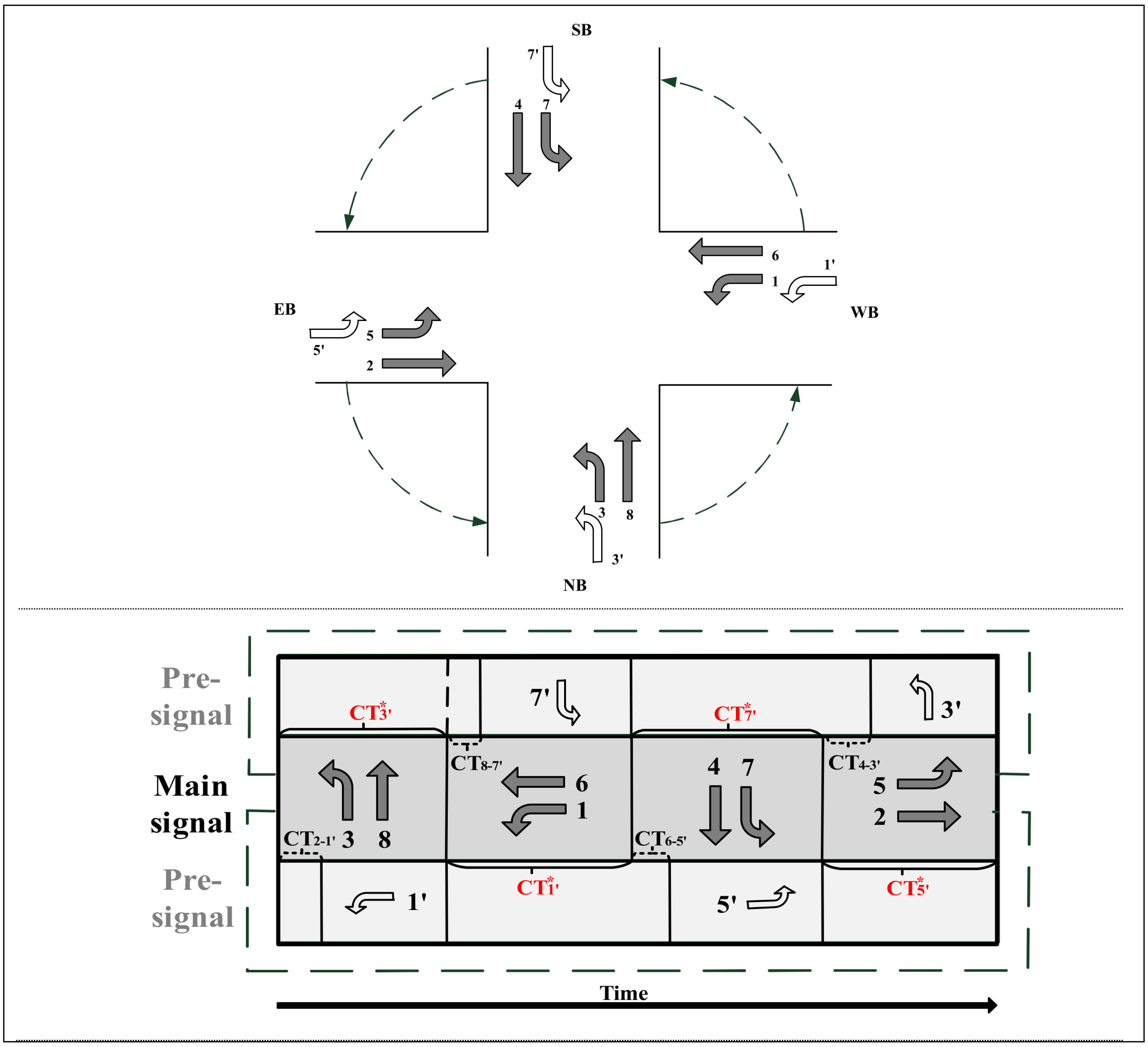


Figure 4. Counterclockwise split phasing (CSP) signal timing for SIWSPs. $CT_{i'}^{*}$ is the time for clearing the left-turn vehicles on the CLLs that entered the CLLs during the pre-signal phase i′. $CT_{j-i'}$ is the pre-clearance time for clearing the conflict through movement j from the CLLs before starting the pre-signal phase i′.

3.3.2. Step 2. Determine the Initial Signal Timing Plan for the Pre-Signals

According to the initial signal timing plan for the main intersection signal, the signal timing plan for the pre-signal lights can be determined as shown in Figure 4. In Figure 4, there are four pre-signal phases 1′, 3′, 5′ and 7′, which correspond to the left-turn movements during the left-turn phases 1, 3, 5 and 7 at the main intersection signal, respectively. From Figure 4, it can be seen that the pre-signal light for phase i′ turns green during the signal phase right before its corresponding left-turn signal phase i. For example, for the SB left-turn movement, the pre-signal phase 7′ turns green during the signal phases 6 or 1, which are right before the left-turn phase 7. However, pre-signal phase 7′ should start a little later than phase 6 or 1. This is because the opposing through traffic moving in Phase 8 needs to be cleared from the CLL before allowing the left-turn vehicles to enter the CLL during the pre-signal Phase 7′. This type of clearance time, which is for clearing the conflict through movement from CLLs before starting the pre-signal phase, is referred to as pre-clearance time. As shown in Figure 5, the pre-clearance time depends on the length of CLLs and the vehicle speed, and it can be estimated by the following Equation:

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

where $CT_{j-i'}$ is the pre-clearance time for clearing the conflict through movement j from the CLLs before starting the pre-signal phase i′, sec; L_{CLL_i} is the length of CLL at the approach corresponding to signal phase i′, ft; $V_{15\%}$ is the 15th percentile approach speed or speed limit, mi/h and 1.47 is the factor that coverts mi/h to feet/sec.

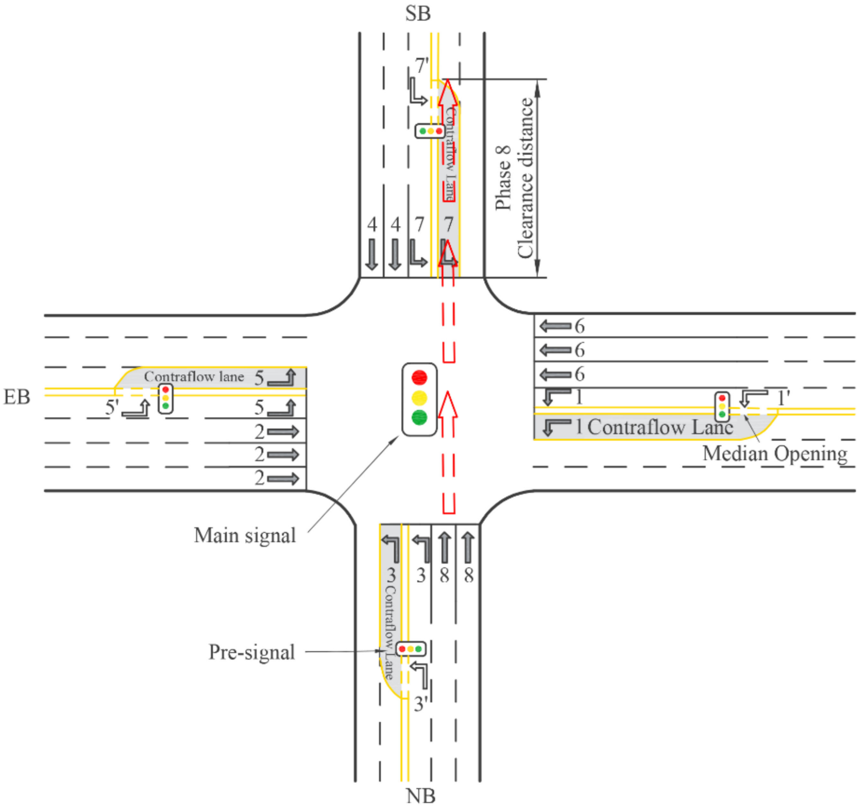


Figure 5. Clearance distance for the conflict through movements.

3.3.3. Step 3. Check the Minimum Clearance Time Requirement

After developing the initial signal timing plan, the time allocated for clearing the left-turn vehicles on the CLLs needs to be greater than the minimum required CLL clearance time given in Equation (1). As we introduced before, for the proposed CSP signal timing, the whole left-turn phase will be used for clearing the left-turn vehicles on the CLLs. For example, according to Figure 4, the SB left-turn vehicles on the CLLs (that enter the CLLs during the pre-signal phase 7′) will be cleared from the CLLs during the left-turn phase 7. Therefore, the length of signal phase 7 should be greater than the min_$CT^*_{7'}$ given in Equation (1), which can be mathematically expressed as

$$CT^*_{i'} = Length\ of\ Phase_i > \min\_CT^*_{i'}, i = 1,3,5,7 \tag{3}$$

where i indicates the left-turn phase number and i' is the corresponding pre-signal phase for this left-turn movement. If Condition (3) is met, the signal timing plan developed in Step 1 and 2 is the final CSP signal timing plan. Otherwise, it will continue to Step 4.

3.3.4. Step 4. Check the Maximum Pre-Signal Time Requirement

If Condition (3) is not met, the length of the pre-signal time needs to be adjusted to control the number of vehicles that can enter the CLLs during the pre-signal phase. The basic idea is that the total number of left-turn vehicles that enter the CLLs during the pre-signal phase i′ should not be greater than the number of vehicles that can be cleared during the following left-turn phase i at the main intersection. According to this idea, the maximum length of the pre-signal phase i′ can be estimated by the following equation:

$$\max Length\ of\ Phase_{i\prime} = t\prime_{dh} \times \frac{Length\ of\ Phase_i - l_s}{t_{dh}} + l\prime_s \tag{4}$$

where $t\prime_{dh}$ is the saturation discharging headway of left-turn vehicles at the pre-signal, t_{dh} is the saturation discharging headway of left-turn vehicles at the main intersection, $l\prime_s$ is the start-up lost time of the left-turn vehicles at the pre-signal, and l_s is the start-up lost time of the left-turn vehicles at the main intersection.

In this study, we assume that t_{dh} is equal to $t\prime_{dh}$ and l_s is equal to $l\prime_s$. Then, according to Equation (4), the maximum length of pre-signal phase i′ is equal to the length of its corresponding left-turn phase i. Therefore, if the pre-signal phase i′ is less than its corresponding left phase i, all the left-turn vehicles that enter the CLLs can be cleared before the signal at the major intersection turns red. Otherwise, the length of the pre-signal phase needs to be reduced to its maximum length (which is equal to the length of its corresponding left-turn phase i) to control the number of left-turn vehicles that can enter the CLLs. Mathematically, this step can be expressed as:

$$\text{If the } Length\ of\ Phase_{i\prime} > Length\ of\ Phase_i,$$

Then, reduce the length of pre-signal phase i′ by delaying its start and setting

$$Length\ of\ Phase_{i\prime} = Length\ of\ Phase_i$$

Based on this four-step procedure, the signal timing plan for both the main intersection signal and pre-signals can be determined. The overall procedure for the development of the CSP signal timing plan is presented in Figure 6.

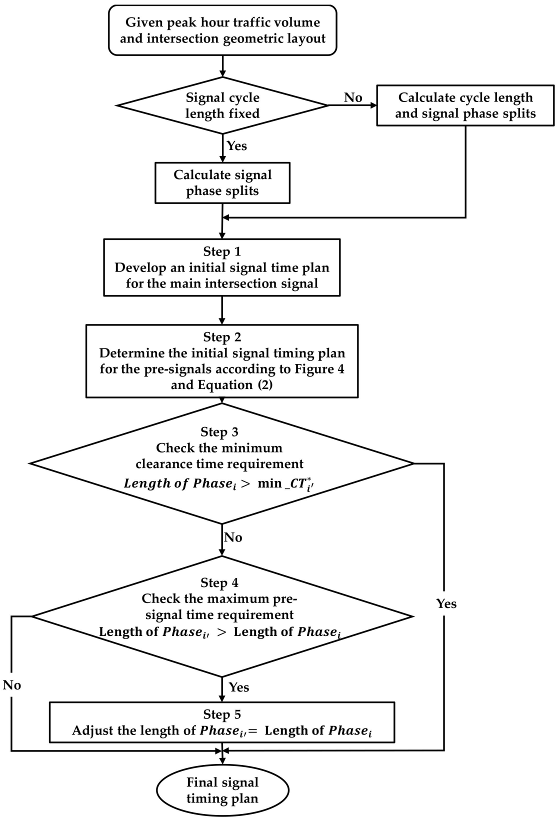


Figure 6. CSP signal timing development flow chart.

The above is the introduction of the basic concept of the CSP signal timing strategy and the procedure for developing the signal timing plan according to this strategy. By using this new time strategy, the CLL treatment can be applied at the SIWSPs. To demonstrate the operational benefits of using CLLs at SIWSPs and to identify the appropriate traffic conditions for implementing it, a hypothetical case study was conducted by using traffic simulation.

4. Hypothetical Case Study

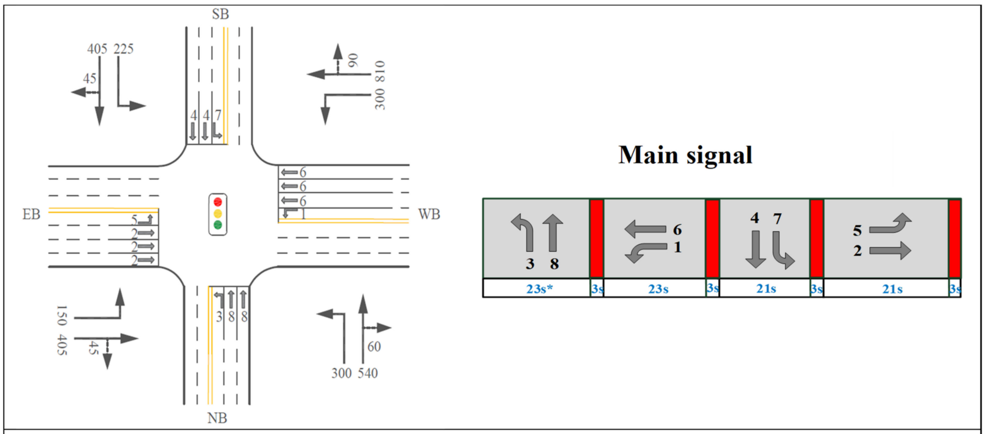
4.1. Baseline Conditions of the Hypothetical SIWSP

4.1.1. Without CLL Treatment

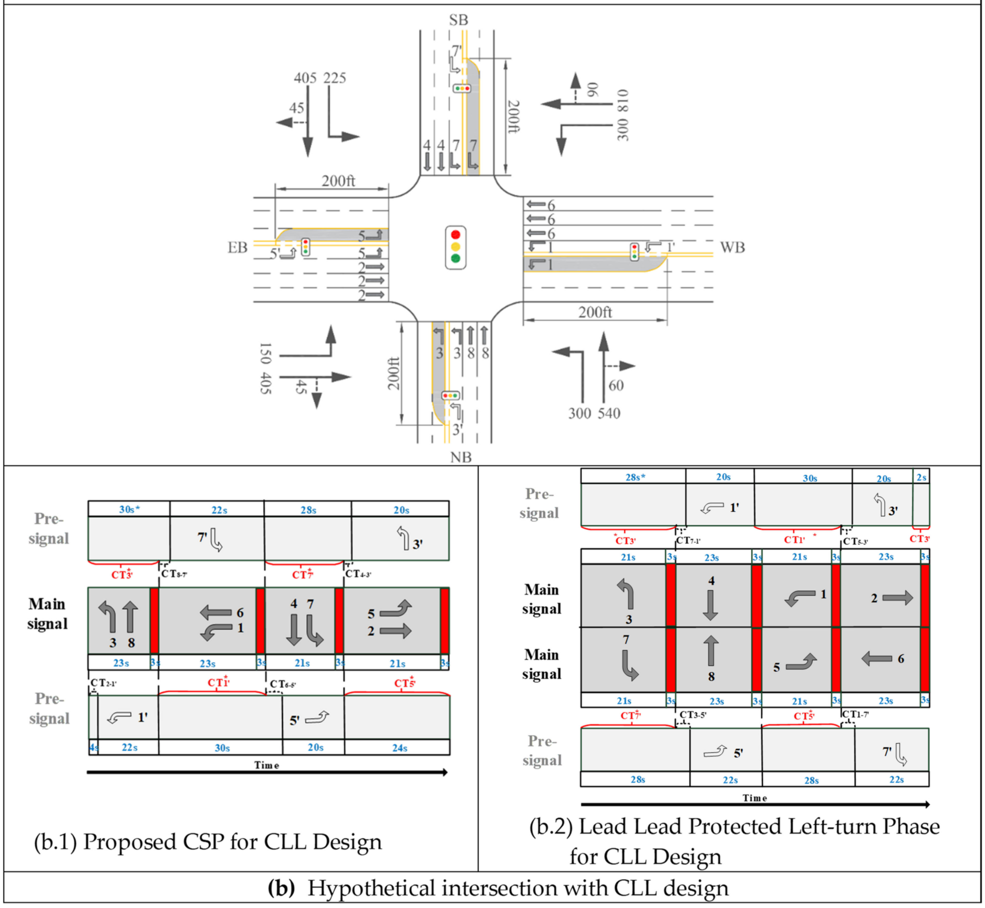
The proposed signal timing strategy was evaluated through a series of microscopic traffic simulations completed in VISSIM. The test intersection was a hypothetical four-leg SIWSP, as illustrated in Figure 7a. The traffic volume conditions for this hypothetical intersection are presented in Figure 7a. Basically, it was assumed that, at this intersection, the lane volumes of left-turn traffic were approximate to the lane volumes of the through vehicles and the total approach volumes were significantly different on the two approaches (WB and EB) because this was one of the typical situations where split phasing is recommended [5]. In this case study, the lane volume for the WB/NB approach was 300 vehicles per lane, for the EB approach was 150 vehicles per lane, and for the SB approach was 225 vehicles per lane. The current signal timing plan for this intersection was developed by using the Synchro signal optimization function. The developed signal timing plan for this hypothetical intersection is also presented in Figure 7a. Note that it was assumed that the speed limit was 35mph at this intersection for all the approaches.

4.1.2. With CLL Treatment

As shown in Figure 7b, the CLL treatment was applied to this hypothetical intersection in four approaches, and the length of CLL was assumed to be 200 ft in each approach. The signal timing for this CLL intersection was designed by two different approaches: (1) using the proposed CSP signal timing strategy, as shown in Figure 7(b1,b2) using the conventional lead-lead protected left-turn phases for the CLL design, as shown in Figure 7(b2). For the first approach, according to the four-step produces presented in Figure 6, the CSP signal timing plan was developed for this intersection based on the assumed intersection geometric layout and the traffic volume condition. In Step 1, the initial signal timing plan for the main signal was developed by treating the CLLs as the regular left-turn lanes and according to the traffic volume conditions presented in Figure 7. In Step 2, at first the pre-clearance time was calculated for each approach based on the length of CLL (200 ft) and the speed limit (35 mile/h) using Equation (2). The estimated pre-clearance time was 4s for each approach. Then, the initial signal timing plan for the pre-signals could be determined according to the signal timing diagram presented in Figure 4 and the results of Step 1. In Step 3, the required minimum clearance time for CLL was calculated for each approach by using Equation 1. In this case study, the discharging headway of left-turn vehicles was assumed to be 2.39 s according to Wu et al. [1]. Thus, the estimated minimum CLL clearance time was 21s for each approach, which is less than the length of the left-turn phase of each approach. Therefore, the minimum clearance time requirement was met, and Step 4 could be skipped. For the second signal timing approach presented in Figure 7(b2), the left turns from the two opposing approaches moved together during the leading left-turn phase. The similar four-step procedure presented in Figure 6 can also be applied for this case. At first, based on the same intersection geometric layout and traffic conditions, the lead-lead protected left-turn phase signal timing plan for the main signal was developed by using the Synchro signal optimization function. Note that, to make the experiments comparable, the initial main signal timing was also developed by treating the CLLs as the regular left-turn lanes. Then, in step 2, the initial pre-signal time was calculated by deducting the required pre-clearance time $(CT_{j-i'})$, as shown in Figure 7(b2). After that, to ensure the safe operation of the CLL intersection, we also went through Steps 3 and 4 in Figure 6 to ensure that all the vehicles entering CLL could be cleared from the CLL before the end of the left-turn phase at the main signal. The final developed lead-lead protected left-turn phases signal timing plan for this CLL intersection is presented in Figure 7(b2).



(a) Hypothetical SIWSP without CLL



(b.1) Proposed CSP for CLL Design

(b.2) Lead Lead Protected Left-turn Phase for CLL Design

(b) Hypothetical intersection with CLL design

Figure 7. Geometric layout and signal timing plan of the hypothetical intersection. (**a**).Hypothetical SIWSP without CLL; (**b**). Hypothetical intersection with CLL design. * Signal timing plan in seconds (S).

5. Simulation Analysis

In this study, VISSIM, a microscopic multi-modal traffic flow simulation software, repeet was used for analyzing the operational performance of the hypothetical intersection with and without CLL. To simulate the operation of CLLs, the bi-directional characteristic of the CLLs was achieved by overlapping CLLs with their opposing through lanes. Figure 8 shows the setting of the contraflow left-turn lanes in VISSIM. Then, the dynamic rerouting function was employed to allow left-turn vehicles to choose appropriately between the conventional left-turn lanes and the CLLs. The dynamic rerouting decision was made based on the following attributes: the status of the main signal, the status of the pre-signal, the queuing length on the regular left-turn lane, and the queuing length on the CLLs.

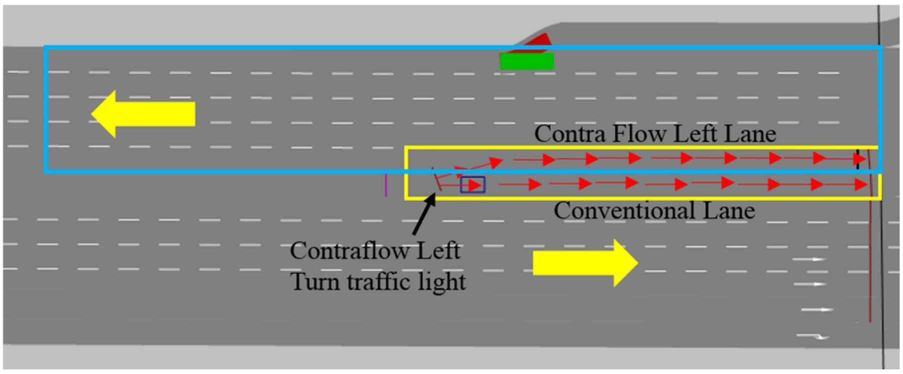


Figure 8. Contraflow lane setting up in VISSIM.

Simulation Scenario Design

Besides the three baseline scenarios presented in Figure 7, this study also investigated the operational performances of the hypothetical intersection under different traffic volume conditions. For this purpose, the following three different sets of alternative simulation scenarios were designed:

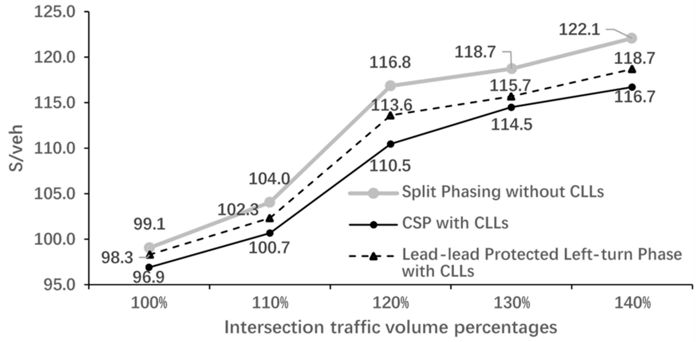
(A) Scenarios with varied intersection traffic volume conditions at the hypothetical intersection. In this set of scenarios, the traffic volume of all types of movements (left-turn, through and right-turn) from all approaches increase proportionally. Note that when the traffic volume increases to 150% of the original traffic volume, the overall intersection will be oversaturated. Thus, in this study, the traffic volume varied from 110% to 140% of the originally assumed traffic volume in increments of 10%.

(B) Scenarios with varied left-turn traffic volume conditions at the hypothetical intersection. In this set of scenarios, only the left-turn volume from all approaches increases proportionally and the traffic volume for other moves is maintained at the same level. This is to test the impacts of the proposed CSP signal timing strategy and CLL treatments on the operation of the intersections with different levels of left-turn traffic volume. In this study, the left-turn traffic volume varied from 110% to 150% of the originally assumed left-turn traffic volume in increments of 10%.

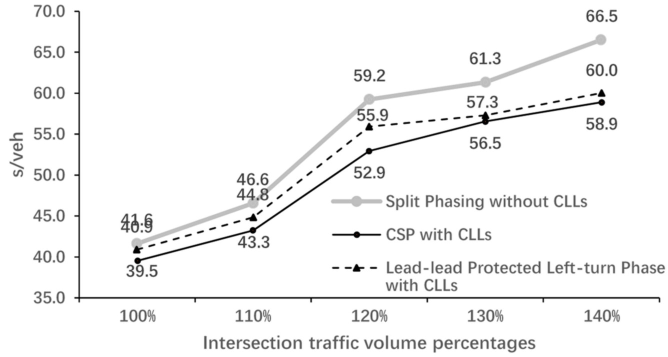
(C) Scenarios with varied levels of unbalanced traffic volume conditions at the hypothetical intersection. Since the split phasing is recommended for the intersections where the traffic volumes on two opposing approaches are unbalanced, it is necessary to test the performance of the proposed CSP signal timing under different levels of unbalanced traffic volume conditions. At the studied hypothetical intersection, the EB and WB traffic volumes are unbalanced (as shown in Figure 7, WB traffic volumes are twice the EB traffic volumes). To increase the level of unbalance at this intersection, the WB traffic volumes increased from 130% to 160% of the originally assumed volumes in increments of 30%.

For each set of scenarios, the performance of the hypothetical intersection with split phasing but without CLLs, with proposed CSP and CLLs, and with the lead-lead protected left-turn phase and CLLs are tested. Similar to the developments of the three baseline scenarios explained before, the signal timing plan for the split phasing without CLLs was developed by using the Synchro signal optimization function, the CSP signal timing plan for the CLL treatment was developed according to the procedure presented in Figure 6, and the lead-lead protected left-turn phase signal timing plan for the CLL treatment was developed by following a similar four-step procedure. Note that, since the use of CLLs increase the intersection capacity, the optimized cycle length with CLL treatment tends to be a little shorter than the cycle length without CLLs. To make the scenarios comparable, the cycle lengths for the intersections with CLLs are expanded to be the same as that for the intersections without CLLs at the same traffic volume level.

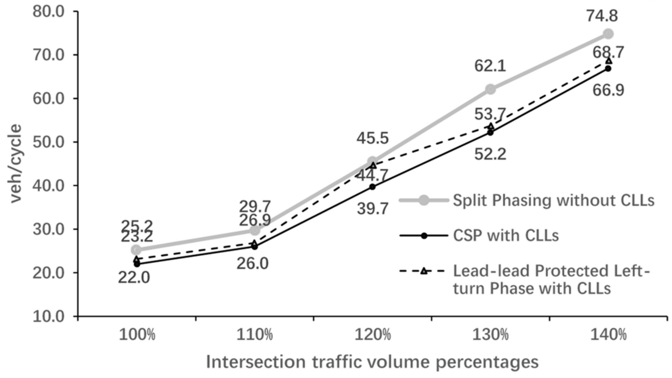
For each scenario, a 1-h traffic simulation was conducted, and the first half-hour simulation results were discarded to ensure the simulation analysis started after reaching the steady-state condition. Multiple runs were conducted to overcome the randomness in the simulation outputs. In this study, 10 simulation runs were conducted for each scenario and the simulation results were averaged among the ten simulation runs. Based on the simulation results, operational performance measures, including average traffic delay, average vehicle travel time, and average queue length at the hypothetical intersection with split phasing but without CLLs, with the proposed CSP and CLLs, and with the conventional lead-lead protected left-turn phase and CLLs were compared, as shown in Figures 9–11.



(a) Average Travel Time

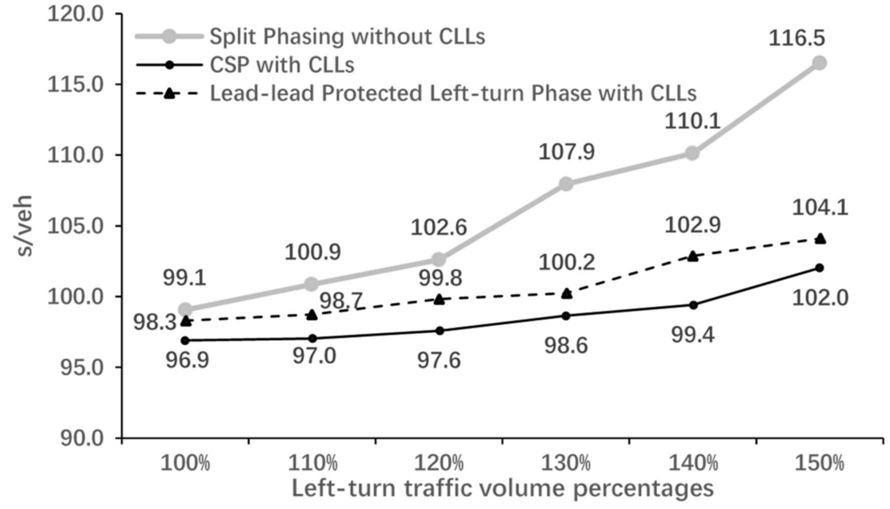


(b) Average Delay

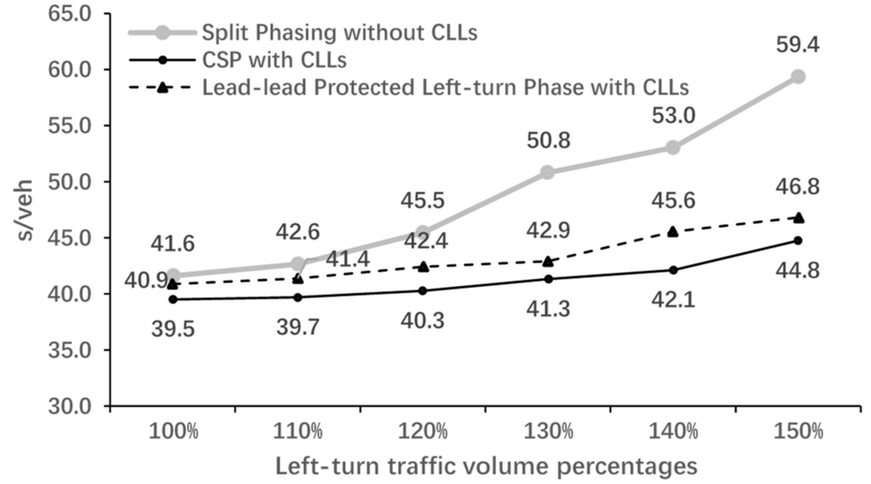


(c) Average Queue Length

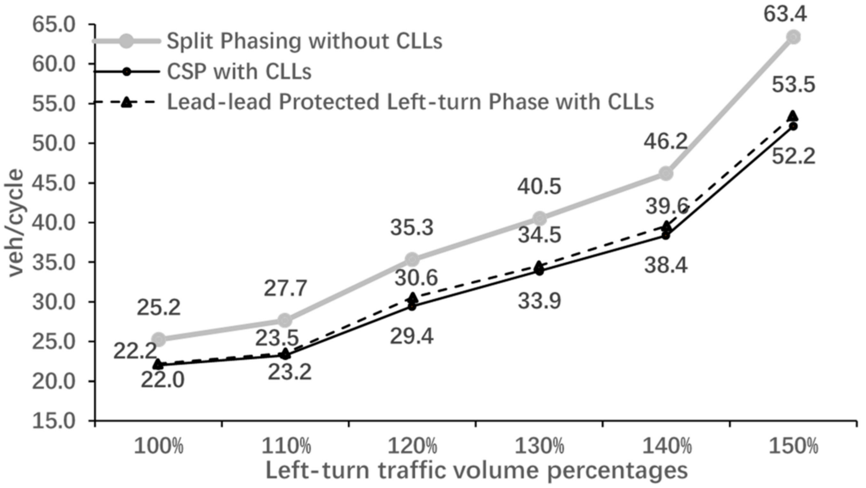
Figure 9. Comparisons of the operational performances of the hypothetical intersection with varied traffic volume conditions (Type A scenarios). (**a**). Average travel time; (**b**). Average delay; (**c**). Average queue length.



(a) Average Travel Time

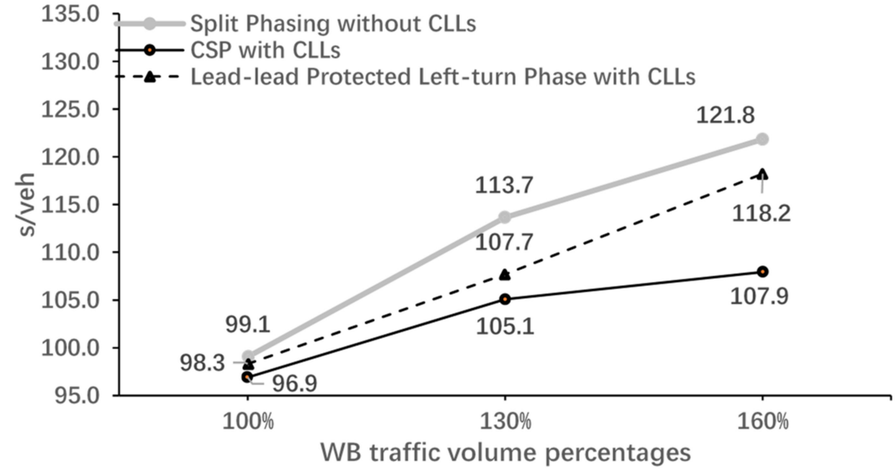


(b) Average Delay

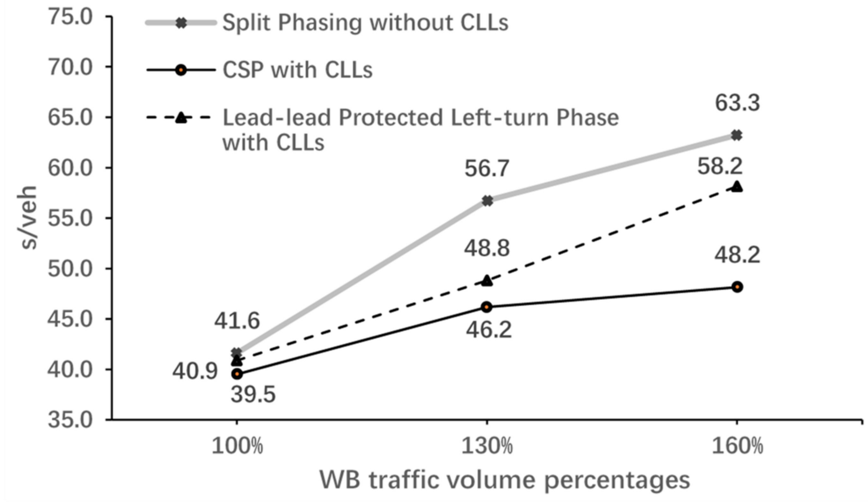


(c) Average Queue Length

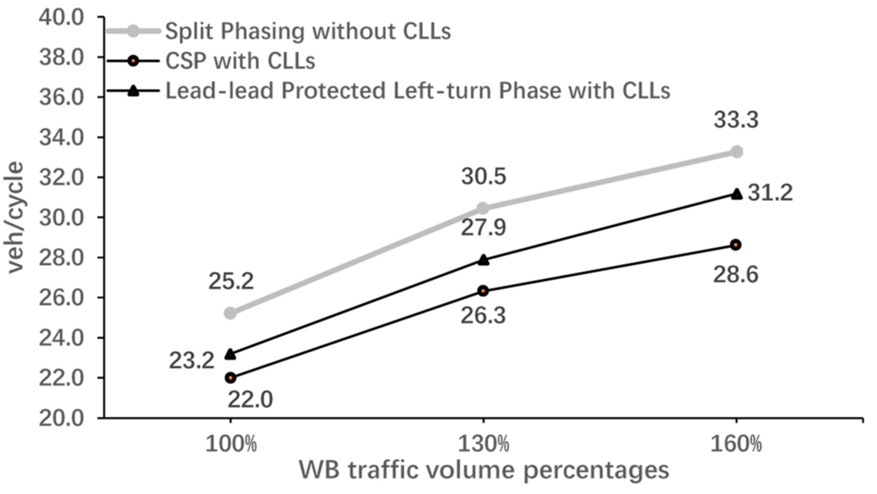
Figure 10. Comparisons of the operational performances of the hypothetical intersection with varied left-turn traffic volume conditions (Type B scenarios). (**a**). Average travel time; (**b**). Average delay; (**c**). Average queue length.



(a) Average Travel Time



(b) Average Delay



(c) Average Queue Length

Figure 11. Comparisons of the operational performances of the hypothetical intersection with varied levels of unbalanced traffic volume conditions (Type c scenarios). (**a**). Average travel time; (**b**). Average delay; (**c**). Average queue length.

The simulation results in Figures 9 and 10 show that, under different traffic conditions, the hypothetical intersection with CLLs using both signal timing strategies (the proposed CSP and the conventional lead-lead protected left-turn phase) perform better than the same intersection using split phasing without CLLs. This result is reasonable because the CLLs can provide additional capacity to the left-turn vehicles which results in improved intersection operation. It was also found that the proposed CSP signal strategy outperforms the conventional lead-lead protected left-turn phase at the studied intersection with the CLL design. From the results presented in Figure 11, it can be seen that with the increase of the level of unbalanced traffic on the WB and EB approaches, the benefits of using the proposed CSP become more significant. This is because, for the lead-lead protected left-turn phase, left-turn vehicles on both opposing directions need to move simultaneously during the same left-turn phase. As a result, the green time allocated to the direction with the lower left-turn volume exceeds the required time, thereby reducing the operational efficiency of the intersection. On the other hand, the proposed CSP signal timing strategy has the advantage of the split phasing that can accommodate the unbalanced traffic at the intersections. Therefore, it outperforms the lead-lead protected left-turn phase at the CLL intersections where traffic volumes on the two opposing approaches are unbalanced. Most importantly, without the proposed CSP, the CLL design cannot be implemented at the intersections where split phasing is used. Thus, the benefits of CLL design cannot be realized at those intersections.

6. Conclusions

In this study, an innovative CSP signal timing strategy was proposed for implementing CLLs at the SIWSP. A four-step signal timing design procedure was developed. A traffic simulation-based case study was conducted to demonstrate the application of the proposed CSP signal timing strategy at a hypothetical SIWSP intersection. In addition, the operational benefits of using the proposed CSP signal timing strategy under different traffic volume conditions were tested and analyzed. The results of the case study indicate that the use of the proposed CSP signal timing strategy for the CLL design can significantly reduce the traffic congestions at the intersections where the traffic volumes on two opposing approaches are unbalanced. Most importantly, by using the proposed CSP, the CLL design can be implemented at the intersections where split phasing is recommended or required. Thus, the benefits of the split phasing and the CLL design can be combined at those intersections. Furthermore, the proposal CSP signal timing design procedure has fully considered the clearance time requirements for the left-turn vehicles on the CLLs. As a result, sufficient clearance time can be provided for all the approaches with CLLs, which reduces the risk associated with the use of CLLs and makes it safe for being implemented at the SIWSPs.

In this study, the proposed procedure for CSP signal timing design is based on the assumption that CLL is used as a regular left-turn lane, which is an ideal situation and may not be true under some traffic and geometric conditions [1,9,10]. Therefore, in a future study, this proposed procedure for CSP signal timing design needs to be refined to reflect various factors that may affect the utilization of the CLLs at SIWSPs. In addition, in this study, hypothetical traffic volumes were used in the case study. In the future, traffic volume data from real-world intersections need to be collected to further assess the performance of the proposed CSP signal timing strategy for CLL design. Furthermore, some operational issues in the implementation of CLL design, such as making U-turn maneuvers, also need to be investigated in a future study.

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