A TRAFFIC SIGNAL SPLIT OPTIMIZATION USING TIME-SPACE DIAGRAMS

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ABSTRACT

Traffic signals are the main devices for controlling traffic to guarantee the safe crossing of opposing streams of vehicles and pedestrians. As traffic demand increases, signal operations become more important. Efficient signal controls lead to less congestion and smooth operations while poor signal controls could result in severe congestion or even a network gridlock. Dynamic controls, where signal parameters are automatically optimized to the change of traffic demand monitored by detectors, become important. In this study, a simple split optimization method is developed. The proposed methodology is based on the notion of minimizing delay per cycle. Traffic dynamics at signalized intersections are represented on time-space diagrams using the shockwave theory and information from detectors installed upstream of intersections. Splits are incrementally adjusted so that the delay per cycle is gradually minimized. Unlike most algorithms, the proposed method can manage traffic even when queues extend beyond detector locations. Simulation experiments on a single fixed-cycle-length intersection with five demand scenarios are conducted to demonstrate efficiency of the developed algorithm. It is found that in case of fixed demand the proposed method can optimize splits, which eventually converge to the optimal fixed-time signal settings. For the variable demand case, the result indicates that the algorithm can correctly adjust splits in response to the change of demand. The proposed algorithm has demonstrated itself to be a potential split optimization for an adaptive signal control system.

1. INTRODUCTION

The purpose of installing traffic signals at intersection is to manage conflicting traffic streams to proceed efficiently and safely through a common space. The first traffic signal can be traced back to the manually controlled semaphores in London as early as 1868. Since then, the traffic signal has become a critical element of modern traffic control and management systems. In cities, traffic signals are the main devices for controlling traffic to guarantee the safe crossing of opposing streams of vehicles and pedestrians. As traffic demand increases, signal operations become more and more important. Efficient signal controls lead to less congestion and smooth operations while poor signal controls could result in severe congestion or even a network gridlock.

Traffic demand is greatly dependent on time, day, season, weather, and unpredictable situations such as accidents, special events, or construction activities. Currently, cities in different continents have been implementing traffic signal control systems that can continuously optimize the signal plan according to the actual traffic demand, which is called an adaptive traffic control system. Changes to the active signal plan parameters are automatically implemented in response to the current traffic demand as measured by a vehicle detection system. Adaptive traffic control systems are categorized according to their generation. First-generation traffic adaptive systems employ a library of pre-stored signal control plans, which are developed off-line on the basis of historical data. Plans are selected on the basis of the time of day and the day of week. First-generation traffic adaptive systems are often referred to as traffic-responsive signal control. A limitation of traffic-responsive signal control is that by the time the system responds, the registered traffic conditions that triggered the response may have become obsolete. Second-generation traffic-adaptive systems use an on-line strategy that implements signal timing plans based on real-time surveillance data and predicted values. The optimization process can be repeated every five minutes. To avoid transition disturbances, new timing plans cannot be implemented more than once every 10 minutes. Third-generation of control allows the parameters of the signal plans to change continuously in response to real-time measurement of traffic variables, which allows for acyclic operations. There are numerous adaptive signal control systems. Hunt et al. (1981) developed SCOOT (Split Cycle and Offset Optimizing Technique) system, which is a centralized system based on a traffic model with an optimization algorithm adapted for an on-line application. Optimization takes place by incrementally updating a fixed-time plan. Signal optimization is divided into three types of adjustments: splits, offsets, and cycle length. It predicts the profile arrivals to the intersection based on the updated flow information collected by the upstream detectors. This arrival is compared with the departure profile, and the differences represent those vehicles delayed and queued at the intersection. These flow profiles are estimated for each cycle from a combination of the vehicles approaching, the time to clear the queue, the impact of offset and split adjustment. SCATS (Sydney Coordinated Adaptive Traffic System) was developed in the early 1970's by the Roads and Traffic Authority of New South Wales, Australia. In this system, Degree of Saturation (DS), which is defined as the ratio of fully-used green length to effective green length, is used to decide signal parameters. Cycle length is changed in every cycle by several seconds. Splits and offsets are selected from predetermined patterns. Gartner (1983) developed OPAC (Optimization Policies for Adaptive Control), which is the demand-responsive signal control system. By introducing rolling horizon approach, signal parameters are changed according to the estimated queue length. Koshi (1972), Koshi (1989), and Asano et al. (2003) developed a signal control system using the concept of shifting the cumulative diagrams by investigating whether or not a small advance or delay of the next traffic light phase may decrease the aggregate delay to the users. If it does, the change in the offset, split, and cycle is implemented.

These systems rely on detectors installed at upstream and/or at the stop lines of intersections to provide traffic demand information for an optimization process. However, when queue extends beyond the detector locations, the arrival pattern cannot accurately be determined. Figure 1 shows a situation when a queue extends beyond the detector location. The detector cannot recognize the arrival of vehicles 4 and 5. Signal control algorithms would not receive the correct information on the arrival pattern. This can lead to an inadequate signal optimization in the process.

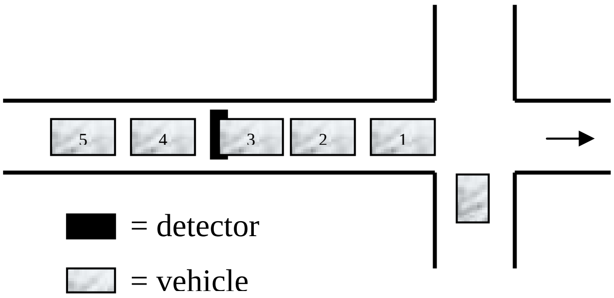


FIGURE 1: A Queue Extends beyond Detector Location

Therefore, this research attempts to solve this problem by constructing the time-space diagrams from occupancy information instead of using the flow of the arriving traffic, which is normally employed in the cumulative-diagram-based techniques. Traffic shockwave theory is utilized to complete the time-space diagrams. In this way, the problem of queue extending beyond the detector locations can be avoided. Nonetheless, only split optimization is considered at this stage. The objectives of this research are:

- To develop a dynamic split optimization using the time-space diagrams
- To investigate the efficiency of the proposed method on simulation experiments.

In the remainder of this paper, the proposed methodology to dynamically optimize traffic signal splits is presented followed by a section on simulation experiments to examine the validity of the proposed method. Splits obtained from the proposed model are compared to the optimal values obtained from the best fixed-time plans. The paper is closing with conclusions and recommendations for future research.

2. METHODOLOGY

This section outlines the methodology for dynamically optimizing traffic signal splits at isolated intersections. The proposed methodology is based on the concept of constructing the time-space diagrams from shockwave theory and occupancy information obtained from the upstream detectors. Once the time-space diagrams from all competing phases are constructed, splits are optimized by investigating whether a small increase or decrease of the subject phase will reduce the total delay per cycle of the intersection of interest. Note that, for an intersection with two signal phases, an increase of the green time for one phase will decrease the green time of the other given that the cycle length is assumed constant from cycle to cycle. The following paragraphs provide the detail of the proposed methodology.

2.1 Construction of Time-Space Diagram from Detector Information

Let us consider a signalized intersection with two one-way streets as shown in Figure 2. This intersection requires two phases to accommodate two competing traffic demand. Two loop detectors are installed at the upstream of the stoplines. The loop detectors provide occupancy and flow measures at the end of each cycle. For an illustration purpose, the triangular fundamental diagram of flow and density is assumed as shown in Figure 3. Any shape of the fundamental diagrams is also valid with the proposed method. To optimize splits of the intersection, the time-space diagrams are drawn for the two approaches at the end of each cycle using the shockwave analysis. Figure 4 shows the time-space diagram of the northbound approach and the similar can be depicted for the eastbound approach. Since detectors can provide only occupancy and flow information, the flows obtained from the detectors, however, do not represent the true arrival pattern when queues extend beyond the detector locations.

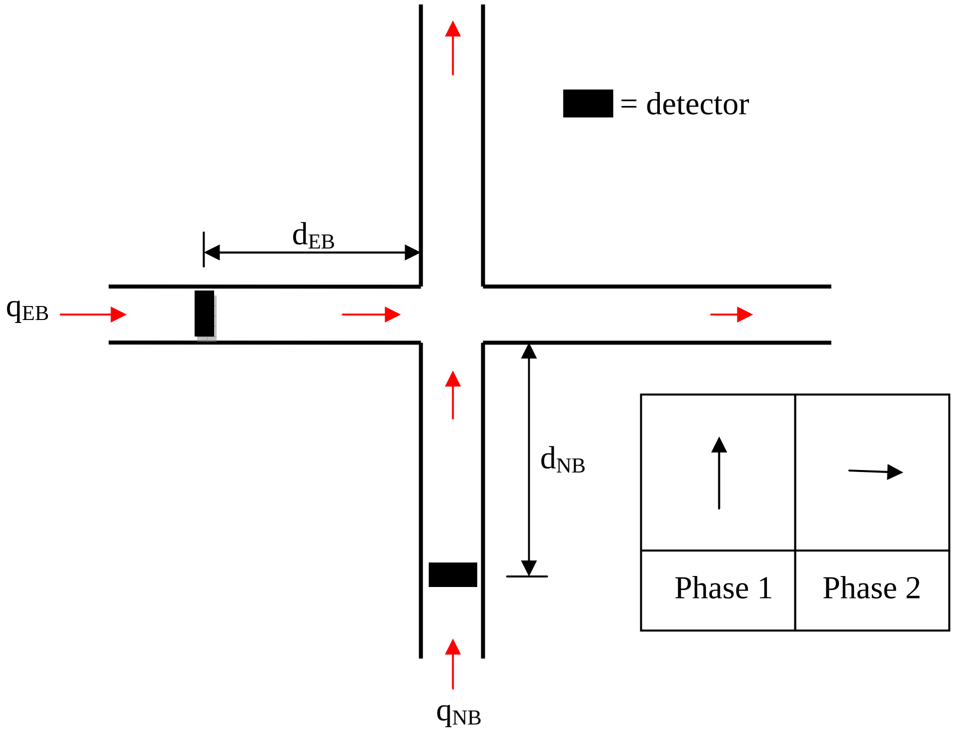


FIGURE 2: A Two-One-Way-Street Intersection with Two Phases

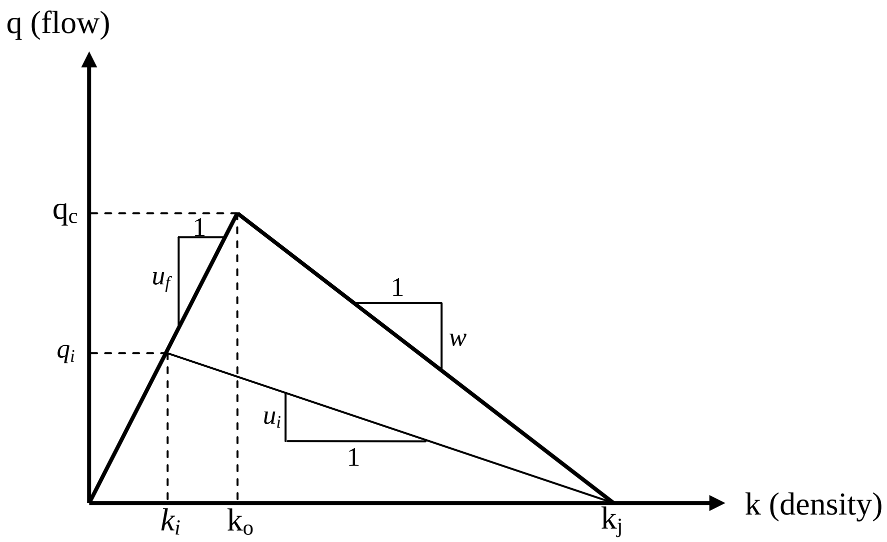


FIGURE 3: A Triangular Fundamental Diagram

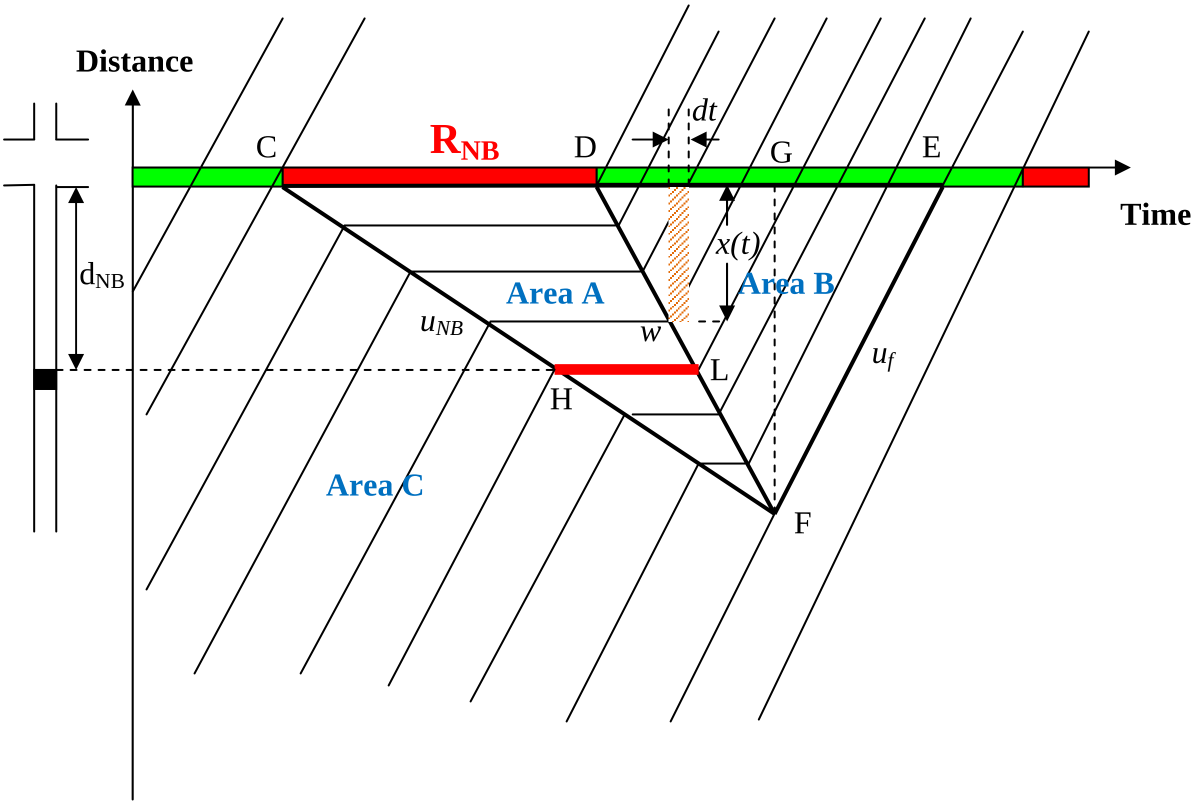


FIGURE 4: The Time-space Diagram of the Northbound Approach

To construct the time-space diagram from detector information, the detector occupancy over one cycle is used to estimate time HL in Figure 4, which can be expressed as:

$$t_{NB}^{HL} = C \cdot \left(O_{NB} - \frac{q_{NB} \cdot L_{eff}}{u_f} \right) \tag{1}$$

Where C = Cycle length
t_{NB}^{HL} = Time HL of the northbound approach
O_{NB} = Average occupancy of the northbound approach at the detector over one cycle
q_{NB} = Average flow of the northbound approach at the detector over one cycle
L_{eff} = Effective length of vehicle plus detection zone
u_f = Free-flow speed

This expression was proposed by Skabardonis and Geroliminis (2008), and then used by Liu et al (2009) to estimate queue length at signalized intersections. Provided that the t_{NB}^{HL}, the red time (R), and the backward wave speed (w) are known, the time-space diagram can, therefore, be depicted from geometric relation. The same procedure is also applied to the eastbound approach. Based on the constructed time-space diagram, delay per cycle is evaluated by considering the areas under the diagram and their associated densities, which is written as:

$$\begin{aligned} TDC &= (Area\ A)(k_j - k_C) + (Area\ B)(k_B - k_C) \\ &= \frac{1}{2}(k_j - k_C)(\frac{R^2 \cdot w \cdot u}{w-u}) + \frac{1}{2}(t_{DG} + t_{GE})(\frac{R \cdot w \cdot u}{w-u})(k_B - k_C) \end{aligned} \tag{2}$$

Where TDC = Total delay per cycle

k_j = Jammed density

k_i = Density in area "i" of Figure 4

R = Red time in Figure 3

$t_{DG} = \frac{R \cdot u}{w-u}$ = Time between points D and G in Figure 4

$t_{GE} = \frac{R}{u_f} \cdot \frac{w \cdot u}{w-u}$ = Time between points G and E in Figure 4

The delays per cycle can be evaluated for both traffic approaches of the intersection. In the next section, a procedure to dynamically optimize split is presented.

2.2 Split Optimization Policy

Once the delays per cycle of each competing approaches are known, the change in delay per cycle with respect to the small change in split is evaluated by differentiating the delay per cycle in Equation (2) as follows.

$$\begin{aligned} \frac{d(TDC)}{dR} &= (k_j - k_C)(\frac{R \cdot w \cdot u}{w-u}) + (\frac{R \cdot u}{w-u} + \frac{R}{u_f} \cdot \frac{w \cdot u}{w-u})(\frac{w \cdot u}{w-u})(k_B - k_C) \\ &= \frac{R \cdot w \cdot u}{w\text{-}u} \cdot k_j \end{aligned} \tag{3}$$

The resulting expression for the change in delay per cycle with respect to the small change in split is in fact the maximum queue length in term of the equivalent number of vehicles. If the change in delay per cycle with respect to the change in split of the northbound approach is compared to that of the eastbound approach, while holding the cycle length fixed, a simple dynamic split optimization can be established as follows.

1. If $\frac{d(TDC_{NB})}{dR_{NB}} - \frac{d(TDC_{EB})}{dR_{EB}} > \varepsilon$, then $G_{NB}^{i+1} = G_{NB}^{i} + \Delta_S$ and $G_{EB}^{i+1} = G_{EB}^{i} - \Delta_S$.

   This means that the change in split of the northbound approach will make a bigger change in delay per cycle than that of the eastbound approach. ε is a small positive number, which is used as a threshold to trigger split adjustment. Therefore, the green time of the northbound approach should be increased by ΔS and the green time of the eastbound approach should be decreased by Δ_S in the next cycle given that the cycle length remains constant.

2. If $\frac{d(TDC_{EB})}{dR_{EB}} - \frac{d(TDC_{NB})}{dR_{NB}} > \varepsilon$, then $G_{NB}^{i+1} = G_{NB}^{i} - \Delta_S$ and $G_{EB}^{i+1} = G_{EB}^{i} + \Delta_S$.

   This means that the change in split of the eastbound approach will make a bigger change in delay per cycle than that of the northbound approach. ε is a small positive number, which is used as a threshold to trigger split adjustment. Therefore, the green time of the northbound approach should be decreased by Δ_S and the green time of the eastbound approach should be increased by Δ_S in the next cycle given that the cycle length remains constant.

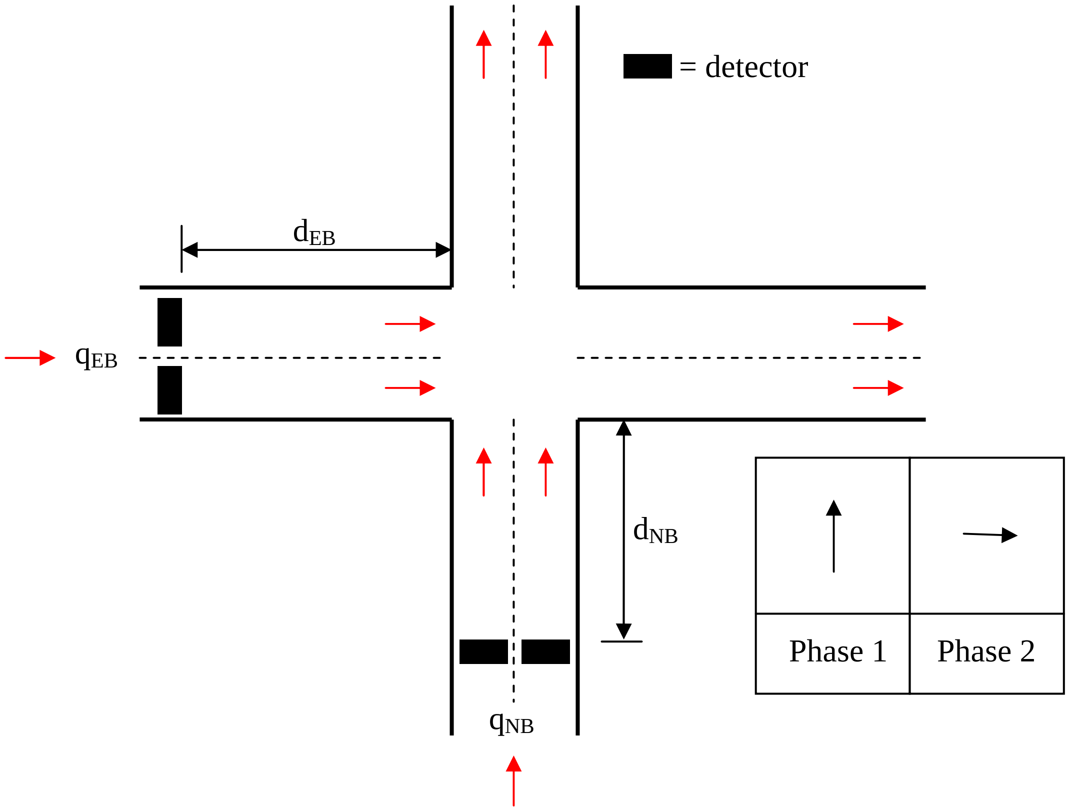
3. If $|\frac{d(TDC_{NB})}{dR_{NB}} - \frac{d(TDC_{EB})}{dR_{EB}}| \leq \varepsilon$, then $G_{NB}^{i+1} = G_{NB}^{i}$ and $G_{EB}^{i+1} = G_{EB}^{i}$.

   This means that the change in split of the northbound approach will make only a minute difference in delay per cycle when compared to that of the eastbound approach. ε is a small positive number, which is used as a threshold to trigger split adjustment. Therefore, it is no need to adjust the splits of both approaches given that the cycle length remains constant.

This algorithm is a simple split optimization based on the change of delay per cycle on the time-space diagram.

3. SIMULATION EXPERIMENTS

In this section, the proposed method for optimizing splits is applied in simulation experiments to examine its efficiency and performance. Five demand scenarios are considered for a simple two-one-way-street intersection as shown in Figure 5. Scenarios 1 – 4 are the fixed demand scenarios while scenario 5 is the variable demand scenario. It is assumed that the cycle length is fixed at 90 seconds with the initial green times of 40 seconds for both approaches and the lost time of 5 seconds per phase. Saturation flow rates are 3600 veh/h with the jammed density of 200 veh/km/lane and the free-flow speed of 60 km/h for both approaches. The green time increment (Δ_S) of 2 seconds and the split adjustment threshold (ε) of 2 vehicle-second per cycle are used for split optimization. Each scenario is simulated for one hour using AIMSUN traffic simulation software. The API (Application Programming Interface) to represent the algorithm of the proposed method is written for the validation purpose. The resulting splits from the proposed model are compared to the optimal fixed-time splits obtained from the Webster's method.



Scenario	q_{EB} (veh/h)	q_{NB} (veh/h)
1	1750	2250
2	2500	1500
3	2750	1250
4	3000	1000
5	1250 (1st 20 minutes) 2000 (2nd 40 minutes)	2750 (1st 20 minutes) 2000 (2nd 40 minutes)

FIGURE 5: Simulation Experiments with Five Demand Scenarios

The results of each scenario are summarized in Figure 6, 7, 8, 9, and 10.

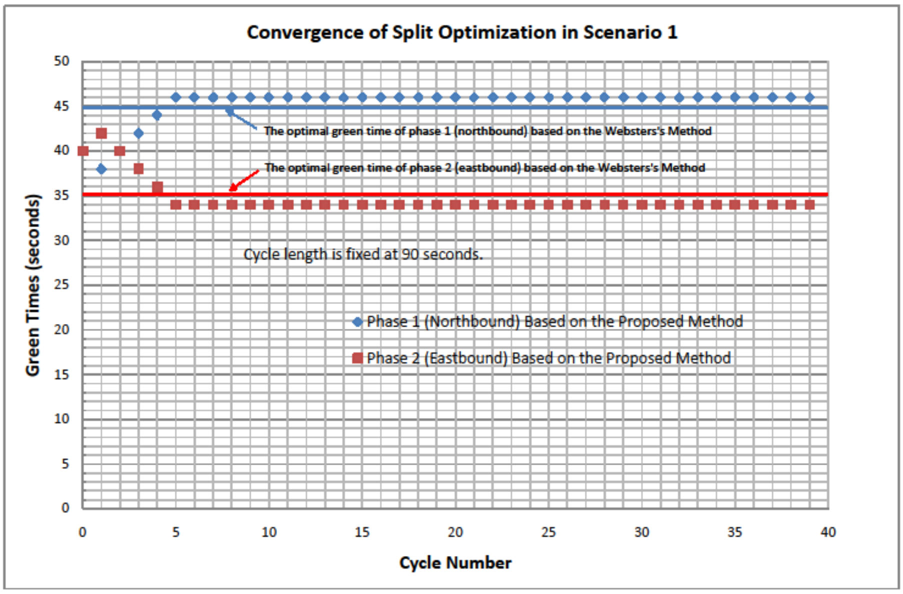


FIGURE 6: Simulation Result of Scenario 1

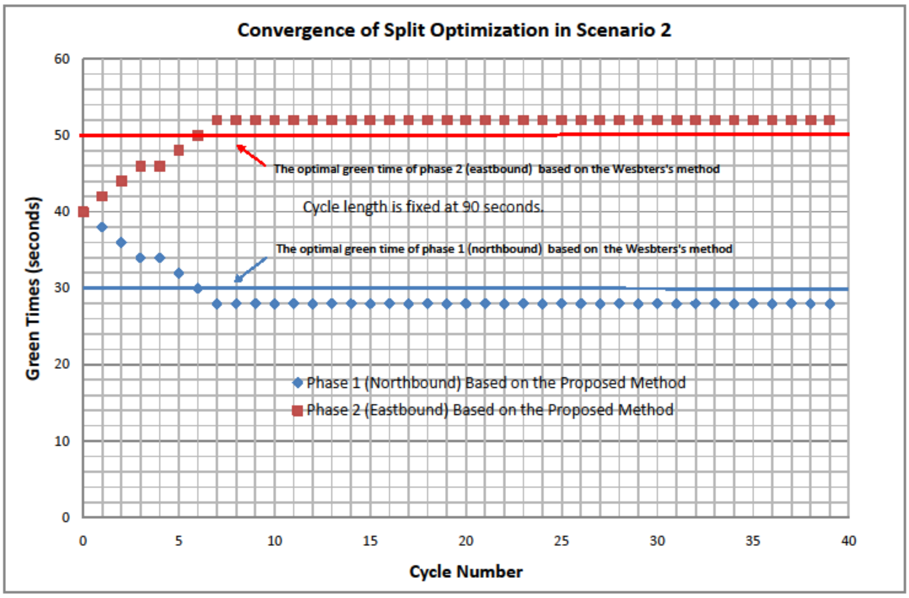


FIGURE 7: Simulation Result of Scenario 2

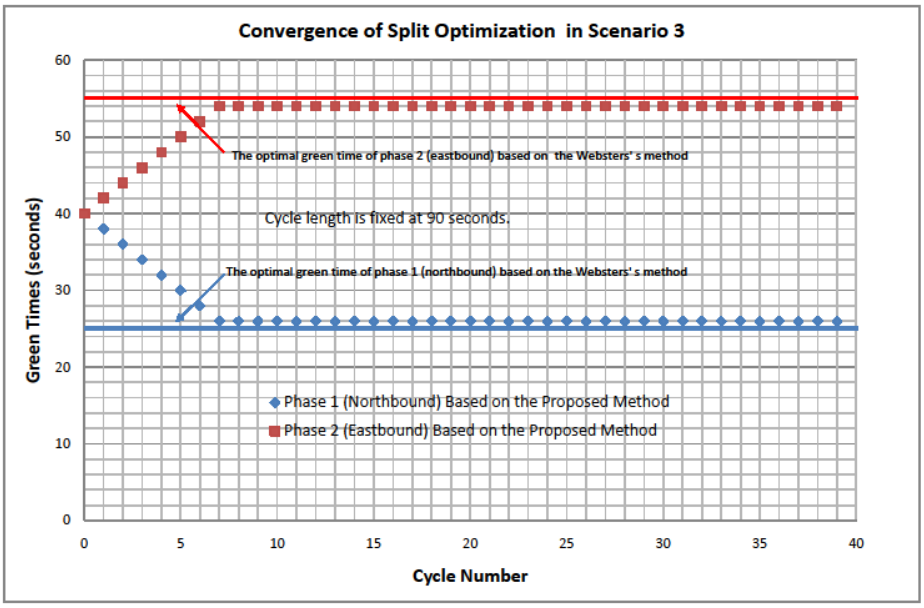


FIGURE 8: Simulation Result of Scenario 3

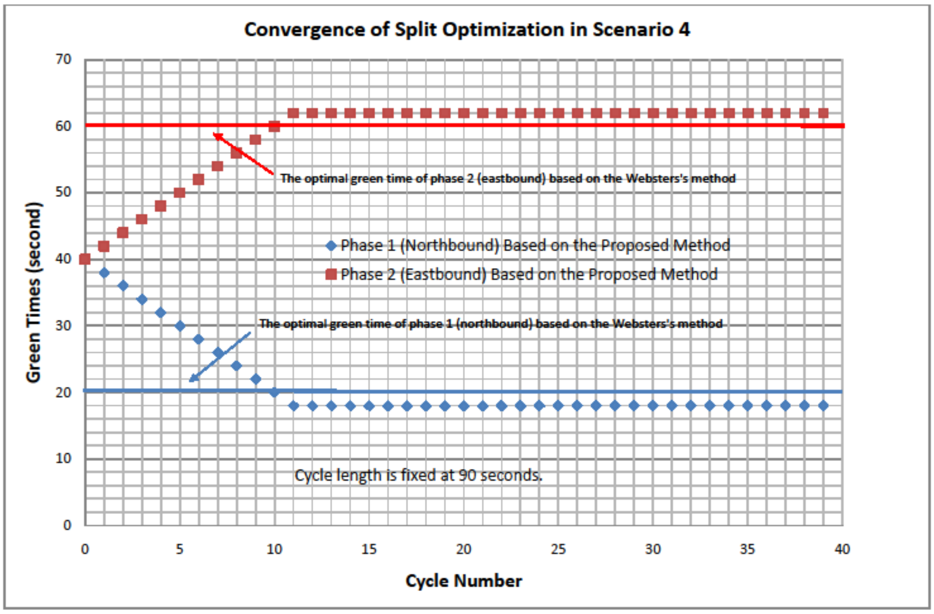


FIGURE 9: Simulation Result of Scenario 4

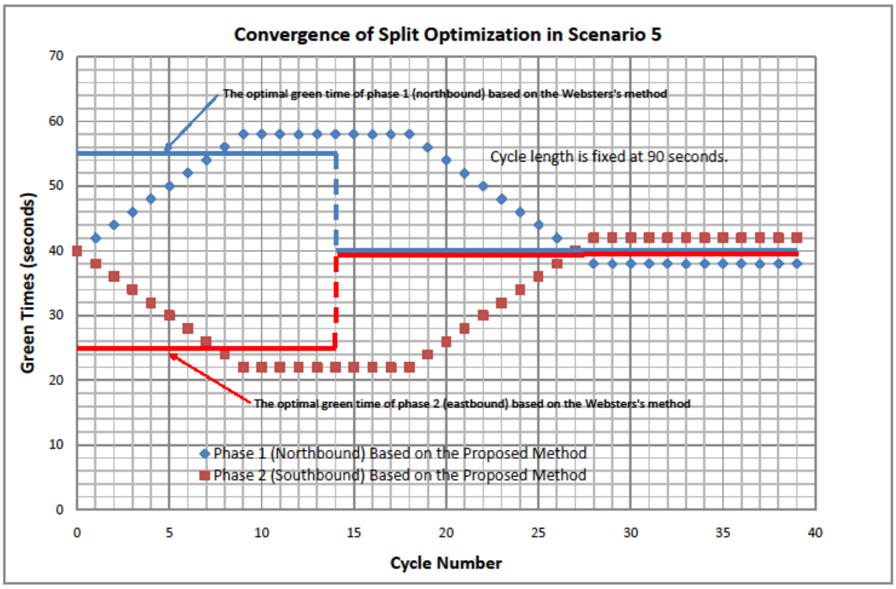


FIGURE 10: Simulation Result of Scenario 5

From the simulation results, it is found that splits according to the proposed method are gradually adjusted and converged to the optimal green time based on the Webster’s method. The convergence times of the proposed algorithm to the optimal settings depend on the initial settings of splits. In scenario 1, the proposed method provides the converged green time of phase 1 northbound approach 46 seconds and 34 seconds for the eastbound phase. These are close to the optimal fixed-time settings of 45 seconds for the northbound phase and 35 seconds for the eastbound phase. The difference is 1 second. In scenario 2, the proposed method provides the converged green times of 28 seconds and 52 seconds for the northbound and eastbound approaches respectively. These are only 2 seconds different from the optimal fixed-time settings of 30 seconds and 50 seconds for the northbound and the eastbound phases. In scenario 3, the proposed method gives the converged green times of 26 seconds for the northbound approach and 54 seconds for the eastbound approach while the optimal fixed-time settings are 25 seconds and 55 seconds for the northbound and the eastbound approaches respectively. In scenario 4, the proposed method provides the converged green times of 18 seconds and 62 seconds for the northbound and eastbound approaches respectively while the optimal fixed-time setting are 20 seconds for the northbound approach and 60 seconds for the eastbound approach. In scenario 5, the demand consists of two patterns: 1) the first 20 minutes, and 2) the last 40 minutes as shown in Figure 5. The proposed method gradually adjusts splits, in accordance with the approach demand, to the optimal fixed-time settings for both demand periods. It takes longer to converge to the optimal settings in the second period than the first because simulation does not start from an empty network. Note that the demand levels in all scenarios are higher than the intersection capacity: $(\frac{v_{EB}}{S_{EB}}+\frac{v_{NB}}{S_{NB}}+\frac{L}{C}>1)$. It indicates that the proposed algorithm can also sustain an oversaturation. This is due to the fact that the proposed method can still process traffic demand information even if queues extend beyond the detector locations at which most existing algorithms cannot.

4. CONCLUSIONS AND FUTURE RESEARCH

In this research, a new signal split optimization is developed based on the concept of minimizing delay per cycle. Traffic dynamics at signalized intersections are represented on the time-space diagrams using the shockwave theory and information from detectors installed upstream of intersections. A split optimizing policy is established by incrementally adjusting splits in order that the total intersection delay per cycle is gradually minimized. Unlike most algorithms, the proposed method can still dynamically adjust splits when queues extend beyond detector locations. This is because, instead of direct flow patterns, the proposed method is based on the shockwave information, detected by loop detectors. Simulation experiments on a single fixed-cycle-length intersection with five demand scenarios are conducted to demonstrate efficiency of the developed algorithm. It is found that in case of fixed demand the proposed method can optimize splits, which eventually converge to the optimal fixed-time signal settings. For the variable demand case, the result indicates that the algorithm can correctly adjust splits in response to the change of demand. The proposed algorithm has demonstrated itself to be a potential split optimization for an adaptive signal control system. In future, this concept of time-space diagram will be expanded to cycle time and offset optimization to complete all components of signal control systems.

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