A Study on the Introduction of the Dual-ring Traffic Signal Control for Mitigating Traffic Impacts

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EXTENDED ABSTRACT

Motor vehicles provide us mobility and convenience but at the cost of chronic traffic congestion, accidents and air pollution. Improved traffic-management systems, particularly the traffic-signal control system that can directly control traffic flows would mitigate these problems. The most popular signal-control systems assign two phases per signal cycle. These conventional signal-control systems have been unchanged for the past few decades. We focus on signal phases and propose a dual-ring signal-control system that assigns signal phase more dynamically than conventional systems.

A dual-ring signal-control is a kind of vehicle-actuated signal-control system that determines the timing of each of the eight different vehicle movements at an intersection. The eight different vehicle movements in the intersection that do not cross mutually consist of four phases for straight and left-turn vehicles and four right turn phases.

A simple example is shown in Figure 1. Phases 1 through 4 and phases 5 through 8 are the members of ring 1 and ring 2, respectively. Phase change sequentially within ring 1 and ring 2 (i.e., phase 1, phase 2, phase 3, phase 4 and phase 5, phase 6, phase 7, phase 8, respectively).

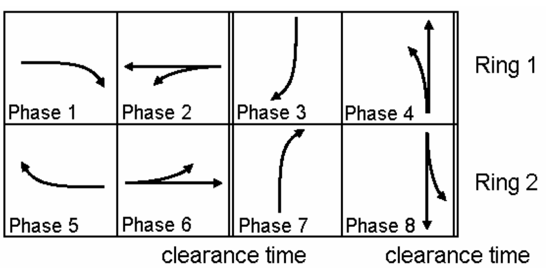

Figure 1. Proposed dual-ring signal-control system.

The road network as shown in Figure 2 is used to show the superiority of the dual-ring signal control system. The traffic volume for minor road and right-turn rate for northbound vehicles is subject to change in order to check sensitivity and effects. Signal-phase splits were calculated every six minutes based on the detected traffic volume. The dual-ring signal control would become more effective utilizing dynamic traffic flow data. Two methods were compared for determining signal-phase splits. They are: the demand-rate distribution method and the total-delay minimization method.

Simulation experiments were done using the microscopic traffic simulator 'VISSIM' in order to compare the conventional signal and the proposed dual-ring signal controls. The following results were observed:

1) The dual-ring signal control system can reduce the delay time more effectively than a conventional signal-control system.

2) The total-delay-minimization method is more effective than the demand-rate distribution method within an intersection that has heavy, unbalanced traffic volume with high right-turning ratios.

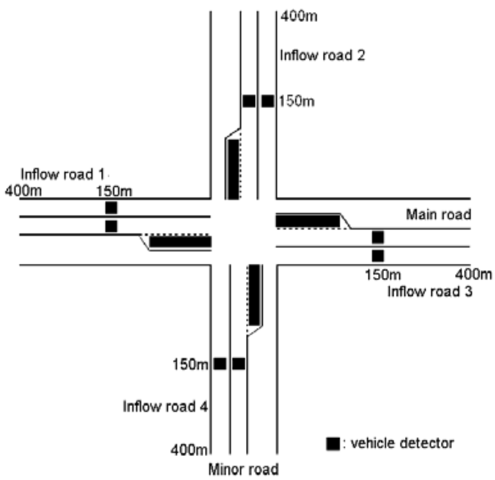

Figure 2. Road network used in this study and position of detectors.

1. INTRODUCTION

Motor vehicles provide us mobility and convenience; but at the cost of chronic traffic congestion, accidents and air pollution. One typical solution for common traffic problems is to expand the existing road network; but at an enormous amount of investment at a high social cost.

A couple of alternative solutions are to employ travel-demand management and to enhance the traffic (signal) control system. The most popular signal-control systems assign two phases per signal cycle. In some cases, three or four phases are used in order to allocate the separate right-turn period per direction. These conventional signal-control systems have been unchanged for the past few decades.

In this research, we focus on the number of phases and we propose a dual-ring signal-control system that is more efficient and is more dynamic; based on road traffic. We have evaluated traffic load via our proposed dual-ring signal-control system versus a conventional signal-control system.

2. PROPOSED SIGNAL CONTROL SYSTEM

2.1. Dual-ring Signal-control System

A dual-ring signal-control is a kind of vehicle-actuated signal-control system that determines the timing of each of the eight different vehicle movements at an intersection. These eight non-crossing movements consist of four phases for straight and left-turn vehicles, and four right-turn phases.

A simple example is shown in Figure 1. Phases 1 through 4 are members of 'ring 1' and phases 5 through 8 are members of 'ring 2'. The phases change sequentially within rings #1 and #2 (e.g., phases 1 through 4 and phases 5 through 8, respectively). The phases within the same 'ring' change in principle, regardless of the other rings.

If phase 1 and phase 5 were blue, then phase 1 can change into phase 2 before finishing its allocated blue time if the lane is free of waiting vehicles and the permitted phases became to be 2 and 5. This phase change is allowed within ring 1 for there is no conflict between vehicle movements for phases 2 and 5.

The phase changes into 6 after confirming the no-waiting vehicle exists or finishing the allocated blue time for phase 5, and the permitted phases would became to be phase 2 and 6. A phase change from phase 5 to phase 6 is allowed within ring 2 for there is no conflict between vehicle movements for phases 2 and 6.

These controls can be performed for phases 3 and 4 in ring 1 and for phases 7 and 8 in ring 2. The proposed dual-ring signal-control system is able to permit the phases that have no conflicts between phases and hence, is able to be a more-dynamic signal control.

2.2. Constraint Conditions

Two limiting conditions are required to operate the dual-ring signal-control system efficiently and safely:

1) a right-turn phase will be skipped if there is no waiting queue for the designated right turn. For example, phase 2 will change into phase 4 when there is no waiting vehicle for phase 2 in Figure 1. Similar controls can be done between phases 4 and 1, between 6 and 7, and between 8 and 5 in accordance with the waiting queue for the designated right-turns. As a result, a more-efficient signal control is achieved.

2) a phase change from an east-west direction (left half of a ring) to a north-south direction (right half of a ring) must be changed at the same time for both rings (i.e., ring 1 and ring 2); and vice versa. The clearance time is required to avoid collisions between the east-west and the north-south flows (Figure 1).

3. SIGNAL-SPLIT CALCULATION

The algorithm of how the dual-ring signal-control change from phase to phase was explained in the previous section. Here, the method of calculation for the blue time per phase and hence, the 'signal split' was left to the implementation of the proposed signal-control system. Two kinds of signal-split calculation are studied in this paper.

3.1. Demand-rate Distribution Method

The demand-rate distribution method computes the signal split directly from the traffic index that is the demand flow-rate per direction. The basic idea assumes that each signal split per specific phase is proportional to the demand flow-rate per direction.

Traffic index

Demand flow-rate ρ_i on phase i is defined using traffic volume 'q_i' and saturation traffic flow-rate 'si' in equation (1).

$$\rho_i = \frac{q_i}{s_i} \tag{1}$$

Signal split determination

The 'demand-rate distribution method' determines the signal split based on the demand flow-rate. Demand flow-rates for the left and right hand sides in Figure 1 are calculated as follows:

$$(q/r)_{ij} = \frac{q_i}{s_i} + \frac{q_j}{s_j} \tag{2}$$

where (i, j) = (1, 2), (5, 6) and (7, 8).

Next, maximum demand flow-rates for left and right hand sides in Figure 1 are calculated as follow:

$$(q/s)_L = \max\left(\frac{q_1}{s_1} + \frac{q_2}{s_2}, \frac{q_3}{s_3} + \frac{q_4}{s_4}\right) \tag{3}$$

$$(q/s)_R = \max\left(\frac{q_3}{s_3} + \frac{q_4}{s_4}, \frac{q_7}{s_7} + \frac{q_8}{s_8}\right) \tag{4}$$

Then the given signal cycle-time C is divided into G_1 and G_2 for the left- and right-hand sides respectively, in Figure 1; based on the demand flow-rates as follows:

$$G_1 = C \times \frac{(q/s)_L}{(q/s)_L + (q/s)_R} \tag{5}$$

$$G_2 = C \times \frac{(q/s)_R}{(q/s)_L + (q/s)_R} \tag{6}$$

Finally, G_1 is assigned into phases 1 and 2, or 5 and 6; and G_2 is assigned into phases 3 and 4, or 7 and 8. These procedures depend upon the demand flow-rate per phase and are used to determine each blue-time period. For example, blue time for phase 1 and 2 are calculated as follows:

$$G_{11} = G_1 \times \frac{(q_1/s_1)}{(q_1/s_1) + (q_2/s_2)} \tag{7}$$

$$G_{12} = G_1 \times \frac{(q_2/s_2)}{(q_1/s_1) + (q_2/s_2)} \tag{8}$$

The same procedures in equations (7) and (8) are performed to determine the blue-time periods of phases 3 and 4, phases 5 and 6, and phases 7 and 8. The minimum blue-time period for this study is set at 6 seconds. The blue-time period is reset to 6 seconds whenever the computed blue-time period via equations (7) and (8) is less.

3.2. Total-delay-time Minimization Method

A vehicle's 'delay-time' is the time required to pass through an intersection influenced by a signal-control system within real-time traffic conditions. According to the Highway Control Manual, the equation of a vehicle's delay-time that can be applied to both non-saturated and saturated conditions is expressed as follows:

$$\delta_{ij} = \frac{0.38 \cdot C(1-\lambda_i)^2}{1-\lambda_i x_{ij}} + 173 x_{ij}^2 \left\{ (x_{ij} - 1) + \sqrt{(x_{ij} - 1)^2 + \frac{16 x_{ij}}{\lambda_i s_{ij}}} \right\} \tag{9}$$

δ_{ij} : delay-time per vehicle for phase i and inflow road j (sec/vehicle),

C: signal cycle period,

q_{ij} : traffic volume for phase i and inflow road j (vehicle/sec),

s_{ij} : saturation traffic flow-rate for phase i and inflow road j (vehicle/sec).

λ_i : split for phase I, and

$$x_{ij} = \frac{q_{ij}}{\lambda_i s_{ij}}.$$

The total delay-time D_{ij} for phase 'i' and inflow road 'j' is calculated using the delay-time (δ_{ij}) defined by equation (9) as follow:

$$D_{ij} = q_{ij}\delta_{ij} \tag{10}$$

The total delay-time for entire intersection is calculated as follows:

$$D = \sum_i \sum_j D_{ij} \tag{11}$$

For the signal control as shown in Figure 1, the optimized signal-split 'λ_i' with respect to given traffic volume 'q_{ij}' and saturation traffic flow-rate 's_{ij}', is determined by minimizing D under constrain condition as follows:

i=8 and j=4,

$$\sum_{i=1}^{4} \lambda_i = 1,$$

$$\sum_{i=5}^{8} \lambda_i = 1,$$

$$\sum_{i=1}^{2} \lambda_i = \sum_{i=5}^{6} \lambda_i \text{ , and}$$

$$w_L \le \lambda_i \le w_U .$$

where w_L and w_U are the lower and upper boundary values, respectively.

4. TRAFFIC SIMULATION

The dual-ring signal-control system's effects on the traffic load as proposed in the previous section have been examined via simulation. The simulator VISSIM re-produces the traffic flow using a conventional signal-control prior to applying the proposed dual-ring signal-control. The various traffic conditions are assumed to assess the proposed dual-ring traffic signal control system.

4.1. Road Network

The road network as shown in Figure 2 is used to show the superiority of the dual-ring signal control and the characteristics of the demand-rate distribution and total-delay-minimization methods. The traffic volume for minor road and the right-turn rate for northbound vehicles are subject to change in order to check sensitivity and effects.

The inflow roads #1 and #2 consist of a main road that has two lanes, and a right-turn lane before the intersection as shown in Figure 2. The inflow roads #2 and #4 consist of a minor road that also has two straight lanes, and a right-turn lane before the intersection as shown in Figure 2. The vehicle detectors are set to count passing vehicles 150 meters upstream from the stop lines and near the starting point of the right-turn lane. Also, an extend-vehicle detector is set on the entire right-turn lane.

The signal-cycle time is set to 120 seconds based on field measurement. The inflow traffic volume is also based on filed measurements. The current traffic-information center updates the traffic condition's 6-minute intervals. Then, the 'signal split' is calculated every 6 minutes based on the detector data via the demand-rate distribution and total-delay-minimization methods in this study. The constraint conditions to calculate the optimal solution by the total delay minimization method are as follows:

$$0.06 \le \lambda_i \le 0.8,$$

$$\sum_{i=1}^{4} \lambda_i = 1,\ \sum_{i=5}^{8} \lambda_i = 1,\ \sum_{i=1}^{2} \lambda_i = \sum_{i=5}^{6} \lambda_i .$$

4.2. Traffic Conditions

One-hour traffic simulations were performed using various traffic conditions under constant traffic volume for the minor road. Let the traffic volume for the minor road be 'Q' and the traffic volumes for inflow roads #2 and #4 to be 'q_2' and 'q_4'; respectively. Then the relationship is as follows:

$$Q = q_2 + q_4 \tag{12}$$

The traffic volume on the main road is constant, based on the field measurements. The ratio of the inflow road #4's traffic volume to the traffic volume for the minor road is denoted as 'r_s':

$$r_s = \frac{q_4}{Q} \tag{13}$$

The list of 'r_s' used in our traffic simulation is shown in Table 1. The inflow traffic volume for the minor road is 'Q' and has three different traffic volumes (i.e., 200, 900, and 1600 vehicles per hour). These three different traffic volumes correspond to the free-, average- and heavy-traffic conditions. Also, the ratio of the traffic volume on inflow road #4 to the total traffic volume 'q4' is set to 0.5 or 0.7; as shown in Table 1. Moreover, the right-turn ratio for the vehicle from inflow road #4 is set to 0.1 or 0.2 as shown in Table 1.

Table 1. Traffic condition for each simulation case.

Case	Total origin traffic volume (Vehicle/hour)	r_s	Right-turn ratio
1-1(0.1)	200	0.5	0.1
1-2(0.1)	200	0.7	0.1
2-1(0.1)	900	0.5	0.1
2-2(0.1)	900	0.7	0.1
3-1(0.1)	1600	0.5	0.1
3-2(0.1)	1600	0.7	0.1
1-1(0.2)	200	0.5	0.2
1-2(0.2)	200	0.7	0.2
2-1(0.2)	900	0.5	0.2
2-2(0.2)	900	0.7	0.2
3-1(0.2)	1600	0.5	0.2
3-2(0.2)	1600	0.7	0.2

4.3 Results And Discussion

Ten simulations have been done for each case in Table 1 using ten different random number series. The average of ten simulations per case is shown in Table 2. The values are vehicle delay-time per hour for the entire intersection. The values in parentheses denote the relative value when the delay-time for the conventional signal-control is 100.

The demand-rate distribution and the total-delay-time-minimization methods reduce the delay-time versus a conventional signal-control system as shown in Table 2. This is due to using detector data to respond to traffic changes per 6-minute interval versus a conventional signal-control system which uses a fixed-signal cycle. This is also due to saving the unnecessary blue time via changing the signal phase within each independent ring.

The relative values of the demand-rate distribution method are shown in Table 3. The values in parentheses denote the relative values when the delay-time for the demand-rate distribution method is 100. The total-delay-time-minimization method reduces the delay time for all cases versus the demand-rate distribution method. The differences between the split-calculation methods are remarkable for case 2-2 and case 3-2 because the traffic volume is large and un-even for inflow roads 2 and 4.

Table 2. Delay-time for each case.

case	Total delay Mini-mization method (sec)	Demand flow-rate distribution method (sec)	Conven-tional Signal Control
1-1(0.1)	19.0(40.6)	18.9(40.4)	46.8(100)
1-2(0.1)	19.3(43.3)	19.0(42.6)	44.6(100)
2-1(0.1)	34.0(68.0)	34.0(68.0)	50.0(100)
2-2(0.1)	36.9(72.1)	37.7(73.6)	51.2(100)
3-1(0.1)	62.4(57.2)	65.4(60.0)	109.0(100)
3-2(0.1)	82.7(75.9)	87.7(80.5)	109.0(100)
1-1(0.2)	19.0(42.5)	19.0(42.5)	44.7(100)
1-2(0.2)	19.2(42.7)	18.9(42.0)	45.0(100)
2-1(0.2)	35.3(72.8)	35.3(72.8)	48.5(100)
2-2(0.2)	35.9(72.1)	44.3(89.0)	49.8(100)
3-1(0.2)	72.6(60.5)	86.9(72.4)	120.0(100)
3-2(0.2)	80.8(75.4)	108.1(100.8)	107.2(100)

Table 3. The comparison of the signal split calculation difference.

case	Total delay Minimization method (sec)	Demand flow-rate distribution method (sec)
1-1(0.1)	19.0(100.5)	18.9(100.0)
1-2(0.1)	19.3(101.6)	19.0(100.0)
2-1(0.1)	34.0(100.0	34.0(100.0)
2-2(0.1)	36.9(97.9)	37.7(100.0)
3-1(0.1)	62.4(95.4	65.4(100.0)
3-2(0.1)	82.7(94.4)	87.7(100.0)
1-1(0.2)	19.0(100.0)	19.0(100.0)
1-2(0.2)	19.2(101.6)	18.9(100.0)
2-1(0.2)	35.3(100.0)	35.3(100.0)
2-2(0.2)	35.9(81.0)	44.3(100.0)
3-1(0.2)	72.6(83.5)	86.9(100.0)
3-2(0.2)	80.8(74.7)	108.1(100.0)

The minor road has the highest demand-flow-rate, even when the main road's demand-flow-rate is high; whenever the traffic volume is large, such as in case 3-2 and is unbalanced between the inflows of minor roads (i.e., r_s = 0.7). Hence, the signal split for the main road is suppressed which induces the traffic congestion; and the delay time shall became large by the demand-rate distribution method.

The higher right-turn ratio (ref.: 3-2(0.2) and 3-1(0.2)) shows the superiority of the total-delay-time-minimization method versus the smaller right-turn ratio (ref.: 3-2(0.1) and 3.1(0.1)). This must be due to the lane-number difference. There is only one right-turn lane per two through-traffic lanes. Therefore, the demand flow-rate for a right-turning vehicle corresponds to two vehicles per through traffic. As a result, a vehicle moving from the main lane to the right-turn lane doubles the demand flow-rate for that vehicle. Therefore, the increase numbers of right-turning vehicles expand the demand flow-rate for the right-turn; and hence, allocate more signal split to the minor road by reducing the signal split for the main road. And hence, traffic congestion occurs on the main road.

5. SUMMARY AND PLAN FOR FUTURE

Simulation experiments were done using the microscopic traffic simulator 'VISSIM' in order to compare the conventional signal with proposed dual-ring signal controls; and the following results were observed:

1) The dual-ring signal control system can reduce the delay time more effectively than a conventional signal-control system.

2) The total-delay-minimization method is more effective than the demand-rate distribution method within an intersection that has heavy, unbalanced traffic volume with high right-turning ratios.

We should apply the proposed signal-control system to consecutive intersections to confirm the superiority of the proposed signal-control system in the real world.

6. REFERENCES

Japan Society of Traffic Engineers (2006), Manual on Traffic Signal Control (in Japanese), Maruzen, 164 pp., Tokyo.

Oda, T. (1996), Traffic signal-control- system optimization method for the main intersection (in Japanese), *Journal of the Institute of Systems, Control and Information Engineers*, 9(11), 520-530.

Ookura, I. (2001), Traffic Engineering (in Japanese), Tokyo, Corona Pub., 254 pp., Tokyo.

Transportation Research Board (2003), Highway Capacity Manual Applications Guidebook, Washington, D.C., http://hcmguide.com/.