EVALUATION OF GROUP-BASED SIGNAL CONTROL THROUGH FIELD OPERATIONAL TESTS*

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1. Introduction

At signalized intersections, green times should be assigned to satisfy the traffic demand for all approaches. Stage-based signal control is the most common and basic control policy worldwide particularly at Japanese signalized intersections. It is defined as a signal control policy in which compatible traffic movements are grouped to move together in a specific time span within a signal cycle, which are referred to stages, and green times are then assigned to each stage depending on the movement with the highest demand in each stage. At intersections with relatively balanced traffic demand in opposite approaches, the stage-based signal control can assign green time reasonably for each stage. However, at intersections with imbalanced traffic demand in opposite approaches, a portion of the assigned green time to the approaches with minor traffic demand will not be used since stage-based signal control assigns equal green time to major and minor traffic demand approaches. Since this control policy has a stable phasing plan and the green time is assigned for an approach not for movements, long cycle length and large delay are likely to occur at such intersections.

In order to overcome such deficiencies, group-based signal control was invented and widely used in different countries. It is defined as signal control which directly assigns green times to traffic movements without the need to maintain a specific stage structure. This policy can assign the green time to each traffic movement rather than a stage of different movements, therefore the unused green time which is assigned by stage based signal control to the approaches with minor traffic demand can be avoided. Such control policy provides flexible phasing structure where different non-conflicting movements can be joined together in one phase. This mechanism might reduce the cycle length by saving the unused green time, and furthermore delay as well. Furthermore, the flexible phasing structure is advantageous in avoiding several conflicts between traffic movements which might have positive impact on the safety phases, the flexible phasing patterns which might confuse drivers at the beginning and the end of green phases. This possible negative impact might be the main reason behind the limited application of this policy in Japan.

In this study, the operational and safety performance before and after the implementation of group-based signal control at two test intersections are evaluated and compared.

2. Literature review

Many studies found that traffic flow characteristics at signalized intersections, such as start-up lost time *SULT*, clearance lost time *CLT* and saturation flow rate *SFR* are influenced by geometric design, signal control and user attributes (Noyce et al. 2000[1)]; Lin et al. 2004[2)] and 2005[3)]; and Tang and Nakamura 2007[4)]). The differences in these variables under group-based signal control and stage-based signal control were also explored by the authors recently. An international comparative study between Germany and Japan analyzed *SULT*, *CLT*, and *SFR* at typical signalized intersections with pretty close intersection size and traffic demand (Tang and Nakamura, 2007[5)]). Following that, a before-and-after study at Yokkaichi City in Japan was performed to further explore the impacts of group-based signal control on operational performance and safety performance (Tang and Nakamura, 2008[6),7)]). However, Tang and Nakamura included in their analysis one Japanese intersection with a specific traffic condition. This study aims to evaluate the operational and safety performance of group-based signal control at an intersection in Tahara City, Japan and compare this performance with that of Yokkaichi city intersection which was analyzed by Tang and Nakamura, 2008[6),7)].

3. Site description and data collection

Two intersections in Japan have been chosen to evaluate the performance of group-based signal control. One is located in Yokkaichi City of Mie Prefecture (site Y) which connects national Route 23 and a prefectural road. It is characterized by complex geometry, high vehicular traffic demand, very low pedestrian demand, large proportion of heavy vehicles, and apparent demand fluctuations during different time of the day. The other one is located in Tahara City of Aichi Prefecture (site T) connecting prefecture Route 2 and a city road. This intersection has a common

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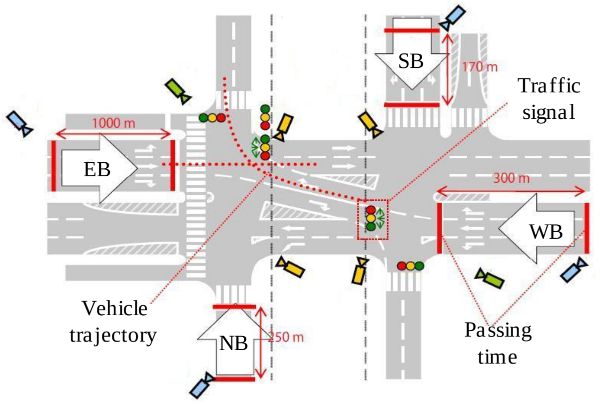


Figure 1 Configuration, signal light settings and detector arrangement for site Y

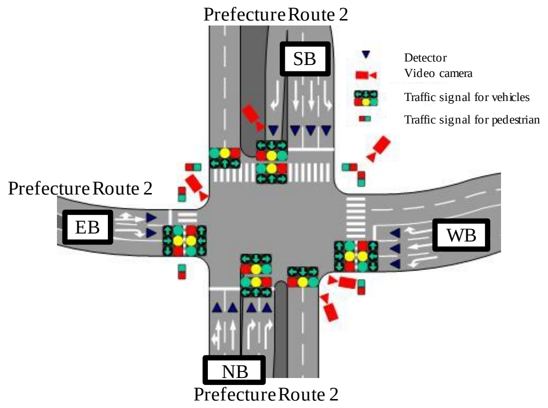


Figure 2 Configuration, signal light settings and detector arrangements for site T

Table 1 Survey times and weather conditions at sites Y and T

Location	*Condition*	*Date*	*Time*	*Weather*
Yokkaichi	Before	2007.02.26(Mon)	14:00~15:30 (PM off peak)/17:00~18:30 (PM peak)	Sunny
		2007.02.27(Tue)	7:00~8:30 (AM peak)/10:00~11:00 (AM off peak)	Sunny
	After	2007.06.18(Mon)	17:00~18:30 (PM peak)	Rainy
		2007.06.19(Tue)	7:00~8:30 (AM peak) /10:00~11:00 (AM off peak) /14:00~15:30 (PM off peak)	Sunny
Tahara	Before	2008.11.05(Wed)	14:00~15:30 (PM off peak)/15:30~17:00 (PM peak)	Sunny
	After	2008.12.10(Wed)	14:00~15:30 (PM off peak)/15:30~17:00 (PM peak)	Sunny

geometric layout and relatively low pedestrian demand. Vehicular traffic demand and heavy vehicle proportion are high since the Toyota Automobile Factory is very close to the site. Furthermore, vehicular traffic demand is imbalanced at both of the two directions.

At site Y, the upstream and downstream of both NB and SB are separated however the EB and WB have a combined upstream and downstream as show in **Figure 1**. While site T is a common 4-leg intersection as shown in **Fugure2**.

Table 1 shows the time and weather condition of the before and after surveys for site Y and site T. Since Tahara intersection was surveyed during the PM peak and off peak hours only, the PM peak hour was chosen as the analysis period for the performance evaluation in this paper. As shown in **Table 1**, one rainy day was included in the survey at site Y. Signal timing, phasing information and traffic flow characteristics are extracted from the video tapes.

According to the observations at site Y, imbalanced traffic demands prevail at east-bound (EB) and west-bound (WB) approaches. The traffic demand of EB-LT in AM peak-hour is higher than that of WB, in contrast, the opposite situation often takes place during PM peak. At site T in PM peak hour, the traffic demand of SB-LT is higher than that of NB. However, the traffic demand of NB-R is higher than that at of SB. Meanwhile, all traffic movements at WB have higher demand than EB.

During the PM peak hour, initial queues occurred on WB (the critical traffic movement) at site Y when stage-based signal control was applied which resulted in significantly large delays. This means that the assigned green time to the phase ϕ1 which includes the through and left turning of WB and EB could not satisfy the traffic demand at the WB. Moreover, the assigned green time to the through and left turning of EB is partially used since the demand was low. In order to overcome these problems, group-based signal control was installed at site Y on the WB and EB. **Figure 3** shows the phasing plans for site Y in before and after cases. The extra green phases (ϕ2a, ϕ2b) are implemented depending on the traffic demand.

At site T, initial queue did not occurred at any traffic movement in the before condition which means that the assigned green time for each traffic movement was sufficient. Due to the imbalanced traffic demand between the NB and SB, EB and WB, the assigned green time by stage-based signal control was partially used by the minor traffic movements (NB and EB). In order to improve this deficiency and to investigate the possible effects on the safety performance, group based signal control was implanted at all approaches. **Figure 4** shows the phasing plans for site T in before and after cases. By comparing the phasing plans after the implementation of group-based signal control in site Y and site T, phases ϕ2a-1, ϕ2b-1, ϕ5a-1 and ϕ5b-1 are applied only at site T in order to provide a clearance time between the right turning traffic and the opposing through traffic.

To provide a general view on the traffic conditions during the before and after surveys for site Y and site T, traffic

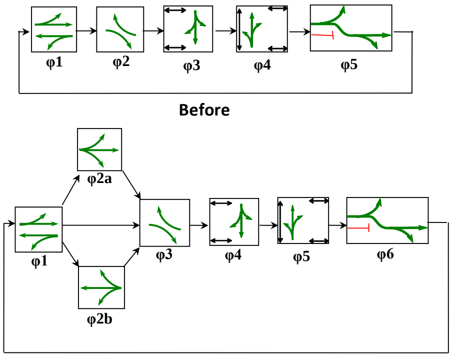


Figure 3 Phasing plans applied at the site Y in the before and after study

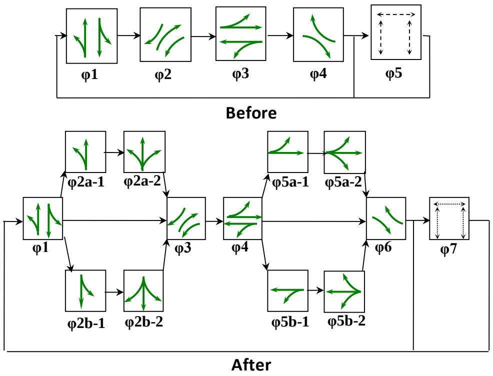


Figure 4 Phasing plans applied at the site T in the before and after study

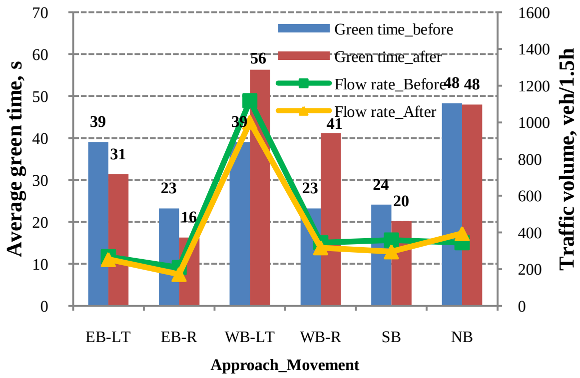


Figure 5 Observed average flow rates and green times at site Y in the before and after study

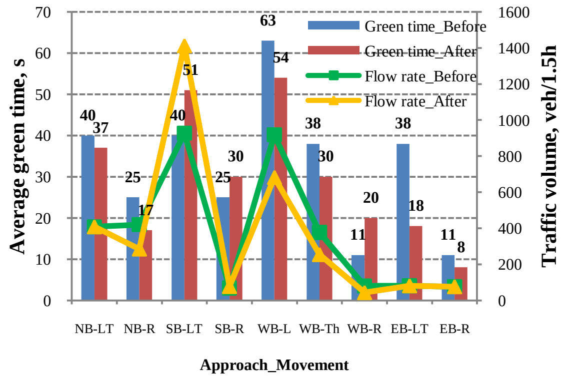


Figure 6 Observed average flow rates and green times at site T in the before and after study

demand and green times for each movement are presented in **Figure 5** and **Figure 6** respectively. The critical movement at site Y is WB approach (WB-LT) while SB approach (SB-LT) and WB approach (WB-LT) are the critical movements at site T. Meanwhile WB-LT at site Y and SB-LT at site T were chosen as the subject traffic movements for intersection performance evaluation in this study. As shown in **Figure 5 and Figure 6**, after the implementation of group-based signal control, the green time is assigned reasonably to each movement according to traffic demand. However, there is an exception at site T where the assigned green time to NB-R is shorter than that of SB-R although the traffic demand of NB-R is higher than that of SB-R. This can be referred to the existence of phase ϕ 2b-2 which provides the SB-R with an extra green time. But this green time is not used since the demand of right turn traffic is very low. The same situation occurred at the WB-R of site T.

In the before study, oversaturated condition is observed at the WB-LT of site Y, which means that the assigned green time did not satisfy the traffic demand. Therefore, after the implementation of group-based signal control a longer green time is assigned to the WB-LT which eliminated the oversaturated condition as shown in **Figure 5**.

After the implementation of the group-based signal control, it was observed that at site Y, the average cycle length remained the same as the before condition. However, at site T, the average cycle length was reduce at site T from 144s to 135s (exclude pedestrian phase). This can be referred to the traffic characteristics of site T where all the opposite directions are characterised by imbalanced traffic demand which is advantageous for group based signal control.

4. Results and discussion

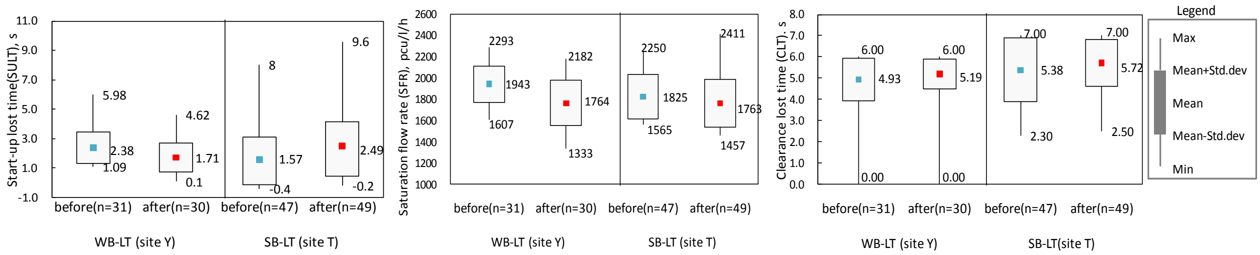
(1) Operational performance

a) Traffic flow characteristics

Start-up lost time (*SULT*), clearance lost time (*CLT*), and saturation flow rate (*SFR*) were used to represent traffic flow characteristics in this study as they are key parameters in the calculation of capacity. These three parameters can only be measured under saturated conditions, and are computed according to the equations provided by the Highway Capacity Manual 2000[8)] as shown in **Equations (1)**, **(2)** and **(3)**.

$$SULT = \left(\frac{H_1 + H_2 + H_3 + H_4}{4} - \frac{H_5 + \cdots + H_n}{n-4}\right) \times 4 \tag{1}$$

$$SFR = 3600 / \left(\frac{H_5 + \cdots + H_n}{n-4}\right) \tag{2}$$



a) Observed *SULT* **b)** Observed *SFR* **c)** Observed *CLT*

Figure 7 Observed *SULT*, *SFR* and *CLT* at site Y and site T in the before and after study (n : number of samples)

$$CLT = Y + AR - T_e \quad (3)$$

Where H_i is time headway of the *i*th vehicle passing the stop-line in queue (s); *n* is total number of queued vehicles; *Y* is yellow time (s); *AR* is all-red time (s) and T_e entry time of the last cleared vehicle after the start of intergreen (s). Note that T_e equals to $Y+AR$ if no vehicle enters after the start of intergreen, while T_e equals to 0 if a vehicle enters after the end of all-red.

Figure 7a) presents the observed *SULT* of the subject traffic movements at site Y and site T. *SULT* of WB-LT is reduced after the implementation of group-based signal control at site Y, however, it increased at site T on SB-LT. As mentioned in the introduction part, group-based signal control has a variable phasing plan which is changing dependent on the traffic condition. Such flexible phasing plan might confuse the drivers who are waiting for the start of green time at the head position of the queue. Actually the first and the second vehicle spend longer response time since they cannot expect which phase will be displayed. According to the computing method, *SULT* should increase after the implementation of group-based signal control which is in accordance with the observation at site T. However at site Y, *SULT* decreased which can be referred to the rainy weather condition during the survey. Due to the rainy condition, drivers might try to keep longer headways, especially in the back of the queue which will result in smaller *SULT* (Equation 1). Although this does not reflect any kind of improvement since the reduction is only because of the methodology which is used for calculating *SULT*.

Figure 7b) shows the observed *SFR* for the subject traffic movements. It was found that *SFR* of WB-LT at site Y was slightly reduced in the after condition due to the rainy weather. At site T, *SFR* of SB-LT did not significantly change after the implementation of group-based signal control, because there is no change in road and weather conditions in the before and after cases. Meanwhile, the result can imply that group-based signal control may not influence the driver behavior in the rest part of the queue excluding the first several drivers.

Figure 7c) presents the observed C*LT* of the subject traffic movements at site Y and site T. *CLT* refers to the time between signal phases during which an intersection is not used by any traffic. It is composed from the lost time in yellow and all-red clearance interval. The results show that *CLT* slightly increased at both sites.and that drivers become more conservative when they decide to pass or stop after the onset of yellow signal as they can hardly presume what conflicting traffic movements will be released in the next phase.

b) Capacity

Capacity is computed according to the methodology proposed by Highway Capacity Manual 2000[8] as shown in **Equation (4)** and **(5)**.

$$c = SFR \times \frac{G_e}{C} \quad (4)$$

$$G_e = G + Y + R - (SULT + CLT) \quad (5)$$

Where *C* is cycle length(s) and G_e is effective green time(s).

The capacities of the subject traffic movements at site Y and site T are shown in **Figure 8**. The result shows that the capacities of WB-LT at site Y and SB-Th at site T increased after group-based signal control was implemented. The capacity is mainly dependent on *SFR*, lost time (*SULT, CLT*), and the green time allocation. According to the results on *SFR* and lost time discussed before, it is concluded that the major reason behind the increasing in the capacity is the green time allocation. It can imply that group-based signal control can provide better green time allocation to the subject traffic movements.

c) Control delay

Control delay is computed according to the methodology proposed by Highway Capacity Manual 2000[8] as shown in **Equation (6)**.

$$control\ delay = d_1(PF) + d_2 + d_3 \quad (6)$$

Where d_1 is uniform control delay(s/veh); *PF* is uniform delay progression adjustment factor; d_2 is incremental delay(s/veh) and d_3 is initial queue delay(s/veh).

The initial queue delay was considered only at site Y due to the observed residual queues before the implementation of group-based signal control, but was not considered in the delay estimation at site T since no residual queues existed in the before and after surveys.

Figure 9 shows the estimated control delay for site Y and site T. It can be concluded that control delay at both sites significantly reduced after the implementation of group-based signal control. This can be referred to the cycle length reduction and the better allocation of green time to the subject traffic movements. Although the cycle length of site Y did not change significantly in the before and after conditions, the control delay remarkably reduced. This can imply that control delay might be also strongly related to the green time allocation, not only to the cycle length.

(2) Safety performance

As mentioned in the introduction, the influence of the frequent and flexible phase switching pattern of group-base signal control on the safety performance is one of the major reasons behind the limited application of this control policy in Japan. Thus, this study tries to investigate the effect of group based signal control upon intersection safety during intergreen intervals rather than green intervals.

To evaluate the safety performance, particularly the conflict risk during intergreen, the post-encroachment time index (*PET*) is used in this paper. *PET* is defined as the time between the last clearing vehicle and the first entering vehicle of two conflict traffic movement during intergreen. For example, *PET* bewteen SB-T and NB-R is the time between the last clearing vehicle of SB-T and the first entering vehicle of NB-R.

Figure 10 shows the observed *PET* values for the conflict point between WB-Th and EB-R at site Y and the conflict point between SB-Th and NB-R at site T. It was found that *PET* increased after group-based signal control was implemented. According to the definition of *PET*, two reasons might contribute to this result. After the implementation of group-based signal control, the clearing vehicle after the onset of yellow might hesitate to enter the intersection since the driver cannot make sure which conflicting movement will be released. On the other hand, since the phasing pattern will become more flexible due to the implementation of group-based signal control, the first entering vehicle will spend longer response time since the drivers cannot expect which phase will be displayed. This makes the first entering vehicle enter the intersection more late.

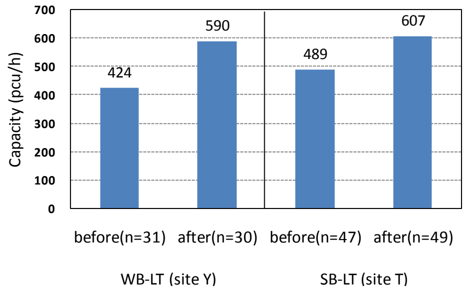


Figure 8 Estimated capacities of subject traffic movements in the before and after study
(n: number of samples)

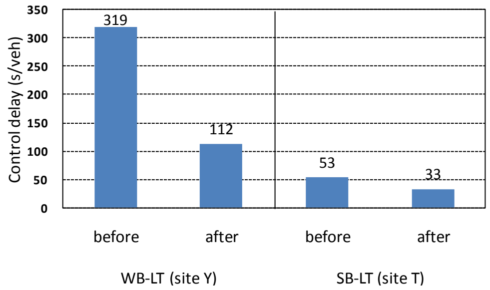


Figure 9 Estimated control delay of subject traffic movements in the before and after study

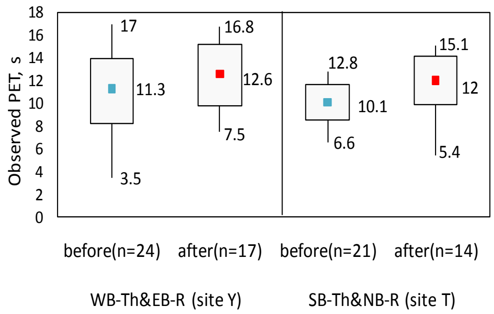


Figure 10 Observed *PET* in the before and after study (n: number of samples)

5. Conclusion

In this paper, the operational and safety performance after the implementation of group-based signal control at two different sites were evaluated and compared with the before condition where stage-based signal control was applied. The two sites are located in Yokkaichi City and in Tahara City in Japan.

Generally, it is concluded that group-based signal control can assign green time more reasonably to each traffic movement and improve the operational performance by providing higher capacities and lower delays. Due to this flexible phasing pattern, drivers especially in the first several vehicles and the last several vehicles might hesitate to enter the intersection which leads to longer *SULT* and *CLT*. However, such phenomena will result in larger *PET*s between the clearing and the entering vehicles which can be considered as safety improvement.

By comparing the performance of the two intersections, it is concluded that group-based signal control resulted in better performance at the intersection of Tahara City since all opposing traffic movements have imbalanced demand. However the improvements at the intersection in Yokkaichi City were limited since only two opposing traffic movements have imbalanced traffic demand.

Since the traffic condition at WB-LT of the intersection in Yokkaichi City was oversaturated in the before survey, the implementation of group-based signal control was very effective in relieving the traffic condition by providing longer green times. This led to an increase in the capacity by 39.1% and a reduction in control delay by 64.9%. However at the intersection in Tahara City, although the oversaturated condition did not occur in the before survey, improvements were observed after the implementation of group based signal control, for example the capacity increased by 24.1% and a control delay was reduced by 37.7% on SB-LT traffic movement. This can be referred to the better allocation of green time which led to a significant reduction in cycle length.

The average *PET* for both intersections increased after the implementation of group based signal control. However the increase in *PET* at the intersection in Tahara City was higher than that of the intersection in Yokkaichi City. This can be contributed to the different phasing plan of group-based signal control which is used at the intersection in Tahara City.

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