Performance Evaluation of Adaptive Group-based Signal Control through a Field Test in Japan

Keshuang Tang, Dr. -Eng
JSPS Postdoctoral Research Fellow
Institute of Industrial Science
The University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505
TEL: +81-3-5452-6419
FAX: +81-3-5452-6420
E-mail: tang@iis.u-tokyo.ac.jp

Nan Kang
M.-Eng Student
Department of Civil Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603
TEL: +81-52-789-5175
FAX: +81-52-789-3837
Email:kang@genv.nagoya-u.ac.jp

Hideki Nakamura, Dr. -Eng
Professor
Department of Civil Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603
TEL: +81-52-789-2771
FAX: +81-52-789-3837
Email:nakamura@genv.nagoya-u.ac.jp

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Abstract: The group-based signal control approach (GA) refers to such a control pattern that the controller is capable of separately allocating time to each signal group instead of stage. It is a consensus that GA is more efficient in terms of operational performance than the conventional stage-based signal control approach (SA) predominantly applied in Japan, particularly if adaptive control is applied. In order to investigate the applicability of adaptive GA in Japan, one intersection was recently selected as the field test site by Universal Traffic Management Society of Japan. Utilizing the data collected at the test intersection before and after the implementation, this study evaluated the operational and safety performance of adaptive GA.

Operational traffic flow characteristics, including start-up loss time (*SULT*), clearance loss time (*CLT*), and saturation flow rate (*SFR*), were first measured and compared between before and after. It was found that *SULT* and *CLT* increased averagely by 0.6s and *SFR* however remained stable after the implementation of adaptive GA. Capacity and delay were then estimated based on those measured traffic flow parameters. It was found that capacity of the intersection slightly ascended by 3%, and the total average delay was considerably improved by 24% after adopting the adaptive GA. In addition, a new methodology based on Traffic Conflict Technique was developed to evaluate safety performance of GA during intergreen intervals. Post-encroachment time at the conflicting area of the last clearing vehicle in the previous phase and the first entering vehicle in the next phase was proposed to be the measure to conflict severity. Results showed that safety was considerably improved by 12% by the use of adaptive GA. This study thus suggests that GA may be an alternative for signal control at intersections in Japan, in order to improve the mobility on urban roads.

Key Words: adaptive group-based signal control, operational performance, intergreen interval, traffic conflict, before-and-after study

0. Introduction

To achieve both mobility and safety, a variety of control approaches have been applied at signalized intersections across the world. Conventional methods include the stage-based and group-based (often called movement-based in traffic control industry in Japan) approaches. In the stage-based approach (SA), compatible traffic movements are grouped to move together in a specific time span within a signal cycle, which are referred to as stages, and green times are then assigned to each stage. The group-based approach (GA), in contrast, directly assigns green times to traffic movements without the need to maintain a specific stage structure (Wong et al, 2005). Comparing with the conventional SA, GA is considered as a more efficient control pattern in terms of operational benefits indicated by delay, owing to its flexibility in the assignment of green times to traffic movements (Bell Michael and Brookes, 1993; Heydecker, 1996; Wong, 1996).

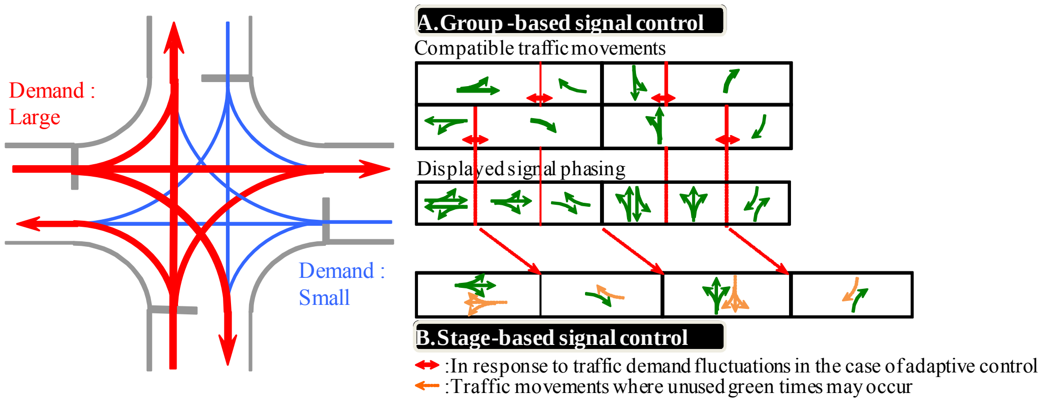


Figure 1 Typical phasing plans under the group-based signal control approach (GA) and the stage-based signal control approach (SA)

As an example, **Figure 1** shows two typical phasing plans under SA and GA at an intersection where traffic demand at east-bound and north-bound approaches are significantly larger than those at the other two approaches. Because of the capability of signal controller to assign green time to signal group rather than stage, GA is able to drastically shorten cycle length and thus reduce control delay. However, SA tends to produce unused green times for west-bound and south-bound approaches. In addition, GA is more flexible to adjust green times in response to demand change in the case of adaptive control. Thus, it is particularly effective when unbalanced or largely fluctuated traffic demand prevailing.

In Japan, due to the concern on safety issue and capacity loss with the switch of phases, SA is preferred and predominantly being applied so far, which usually has stable phasing structure but is relatively easy to result in unnecessarily long cycle lengths, e.g., 150s~180s. Those long cycle lengths impose large delays on drivers (deteriorating mobility), and also induce their risky behavior, e.g., red-light-running, as they are often impatient with too long waiting time (Suzuki et al, 2004). However, GA has been successfully operating in several European countries such as Germany and the United Kingdom. In view of that, a few Japanese professionals have proposed GA as an alternative solution to resolve the problems in mobility on urban road network, resulted from those long cycle lengths at signalized intersections.

Nevertheless, Universal Traffic Management Society of Japan launched a research project in 2007, aiming to investigate the applicability of GA at signalized intersections in Japan. An intersection located in Mie Prefecture was selected as the first field test site in 2007, where GA was only applied to the major approaches with adaptive control on right-turn traffics. In 2008, another intersection located in Aichi Prefecture was selected as the second test site, where adaptive GA was applied for all approaches and traffic movements. Utilizing the data collected at the first test intersection before and after the implementation, the authors evaluated GA in terms of its operational and safety performance. This study intends to continuously assess the performance of adaptive GA, through a before-and-after study at the second test site.

The rest of the paper is organized as follows. Section 1 outlines the existing research related to the evaluation of GA. Section 2 and 3 describe the field test intersection as well as field surveys and data reduction. Section 4 investigates operational benefits of GA in terms of traffic flow characteristics, capacity, and delay, as well as assesses its safety performance during the change of phases based on traffic conflict technique. Section 5 highlights the conclusions.

1. Literature review

In the procedure of performance evaluation at signalized intersections, common representative traffic flow characteristics consist of start-up lost time (*SULT*), clearance lost time (*CLT*), and saturation flow rate (*SFR*). Meanwhile, capacity (*c*) and delay (*d*) have been considered as the most significant measures to quantify operational performance so far.

Many studies indicated that traffic flow characteristics may vary from location to location due to geometric design, signal control and user attributes, such as Noyce et al. (2000), Lin et al. (2004 and 2005), and Tang and Nakamura (2007[1]). An international comparative study done by Tang and Nakamura, 2007[2] analyzed the difference in *SULT*, *CLT*, and *SFR* respectively under GA and SA, taking a few typical signalized intersections with close geometry and traffic demand in Germany (GA) and Japan (SA) as study sites. A subsequent before-and-after study at the first field test site of GA in Japan was performed by Tang and Nakamura in 2008[1] to further look into the impacts of GA on *SULT*, *CLT*, and *SFR*, in the context of identical driver behavior and intersection geometry. Conclusions supported that for a short term flexible signal phasing produced by GA may have negative influence on *SULT*, i.e., larger *SULT*; on the other hand, GA tends to slightly increase *CLT* and has no significant impacts on *SFR*.

In addition, the advantage of GA in optimizing signal programs and obtaining operational benefits, e.g., delay, both at isolated intersections and in area wide control have been well proved in theory and simulations (Gallivan and Heydecker, 1988; Heydecker, 1996; Wong, 1996; Silcock, 1997). However, very little empirical research has validated those conclusions. Tang and Nakamura (2008[1]) compared the measured delays before and after the implementation of GA at the first field test site in Japan. It was found that delay was considerably reduced by adopting GA when traffic demand is fairly unbalanced, and it is however difficult to achieve so, provided balanced traffic demand at each approach. The results are consistent with the conclusions drawn from the aforementioned theoretical and simulation analyses.

With respect to safety, the principal methods available to the practitioner presently are accident analyses and traffic conflict technique (TCT). The former one assesses safety by the use of accident data as a direct measure of safety. It has been widely applied in past research, e.g., Porter and England (2000) and Retting et al (1999). However, Hauer et al (1986) and Plass and Berg (1987) pointed out its disadvantages associated with compensating for regression-to-the-mean phenomena, obtaining an adequate sample size, the potential bias caused by accident measurement, and the reliability of reported traffic crash. The latter approach assesses safety through conflict opportunity and severity represented by certain indices such as post encroachment time (PET) and time to collision (TTC), etc. It provides useful information for determining the predominant conflict types, identifying hazardous intersections, and assessing the effectiveness of safety countermeasures. Although some studies, such as Glennon et al, 1977 and Williams, 1981, pointed out less or poor correlations existed between conflicts and crashes, other research, e.g., Cooper and Feguson, 1976, however supported TCT and reported the ratio between a traffic conflict occurrence and a real accident occurrence as 2000:1. Hauer (1986) also argued that if the technique is only used for a “before-and-after” or “with-or-without” comparison in which the same accident-to-conflict ratio applies, it is a valid and useful tool to provide good insights on relative safety of a traffic facility.

Based on TCT, Tang and Nakamura (2008[2]) attempted to assess safety performance of GA with the change of phases through a before-and-after study at the first field test site in Japan. The results revealed that conflict opportunity as well as its severity may apparently drop for a short term after the implementation of GA, due to the reduction of red light running and its time-into-red. Another study (Tang and Nakamura, 2009) through computational simulations suggested that safety may be maintained if applying the GA at signalized intersections in Japan, together with other supplementary countermeasures.

In summary, despite tremendous research has been undertaken in the performance evaluation of signalized intersections, those studies comparing the performance of the conventional control approach with the adaptive GA through field tests are still of great shortage. This research was thus intended to fill in that gap, by the use of the data collected at the second test intersection in Japan.

2. Site description

The second selected intersection for field test is Midorigahama No.3 intersection, located in Tahara City of Aichi Prefecture. To facilitate the application of adaptive GA, extra signal heads were installed in order to indicate green arrow for different directions of traffic. Meanwhile, ultrasonic detectors were mounted upon the road at upstream to detect traffic volume and at stop-lines to detect the existence of vehicles. Figure 2 shows basic configuration of the study intersection as well as the positions of detectors and signal heads.

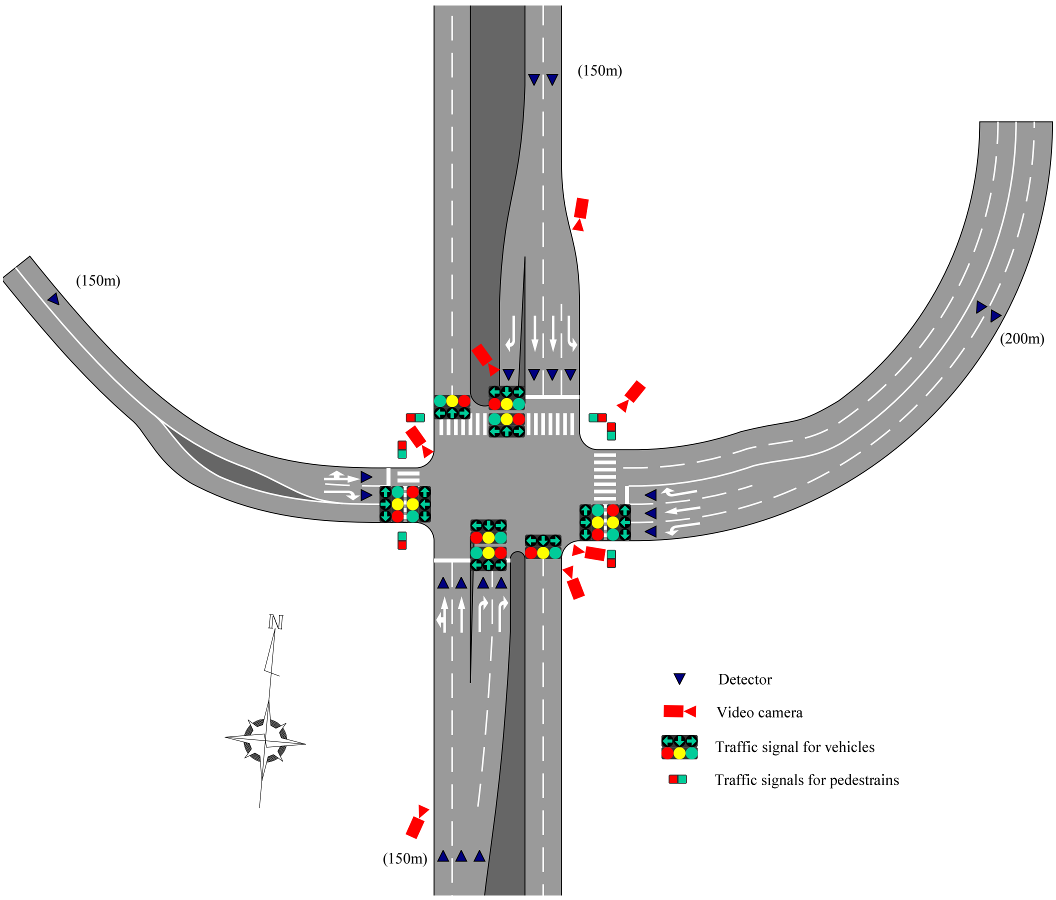


Figure 2 Configuration, signal settings and detector installment of the study intersection

Before the implementation of adaptive GA, the intersection was operated under a five-phase plan with an exclusive pedestrian phase (Φ5) shown in Figure 3. The phasing plan remained same for all the cycles, though phase green times may slightly vary cycle by cycle according to the predetermined time-dependent signal programs in the controller. Since November 2008, a more flexible group-based phasing plan shown in Figure 3 started to be adopted. The fundamental difference in the new signal control approach is that signal controller allocates green times to each signal group, i.e., a combination of two or more traffic movements defined in the phasing plan, according to the preset control algorithm. More specifically, the phases, Φ2a, Φ2b, Φ5a, and Φ5b, may appear if traffic demand is not balanced, and otherwise they might be skipped. Moreover, the durations of those phases as well as their previous and subsequent phases are adjusted based on the detected traffic status cycle by cycle.

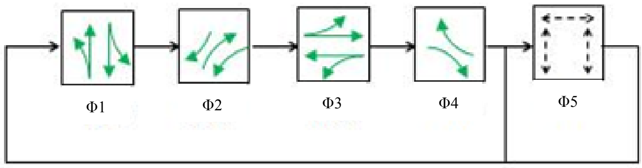
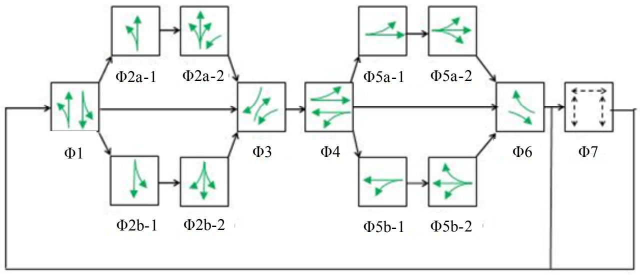
	Phasing plan
Before	 (Φ1~Φ4: vehicle phases; Φ5: exclusive pedestrian phase)
After	 (Φ1~Φ6: vehicle phases; Φ7: exclusive pedestrian phase)

Figure 3 Phasing plans applied at the study intersection before and after

3. Data collection and reduction

To collect traffic operation and driver behavior data at the test site, field surveys were conducted before and after the implementation respectively. The before survey was done in October 2008, and the after survey was undertaken one month after the implementation in order for the familiarity of drivers to the new control approach. To allow for a meaningful comparison study, a same weekday and identical time periods (15:30~17:00) were chosen in the before and after surveys.

Also, the field test was not announced to intersection users to avoid psychological influence on them. Seven video cameras shown in Figure 2 were simultaneously used to record traffic operation and driver behaviour of the whole intersection. Video data recorded by different cameras were firstly synchronized. Necessary information containing signal timings, traffic volumes and each vehicle's passing time at the stop-lines, was then extracted by using a lab-developed image-processing software with a resolution of 1/30 second.

To provide a general picture on traffic conditions during the before and after surveys, average flow rates and green times of each movement group are presented in Figure 4. Left-turn and through traffics at SB approach (SB_LT) and left-turn traffic at WB approach (WB_L) can be easily identified as are the most critical movements by their flow rates. It was also found that after the implementation of adaptive GA, the altering trend of green times for most of the movements is consistent with that of flow rates, and the average cycle length was reduced from 162s to 146s.

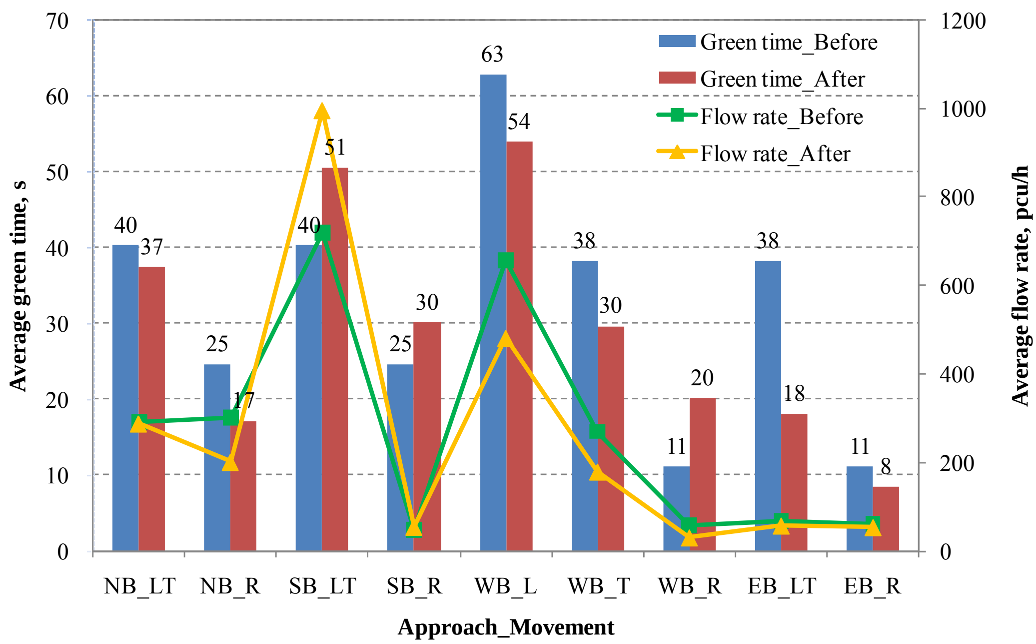


Figure 4 Observed average flow rates and green times of each movement group at the study intersection before and after

4. Performance Evaluation

4.1 Operational performance

4.1.1 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. *SULT* is the sum of the starting response time of the first vehicle in queue and the additional time it took the first four vehicles to discharge. *CLT* refers to the time between signal phases during which an intersection is not used by any traffic. It comprises of the lost time in amber change and all-red clearance intervals. *SFR* is defined as the maximum rate of flow that can pass through a given lane under prevailing traffic and roadway conditions, assuming that the lane has 100 percent of green time interval.

Through traffic at SB approach (SB_T) and left-turn traffic of WB approach (WB_L) were selected as the subject traffic movements to measure the above parameters. The reason is that they are both critical movements, and also have relatively high degree of saturation beneficial for obtaining enough samples. *SULT*, *SFR*, and *CLT* were estimated by following the Highway Capacity Manual 2000 (*Transportation Research Board*, 2001) in the United States.

Figure 5 presents the observed *SULT* of the subject traffic movements. It is apparent that the mean *SULT* of SB_T increased from 1.57s to 2.49s and that of WB_L increased from 1.83s to 2.15s after the use of adaptive GA. Statistical analysis results showed that both of the rises are significant at the confidence level of 95%. A possible explanation would be that the onset of green under the new adaptive GA is more difficult to predict due to its comparably flexible phasing plan. For instance, optional selection of the exclusive pedestrian phase (Φ7) may influence on the starting behavior of through-ahead drivers at SB approach (SB_T), and the overlap phase Φ2a or Φ2b for WB_L as well. Consequently, the first several drivers in the queue did experience longer reaction-and-perception time before moving. It is consistent with the conclusion drawn from a previous study by the authors (Tang and Nakamura, 2008[1]).

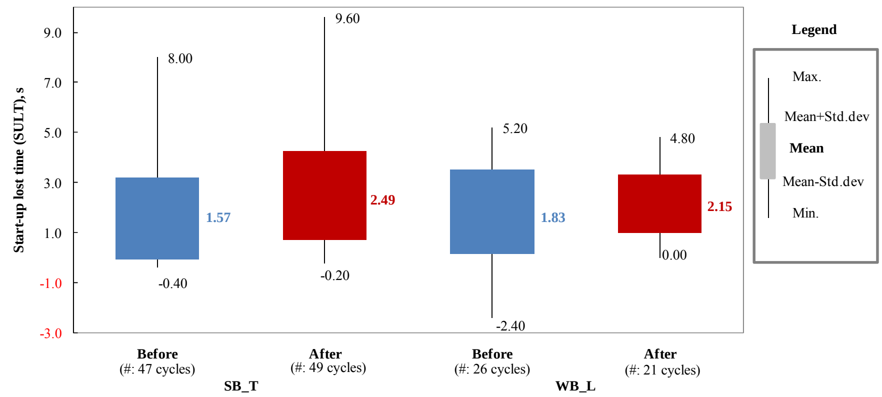


Figure 5 Observed start-up lost time (*SULT*) of the subject traffic movements at the study intersection before and after

Figure 6 shows the observed *SFR* of the subject traffic movements. It was found that *SFR* didn't significantly change at the confidence level of 95% after the implementation of adaptive GA. The results imply that drivers in the rear part of the queue (excluding the first several drivers) may no longer be affected by the new control approach, once they became aware of their right of way. It also matches with the earlier study done by the authors.

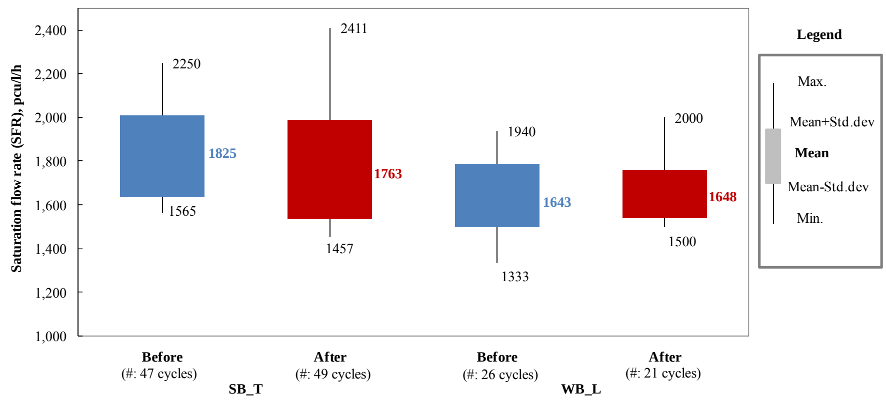


Figure 6 Observed saturation flow rate (*SFR*) of the subject traffic movements at the study intersection before and after

Figure 7 exhibits the observed *CLT* of the subject traffic movements. A slight increasing trend after the use of adaptive GA can be seen from the figure, the mean value rising from 5.38s to 5.72s at SB_T and from 4.95s to 5.85s at WB_L. A larger *CLT* translates a smaller entry-time of the last cleared vehicle after the start of intergreen time. Such tendency may be attributed to conservative behavior of drivers when making decision of pass/stop after the onset of yellow. In other words, they behaved more cautiously in entering the intersection at a late stage of the intergreen interval, as they don't know what conflicting traffic movements will be released in the next phase.

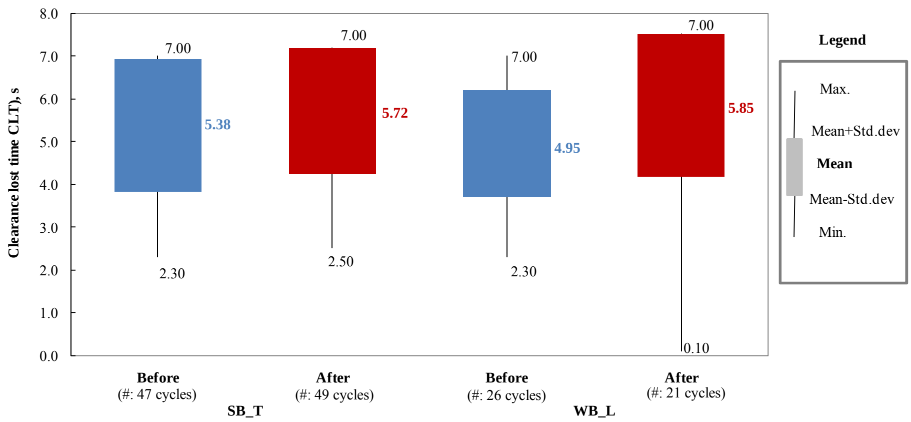


Figure 7 Observed clearance lost time (*CLT*) of the subject traffic movements at the study intersection before and after

4.1.2 Capacity

To estimate capacity, the measured values of *SULT*, *CLT*, and *SFR* at SB_T and WB_L presented in the previous part were used for those of the other traffic movements. More specially, SB_T is representative for all the shared through and left-turn lanes and the exclusive through lanes, while WB_L is referred for the rest of the lanes. When estimating *SFR*, lane width and heavy vehicle ratio were also accounted for, by adding an adjustment factor derived from the differences between the observed and estimated lanes. Capacity of each traffic movement was subsequently estimated cycle by cycle according to the estimated saturation flow rates and loss times as well as the observed cycle lengths and displayed green times. Mean of the estimated capacities of the entire cycles within the observation period was regarded as the capacity of the correspondent traffic movement. Figure 8 summarizes the estimated capacities of all the traffic movements. Eventually, the capacity of the whole intersection was calculated by summing all of them.

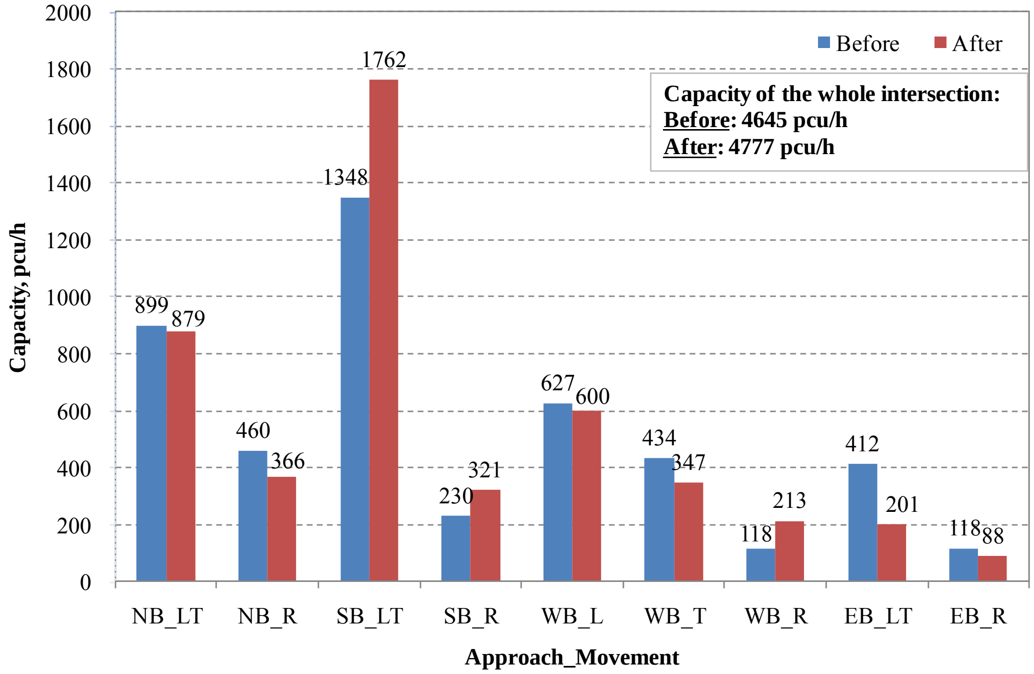


Figure 8 Estimated capacities of all the traffic movements at the study intersection before and after

It was found that the capacities for traffic movements at SB approach (SB_LT and SB_R) and right-turn traffic of WB approach (WB_R) go up drastically after the use of adaptive GA. On the other hand, the capacities for right-turn traffic at NB approach (NB_R) and left-turn and through traffics at EB approach (EB_LT) drop down greatly. For the rest, the differences between before and after are not very significant. The overall tendency indicates that the adaptive GA may have the capability of increasing the capacity for critical movements, e.g., SB_LT, by assigning more green times to them and reducing those for the non-critical movements, e.g., EB_LT. Regarding the capacity of the whole intersection, it slightly increased from 4, 645 pcu/h to 4, 777pcu/h. The results supported that the adaptive GA is capable of maintaining capacity by the means of more efficient green time assignment despite it results in relatively large loss times as presented earlier. It reveals that one of the major concerns with regard to GA, i.e., frequently switching phases might cause a reduction of capacity, is not always necessary.

4.1.3 Control delay

Control delay was estimated according to the HCM 2000 delay model, while treating the duration of observation as the analysis period, i.e., 1.5h. The study intersection is located in suburban area and not coordinated with the upstream and downstream intersections. Hence, random arrival pattern and isolated intersection were assumed when estimating delay, i.e., supplemental adjustment factor for platoon arriving during green f_{PA}=1.0 and upstream filtering/metering adjustment factor I=1.0. Average cycle length and green times of the entire cycles were used in the delay estimation. The initial queue delay was not considered in the estimation because no residual queues existed before the start of the observation both in the before and after surveys.

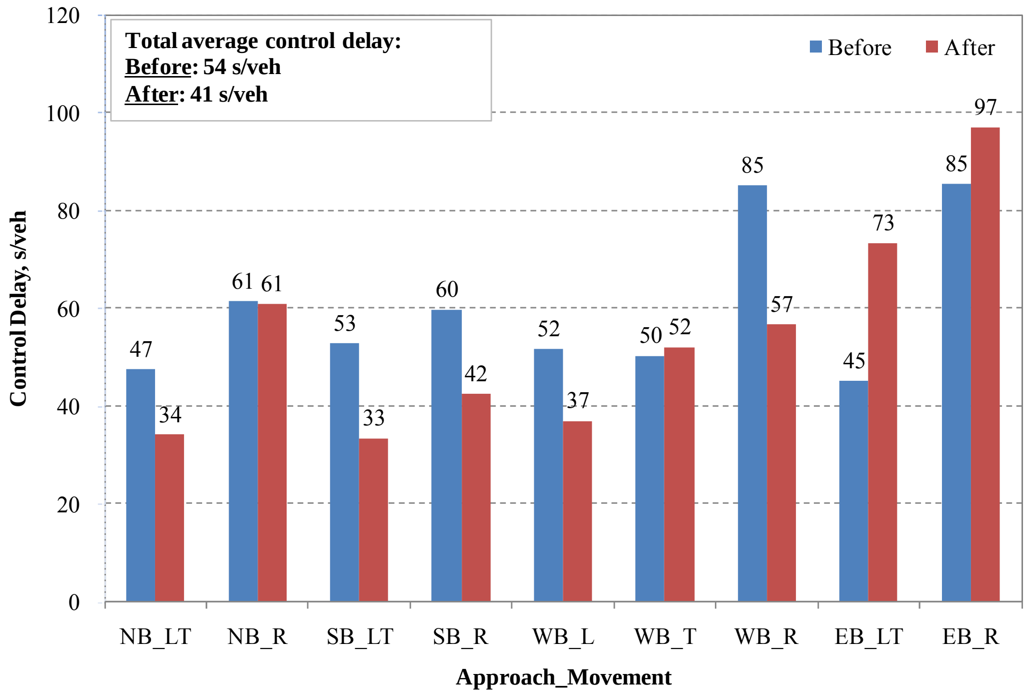


Figure 9 Estimated delays of all the traffic movements at the study intersection before and after

Figure 9 presents the estimated delays for all the traffic movements before and after respectively. It can be seen that, after the use of adaptive GA, delays of those critical movements including SB_LT, WB_L and NB_LT decreased, while those of the non-critical movements such as EB_LT and EB_R increased. As a result, the total average control delay of the whole intersection was significantly improved from 54 s/veh to 41 s/veh, a 24% of reduction. This finding consists with the measurement results at the first test site presented in Tang and Nakamura (2008[1]).

4.2 Safety performance

As previously discussed, it is highly concerned in Japan that the frequent and flexible phase switching of GA may induce safety problem. It is due to that different conflicting traffic movements are more often exposure to each other. Thus, this study particularly focuses on intersection safety during the change of signal phases rather than green intervals.

4.2.1 Traffic conflicts with the change of phases

At a phase change within the signal cycle, traffic movements released in the previous phase (i.e., clearing movements) are first given yellow and/or all-red times (i.e., intergreen interval) to make a stop before the stop-line or proceed to clear from the intersection; traffic movements released in the subsequent phase (i.e., entering movements) are then given green signals to start to move, immediately following the previous intergreen interval. As a result, a variety of conflicts may happen since different directions of traffic exist.

Figure 10 and 11 depict the possible traffic conflicts with the change of phases as well as their occurring locations inside the field test intersection, associated with the phasing plans before and after the implementation of adaptive GA. For each phase change and conflicting point, the entering and clearing distances of the conflicting traffic movements, S_e and S_c, are also provided in the figure. In the case of stable phasing plan shown in Figure 10, traffic conflicts appear regularly for each phase change and thus drivers always know their potential conflicting locations with one and another. However, traffic conflicts dynamically vary dependent upon the phase sequences in the case of flexible phasing plan shown in Figure 11. Conflict opportunity is supposed to arise when cycle length becomes shorter, which often happens when the control approach at an intersection is switched from SA to GA as explained at the beginning of the paper. Note that only crossing conflicts are included in the analysis of this study, owing to its vital significance for safety in terms of conflict severity. Moreover, traffic conflicts between vehicles and pedestrians are not taken into consideration, with the consideration of extremely low pedestrian volume at the test site.

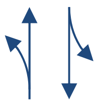
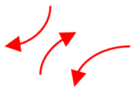
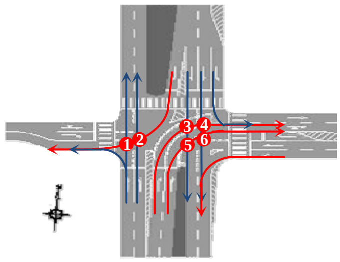
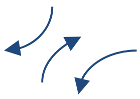
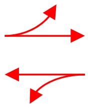
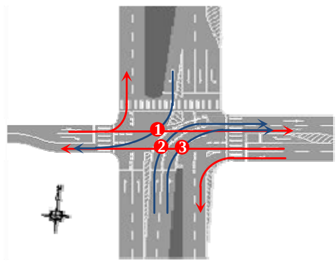
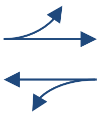
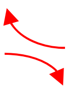
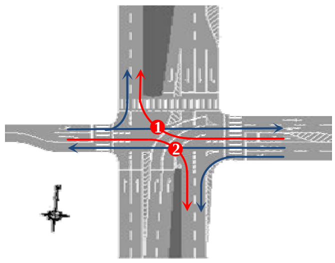
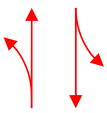
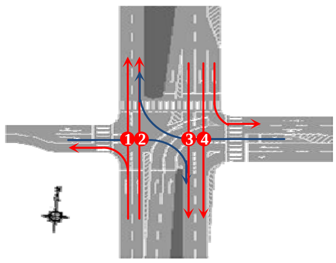
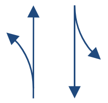
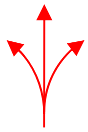
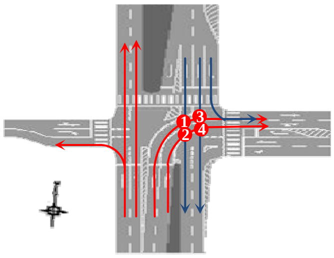
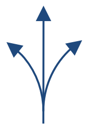
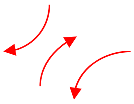
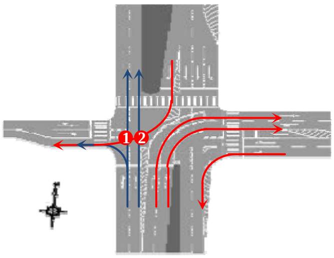
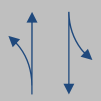
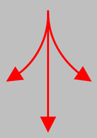
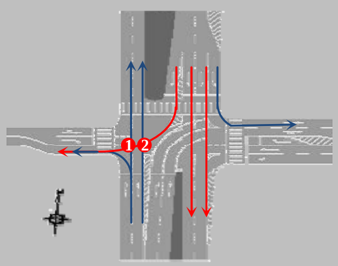
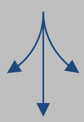
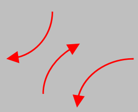
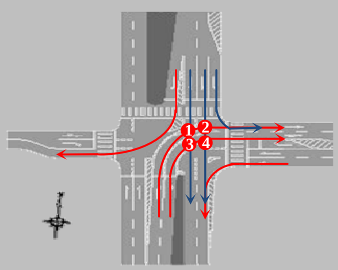
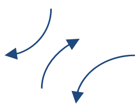
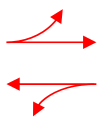
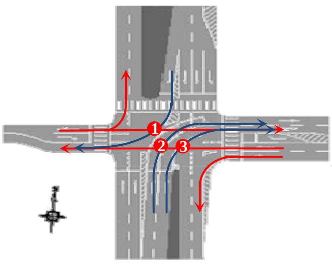
Change of phases		Traffic conflicts	Entering and clearing distances (S_e, S_c), m
Clearing	Entering		
 (Φ1)	 (Φ2)		S_{e1}=54.5, S_{c1}=24.0 S_{e2}=49.6, S_{c2}=25.9 S_{e3}=36.8, S_{c3}=27.8 S_{e4}=41.4, S_{c4}=26.9 S_{e5}=33.0, S_{c5}=35.2 S_{e6}=29.7, S_{c6}=33.3
 (Φ2)	 (Φ3)		S_{e1}=41,7, S_{c1}=29.9 S_{e2}=40.7, S_{c2}=29.7 S_{e3}=29.6, S_{c3}=29.7
 (Φ3)	 (Φ4)		S_{e1}=25.9, S_{c1}=50.0 S_{e2}=42.5, S_{c2}=35.1
 (Φ4)	 (Φ1)		S_{e1}=25.9, S_{c1}=20.4 S_{e2}=25.9, S_{c2}=25.9 S_{e3}=27.8, S_{c3}=29.6 S_{e4}=27.8, S_{c4}=25.9

Figure 10 Traffic conflicts with the change of phases before the implementation of adaptive GA at the study intersection

Change of phases		Traffic conflicts	Entering and clearing distances (S_e, S_c), m
Clearing	Entering		
 (Φ1)	 (Φ2a)		S_{e1}=36.8, S_{c1}=27.8 S_{e2}=33.0, S_{c2}=35.2 S_{e3}=41.4, S_{c3}=26.9 S_{e4}=29.7, S_{c4}=33.3
 (Φ2a)	 (Φ3)		S_{e1}=54.5, S_{c1}=24.0 S_{e2}=49.6, S_{c2}=25.9
 (Φ1)	 (Φ2b)		S_{e1}=54.5, S_{c1}=24.0 S_{e2}=49.6, S_{c2}=25.9
 (Φ2b)	 (Φ3)		S_{e1}=36.8, S_{c1}=27.8 S_{e2}=41.4, S_{c2}=26.9 S_{e3}=33.0, S_{c3}=35.2 S_{e4}=29.7, S_{c4}=33.3
 (Φ3)	 (Φ4)		S_{e1}=41,7, S_{c1}=29.9 S_{e2}=40.7, S_{c2}=29.7 S_{e3}=29.6, S_{c3}=29.7

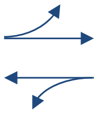
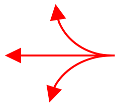
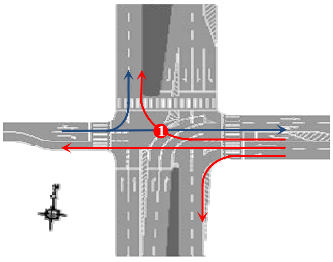
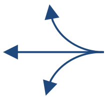
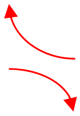
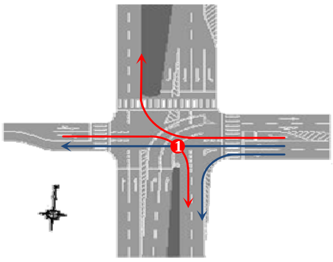
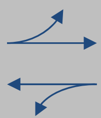
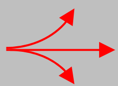
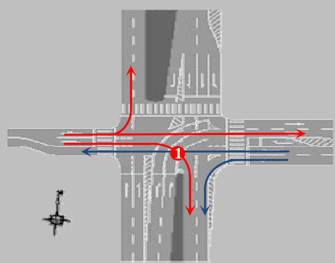
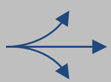
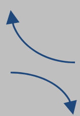
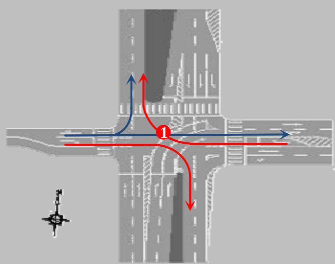
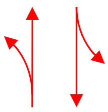
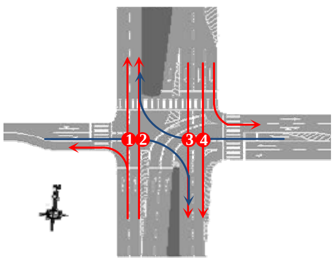
Change of phases		Traffic conflicts	Entering and clearing distances (S_e, S_c), m
Clearing	Entering		
 (Φ4)	 (Φ5a)		S_{e1}=25.9, S_{c1}=50.0
 (Φ5a)	 (Φ6)		S_{e1}=42.5, S_{c1}=35.1
 (Φ4)	 (Φ5b)		S_{e1}=42.5, S_{c1}=35.1
 (Φ5b)	 (Φ6)		S_{e1}=25.9, S_{c1}=50.0
 (Φ6)	 (Φ1)		S_{e1}=25.9, S_{c1}=20.4 S_{e2}=25.9, S_{c2}=25.9 S_{e3}=27.8, S_{c3}=29.6 S_{e4}=27.8, S_{c4}=25.9

Figure 11 Traffic conflicts with the change of phases after the implementation of adaptive GA at the study intersection

4.2.2 Methodology

Based on literature review, Traffic Conflict Technique (TCT) was chosen for safety evaluation in this study. Based on the concept of TCT, risk is assessed by conflict occurring opportunity and severity, illustrated in Eq. (4).

$$R = P \times I \tag{4}$$

Where, R=risk; P=conflict occurring frequency or probability; I=conflict severity.

In this study, a conflict is defined as a consecutive pass at the conflict area of the last vehicle entering the intersection after the onset of yellow in the previous phase and the first vehicle in the queue of the conflicting movement released in the subsequent phase. It translates that no traffic conflicts will occur if no vehicle crosses the stop-line during the intergreen interval and/or no conflicting vehicle exists at the beginning of the next phase. Therefore, number of conflicts per hour can act as the measure to conflict occurring frequency, and it is calculated by Eq. (5), for each pair of the conflicting movements.

$$P = \frac{N_c}{T} \tag{5}$$

Where, N_c=number of the observed cycles with a conflict; T=the total observation period, h.

To quantify the severity of the conflicts during the change of phases, a time-based index of post-encroachment time (*PET*) was originally proposed by Tang and Nakamura in 2009. Its basic concept is described in Figure 12, where the last clearing vehicle of through traffic at WB approach and the first entering vehicle of through traffic at SB approach are used for illustration purpose. The observed *PET* and the planned *PET* are then derived via a time-space diagram. The fundamental difference between them is that the former is the *PET* which can be directly observed in the real world and the later is the potential *PET* which is estimated by assuming the entering vehicle not affected by the clearing vehicle. In this study, the planned *PET*, $PET_{planned}$, is applied to measure conflict severity, and it is calculated by Eq. (6), assuming a static acceleration rate for the entering vehicle and a stable speed for the last clearing vehicle.

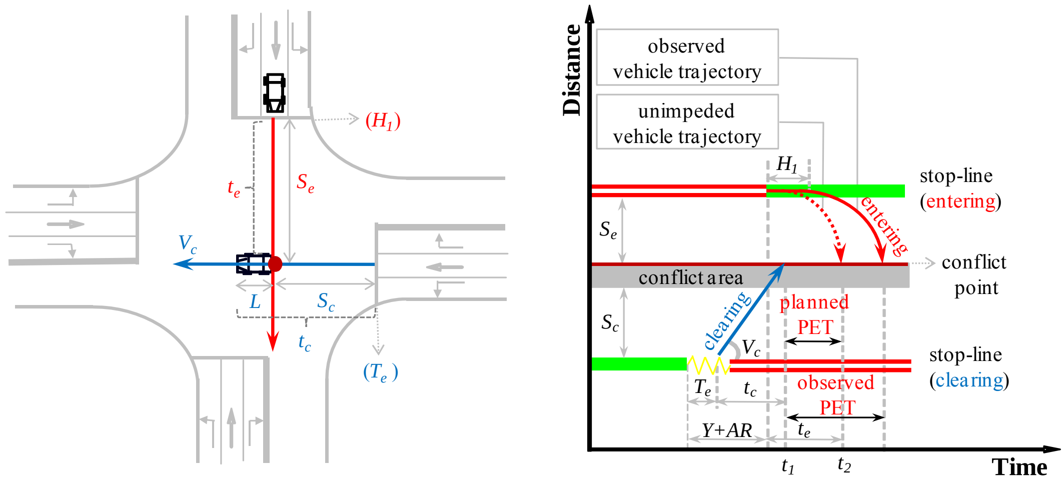


Figure 12 Planned post-encroachment time (*PET*) of the last clearing and the first entering vehicles at the change of phases

$$PET_{planned} = (Y + AR + t_e) - t_c - T_e \tag{6}$$

$$t_e = H_1 + \frac{-V_0 + \sqrt{V_0^2 + 2aS_e}}{a} \tag{7}$$

$$t_c = \frac{S_c + L}{V_c} \tag{8}$$

Here, Y=yellow time, s; AR=all-red time, s; t_e=entering time, s; t_c=clearing time, s; T_e=entry time of the last cleared vehicle, regarding the onset of yellow as the beginning, s; H_1=stop-line crossing time of the first vehicle in the subsequent phase (containing driver's perception and reaction time), regarding the onset of green as the beginning, s.; V_o=initial speed when the first entering vehicle passes the stop-line, m/s; a=acceleration rate of the first entering vehicle, m/s^2; S_e=entering distance, m; S_c=clearing distance, m; L=vehicle length, m.

For each pair of the conflicting traffic movements, only the most critical (i.e., smallest) *PET*s should be taken if multiple lanes are present. In addition, instead of *PET* itself, *1/PET* was used in the safety evaluation in order to allow for a straightforward aggregation because *1/PET* is positively related to conflict severity. The total risk within a certain observation period, *R*, can thus be estimated by Eq. (9).

$$R = P \times I = \frac{N_c}{T} \times (\frac{1}{N_c} \sum_{i=1}^{N_c} \frac{1}{PET_{planned}^i}) = \frac{1}{T} \sum_{i=1}^{N_c} \frac{1}{PET_{planned}^i} \quad (9)$$

Where, *i*=denotation of a phase change with a conflict.

4.2.3 Results analysis

To facilitate the application of the proposed method, the involved parameters in Eq. (6)~(8) need to be known. S_e and S_c of each conflicting traffic movement pair were measured at the test intersection and provided in Figure 10 and Figure 11. H_1 and T_e for all the traffic movements except those at EB approach were recorded from the video data. Due to the limitation of camera coverage, it was unable to specifically determine H_1 and T_e for EB approach. However, such a shortage of data at EB approach may not affect the final results significantly because of its extremely low traffic demand. For the remaining parameters, measurement results reported in Tang and Nakamura (2009) are referred, i.e., V_0=2.0m/s, a=2.27m/s^2, and V_c=50km/h for through traffics and 23.7km/h for turning traffics. Eventually, conflict occurring frequency, P, and conflicting severity, I, of each conflicting movement pair were estimated and presented in Figure 13.

It was found that the average *1/PET* for SB_R&EB_T and WB_R&SB_T dropped to a great extent, while the others didn't vary so much. Moreover, the highest conflict occurring frequencies were found at SB_T&NB_R and WB_T&EB_R and they decreased a little after the use of adaptive GA. Consequently, the total estimated risk per hour descended from 4.55 to 4.01, i.e., a 12% improvement in safety. As discussed earlier, two factors may have contributed to this result. Firstly, after the implementation of adaptive GA, drivers behaved more conservatively when entering the intersection after the onset of yellow, leading to less stop-ling crossings during intergreen intervals and smaller T_e; Secondly, drivers became more cautious when they start to move at the onset of green, leading to larger H_1. This finding is supported by an earlier study of the authors (Tang and Nakamura, 2008[2]), in which the observed *PET* was found to be evidently larger after the use of GA.

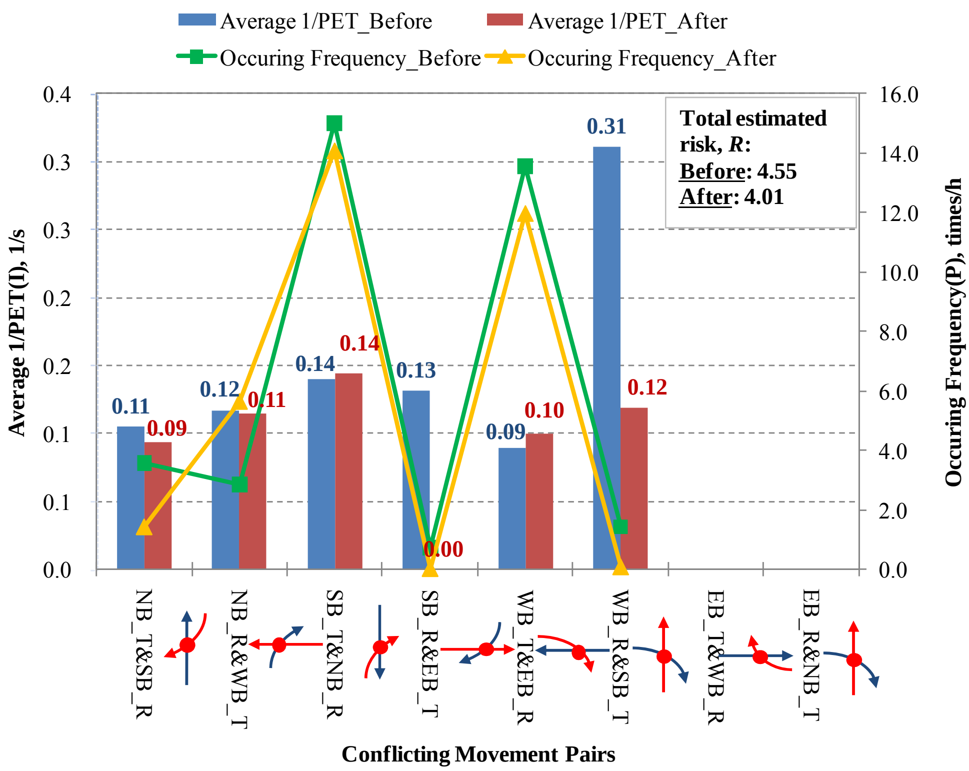


Figure 13 Estimated conflict frequency (*P*) and severity (*I*) during the change of phases at the study intersection before and after

5. Conclusions

This study evaluated the operational and safety performance of adaptive GA through a recent field test in Japan. Operational traffic flow characteristics, start-up loss time (*SULT*), clearance loss time (*CLT*), and saturation flow rate (*SFR*), were firstly examined. It was found that both *SULT* and *CLT* increased approximately by 0.6s, and *SFR* however remained stable after the implementation of adaptive GA. Capacity and delay were then estimated based on those measured parameters as well as the observed green times and cycle lengths. It was found that the capacity of the whole intersection slightly rise by 3% and the total average delay considerably dropped by 24%. Meanwhile, a new methodology based on Traffic Conflict Technique was developed to evaluate safety performance of adaptive GA during the change of phases, i.e., intergreen intervals. Conclusions supported that safety was considerably improved by 12%.

The above findings are basically consistent with those gained from the previous studies of the authors. It reinforces again that safety drop and capacity loss may not always be associated with the flexible and frequent phase switching pattern of GA. GA could be an alternative in signal control to help in solving the current mobility problems on urban roads in Japan.

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