IMPACTS OF GROUP-BASED SIGNAL CONTROL POLICY ON DRIVER BEHAVIOR AND INTERSECTION SAFETY

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Unlike the typical stage-based policy commonly applied in Japan, the group-based control (often called movement-based in the traffic control industry in Japan) refers to such a control pattern that the controller is capable of separately allocating time to each signal group instead of stage based on traffic demand. In order to investigate its applicability at signalized intersections in Japan, an intersection located in Yokkaichi City of Mie Prefecture was selected as an experimental application site by the Japan Universal Traffic Management Society (UTMS). Based on the data collected at the intersection before and after implementing the group-based control policy respectively, this study evaluated the impacts of such a policy on driver behavior and intersection safety. To specify those impacts, a few models utilizing cycle-based data were first developed to interpret the occurrence probability and rate of red-light-running (RLR). Furthermore, analyses were performed on the yellow-entry time (Y_e) of the last cleared vehicle and post encroachment time (PET) during the phase switching. Conclusions supported that the group-based control policy, along with certain other factors, directly or indirectly influenced the RLR behavior of through and right-turn traffics. Meanwhile, it has potential safety benefits as well, indicated by the declined Y_e and increased PET values.

Key Words: Group-based signal control, Driver behavior, Intersection safety, Before-and-after study

1. INTRODUCTION

Signalized intersections are a key component of the road network. Its operations considerably affect the performance of the whole road system. To achieve both mobility and safety, a variety of control approaches have been applied at signalized intersections all over the world. Conventional methods include the stage-based and group-based (often called movement-based in the traffic control industry in Japan) approaches. The stage-based approach, 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. In the group-based approach, in contrast, directly assigns green times to traffic movements without the need to maintain a specific stage structure[1]. Thereby, the group-based control policy is more flexible and easier to generate complicated phasing plans. As significant operational and/or safety benefits can sometimes be achieved by the use of complex phasing[2], it is thus widely agreed that the group-based control policy is generally more efficient than the stage-based method in terms of operational performance[1, 3-6].

In Japan, the stage-based approach has predominantly been applied so far. The so-called group-based approach has been successfully operating in several European countries such as Germany, particularly at key intersections. However, it is often argued in Japan that complex phasing may bring negative effects on intersection safety since it increases phase switching frequency and might cause users misbehavior as well, perhaps leading to traffic accidents. With those considerations, the stage-based control approach is preferred in Japan, which usually has stable phasing but results in long cycle lengths (120-180 s). In view of that, the Japan Universal Traffic Management Society (UTMS) launched a research project aiming to investigate the applicability of the group-based control for signalized intersections in Japan. An intersection located in Yokkaichi City of Mie Prefecture was selected as the experimental site. The authors were involved with a part of the project, which is to evaluate the actual performance of the group-based control policy. Hence, a before-and-after survey was conducted to collect user behavior and traffic operation data at the intersection. Utilizing the data, the authors assessed the impacts of such a policy on driver behavior as well as operational and safety performance at the intersection.

The results regarding operational performance have been addressed in another study by the authors[7]. It was found that key operational traffic characteristics such as start-up lost time and saturation flow rate did not vary significantly before and after the implementation of the group-based control policy. Meanwhile, delay was considerably improved when unbalanced traffic demands appeared, particularly for those critical movements during peak periods. It suggests that the group-based policy generally possesses a better operational performance compared with the stage-based policy as stated earlier. Succeeding the study, this paper presents the part of works on driver behavior and intersection safety, which is much more concerned in Japan and helpful for more comprehensively understanding the performance of such a control policy.

2. LITERATURE REVIEW

A lot of research on driver behavior and safety at signalized intersections has been done in past decades, covering different types of control approaches. Most of them focused on red-light-running (RLR) behavior, which has been increasingly recognized as a principle cause for severe crashes and injuries at signalized intersections. The factors influencing RLR behavior were deeply investigated. The earlier study done by Retting and Williams[8] suggested that unbuckled drivers were more likely to run red lights. Retting, et al.[9] further analyzed the prevalence and characteristics of RLR crashes in the United States on a national basis. It concluded that red light runners involved with crashes were more likely to be young, male, and have prior moving violations, and so on. Porter and England[10] found that larger intersections and higher traffic volumes were associated with higher RLR rates. Time of day and two driver factors, safety belt use and ethnicity, were important to predict RLR. Bonneson and Son[11] stated that RLR increased with flow rate, speed, and dense platoons arriving at the end of the phase. Also, RLR decreased with increasing cycle length, cross street width, and when back plates are used on the signal heads. Grembek, et al.[12] predicted RLR by using cycle-based data. Results showed that the yellow arrival flow at the advance loops had the highest impact on RLR probability, in addition to the average traffic flow. Elmitiny, et al.[13] suggested that vehicle's yellow-onset distance, operating speed, and position in the traffic flow were the most important predictors for RLR.

Meanwhile, the effects of yellow and all-red time on RLR behavior have gained extensive research attention. Retting, et al.[14] studied the effects of signal timing design on red light compliance as a result of an increase in change intervals to values recommended by the Institute of Transportation Engineers (ITE). The study showed that increasing the length of the yellow signal toward the ITE recommendations significantly decreased the chance of RLR, and the length of the all-red interval did not seem to affect RLR. Schattler, et al.[15] examined driver behavior at the test sites where the change and clearance intervals have been re-calculated according to ITE guidelines, and at the control sites. The RLR at the test and control sites did not exhibit a significant difference. Datta, et al.[16] compared the red light violation characteristics of intersections with the all-red interval and those without all-red intervals. They supported that significantly lower red light violations and an extraordinary reduction in right-angle and injury at the intersections with all-red intervals. However, a study by Souleyrette, et al.[17] indicated that all-red clearance interval is not effective in reducing intersection crashes at low speed intersections in the long term. Bonneson and Son[11] found that the frequency of RLR is higher when the yellow interval duration is shorter than the value computed with the equation offered by Kell and Fullerton[18].

In addition, yellow- and red-entry time provides important clues about the nature of RLR and RLR-related crashes. A yellow- or red-entry time for a clearing vehicle is defined as the time duration from the onset of yellow or all-red till when the vehicle crossed the stop-line. Elmitiny, et al.[13] stated that yellow-entry time is positively related to the yellow-onset distance, and negatively related to the operating speed in their study. Moreover, the average yellow-entry time for the leading vehicles in traffic flow is significantly shorter than that for the following vehicles. Another study by Bonneson, et al.[19] showed that the median red-entry time was less than 0.5 s, and approximately 80 percent of drivers entered the intersection within 1.0 s after the start of red. Zimmerman and Bonneson[20] continued to look into the relationship of red-entry time and RLR-related crash type.

In spite of the tremendous research that has been undertaken in the field of driver behavior and safety at signalized intersections, such studies concerning the group-based control approach remain few. The advantage of the group-based control approach in optimizing signal programs and obtaining operational benefits both at isolated intersections and in area wide control have been well proved in theory, simulations and empirical analyses[4,5,7,21,22]. On the other hand, little research has shown that safety performance can be anticipated by applying such a policy, due to the difficulties of completely understanding driver behavior and its impact on safety at signalized intersections. One of the critical reasons is that distinguished driver attributes and human factors result in various reactions to signal control, which prevents from definitive conclusions. Another major reason may lie in that signal timings significantly influence driver behavior no matter what type of signal control approach is applied. As a result of that, the impacts of signal control policy are hard to be explicitly specified. An effort made by the authors[6] has clearly indicated that the intersections under the group-based control in Germany had significantly lower RLR rates as compared to the intersections under the stage-based control in Japan, provided close traffic conditions. Even so, the research in this aspect is still insufficient.

Therefore, with the rare opportunity offered by the Japan UTMS project, this study intends to continuously enhance the understanding on driver behavior and safety performance at the signalized intersections under the group-based control approach in the context of traffic situations in Japan. Based on the review work and the purpose of this study, RLR occurrence probability and rate are first analyzed. Throughout the analysis, those influencing factors introduced above are taken into consideration while investigating the specific impacts of the group-based control approach. Following that, the analyses on yellow-entry time of the last cleared vehicle and post encroachment time (PET) when phase switching are performed to evaluate intersection safety. Finally, the authors give some concluding remarks regarding the application of such an approach in Japan.

3. SITE DESCRIPTION

The selected intersection, connecting national route 23 and a prefectural road, is large-scaled and located in Yokkaichi City of Mie Prefecture. It has a complex geometry, high traffic and very low pedestrian demand, a large proportion of heavy vehicles, and apparent demand fluctuations during different times of the day. More specifically, drastically unbalanced traffic demands prevail on the east-bound (EB) and west-bound (WB) approaches. Through and left-turn traffic demand at EB (EB-TL) is approximately four times as large as that at WB (WB-TL) during the AM peak. In contrast, the opposite situation often takes place during the PM peak. This fact, combined with the inflexible signal control, caused long queues at EB and WB respectively during AM and PM peak before, almost 750m at EB-TL and 500 m at WB-TL. With those conditions, the intersection was considered as a suitable site for the experimental application of the more advanced group-based control approach. During the before-and-after survey, neither intersection geometry nor signal head positions changed; however, three advance and two departure ultrasonic detectors were installed later for the need to operate the group-based control, as shown in Figure 1. Meanwhile, those fundamental control parameters preset in the signal controller such as minimum and maximum green times remained identical as before, and intergreen times as well. Figures 1 and 2 show its geometric features and phasing plans applied before and after.

As shown in Figure 2 (a), a stage-based five-phase signal plan (refers to Plan 0) with extremely long cycle lengths (approximately 180 s), ran before. WB-TL and WB-TL as well as EB-R and WB-R were released in the same phases (Phase 1 and 2). As for the other approaches, green times were allocated to the whole approaches (Phase 3, 4 and 5). Even though the number of phases was fixed, the green times for Phase 1 through 4 were able to be adjusted slightly according to the detected traffic demands. In addition, Phase 5, giving the right of way to the minor approach of EB, was assigned 8 seconds in all cycles before.

As shown in Figure 2 (b), group-based phasing plans (optional use of Plan 0, 1 and 2) operate after. Compared with the phasing plan applied before (Plan 0 only), the most significant change was that green times for the movements at EB major approach and WB are separately allocated dependent upon their traffic demands. Thereby, a leading green for EB-R or WB-R between Phase 1 and 2 is created for the extension of the green time for EB-TL

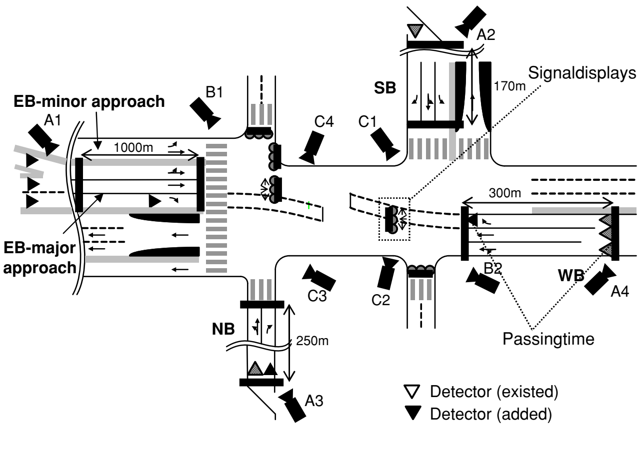
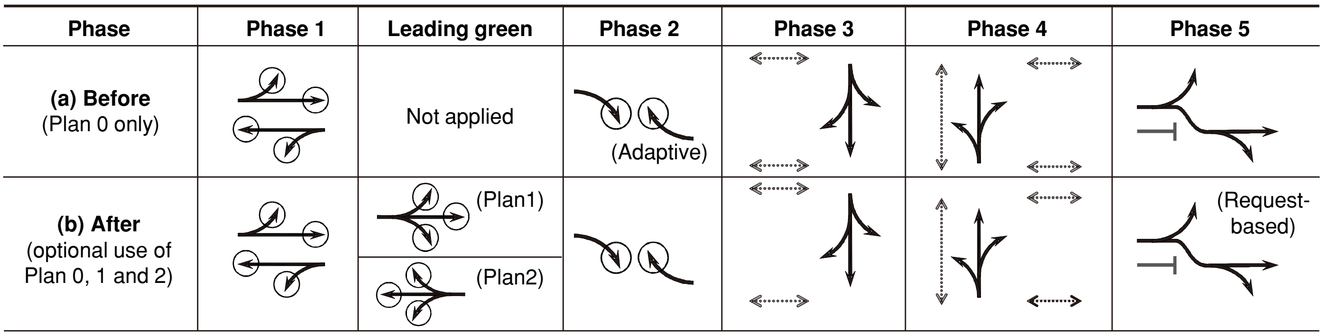


Fig. 1 Intersection geometry, camera settings and detector installations at the intersection



(Note that: : Protected traffic releases; : Pedestrian movements; Yellow is 3 sec for all movements at EB and WB; All-red is 3 sec for EB-TL and WB-TL, 5 sec for EB-R and WB-R)

Fig. 2 Phasing plans applied at the intersection during the before-and-after survey

or WB-TL. Technically, the leading green for EB-R and WB-R (or say lagging green for EB-TL and WB-TL) should be a phase. However, it represents a leading green throughout this study for easy identification of the phase number when comparing the signal programs before and after. In the case that the green time for EB-TL is extended, the applied phasing plan refers to Plan 1, and vice versa, Plan 2 refers to the case that green time for WB-TL is prolonged. If no significant discrepancy between the demands of EB-TL and WB-TL came up, Plan 0 is adopted. The second change is that adaptive control is applied for EB-R and WB-R by using the added detectors mentioned earlier. The third change is that Phase 5 is skipped if no request at the minor approach of EB was detected. Regarding other phases, nothing has been changed but the assigned green times.

4. DATA COLLECTION

Before-and-after field surveys were conducted to collect traffic operation and driver behavior data. The before survey was done in February, 2007. To ensure the familiarity of drivers to the new control approach, the after survey was undertaken in June, 2007, one month after the implementation. The experiment was not announced when obtaining the “before” and “after” data to avoid psychological influence on drivers.

Traffic demand data was obtained from the detectors installed upstream. The other essential data was collected by using video cameras. Entire data collections except that on June 18, 2007 (rain) were done under good weather conditions. In total, 11 cameras were used to observe all the approaches and the inside area of the intersection shown in Figure 1. Among them, A1, A2, A3 and A4 were used for recording the arrival time in upstream (for delay measurements). B1 and B2 were placed 3 m high to capture traffic operations inside the intersection. C1, C2, C3 and C4 were useful for observing discharge flows. To obtain signal programs, all the signal heads were also covered by different cameras. With the considerations of traffic conditions at the intersection and the research objective, the analysis periods were selected as presented in Table 1.

The videos taken by different cameras were first synchronized. Necessary data containing signal timings, discharge headways, arrival time, and passing time at the stop-lines, was then extracted by using image-processing software developed by our laboratory with a resolution of 1/30 second. Traffic demands and average green times during the analysis periods are presented in Figure 3. As exhibited, traffic demands did not vary substantially as the before-and-after survey was undertaken within the same time period of the day and day of the week, which allows a reliable before-and-after study. However, average green times for EB major approach and WB were adjusted remarkably owing to the new control approach, particularly during the AM and PM peaks. Regarding the phasing plans after, Plan 0, 1 and 2 were selected to apply according to traffic status. During AM peak, around a half of the cycles operated under Plan 1 and the other half under Plan 0. During PM peak, most of the cycles oper-

Table 1 Time of the before-and-after field survey

	Date	Time of the day
Before	2007.2.26 (Monday)	14:00~15:30 (PM off-peak) 17:00~18:30 (PM peak)
	2007.2.27 (Tuesday)	07:00~08:30 (AM peak) 10:00~11:30 (AM off-peak)
After	2007.6.18 (Monday)	14:00~15:30 (PM off-peak) 17:00~18:30 (PM peak)
	2007.6.19 (Tuesday)	07:00~08:30 (AM peak) 10:00~11:30 (AM off-peak)

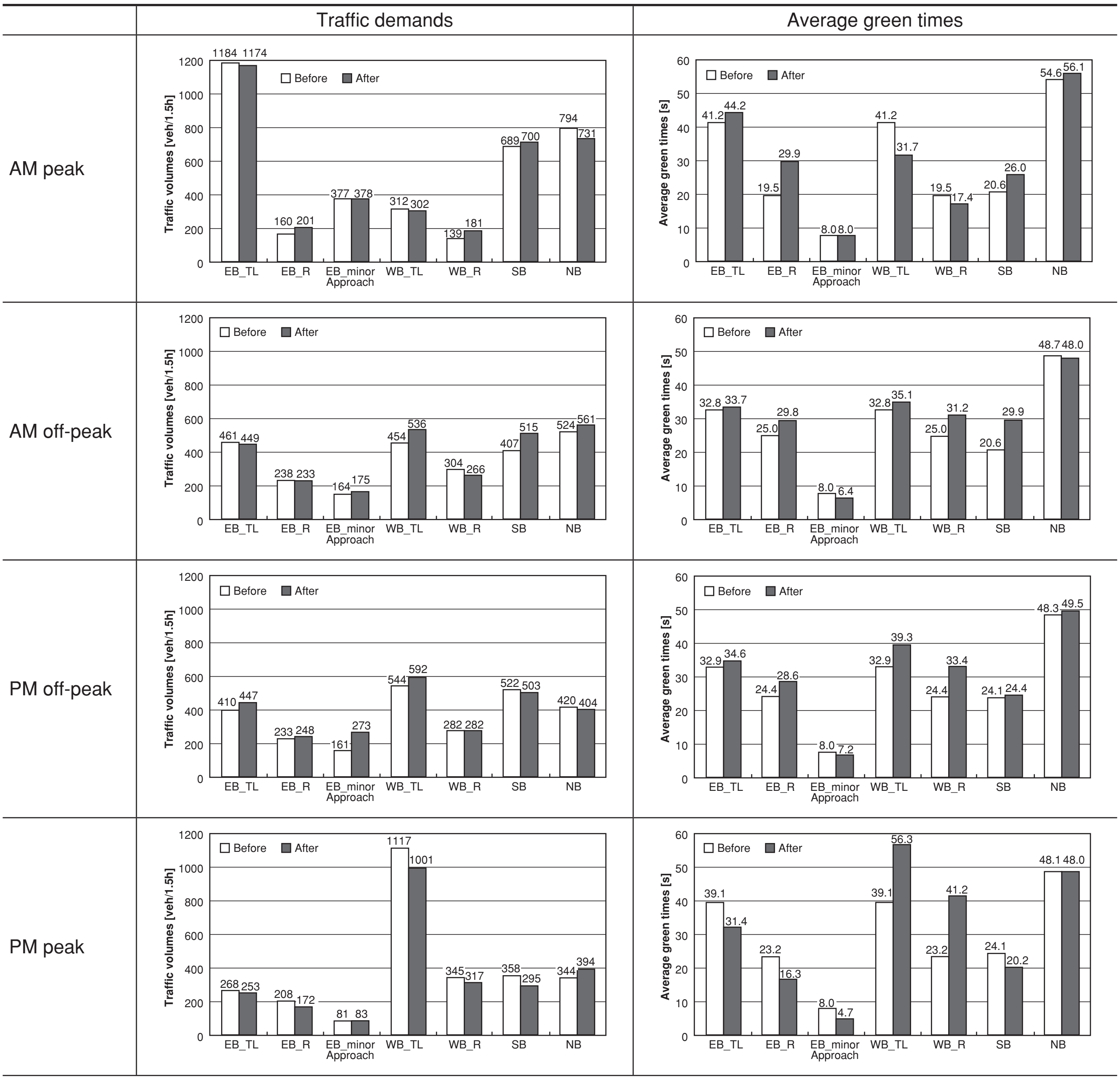


Fig. 3 Traffic demand and average green times during the analysis periods of 1.5 hours

ated under Plan 2. However, Plan 0 was the majority during the AM and PM off-peaks.

5. IMPACTS ON RED-LIGHT-RUNNING BEHAVIOR

Even though traffic demand did not significantly change after the implementation, signal timings were modified to a large extent due to the use of the new control approach. Traffic operations, e.g. green flow rates and degree of saturation for each cycle, differed from before. Thus, many factors together influenced red-light-running (RLR) behavior, not only the new control approach. Because of that, a simple difference T-test is not capable of explaining all those impacts simultaneously. Advanced models were thus used to interpret RLR behavior at the intersection. When developing models, a dummy independent variable (0: before; 1: after) was coded while including other available factors mentioned before in order to specify the impacts of the group-based control policy. Note that as there is no change in phasing for SB and NB, the analyses performed in this study focus on

EB and WB. Both the RLR occurrence probability within each cycle and its occurrence rate within each observation period were modeled. The former is to analyze the RLR behavior from a cycle-based microscopic view, which interprets the presence or absence of RLR events per cycle. The latter is to analyze such behavior from a macroscopic view, which concerns the occurrence frequency of RLR events within each observation period.

5.1 The occurrence probability of RLR within each cycle

In the analysis presented here, each cycle represents a sample. Dependent variable is a dummy code. When the cycle has at least one RLR, the dependent variable takes the value of “1”, otherwise, the variable equals “0”. Considering the binary nature of the dependent variable, the Binary Logistic model is appropriate, which in fact has been widely used in behavior analysis at signalized intersections[11,12,24]. The probability of RLR per cycle is computed by Equation (1).

$$P_{i,1} = \frac{1}{1+e^{-f(x)}} \tag{1}$$

$$f(x) = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \ldots + \beta_j \cdot X_j \tag{2}$$

Where, $P_{i,1}$= probability that cycle i has at least one RLR; X_j = independent variable j; β_j = estimated parameter for variable j.

As yellow and all-red time did not change, they are not included in the independent variables even though their significant impacts on RLR have been shown by past studies[14,18]. Additionally, a few of other effective factors are not available for this study, i.e. vehicle’s operating speed and distance to stop-line at the onset of yellow[13] as well as driver’s attributes[9]. Thus, this study was targeted to evaluate the impacts of traffic operations on RLR, while investigating the particular role of the new control approach in them. The considered independent variables are presented in Table 2.

Table 2 Considered independent variables

Code	Name	Description
B_A	Before or after	Dummy: 0: Before; 1: After
TIME	Time period	Categorized: 0: AM peak; 1: AM off-peak; 2: PM off-peak; 3: PM peak
EB_WB	Lane position	Dummy: 0: EB; 1: WB
PHASING	Phasing plan	Categorized: 0: Plan 0; 1: Plan 1; 2: Plan 2
VT	Vehicle type	Dummy: 0: if the last cleared vehicle is passenger car; otherwise, 1
CLUSTER	Clustered or not	Dummy: 0: if the last cleared vehicle is not clustered; otherwise, 1
G	Green time	Continuous: green time, s
C	Cycle length	Continuous: cycle length, s
GR	Green ratio	Continuous: green time divided by cycle length
VC	Volume-to-Capacity ratio	Continuous: green flow divided by saturation flow rate
HVP	Heavy vehicle proportion	Continuous: proportion of heavy vehicles
TV_1	Traffic volume (veh)	Continuous: traffic volume in vehicle unit
TV_2	Traffic volume (pcu)	Continuous: traffic volume in pcu unit

Where, variable “B_A” represents the particular impacts of the group-based control policy. Such impacts may source from the unstable phasing plans (optional use of Plan 0, 1, and 2), which perhaps make drivers behave more conservatively when choosing to run a red light or not if they have recognized the flexibility of the phasing plan. Variable “TIME” reflects the impacts of travel purposes, corresponding to the different time periods. Lane position was also considered as one variable, “EB_WB”, because of its different traffic conditions and conflicts with the movements released in Phase 3. Variable “PHASING” is included for looking into the impacts of discharge sequences of the movements at EB and WB. Variables “VT” and “CLUSTER” are useful for explaining the impacts of vehicle type and progression, which is defined by following headway size. In the case that the leading vehicle is a passenger car, a following vehicle is defined as “clustered” if its following headway is less than 3 s. In the case that the leading vehicle is a heavy vehicle, the following vehicle is defined as “clustered” if its following headway is less than 6s. The last cleared vehicle was considered here because in most of the cases the RLR vehicles were the last cleared ones. Variables “G” through “TV_2” represent basic traffic operations.

When identifying the particular impacts of the group-based policy on RLR, an important discussion is that the interactions between the variable “B_A” and the other factors. As means to account for those interactions, a series of correlation analyses were firstly run to see the correlations between “B_A” and other listed variables. The results showed that only cycle length “C” was significantly related to the variable “B_A” ($P<0.05$, P: significance level). It implies that if "B_A" appeared in the models together with "C", the impacts of B_A may not be real, but owing to its relation with "C". In that case, a further model modification is necessary. If "B_A" emerged in the models along with other factors, its impacts should be true. Following this logic, models were developed separately for each type of lanes at EB and WB, shared left-turn and through (Lane 1, most outside lane), exclusive through (Lane 2) and exclusive right-turn (Lane 3, most inside lane), due to the existence of distinguished movement directions or signal timings at those lanes. After excluding the cycles without traffic demand at the subject lanes, the total number of valid samples became 1434. SPSS (Statistical Package for Social Science) 10.0 was used to find the most representative models, with a "backward" policy. Table 3 presents the final results.

As shown in the table, all the three models are significant, in which variables, "EB_WB", "TV_1", "HVP", "VC", "TV_2" and "CLUSTER" were found to have significant effects on RLR probability at different confidence levels. Out of them, "VC" and "HVP" are the most significant ones, which appear in all the three models ($P<0.01$ and $P<0.05$), "VC" positively and "HVP" negatively. The impacts of "VC", corresponding to green flow rate, are easy to understand that the RLR probability rises as traffic pressure increases. It is consistent with the results from Bonneson and Son[11]. The estimated parameters for "HVP" indicate that when the proportion of heavy vehicles increases, the RLR probability drops. It can be explained by that at the same level of traffic demand a higher proportion of heavy vehicles is generally correspondent with a lower total number of vehicles, reducing exposure severity to RLR. Moreover, headways involved heavy vehicles are larger than ordinary passenger car headways, which accordingly reduce the probability of RLR in the case that a heavy vehicle has entered the intersection during amber or just before the amber onset.

Table 3 Binary logistic models interpreting the RLR probability per cycle

	Model 1 (Shared TL)		Model 2 (Exclusive T)		Model 3 (Exclusive R)	
	β	Sig.	β	Sig.	β	Sig.
Constant	-5.409	***	-3.873	***	-5.674	***
B_A						
TIME						
EB_WB	1.248	***				
PHASING						
VT						
CLUSTER			-1.113	***	-1.640	***
G						
C						
GR						
VC	7.232	***	6.024	***	6.514	***
HVP	-2.044	***	-1.725	**	-3.884	**
TV_1	-0.090	**			-0.513	**
TV_2			-0.068	*	0.446	***
# of samples	483		471		480	
Chi-Square	159.182		99.133		194.616	
-2L	432.765		303.712		319.683	
Hit ratio	77.6%		85.8%		85.8%	

(*: significance level < 0.1; **: significance level <0.05; ***: significance level <0.01)

Traffic volumes, "TV_1" and "TV_2", were also found to have significant effects on RLR. Logically, traffic volume should be positively related to RLR probability because it presents exposure level[11–13]. However, their impacts are not consistent in the models. "TV_1" has a negative influence in Model 1 and 3 for the shared through and left-turn lanes and exclusive right-turn lanes. "TV_2" has positive effects in Model 2 for the exclusive through lanes, while having negative impacts in Model 3. In fact, they reflect a similar nature of traffic pressure. A possible explanation is that a quite high proportion of heavy vehicles prevailing at the intersection (averagely 37% at Lane 1, 21% at Lane 2 and 50% at Lane 3) makes the "TV_1" and "TV_2" vary considerably. It is to say that a larger "TV_1" corresponds to a higher "TV_2" in some cases, a lower "TV_2" in other cases. Thus, these inconsistent results seem purely due to statistical reasons.

In addition to that, lane position, "EB_WB", has positive influences on the RLR probability ($P<0.01$). It reveals that RLR probability at WB_Lane 1 is significantly higher than that at EB_Lane 1. It can be attributed to the extremely high left-turn traffic proportion at WB_Lane 1 (greater than 95%). Left-turn traffic is more likely to run a red light because its conflict with the movements released in the subsequent phase have comparably low severity, and the distances to the conflict points are relatively short, inducing left-turner's risky behavior. Meanwhile, "CLUSTER" was found to negatively affect RLR probability at exclusive through and right-turn lanes ($P<0.01$), exhibited in Model 2 and 3. It indicates that RLR probability is lower if the last vehicle was clustered with the leading vehicles when it entered the intersection. It translates that, as compared with the cycles without RLR, those cycles with RLR have lower portions of the last cleared vehicles clustered with the leading vehicles. It implies that the intentional or unavoidable RLRs, incapable of stopping or inattentive driving, were greater than those induced by the prior amber entering or red-light violating, largely due to cycle overflow, at the intersection. This result is somewhat inconsistent with the results from Retting, et al.[9], but partly supported by Grembek, et al[12].

On the other hand, the variables, “B_A”, “TIME”, “PHASING”, “VT”, “G”, “C” and “GR” were not found to have any significant relations with the RLR probability per cycle. It suggests that there is no difference between before and after, heavy vehicle and passenger car from the view of RLR probability per cycle when drivers decide to violate a red light or not. Also, there is no difference under different phasing plans and signal timings (not including yellow and all-red times).

In summary, the group-based control policy did not directly influence the RLR behavior if looking at the RLR probability per cycle, which was more likely to be affected by traffic pressure, indicated by “VC”, “TV_1” and “TV_2”. Moreover, intentional or unavoidable RLRs occupied a higher percentage than those induced by the prior moving violations.

5.2 The occurrence rate of RLR within each observation period

The calculation method of the RLR probability per cycle presented above neglects the RLR occurring frequencies of the cycles having RLR. It thus may cover up the impacts of such a policy on RLR behavior somewhat. To overcome the drawbacks, a further investigation was done in this part to see if such a policy had significant effects on RLR occurrence rate within each observation period (1.5h, around 30 cycles). RLR/10,000 veh-cycle proposed by previous research, e.g. Bonneson, et al.[11] and Schattler, et al.[15], was selected as an index to quantify the RLR behavior as it considers both the exposure severity of traffic volume and cycle length. It is calculated by Equation (3).

$$RLR/10{,}000veh-cycle = \frac{N_{RLR} \times 10{,}000}{V \times N_{cycle}} \quad (3)$$

Where, N_{RLR} = total number of RLR events occurred; V = total traffic volume [veh]; N_{cycle} = total number of cycles.

To give a general picture of the overall RLR events, the RLR/10,000 veh-cycle at each subject lane was firstly computed and shown in Figure 4. As can be seen, RLR rates at the exclusive through and right-turn lanes considerably declined. However, fairly small changes took place at the shared left-turn and through lanes, i.e. slightly descending at EB_Lane 1 and ascending at WB_Lane 1. It reveals that the group-based control policy may influence the RLR rates of exclusive through and right-turn traffic.

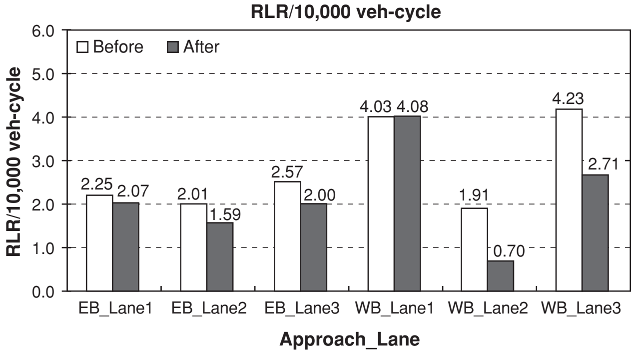


Fig. 4 Observed RLR rates at the subject lanes

To test that, RLR events were aggregated for each observation period and three linear regression models were then built up. Totally, 16 samples were valid for each type of lane. The factors used in the previous part, “B_A”, “G”, “C”, “GR”, “VC”, “TV_1” and “TV_2”, were considered here too. The continuous variables were averaged by number of cycles during each observation period. In addition, other considered factors were TV_3 and TV_4, representing the total volume in vehicles and pcu respectively during each observation period. Table 4 presents the final results.

All the three models are acceptable in terms of the R^2 values. It is shown in the models that the variables “EB_WB”, “TV_1”, “VC”, “B_A”, “G”, “TV_4”, “GR”,

Table 4 Linear regression models interpreting the RLR per 10,000 veh-cycle

	Model 4 (Shared TL)		Model 5 (Exclusive T)		Model 6 (Exclusive R)	
	β	Sig.	β	Sig.	β	Sig.
Constant	-4.658		10.181	***	0.736	
B_A			-1.505	**		
TIME						
EB_WB	7.362	***	-1.113	*		
PHASING						
VT						
CLUSTER						
G			-0.245	***	1.510	*
C						
GR					-425.775	**
VC	30.497	***				
HVP					36.135	***
TV_1	-0.030	**				
TV_2						
TV_3					5.984	***
TV_4			0.379	***	-2.620	*
# of samples	16		16		16	
R^2(Adjusted)	0.706(0.638)		0.855(0.797)		0.884(0.825)	

(*: significance level < 0.1; **: significance level < 0.05; ***: significance level < 0.01)

"TV_3" and "HVP" were significantly associated with the RLR rates. Same explanations for the impacts of "EB_WB", "TV_1", and "VC" hold water here as well. Also, the explanation for the impacts of "TV_1" and "TV_2" can be applied to interpret the impacts of "TV_3" and "TV_4". The reasons why "TV_3" and "TV_4" other than "TV_1" and "TV_2" appeared in Model 5 and 6 are perhaps that they are more representative for the RLR rates at the exclusive through and right-turn lanes. However, it is somehow difficult to explain that "HVP" has positive impacts in Model 6 (P<0.01) because the previous results have shown that "HVP" has negative effects on the RLR probability per cycle, which sounds inconsistent with this result. However, if one has noticed the way to calculate the rate of RLR per 10,000 veh-cycle (Equation (3)), it becomes understandable. As the average number of vehicles at the exclusive right-turn lanes were comparatively small, the calculated RLR rates tended to be larger when the proportion of heavy vehicles increased, leading to smaller total numbers of vehicles. It is more pronounced particularly when the majority of traffic is heavy vehicles.

Furthermore, it was also found in Model 6 that "G" has a positive impact (P<0.10), while "GR" has a negative influences (P<0.05). This is easy to understand because greater green times basically correspond to higher traffic volumes (higher exposure severity), and lower green ratios present heavier traffic pressure, particularly in the case of adaptive control (right-turn traffics were adaptive controlled after the implementation). It should be noted here that "B_A" was found to have a negative effect (P<0.05) at the exclusive through lanes. It indicates that the group-based control policy significantly reduced the RLR rates of though traffic. As explained before, unstable phasing sequence probably makes drivers more conservative in making decision to run a red light. However, such effects seem to be true only for through traffic according to the models. It can be explained by greens for through traffic were most frequently switched off at different timing under Phasing plan 0, 1 and 2, as illustrated in Figure 1. For the shared through and left-turn lanes, most of the traffic was left-turn. It is less influenced by the flexible phasing, as explained earlier for the variable "EB_WB" in Model 1. For the exclusive right-turn lanes, although greens started variedly under Plan 0, 1 and 2, they always ended at the same time point. Thus, the flexibility of phasing was insufficiently reflected by left-turn and right-turn traffics.

In summary, the results here support that the group-based control policy, along with certain other factors, significantly reduced the RLR rates of through traffic. Meanwhile, it indirectly reduced the RLR rates of right-turn traffics by adjusting signal timings, but did not affect the RLR rates of left-turn traffic.

6. IMPACTS ON INTERSECTION SAFETY

Besides driver behavior, the impacts of such a policy on intersection safety are also scoped in this study. A methodology is firstly proposed to evaluate safety. Then, the measurement results of two critical factors essential for the methodology are presented, which are yellow-entry time of the last cleared vehicle (Y_e) and post encroachment time (PET) when phase switching.

6.1 Methodology

As introduced previously, the group-based control policy often generates complex phasing. It does not only cause more intergreens but also more flexible phase switching timing within one cycle than the conventional stage-based phasing plans. Thus, it is of great importance to understand safety performance when phase switching in the case of group-based control.

In past research, the occurrence frequency or rate of reported accidents is always used for the evaluation of safety at intersections. When applying such methods, much historical accident data is necessary, normally not less than three years. Therefore, they are suitable for empirical safety analysis for a long term. However, in the daily work of improving the traffic environment, it is important to identify which places and/or situations are dangerous, and why they are dangerous as well as assessing whether a modification is beneficial prior to any implementations or accidents happening. In those cases, traffic conflict technique (TCT) is applicable in which time indices, e.g. post encroachment time (PET), suggested by Allen, et al.[23], is usually the measures for safety or risk. However, most of them are initially proposed for estimating safety when gap-acceptance or merging maneuvers occur during green intervals. Very few of them have been widely accepted as safety measures for intergreen intervals, due to the complicated traffic situations during the period. In the light of that and the purpose of this study, a PET is proposed here as a measure for safety performance during intergreen intervals. As illustrated in Figure 5, the clearing movement and entering movement produce a conflict point when the phase changes. A PET correspondent to a change of phase is then defined as the elapsed time from when the last cleared vehicle in the previous phase passes the conflict point till when the first entering vehicle released in the subsequent phase arrives there.

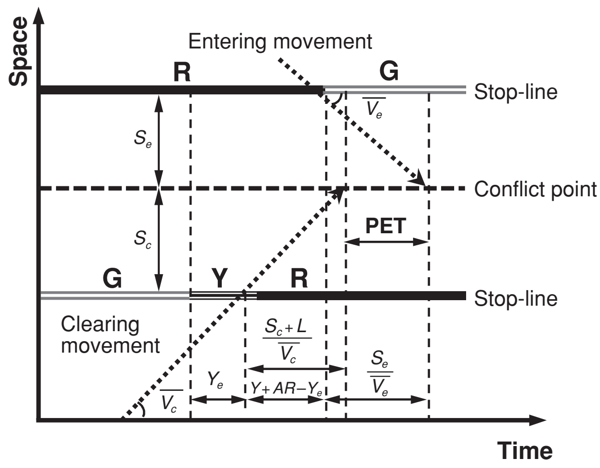


Fig. 5 Post encroachment time (PET) when phase switching

Several facts support the validity of the proposed PET as a measure to safety during intergreen. Firstly, despite slightly variation from the common PET for green intervals, it maintains the fundamental feature of PET as it was originally proposed. Thus, it becomes possible to unify the safety indices for green and intergreen intervals. Secondly, it is able to indicate the extent to which intergreen times fail to clear the intersection before giving the right of way to the next traffic stream, leading to accidents. Thirdly, capacity reduction with a change of phases is largely determined by the occupied time of the conflict area, which is mostly dependent upon the PET. Thereby, it directly connects traffic flow efficiency (capacity) with safety at signalized intersections.

If assuming the entering speed V_e and clearing speed V_c, PET can be estimated by the yellow-entry time of the last cleared vehicle Y_e, as given in Equation (4).

$$PET = (Y + AR - Y_e) + \frac{S_e}{\overline{V_e}} - \frac{S_c + L}{\overline{V_c}} \quad (4)$$

Where, Y = yellow time [s]; AR = all-red time [s]; Y_e = yellow-entry time [s]; S_e = entering distance [m]; $\overline{V_e}$ = mean entering speed [m/s]; S_c = clearing distance [m]; L = vehicle length [m]; $\overline{V_c}$ = mean clearing speed [m/s].

PET strongly relies on Y_e as the other parameters in Equation (4) are comparatively constant at a certain intersection. Thus, intersection safety during phase switching can be roughly determined by Y_e. However, those parameters are often variable in the real world, following a certain type of distribution. In those cases, PET can be estimated by their distributions according to a stochastic method. That is still an ongoing research of the authors. In this paper, only the measured PET and Y_e values as well as some preliminary analysis on Y_e distribution are presented.

6.2 Impacts on yellow-entry time (Y_e)

Figure 6 shows the basic statistics of the measured Y_e of the last cleared vehicle. A general trend can be found that all the mean Y_e except that at WB_Lane 1 declined. This trend matches perfectly with that of the observed RLR rates shown in Figure 4. Thus, the rise of mean Y_e at WB_Lane 1 is very likely caused by the increased RLR rate. It was also found that the mean Y_e ranges from 2.47

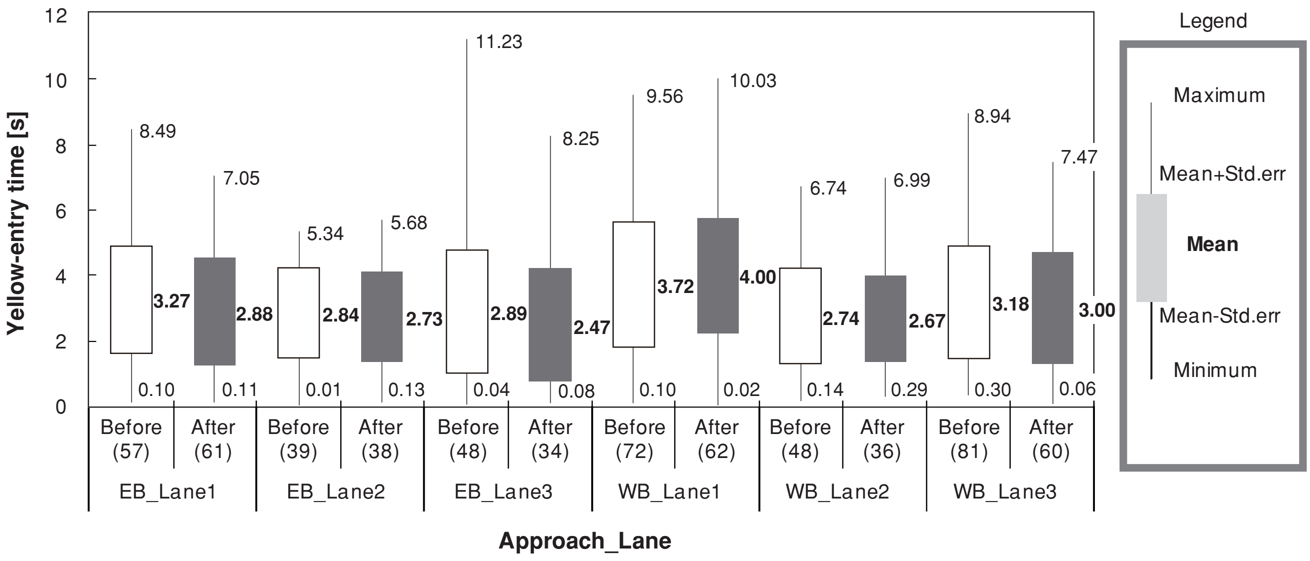


Fig. 6 Basic statistics of Y_e of the last cleared vehicle

to 4.00 sec. Among them, the two largest ones, 3.72 and 4.00 sec, come up with WB_Lane 1, which can be attributed to the largest RLR rates at the lane.

Figure 7 further presents the observed frequencies and cumulative distributions of Y_e. It shows that Y_e is most frequent (over 15%) between 3 and 4 sec at all the subject lanes irrespective of their movement directions and all-red time. Furthermore, approximately 80% of them are less than 4 sec, saying red-entry time less than 1 sec, which is supported by Bonneson, et al.[19]. An interesting finding here is that all the cumulative curves for the after cases are basically located on the left side except the one at WB_Lane 1. It indicates that not only the mean Y_e values decreased, but also the whole distribution of the Y_e shifted. In order to understand if the distribution type of Y_e changed after the implementation, a series of non-parameter tests including Normal, Uniform, Exponential and Poisson distributions were performed in SPSS. It was found that Y_e at the entire subject lanes follow normal distribution but with different means and standard errors, as shown in Table 5.

In summary, the results support that Y_e tended to decrease after the implementation. However, the distribution type of Y_e of the last cleared vehicle, normal distribution, remained unchanged.

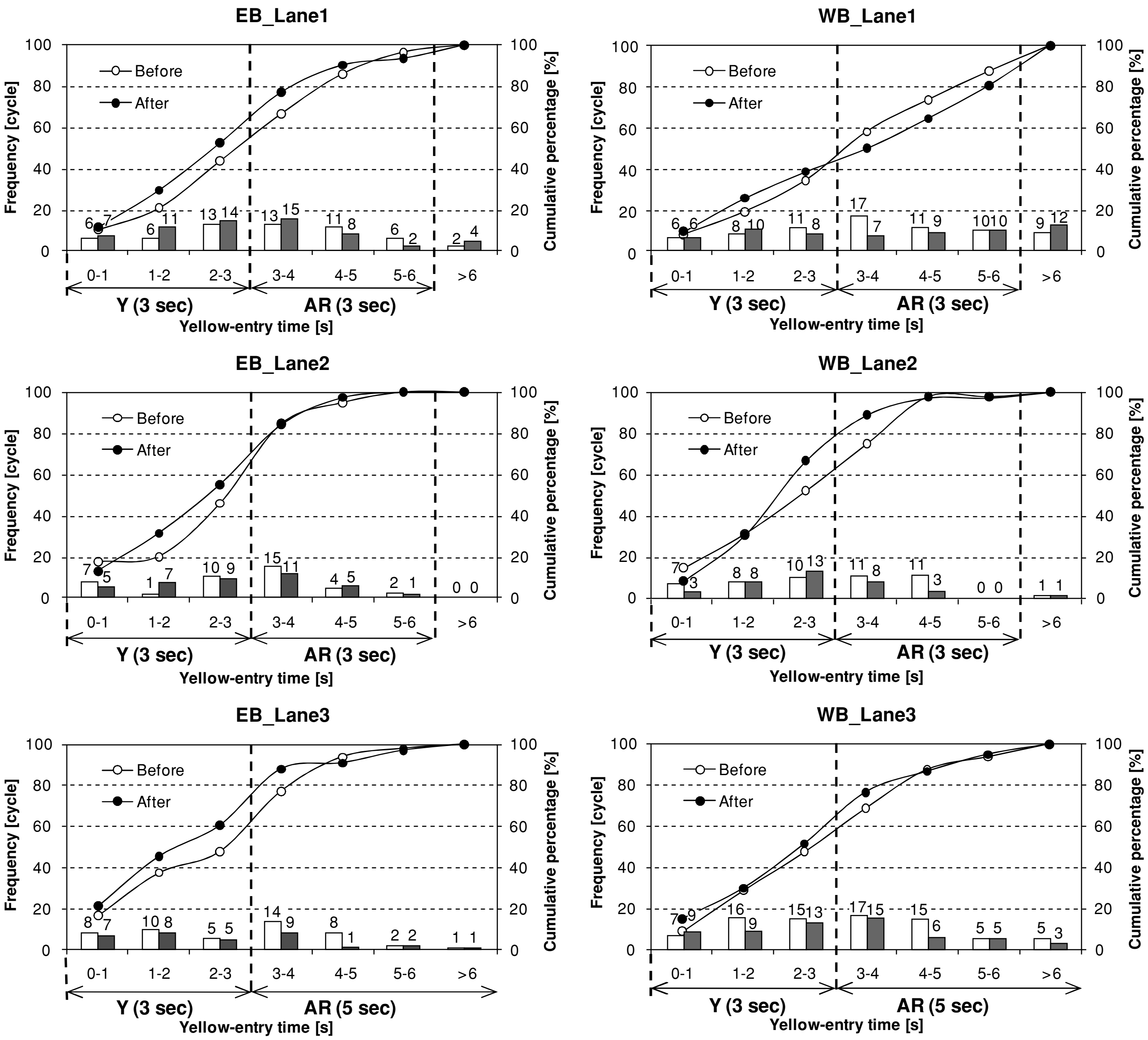


Fig. 7 Observed frequencies and cumulative distributions of Y_e of the last cleared vehicle

Table 5 Normal distribution test results for Y_e

Lane	B or A	Mean [s]	Std.err	Sig.	Pass/not
EB_Lane 1	Before	3.27	1.66	1.000	Pass
	After	2.88	1.66	0.988	Pass
EB_Lane 2	Before	2.84	1.38	0.702	Pass
	After	2.73	1.39	0.928	Pass
EB_Lane 3	Before	2.89	1.88	0.533	Pass
	After	2.47	1.75	0.777	Pass
WB_Lane 1	Before	3.72	1.95	0.994	Pass
	After	4.00	1.77	0.705	Pass
WB_Lane 2	Before	2.74	1.47	0.933	Pass
	After	2.67	1.33	0.853	Pass
WB_Lane 3	Before	3.18	1.73	0.612	Pass
	After	3.00	1.72	0.965	Pass

6.3 Impacts on post encroachment time (PET)

Conflicts appeared in different timing due to the different phasing plans, as exhibited in Figure 8. The correspondent PET defined earlier was measured to estimate safety performance. As very few stop-line crossings during intergreen intervals occurred during off-peak periods, only peak periods were included in the analysis. Figure 9 then compares the observed PET values at the conflict points 1 and 2 before and after.

It is shown that PET values obviously increased after the implementation (P<0.10). In detail, mean PET value went up from 10.8 to 12.6 sec during AM peak and from 11.3 to 12.6 sec during PM peak, which resulted from two factors, yellow-entry time (Y_e) of the last cleared vehicle and entering time of the first vehicle (t_e). Y_e decreased at the exclusive through lanes as presented before. Also, starting response time (SRT) of right-turn traffic at EB and WB significantly decreased after the implementation leading to the decrease of t_e, presented in another paper of the authors[7].

The results here support that safety performance when phase switching, indicated by PET, is possible to be significantly improved by the use of the group-based control policy. One may argue that the improvement of safety, i.e. increase in PET, is partly due to the increased starting response time (capacity reduction). Thus, it is at the expense of traffic flow efficiency. Actually, this inefficient aspect can be overcome by several ways. For instance, a red-and-amber signal display before the onset of green is often applied to indicate to drivers that green will start very soon so as to reduce starting response time in some European countries. Its effectiveness has been proved in a previous study of the authors[6]. Although PET will certainly decrease a little bit if using the red-and-amber signal indication, safety can be maintained at least as Y_e is still relatively low in the case of group-based policy. The reason is that such a policy is possible to enforce

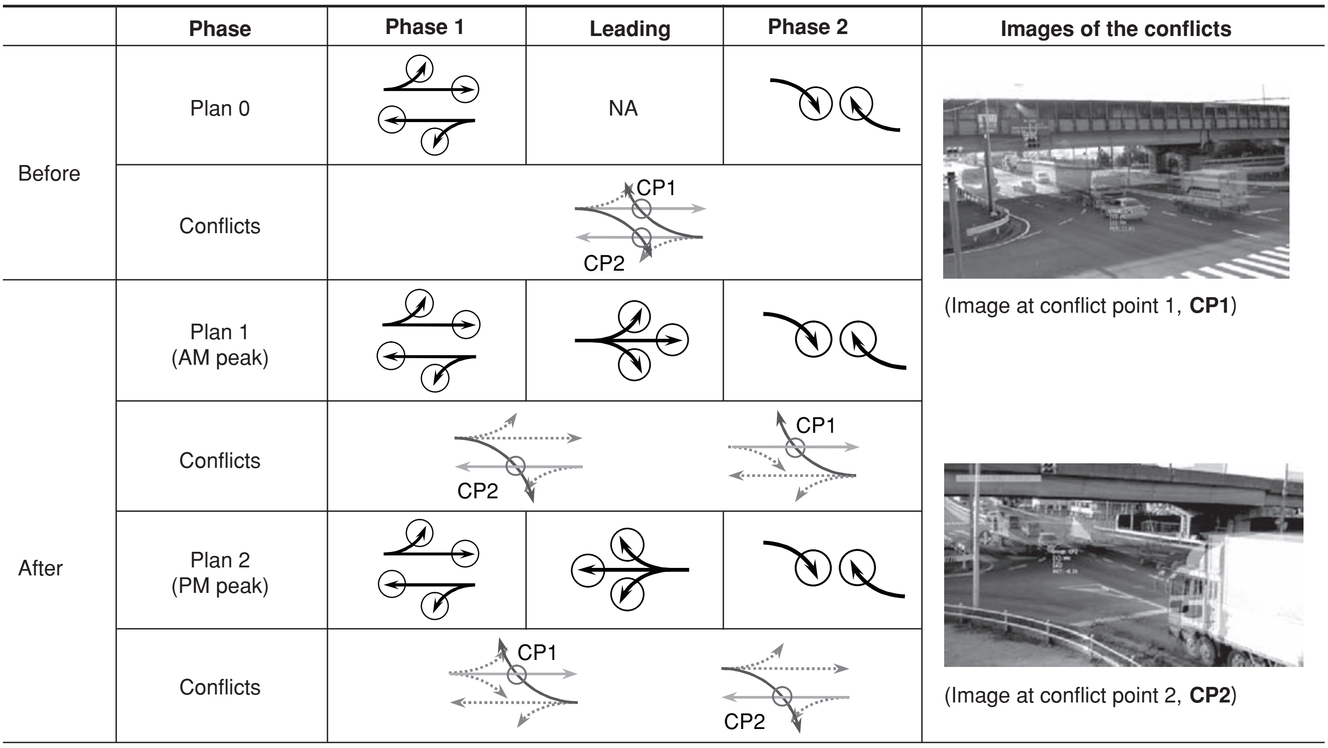


Fig. 8 Phasing plans and associated conflict patterns before and after

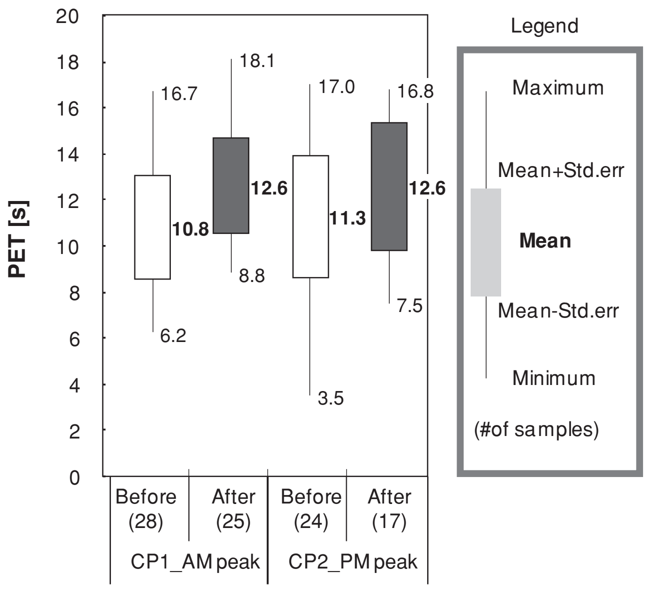


Fig. 9 Observed post encroachment time (PET)

drivers to comply with traffic signals due to its phasing features, accordingly reducing stop-line crossing during intergreen intervals especially RLR, as presented before and in another study of the authors[6].

7. IMPLICATIONS, CONCLUSIONS AND FUTURE STUDY

This study evaluated the impacts of the group-based signal control policy on driver behavior and intersection safety, based on the data collected at an intersection before and after implementing such a policy. The following conclusions can be drawn from this study.

1. The group-based control policy did not directly influence the RLR probability per cycle, which is more determined by traffic pressure, represented by degree of saturation and traffic volume, and certain other factors.
2. The group-based control policy, together with other factors, directly reduced the RLR rates (RLR per 10,000 veh-cycle) of through traffic. Meanwhile, it indirectly reduced the RLR rates of right-turn traffic by influencing signal timings, but did not significantly affect the RLR rates of left-turn traffic.
3. Yellow-entry time (Y_e) tended to be smaller after the implementation of such a policy, mainly due to the decreased RLR rates. However, the distribution type of Y_e, normal distribution, remained unchanged.
4. Safety benefits were also achieved by applying such policy, indicated by the increased PET values.

The conclusions above imply that flexible and complex phasing generated by the group-based signal control policy has a potential to obtain safety benefits instead of losing them. Another previous study of the authors[7] has indicated that significant operational benefits (delay) are also possible to be achieved by applying such a policy. Absolutely, simple and stable phasing often created by the stage-based policy is friendly with intersection users, and easy to operate in terms of traffic control. However, it not only tends to cause long cycle lengths, but also somewhat induces RLR because drivers normally dislike waiting too long[11]. Meanwhile, drivers are more likely to have risky behavior if they are able to easily predict the next released phase[6]. In general, to resolve mobility problems on urban roads in Japan caused by those long cycle lengths, such group-based policy should be an alternative for traffic control at signalized intersections in Japan.

However, this study is based on a single site with very low pedestrian demand. Therefore, the conclusions may be proper only for such types of intersection. Also, some factors relevant to the unique local characteristics might have influenced the results more or less. These facts constrain the extension of the conclusions to other locations. More empirical studies need to be done in Japan to reinforce the conclusions.

In addition, although it has been shown that the group-based control policy is possible to gain better performance than the stage-based policy, a lot of fundamental research is still essential for investigating the applicability of such a policy in Japan. When, various traffic situations at intersections should be carefully considered, e.g. isolated or coordinated, balanced or unbalanced traffic demands as well as high or low pedestrian volumes. Moreover, as phase switching under such a policy is more complicated than those under the stage-based policy in Japan, a more sophisticated safety estimation method is demanded to develop. Such methods need to give particular emphasis on the safety performance when phase changes and enable to account for the reliability of safety as well.

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