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Effectiveness of Signal Coordination for Pedestrian Flows Considering Bi-directional Flow Impacts

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Abstract: Existing signal control strategies do not consider pedestrian flows in optimizing signal parameters, which may impose significant delays on pedestrians. This study aims to investigate the rationality and effectiveness of designing signal coordination for pedestrians. A numerical case study in Japan is analyzed. Field survey is conducted to collect the geometric characteristics, signal timings and vehicular traffic condition information. In a parallel approach, the performances of signal coordination for vehicular and pedestrian traffic are estimated by using the vehicular traffic simulation tool Synchro/SimTraffic and the pedestrian simulation tool NOMAD. The results showed that the coordination for the major pedestrian flow led to a significant reduction in average delay (15%). Generally, it is concluded that the effectiveness of pedestrian signal coordination is not guaranteed but depends on the relationship between pedestrian platoon dispersion and the signal cycle length.

Key Words: *Signal coordination, Pedestrian delay, Platoon dispersion, Bi-directional flow*

1. INTRODUCTION

Existing research regarding optimizing traffic signal operation has focused on maximizing vehicular capacity or minimizing vehicular delay. At the network level, the typical approaches are to maximize green band widths or to minimize delays for vehicular traffic. For pedestrian traffic, existing signal control strategies only focus on safety aspects and fail to pay enough attention to the efficiency aspect, i.e. pedestrians' delay. Such an objective is reasonable for motorways and rural roads where vehicular traffic is dominant over pedestrians. However, it is not the case in metropolitan areas with medium or large pedestrian demands. Ignoring this can lead to unnecessary long delays for pedestrians, further leading to dangerous behavior by impatient pedestrians, and potential reductions in pedestrian traffic and levels of transit usage.

Multi-modal traffic signal operation should consider both efficiency and safety aspects for all travelers at intersections, e.g., those using vehicles, pedestrians and cyclists. Among all the travelers, vehicles and pedestrians are most important from the perspective of demand level. These two groups of travelers also have significant differences in characteristics. For example, vehicles follow each other to travel within dedicated lanes, while pedestrians walk at a much lower speed but are more flexible in choosing their paths and speeds. Due to such dramatic differences, the coordinated timing specifically designed for vehicular traffic might not serve pedestrian traffic well.

Previous studies (Virkler, 1998; Bhattacharya and Virkler, 2005) developed signal coordination strategies to consider both vehicular and pedestrian traffic. However, the unique divergence of pedestrian movement might significantly affect the effectiveness and performance of coordination that is designed for pedestrians. This study aims to investigate the effectiveness of coordination for pedestrians under various design scenarios. It is necessary to do this before any development of integrated multi-modal signal operation strategies that consider vehicular and pedestrian flows for their efficiency and safety.

2. LITERATURE REVIEW

Existing manuals such as HCM (2000) specify procedures to determine the level of service depending on the average control delay experienced by vehicles at intersection approaches. It is clear that pedestrian flow has not been given the same priority as vehicular traffic. However, for many urban areas with large volumes of pedestrians, it is more rational and reasonable to evaluate the level of service from a multi-modal perspective.

Webster's (1958) and numerous other methods for signal optimization focus on reducing vehicle delays without considering pedestrian flows and delays. Li et al. (2010) developed a traffic signal optimization strategy for isolated intersections that considers both vehicular and pedestrian flows. The objective of the proposed model is to minimize the weighted vehicular delays and pedestrian delays. Since their analysis was based on isolated intersections, the effect of signal coordination on pedestrian flows has been not analyzed.

Few studies tried to analyze the possible effects of vehicular traffic coordination on pedestrian delay at network level. Ishaque and Noland (2005; 2007) analyzed the effects of signal cycle timing on pedestrian and vehicle delay assuming a simple hypothetical network. All the signalized intersections in the network are assumed to be isolated and with fixed timing . The VISSIM micro-simulation model was used to analyze the network. It was concluded that the setting of signal timing has a very significant impact on pedestrian delay. Moreover, the authors proposed optimal signal timings under various vehicle and pedestrian demand levels. An important drawback of their analysis is that the version of VISSIM that was used does not consider the interaction between pedestrians. Such absence of a consideration of the pedestrian-to-pedestrian interaction underestimates the experienced delay, which means that the proposed optimal solutions might not really be optimal. Furthermore, at the network level, the coordination of vehicular flow and its effect on pedestrians is more important.

Virkler (1998) explored the potential benefits of reducing pedestrian delay through signal coordination by analyzing field data from 10 signalized intersections. It was concluded that pedestrian platooning due to upstream signals can increase or decrease pedestrian delay depending on the offsets of the downstream signal. However, the difference between the optimal offsets for coordinating pedestrian and vehicle flows was not presented. Furthermore, the interaction between pedestrians and its effect upon delay was not considered.

Bhattacharya and Virkler (2005) proposed a methodology to estimate the offset corresponding to the optimal user cost obtained by incorporating pedestrian delay. They concluded that signal coordination plans along a corridor should account for pedestrian progression because pedestrian delay can comprise a significant portion of the total delay. Furthermore, they emphasized that if motor vehicle congestion restrains vehicular progression, opportunities to provide progression to other competing modes such as pedestrians should be considered. However, the interaction between bi-directional pedestrian flows was not considered in their study. Moreover, the situations where the consideration of pedestrian flows in the road network signal coordination is effective and significant in reducing total delay were not clarified.

The interaction between opposing pedestrian flows at sidewalks or crosswalks is an important factor that might lead to significant delays especially at high pedestrian volumes. Such delays should be considered in the design of efficient coordination for pedestrians. Lam et al. (2003) investigated the effect of bi-directional flow on walking speed and pedestrian flow under various flow conditions at indoor walkways in Hong Kong. They found that bi-directional flow ratios have significant impacts on both the at-capacity walking speed and the maximum flow rates of the selected walkways. Furthermore, Teknomo (2006) proposed a microscopic pedestrian simulation model, which was utilized to demonstrate the effect of bi-directional flows at signalized crosswalks. It was found that the maximum effects occur at a directional split ratio of 0.5 where the average speed of the bi-directional flow dropped up to one third compared to the uni-directional flow. Alhajyaseen and Nakamura (2009a) modeled the speed of the bi-directional pedestrian flows at signalized crosswalks by applying the analogy of drag force theory. It was concluded that crosswalk geometry (width and length) and the ratio of bi-directional pedestrian demand have significant impacts on walking speed.

3. METHODOLOGY

In this study, we would like to evaluate the performance of signal coordination settings from the perspective of vehicular traffic and pedestrian traffic. Since very few simulation packages are capable of simulating both vehicular and pedestrian movements in sufficient detail, a parallel approach is adopted for this study. The Synchro and SimTraffic package, which is one of the most popular signal optimization and simulation suites for vehicular traffic, is chosen to estimate vehicular delay on a given network. Micro-simulation is used for this research to address the deficiencies that the mathematical formulations used by analytical methods suffer from in representing realistic traffic or in analyzing large networks (Mahmassani et al., 1994).

In parallel with the use of Synchro, a pedestrian network with the same geometry is used to analyze pedestrian demand and signal timing information using NOMAD, a microscopic pedestrian simulation model for the assessment of pedestrian walking infrastructure (Hoogendoorn and Bovy, 2003; Hoogendoorn and Bovy, 2004; Hoogendoorn et al., 2007). It is noted that in the use of this parallel approach, the researchers assume that left-turning (Japanese right-turning) phases are protected and ignores the interactions between right-turning (Japanese left-turning) vehicles and pedestrians.

NOMAD is activity based, implying that the actions of the pedestrians (instant velocity and acceleration) are largely determined by the different activities (shopping, going to work etc.) pedestrians are performing while being in the walking facility. The modeling of the pedestrian interaction process is based on known empirical facts (Daamen et al., 2003) and theory on pedestrian behavior (their choice of speed and direction with time). The calibration of the model parameters is done using a microscopic approach, where model results have been compared to observed microscopic pedestrian behavior (Hoogendoorn and Daamen, 2006).

For this paper, NOMAD was used to model traffic signals at a sequence of intersections. The walkable area consists of sidewalks and crosswalks, while the obstacles are formed by the buildings and by the street itself. At each side of a crosswalk, a waiting area is defined. When pedestrians walk from their origin to their destination, they will have to pass three different waiting areas, each located just in front of an intersection. The walking areas are connected to the traffic signals. When the traffic signal is green, the pedestrians finish their activity and start walking to their next activity. The route to their next activity first passes the crosswalk, so the pedestrians cross and then continue towards the next intersection. Once the traffic signal turns to amber, the waiting area is blocked. Pedestrians who arrive have to wait until the traffic light turns green again. Since the waiting area is modeled as a small area, waiting pedestrians will be grouped around this waiting area, just as in reality.

Regarding the calculation of the optimum offsets for pedestrian flows, a simple coordination model is used. The objective of this model is to maximize the green band of the major pedestrian flow (dominant flow). OF_j is the offset at intersection (j) and it can be calculated based on the green wave from intersection ($j+1$) to intersection (j), as shown in Equation (1).

$$OF_j = OF_{j+1} + R_{j+1} - R_j + \frac{L_{sw}^{j+1,j}}{\bar{v}_{sw}^{j+1,j}} + \frac{L_{cw}^{j+1}}{\bar{v}_{cw}^{j+1}} \tag{1}$$

Where OF_j is the offset for signal j; R_j is the red time for signal j; $L_{sw}^{j+1,j}$ is the length of sidewalk from intersection ($j+1$) to intersection (j); $\bar{v}_{sw}^{j+1,j}$ is the average walking speed on the sidewalk from intersection ($j+1$) to intersection (j); L_{cw}^{j+1} is the length of crosswalk at intersection ($j+1$); $\bar{v}_{cw}^{j+1}$ is the average walking speed on the crosswalk at intersection ($j+1$).

Before running the simulation, average pedestrian speed and speed standard deviation are calibrated for Japanese conditions (Alhajyaseen and Nakamura, 2009b). Average pedestrian free flow speed is assumed as 1.34 m/s, while the standard deviation of the speed is assumed as 0.28m/s. Furthermore, the minimum and maximum pedestrian radii are assumed as 0.2 m and 0.23m, respectively. The radius of a pedestrian indicates its size, since a pedestrian is modeled as a circle. The radius, or size, relates to the density, since the smaller the pedestrians are, the more pedestrians will fit on a square meter. It is therefore one of the calibration parameters in NOMAD. In NOMAD, the size also corresponds to the pressure that a pedestrian may exert on other pedestrians to force his way towards his destination.

4. NUMERICAL CASE STUDY

In order to analyze the effectiveness of signal coordination, a three-signal network along a busy corridor in Nagoya, Japan is chosen. The intersections are Horita Eki Mae, Horita Eki Minami and Chikatetsu Horita. Information on the geometric characteristics and existing signal timings are shown in Figure 1. With the help from the members of Interchange Nakamura Laboratory, video data were collected for vehicular flows and pedestrian flows on all approaches and all directional movements during the peak period on a typical weekday. A manual survey was also conducted to collect traffic signal timing data and coordination timing data along both directions during the same period when video data was collected. The vehicular traffic demands along the three intersections are presented in Table 1. For signal coordination, the offset at intersection (1) (Horita Eki Mae) is defined as zero, which is zero on the master clock of the coordinated network. The master clock zero in this study is defined as the beginning of red at intersection (1). The offsets for the two other intersections are referenced to intersection (1).

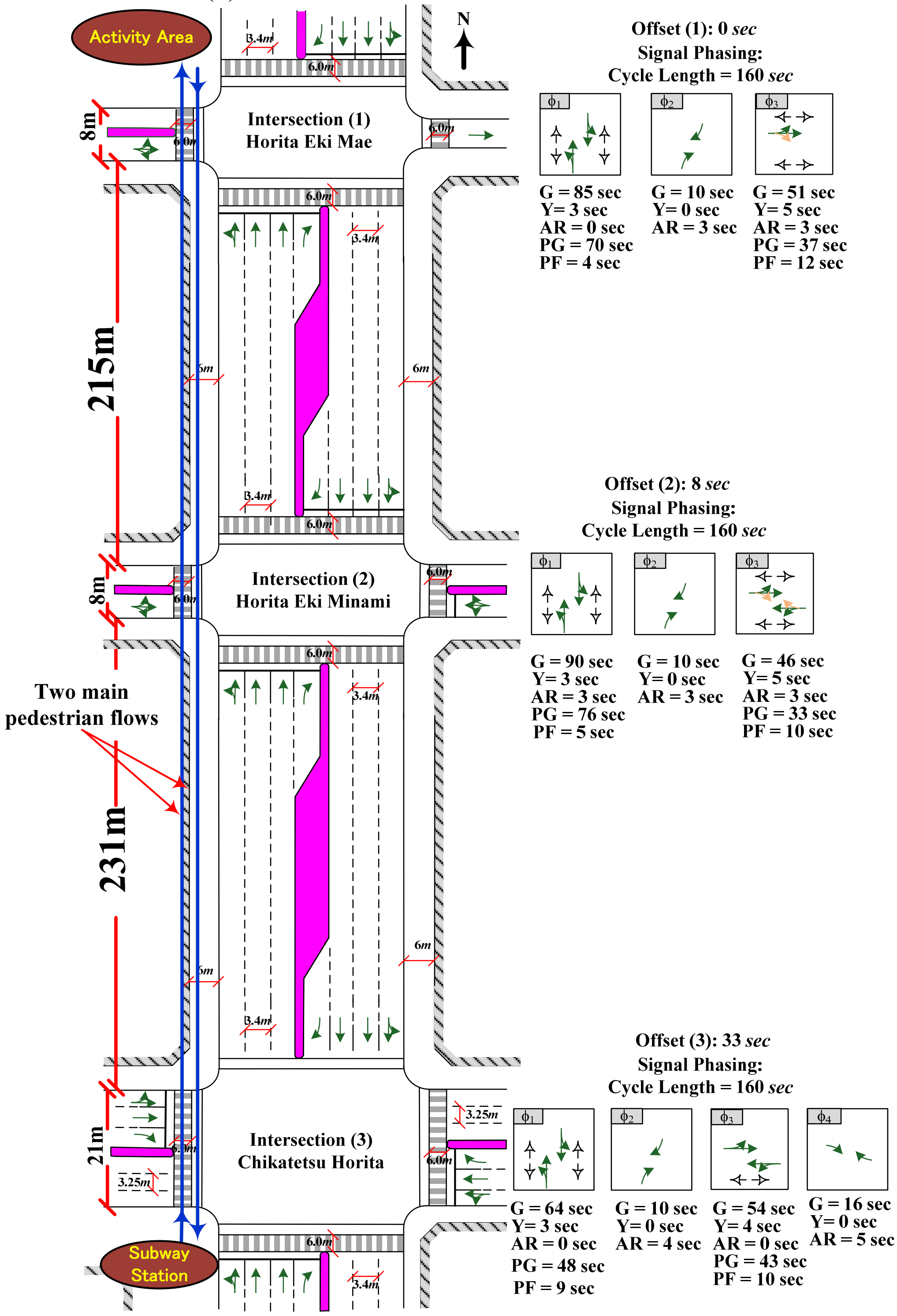


Figure 1. Geometric characteristics and existing signal timings of the case study

Table 1. Observed vehicle demand at each intersection in the corridor

Approach	Horita Eki Mae Intersection			Horita Eki Minami Intersection			Chikatetsu Horita Intersection		
	Vehicle demand *veh/hr*								
	TH	LT	RT	TH	LT	RT	TH	LT	RT
North	1416	21	37	1288	27	88	1076	184	125
South	1166	85	15	1418	26	26	1124	30	120
East	-	-	-	157	38	34	804	74	133
west	45	10	18	48	11	20	688	172	58

Note: TH : through traffic; LT : left turning traffic; RT : right turning traffic.

Regarding pedestrian demand, it was assumed that there are only two pedestrian flows between the two destinations (subway station and the activity area) on the western side of the main corridor as shown in Figure 1. The major flow departs from the subway station to the activity area, while the minor flow goes in the opposite direction. The major flow demand is assumed to be 2500 *ped/hr* while the minor is assumed to be 600*ped/hr*. The major flow is similar to the typical peak-hour demand in business centers in Japan. The selection of high demand is made to easily illustrate the effectiveness of one-way coordination. In this case study, we designed three scenarios to evaluate the signal coordination performance for pedestrian flows and vehicular flows, respectively. Scenario (1) is the existing scenario, consisting of the observed timings from the field, as shown in Figure 1. Scenario (2) is under the optimal signal coordination for vehicular flows. Scenario (3) is based on the maximized bandwidth for major pedestrian flows.

In this case study, all three scenarios have the same cycle length and green splits, as illustrated in Figure 1. Furthermore, trip delay is chosen as the measure of effectiveness for the evaluation of signal coordination. The trip delay is calculated for each vehicle and each pedestrian who moves along the main corridor (main flow). Turning vehicles from the cross roads to the main corridor are also considered. It is noted that the trip delay is the difference between the actual trip travel time and the free-flow trip travel time. Thus, the trip delay does not only include the delay around the intersections, but also that on the links between intersections. In other words, the pedestrian trip delay also covers the delay due to pedestrians' interactions on sidewalk.

In Scenario (2), Synchro is utilized to optimize the network offsets for vehicular traffic. The optimal offsets are (0, 21, 152) with existing green splits and cycle length 160 seconds. For Scenario (3), we tried to maximize the ideal green band width for pedestrian flows. Because the northbound pedestrian demand is dominant, the "optimal" timing only considers the major pedestrian flow walking northbound. To estimate the optimum offset for the dominant pedestrian flow, Equation (1) is used. However, the main problem in using this model is on how to estimate average pedestrian speed at crosswalks.

According to Alhajyaseen and Nakamura (2009a; 2009b), the interaction between bi-directional pedestrian flows at crosswalks can be very significant. They proposed a sophisticated methodology to estimate the average crossing speed as a function of pedestrian demand at each side of the crosswalk, crosswalk geometry and signal timing parameters. Equation (2) presents the model used for estimating average crossing speed for the subject pedestrian flow.

$$\bar{v}_{cw} = \sqrt{(u_o)^2 - \frac{0.02 A_2 (\frac{A_1}{A_1 + A_2})^{0.791} L(u_o)^2 (C - g_p)}{w}} \quad (2)$$

Where: $\bar{v}_{cw}$ is average pedestrian crossing speed (*m/s*), u_0 is average free flow speed (*m/s*), $A_1$and A_2 are the pedestrian arrival rates of the subject direction and opposite direction respectively (*ped/s*), L is crosswalk length (*m*), w is crosswalk width (*m*), C is cycle length (*s*) and g_p is pedestrian green (*s*).

Lam et al. (2003) found that the effect of the interaction between bi-directional pedestrian platoons at walkways is significant mainly at capacity conditions. Unlike the pedestrian interactions on crosswalks that are continuous throughout the whole area during green time, the major interactions on sidewalks occur when the majority of the pedestrian platoon faces the majority of the opposing platoon. According to the empirical data (Alhajyaseen and Nakamura, 2009b), the minor flow suffers much more than the major flow, especially with major flow dominant, since the minor flow faces many more interactions. Thus, for the major pedestrian flow, we assumed the average pedestrian speed is the same as their free flow speed, being 1.34 m/s. Based on Equation (1), the “optimal” offset combination for the major pedestrian flow (northbound) is calculated as (0, 155, 104).

Table 2 summarizes the results of simulation studies. For the major pedestrian flow walking northbound, the average pedestrian delay (APD) for scenario (1) with existing timing and scenario (2) with optimal coordination for vehicular flows are 116.17 (*s*) and 118.15 (*s*) respectively, which are very close. The APD for scenario (3) with “optimal” coordination for northbound pedestrian flow is 96.82 (*s*). The change of APD between scenario (2) and (3) is 15.19%. The statistical t-test shows that the change is statistically significant at the confidence level 95%. The minor pedestrian flow experienced much longer delay than the major pedestrian flow. This was because of a significant reduction in corresponding walking speed and significantly higher delays compared to the major flow. With considerations of the pedestrians on the opposite direction, the APD of both directions for scenario (2) and scenario (3) are 118.15 (*s*) and 108.01 (*s*), respectively. The difference was found to be 8.58%, which is also statistically significant.

Regarding the average vehicular delay (AVD), scenario (2) considers two-way coordination and keeps the delays for both bounds at 18.2 (*s*). Scenario (1) with existing timing has a much smaller delay 17.29 (*s*) for southbound vehicular traffic than 33.08 (*s*) for northbound vehicular traffic. On the contrary, scenario (3) with “optimal” coordination for northbound pedestrian flow also keeps the AVD for northbound vehicular traffic was estimated to be as low as 18.09 (*s*) in comparison with 33.64 (*s*) for southbound vehicular traffic.

In summary, the coordination for vehicular traffic and pedestrian traffic can be quite effective in reducing overall delays. The simple “green band” method can successfully reduce APD by 15% for the major pedestrian direction for this particular network. It means that the assumption of pedestrians walking as platoon is valid for the given network. However, does it mean that the simple “green band” method or other similar methods that assume pedestrian walking as a collective group would guarantee reducing network pedestrian delay?

Table 2. Performance of coordination for vehicles and pedestrians

Scenario		(1) Existing	(2) Vehicular coordinated	(3) Pedestrian coordinated
NB	APD (*s*)	**112.08**	**114.16**	**96.82**
	SPD (*s*)	**51.21**	**70.84**	**52.29**
	t-value*			**-9.33**
	Change*			**-15.19%**
All	APD (s)	**116.17**	**118.15**	**108.01**
	SPD (s)	**52.68**	**68.05**	**52.39**
	t-value*			**-6.22**
	Change*			**-8.58%**
NB	AVD (*s*)	**33.08**	**18.18**	**18.09**
SB	AVD (*s*)	**17.29**	**18.20**	**33.64**
All	AVD (*s*)	**25.11**	**18.19**	**25.94**

Note: t-value* and change* are for the comparisons between scenario (2) and scenario (3); NB: northbound; SB: southbound; APD: average pedestrian delay; SPD: st. dev. of pedestrian delay

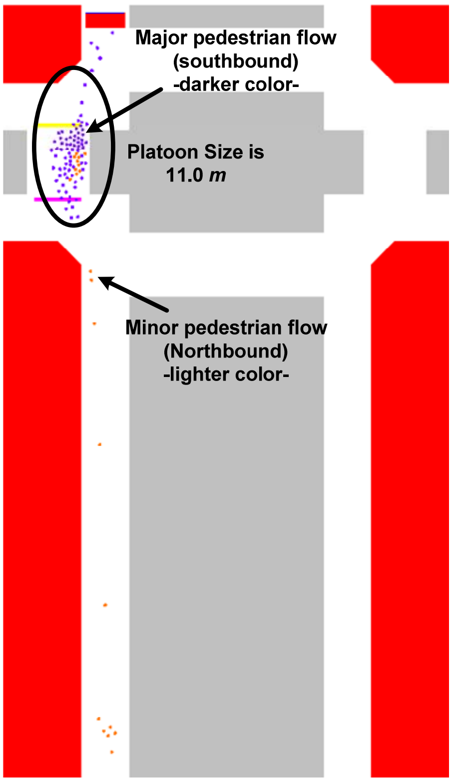
5. DISCUSSION

5.1 Dispersion of Pedestrian Platoons

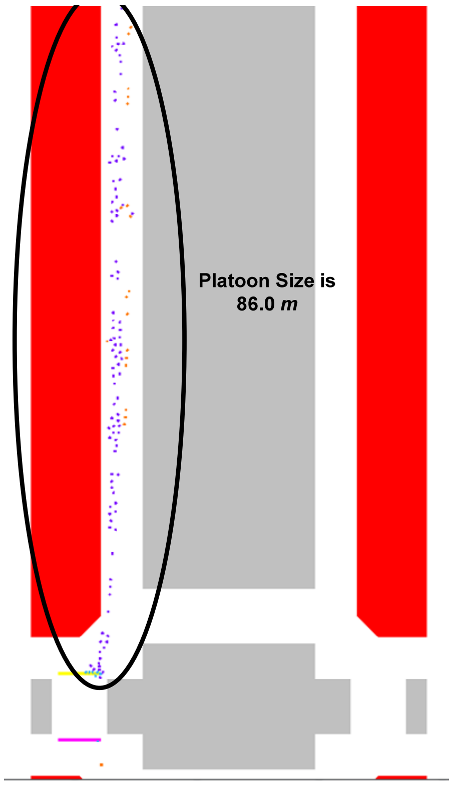
As mentioned earlier, the characteristics of pedestrian flow are quite different from those of vehicular flow. Thus, researchers and engineers should not simply use the same methodology for vehicular traffic to coordinate signal timings for pedestrian traffic. One of the most unique characteristics of pedestrian flow is that pedestrians walk more freely. Pedestrians are not constrained by lanes, thus they easily pass slower pedestrians and form minor platoons within which pedestrians have similar desired walking speeds.

It is essential to understand pedestrian platoon dispersion when designing coordination for pedestrian traffic. The speed difference, platoon formation and the interaction between pedestrians are essential factors in defining the shape of the pedestrian platoon and further in determining the efficiency of the signal coordination. According to the most popular platoon dispersion model for vehicles by Robertson (1969), the vehicular platoon dispersion is mainly due to the external friction of a platoon and not due to the internal interactions among vehicles. Thus, the platoon dispersion factor is given for three types of conditions in relation to such external frictions. Pedestrian platoon dispersion is quite different from that for vehicular platoon because pedestrians choose their speeds more freely than vehicles that follow each other on dedicated lanes. Therefore, pedestrian platoon dispersion should refer mainly to the desired speed difference in a pedestrian platoon.

Given that NOMAD operates as a fully calibrated microscopic simulation model for pedestrian studies, we tried to observe the platoon dispersion from NOMAD. Some platoon dispersion data, e.g. platoon size before and after dispersion as shown in Figure 2, have been collected. In Figure 2a, a pedestrian platoon at intersection (1) with a length of 11.2 meters is moving southbound. The same platoon reaches intersection (2) with a length of 86.0 meters. It is assumed that the distribution of pedestrians' desired speed is linear when a platoon has just been formed after passing a crosswalk. The fastest pedestrian leads the platoon while the slowest is at the end. Since in reality, the fastest pedestrians and slowest pedestrians become very far from the center of the dispersed platoon, therefore, it is assumed that 80% of the original platoon would form the dispersed platoon. Since in NOMAD pedestrians' desired speeds follow a normal distribution, the maximum and the minimum speeds ($\mu \pm 1.28\sigma$) are 1.69 m/sec and 1.03 m/sec, respectively. The observed average size of the platoon at intersection (1) is 11.2 m. By using the difference in speed between the fastest pedestrian and the slowest one, the size of the platoon at intersection (2) would be 99.8 m, assuming there are no interactions among pedestrians. The estimated dispersion (88.6 m) is close to the observed average dispersion (74.8 m) in NOMAD. The difference is mainly due to the ignorance on the interactions and attractions among pedestrians, which are dependent on platoon density and the possibilities of overtaking. Furthermore, the 80% used in this estimation above was arbitrarily selected and still should be calibrated by field data.



a) Pedestrian platoon shape intersection (1)



b) Pedestrian platoon shape at intersection (2)

Figure 2. Platoon formation and dispersion in NOMAD

Given the large dispersion, a pedestrian platoon might become a uniform arrival flow that covers a complete signal cycle at the downstream intersection. Adjusting signal offsets for coordination would benefit some portion of the pedestrian platoon but impair the other portion. In which case, any signal coordination might not be helpful to reduce APD. In order to verify the hypothesis, various network link lengths and different cycle lengths were selected for the sensitivity study using NOMAD. In the existing network with two 220-meter-long links as shown in Figure 1, both links were shortened to 120-meter-long and 160-meter-long links, respectively. Equation (3) can be used to estimate the arrival time difference for a portion (e.g. 80%) of a pedestrian platoon. With the same composition of pedestrian age group, the average walking speed is 1.34 (*m/s*) and the standard deviation is 0.28 (*m/s*). With the link length 120-meter, 160-meter, and about 223-meter for the network in Figure 1, 80%

of the pedestrian platoon would arrive at the downstream intersection with time difference 51.6 (*s*), 68.8 (*s*), and 95.9 (*s*), respectively.

$$t_p = \frac{L}{\bar{v} - \sigma \times \Phi^{-1}(p)} - \frac{L}{\bar{v} + \sigma \times \Phi^{-1}(p)} \tag{3}$$

Where t_p is the arrival time difference for a portion p of the pedestrian platoon; L is the link length; $\bar{v}$ and σ are the mean and standard deviation of walk speed for the given group of pedestrian and $\Phi^{-1}(p)$ is the quantile function for normal distribution.

5.2 Sensitivity Analysis

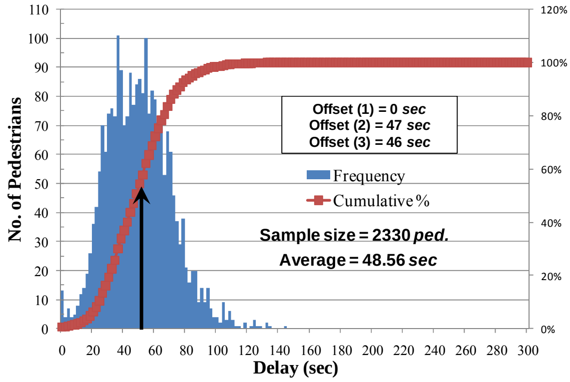
For each of the three networks, three cycle lengths, 50-second, 100-second, and 160-second, were tested in NOMAD. Synchro was used to calculate the optimal green splits for the three cycle lengths. It is noted that none of the three signals is over-saturated under 50-second cycle length.

When evaluating the performance of pedestrian coordination, it is not appropriate to compare the case with the vehicular coordination because the vehicular coordination might also benefit pedestrians in the case of a coincident combination of pedestrian speed, vehicular speed, and link length. In this study, we chose the comparison object as the “worst” coordination for a given network with a selected cycle length. Similarly with the “optimal” coordination that makes the leading average pedestrian face the beginning of green light at all signals, the “worst” coordination makes the leading average pedestrian have to face the beginning of red light at all signals. The difference between “worst” and “optimal” pedestrian coordination reasonably reflects the effectiveness of coordination.

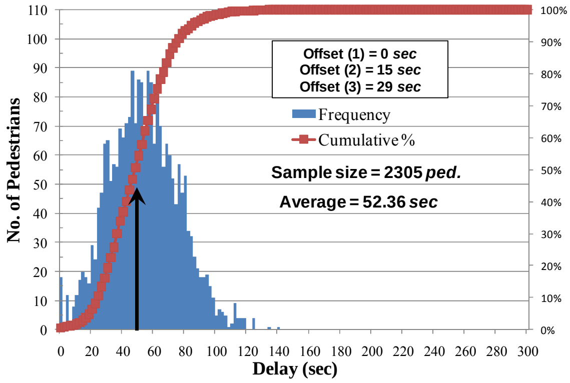
For the network with 120-meter link length, Figure 3 illustrated the distributions of major flow APD under cycle length of 50-second, 100-second, and 160-second. The differences between “worst” and “optimal” pedestrian coordination are 7.27%, 34.66%, and 49.59%, respectively. Although all three differences are statistically significant with a confidence level of 95%, the effectiveness of coordination for cycle length 50-second is not significant and the shapes of the distributions for “worst” and “optimal” coordination are very similar. One of the major reasons is that the 80% platoon arrival time difference 51.6 (*s*) is very close to the cycle length.

Figure 4 demonstrates the distributions of major flow APD for the network with 160-meter links. Under the 50-second cycle length, only 1.81% difference is found between the “worst” and “optimal” pedestrian coordination. The difference is also statistically insignificant. The main reason for the ineffective coordination is that the platoon arrival time difference 68.8 (*s*) is longer than the cycle length. In contrast, the cases with longer cycle lengths have statistically significant differences, i.e. 18.49% and 38.79%, between the “worst” and “optimal” coordination.

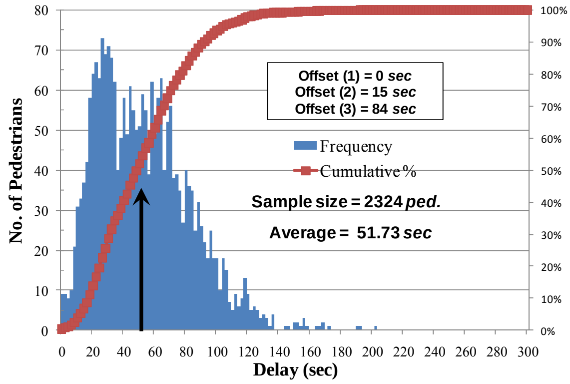
Lastly, the results for the original network with 50-second cycle lengths show no significant change of APD by designing the “green band” for the major pedestrian flow, as shown in Figure 5. It is because the platoon arrival time difference 95.9 (*s*) is much longer than the cycle length. Under 100-second cycle length, the maximum reduction of APD is only 13.18%, which is much smaller than 29.34% for 160-second cycle length. But both of the reductions are statistically significant with confidence level 95%.



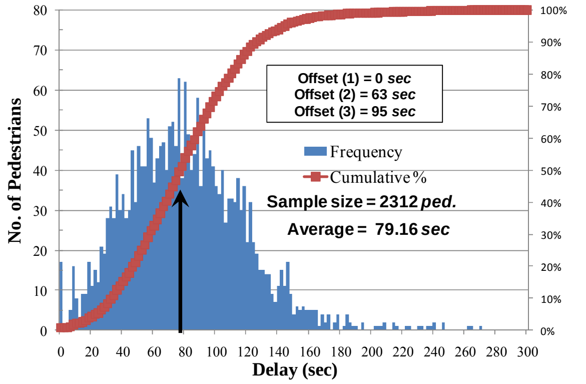
a) Assuming Cycle length of 50 *sec* and optimum offsets for pedestrians



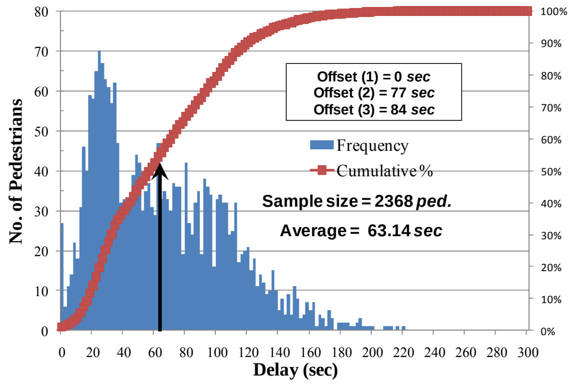
b) Assuming Cycle length of 50 *sec* and worse offsets for pedestrians



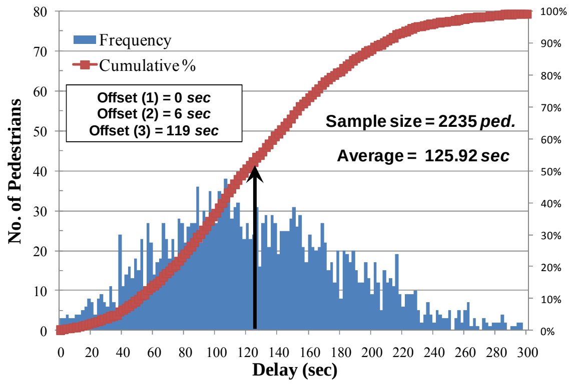
c) Assuming Cycle length of 100 *sec* and optimum offsets for pedestrians



d) Assuming Cycle length of 100 *sec* and worse offsets for pedestrians

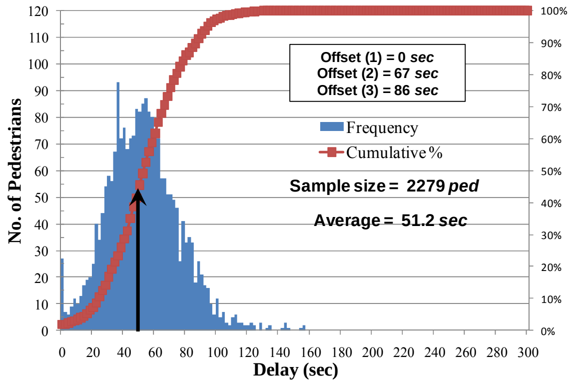


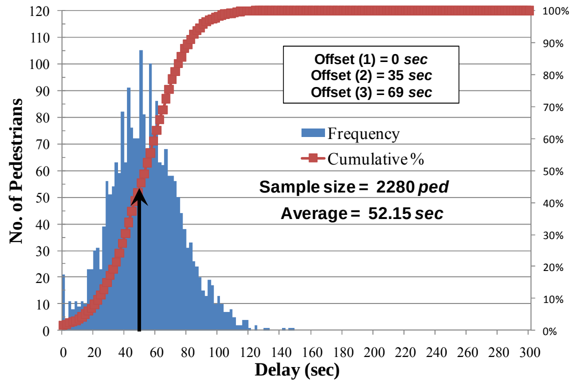
e) Assuming Cycle length of 160 *sec* and optimum offsets for pedestrians



f) Assuming Cycle length of 160 *sec* and worse offsets for pedestrians

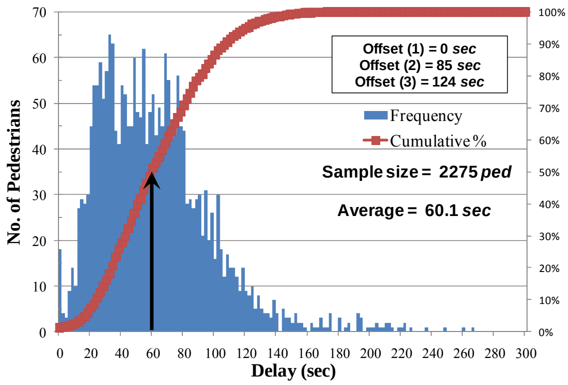
Figure 3. Average total delay for the major pedestrian flow assuming a 120*m* link length network

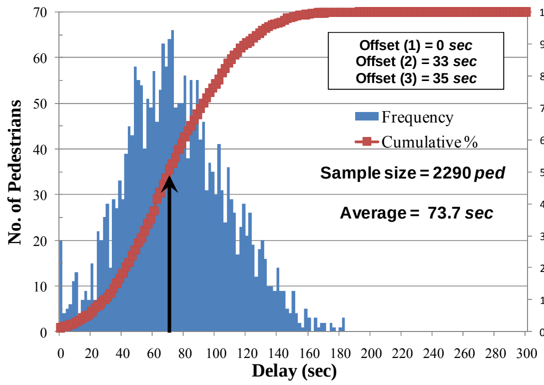




a) Assuming Cycle length of 50 *sec* and optimum offsets for pedestrians

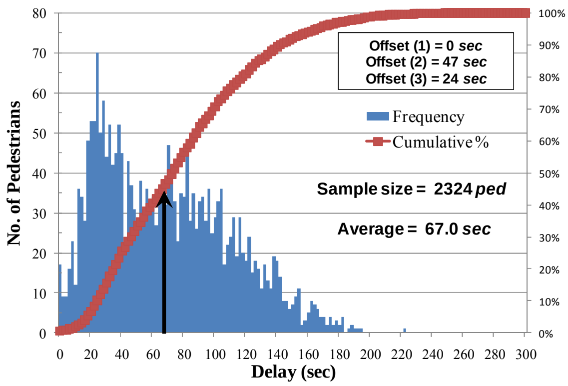
b) Assuming Cycle length of 50 *sec* and worse offsets for pedestrians

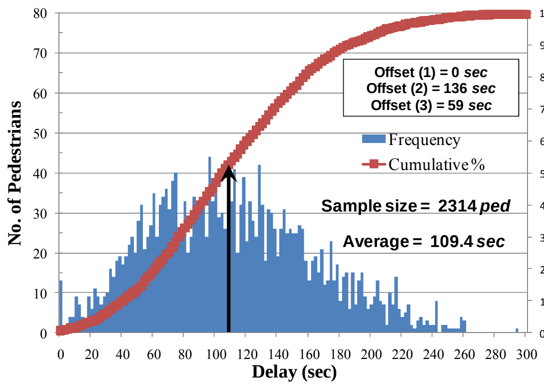




c) Assuming Cycle length of 100 *sec* and optimum offsets for pedestrians

d) Assuming Cycle length of 100 *sec* and worse offsets for pedestrians

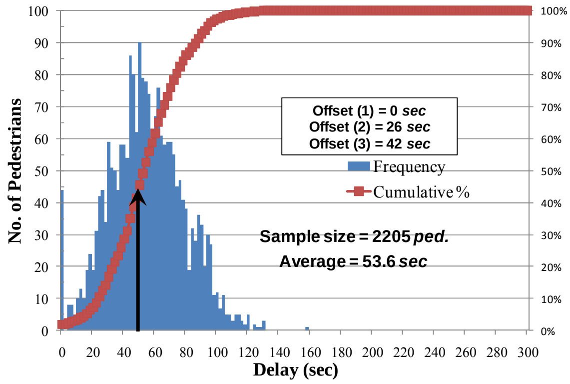




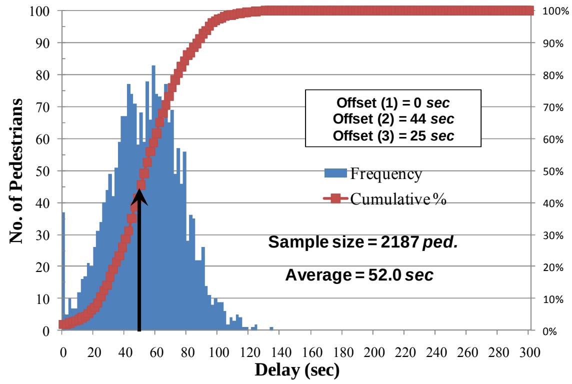
e) Assuming Cycle length of 160 *sec* and optimum offsets for pedestrians

f) Assuming Cycle length of 160 *sec* and worse offsets for pedestrians

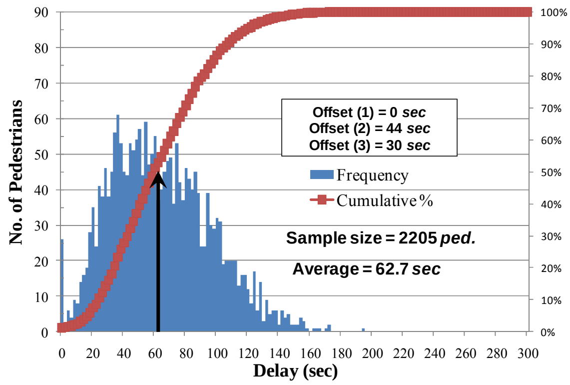
Figure 4. Average total delay for the major pedestrian flow assuming a 160*m* link length network



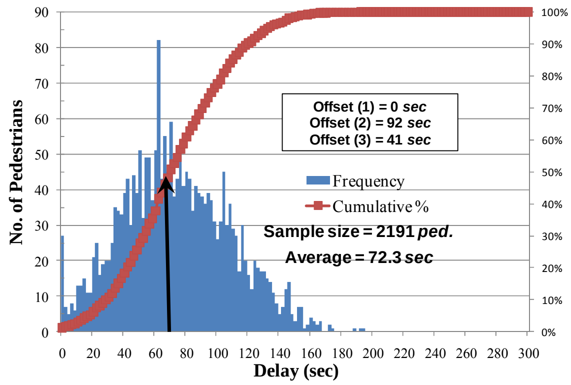
a) Assuming Cycle length of 50 *sec* and optimum offsets for pedestrians



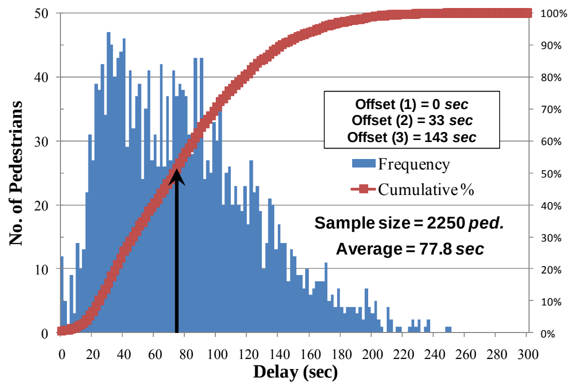
b) Assuming Cycle length of 50 *sec* and worse offsets for pedestrians



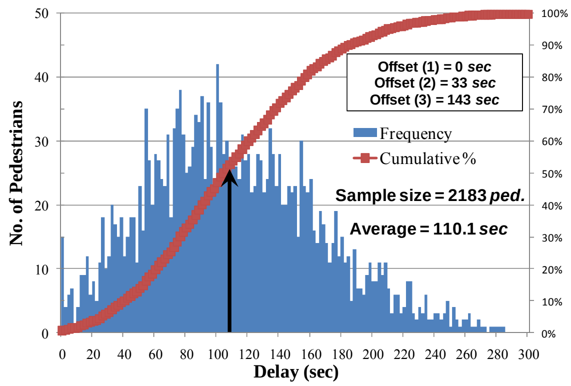
c) Assuming Cycle length of 100 *sec* and optimum offsets for pedestrians



d) Assuming Cycle length of 100 *sec* and worse offsets for pedestrians



e) Assuming Cycle length of 160 *sec* and optimum offsets for pedestrians



f) Assuming Cycle length of 160 *sec* and worse offsets for pedestrians

Figure 5. Average total delay for the major pedestrian flow assuming existing network with the real dimensions (Figure 1)

This means that the efficiency of signal coordination for pedestrian flows is not guaranteed, but depends on a few factors. The first factor is the composition of the pedestrian demand, which defines the distribution of pedestrians' desired walking speeds. The second factor is the link length between intersections. The third factor is the density of pedestrian flow that corresponds to the level of interactions among pedestrians. These three factors will decide the level of platoon dispersion and the arrival time difference at a downstream intersection.

When the arrival time difference is almost the same as the cycle length, the potential of reducing APD by coordination is limited. When the arrival time difference is longer than the signal cycle length, adjusting the signal coordination would not be expected to reduce APD.

6. CONCLUSIONS AND FUTURE WORK

Through this study, the signal coordination has been evaluated for both pedestrian and vehicular flows. A Japanese numerical case study is analyzed. The Synchro and SimTraffic simulation package was utilized to estimate average vehicular delay, while NOMAD was used to estimate pedestrian delay under various signal coordination settings.

Field survey is conducted to collect the geometric characteristics, signal timings and vehicular traffic condition information of the case study. In a parallel approach, the performances of signal coordination for vehicular traffic and pedestrian traffic are estimated by using vehicular simulation tool Synchro/SimTraffic and pedestrian simulation tool NOMAD. The results of the case study analysis showed that the coordination for the major pedestrian flow led to a significant 15% reduction in average delay.

It is found that the effectiveness of signal coordination for pedestrian flows is not guaranteed for all cases, but rather depends on the relationship between pedestrian platoon dispersion and the signal cycle length. Essentially, pedestrian signal coordination would not significantly reduce the pedestrian delay if the arrival time of the dispersed pedestrian platoon approximately covers a whole signal cycle at the downstream intersection. It is because the signal coordination that benefits a portion of pedestrian platoon would also impair the other portion of the platoon. Since Japanese signalized intersections are characterized by long cycle length (120 ~180 sec), pedestrian coordination can be considered as an important tool to reduce total delay especially at high demand conditions.

The design of signal coordination for pedestrian flows is much more complicated than that for vehicular flows. Thus, the effects of road network layout (link length) and platoon dispersion should be carefully considered in the signal operation. A microscopic approach for analyzing the behavior of pedestrian platoons and their dispersion is necessary. Further, an empirical model to quantify such dispersion considering the composition of pedestrian platoon would be very useful.

In developing countries, the behavior of pedestrian platoons and their compliance to traffic rules are different from that of developed countries which can be expected to significantly affect the performance of signal coordination. Therefore, theses differences in pedestrian platoon dispersion behavior and pedestrian compliance need to be further analyzed and considered in the design of signal coordination for pedestrian flows.

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