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Evaluation and Improvement of Coordinated Traffic Signal for One-way Arterial Road in Urban Area in Hanoi City

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Abstract: Coordinated traffic signal by applying green wave's methodology along arterial roads is one of the most common strategies to reduce travel time as well as fuel consumption in the urban area. However, in mixed traffic in Vietnam where four-wheeler vehicles are not the dominant in the road, it is more difficult to optimize traffic signal due to chaotic movement behavior of drivers. The objective of this paper is to introducing speed variations of vehicles among different links, and use those values to increase the effectiveness of signal coordination. A site experiment for observing traffic current situation in a one-way corridor in Hanoi city center was conducted to verify the usage of this method.

Keywords: coordinated traffic, green-wave, travel time, urban arterial road, bandwidth optimize

1. INTRODUCTION

In the urban area, traffic congestion is a crucial issue that not only makes travel time of drivers much longer but also increases emission as well as fuel consumption. According to (Economic Research Institute for ASEAN and East Asia, 2016), the transportation sector is the fastest growth (9.2%) comparing with industrial and residential or commercial sector, and in 2040, the total energy consumption could reach 30 million tons of oil equivalent (mtoe). By applying an alternative scenario to reduce traffic jam, 1.2% of energy consumption could be saved, which equal to 0.4 mtoe.

Among many solutions which have been developed throughout history, traffic signal control is generally known as one of the most effective and efficient countermeasures. At first, an isolated intersection control scheme was used to minimize driver's delay at a single intersection. If the distance between two consecutive junctions is not too long, all intersections in the network could be considered as a group and travel delay could be optimized much better (Baass, 1983). Cars running along the corridor could have a minimum number of stops with well-designed coordination system. Therefore, previous researchers have attempted to develop coordinated signal control strategies to improve the performance of all intersections along arterial roads (e.g. Little, 1966; Messer, 1973; Chang, 1988; and Gartner, 1990).

A concept of green-wave was introduced to optimize traffic signal and showed a great benefit for a linear system. Several researchers have created well-designed signal coordination model such as PASSER II (Messer, 1973) and MAXBAND (C.Little, 1981) to maximize the green bandwidth efficiency with the assumption that all vehicles have the same speed. It could be true for the normal traffic where car is the dominant in the roads and drivers adhere to car following models. However, in mixed traffic with a high proportion of motorbike as well as chaotic movement behavior in Vietnam, the velocity of vehicles among links could vary greatly. As a result, typical signal coordinated algorithms could not work well.

In corridor signal coordination, there are three typical parameters including cycle length, green split, and link length. In addition, we also consider two variables that are the differences in mixed traffic: speed variation and road approaching sensibility, which represents the capability of the driver to go inside or outside the road directly in mid-block section. To simplify the problem, in this paper, we only focus on the one-way arterial road, and further work will be made to apply for the two-way road. Current problems will be recognized by in site experiment, and then coordinated traffic system would be improved by applying our methodology adjustment.

The remaining parts of the paper are organized as follows. Section 2 summarizes some typical coordinated traffic signal control by previous researchers. The methodology to optimize traffic signal coordination will be discussed in section 3. In section 4, in site experiment will be introduced. In this chapter, the current traffic situation of the survey road would be evaluated, and followed by some adjustments for network signal improvement. Finally, we conclude this paper in section 5.

2. LITERATURE REVIEW

2.1 Traffic Signal Coordination

The main objective of traffic signal coronation is to keep the vehicle running without stop through the networks by proper time set. There are four main variables in coordinated signal control including cycle time, green splits, offsets, and bandwidth. Cycle time is the duration from the start of a green phase to the start of the next one while green splits of a direction (inbound or outbound) is the proportion of green light time in that direction. The signal offset is defined as the time displacement of green splits to make uninterrupted traffic flow (Pillai, 1998). Bandwidth concept is the windows of green that vehicle could move without a stop in the whole system. Previous researchers have developed many coordinated signal algorithms, which could be divided into two groups: mathematical model and simulation-based model.

The mathematical methodology mainly focuses on how to maximize the bandwidth (Morgan and Little, 1964; Little, 1966; Gartner, 1975; Cohen, 1983; and Liu, 1988). MAXBAND is one of the most famous bandwidth optimizations (Little, 1981). This program could solve the problem not only for the linear system but also triangular networks. After that, many researchers made further studied to expand the mathematical algorithms to apply to a more complicated system (Chang, 1988; and Tian, 2007).

On the other hand, the simulation-based approach considers traffic flow interactions to minimize system delays as well as the number of stops (Robertson, 1969; Lieberman, 1983; and Wallace, 1988). These models use macroscopic simulation and nonlinear optimization-based gradient search techniques to determine the most suitable time plans for the network.

The mathematical and simulation-based models that were discussed above basically use historical traffic data to optimize the signal timing, or in another way could be known as offline coordinated models. Recently, to help traffic operator control more efficiently, many online programs have also been developed (Hunt, 1981; Sims, 1980; Lowrie, 1992; and Luyanda, 2003). However, online traffic coordination required huge data from the onboard unit to provide vehicle movement information, which is a tough issue for mixed traffic with a high proportion of motorbike as Vietnam case. Therefore, in this research, we aim to use historical data to improve the coordinated traffic system. In addition, up to now, there is no coordinated traffic signal model specialized designed for mixed traffic. Hence, a typical feature of mixed traffic flow, which is road approaching capability will be discussed. Moreover, speed variation, a parameter that most offline coordination methods do not investigate would also be considered.

2.2 Intersection Performance Measures

Performance of intersection could be assessed by the delays, the number of stops and travel speed of vehicles in the corridor. In the Federal Highway Administration's Traffic Signal Timing Manual (FHWA, 2015), bandwidth efficiency is also used to evaluate the coordinated traffic system.

According to the Highway Capacity Manual (HCM), the delay is defined as the additional time that driver have to pay while traveling. HCM also classify level of service (LOS) for signalized intersection in term of delay to six classes with delay thresholds: A: less than 10; B: from 10 to 20; C: from 20 to 35; D: from 35 to 55; E: from 55 to 80 and F: more than 80 sec/veh. The number of stops reflects the effectiveness of the traffic network. If this value is low, the delay of the vehicle along the corridor would be lower, and fuel consumption could be reduced as well. Travel speed could represent for both the delay at intersections and the travel time along the network. In HCM 2000, LOS of the urban street could be grouped based on travel speed as table 1.

Table 1. HCM 2000 Urban Street LOS Criteria

Urban Street Class	I	II	III	IV
Free flow speed	80 km/h	65 km/h	55 km/h	45 km/h
LOS		Average speed (km/h)		
A	> 72	> 59	> 50	> 41
B	> 56 - 72	> 46 - 59	> 39 - 50	> 32 - 41
C	> 56 - 72	> 33 - 46	> 28 - 39	> 23 - 32
D	> 56 - 72	> 26 - 33	> 22 - 28	> 18 - 23
E	> 56 - 72	> 21 - 26	> 17 - 22	> 14 - 18
F	≤ 26	≤ 21	≤ 17	≤ 14

Unlike the above parameters' assessment, bandwidth evaluation purely depends on the function of timing plan. According to (FHWA, 2015), bandwidth efficiency is given as formula (1)

$$E = \frac{B_A + B_B}{2C} \tag{1}$$

Where: B_A, B_B is bandwidths in the inbound and outbound direction;
C is cycle length in second.

If the efficiency value is from 0.37 to 1.00, it is a great coordination. When this number drops to 0.25 to 0.36, it is still good compression. Range from 0.13 to 0.24 means a fair coordinated system, while poor bandwidth efficiency is $E < 0.12$.

In the remaining part, the in-site survey's network will be evaluated based on all the criteria mentioned above to get a full view of the experiment arterial.

3. COORDINATED TRAFFIC SIGNAL APPROACH

From the literature review, we try to optimize cycle time *C*, green splits λ_i (green time over cycle ratio at intersection *i*), offsets oi and bandwidth from input data including traffic volume *V*, link length d_i (distance between intersection *i* and *i-1*), travel speed v_i (speed between intersection *i* and *i-1*), and road approaching capability α_i (the level of how easy vehicle can merge directly in the midblock between intersection *i* and *i-1*).

Intersection *i* will be denoted as Int_i, and Int_C represented the critical intersection, which means the intersection we cannot adjust the green time without creating a loss in total bandwidth. Green time for intersection *i* will be C. λ_i as illustrated in Figure 1.

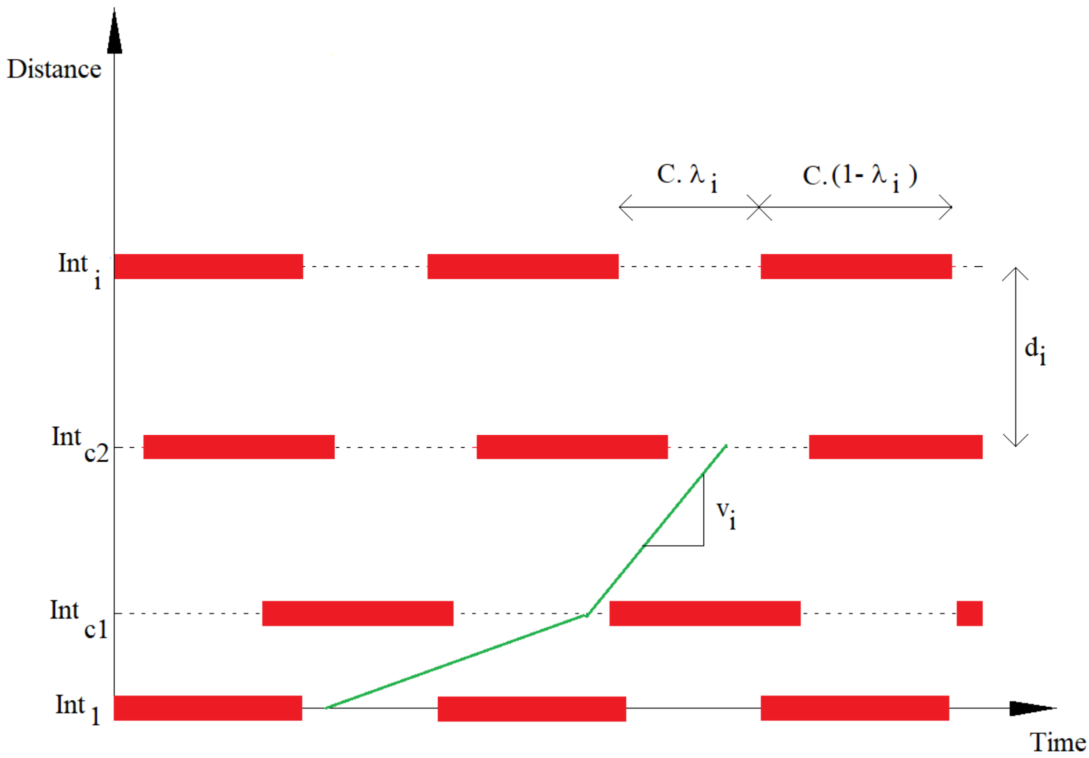

Figure 1. Coordinated signal system variables

In this research, one-way arterial road is targeted, while green splits λ_i depends on the priority level of the arterial over the remaining directions, green time $C.\ \lambda_i$ of each intersection could be estimated proportion with the ratio of traffic volume *V* and the number of lane *b*. If the ratio *V/b* of Int_i is larger than Int_{i+1}, $C.\ \lambda_i$ need to be larger than $C.\ \lambda_{i+1}$. Moreover, $C.\ \lambda_i$ also depends on the road approaching level α_i, a significant feature of mixed traffic in Vietnam. After stopping for a while, a motorcycle could surf in the traffic flow easily in between links, so if there are any special destination such as school, hospital or shopping center in midblock locations. As a result, C. λ_i could be higher since drivers from mainstream loss their speed by confronting with the merged vehicles. The green time C. λ_i of Inti could be estimated from $C.\lambda_{i+1}$ as the following objective function:

$$C.\ \lambda_i = \left(\frac{V_i/b_i}{V_{i-1}/b_{i-1}} + \alpha_i\right) C.\ \lambda_{i-1} \qquad (2)$$

After considering the objective function for all intersections in the corridor, optimum $C.\ \lambda_i$ value of each intersection could be proposed. In addition, Int_C will be the intersection with lowest $C.\ \lambda_C$ since it could not add or remove green time without lose the bandwidth efficiency. From the timing plan of Int_C, offset for other intersections could be identified base on speed between two consecutive junctions. Let P_{UC} and P_{LC} are the projections of the start and end moment of green time in Int_C. To maximize the green bandwidth, there are two cases for the offset as Figure 2. In the first case, there is a time gap between starting green moment of Int_{C-1} and P_{UC}, while the other means the gap lies between ending green moment of Int_{C+1} and P_{LC}. Hence, the offset distance could be calculated as:

$$O_C = (C.\ \lambda_C - C.\ \lambda_{C-1}) + \frac{d_c}{v_c} \qquad \text{(lower case)} \qquad (3)$$

$$or\ O_C = \frac{d_c}{v_c} \qquad \text{(upper case)} \qquad (4)$$

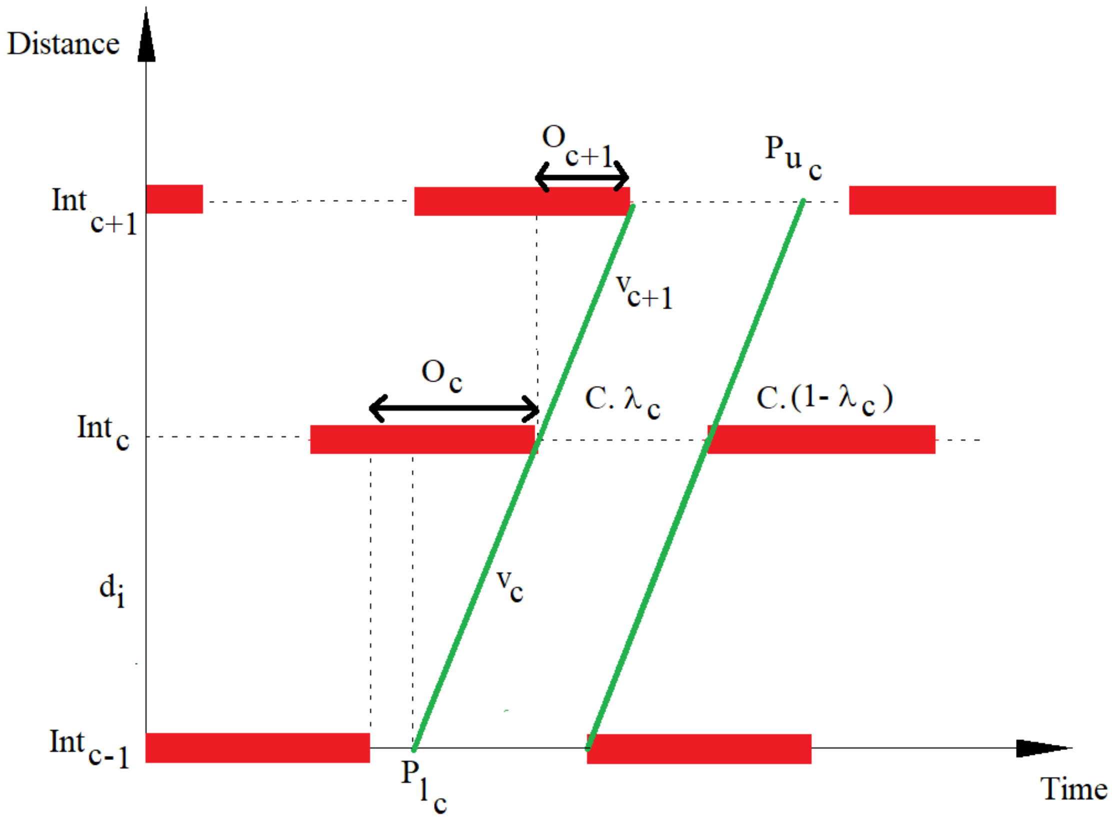

Figure 2. Offset calculation

In concluded, four variables mentioned above could be estimated from the priority level of the arterial over other directions and three objective functions (2), (3), and (4). When applying to improve traffic signal coordination of current network, if we keep C unchanged and just adjust λ_i, the crossing traffic flow could experience a decreasing green time, which can create traffic congestion in this direction. However, keeping the time split λ_i and arrange C may cause higher cycle length for both directions. Therefore, one stream might not need this increasing green time while other traffic flow has a higher waiting time. As a result, after estimating $C.\ \lambda_i$ value of each intersection, the addition or subtraction of green time will be computed directly to the cycle length C, which mean both C and λ_i might be changed after traffic coordination improvement process.

4. EXPERIMENT

4.1 Experiment Overview

The experiment was conducted on Thursday 4nd October 2018 along Ba Trieu Street. This is a crowned one-way road stretching from Hoan Kiem Lake to the south-east area of the city with more than 1,500 passenger car unit per hour. According to HCM, Ba Trieu Street could be classified as urban arterial road class III, with an expected free flow speed of 50 km/h. The network of six consecutive intersections in Ba Trieu Street was chosen to place a video camera for traffic information gathering as Figure 3. The distances among sets of intersections are 200 m, 350 m, 175 m, 205 m, and 200 m, respectively, which are fit for green-way strategy implementation.

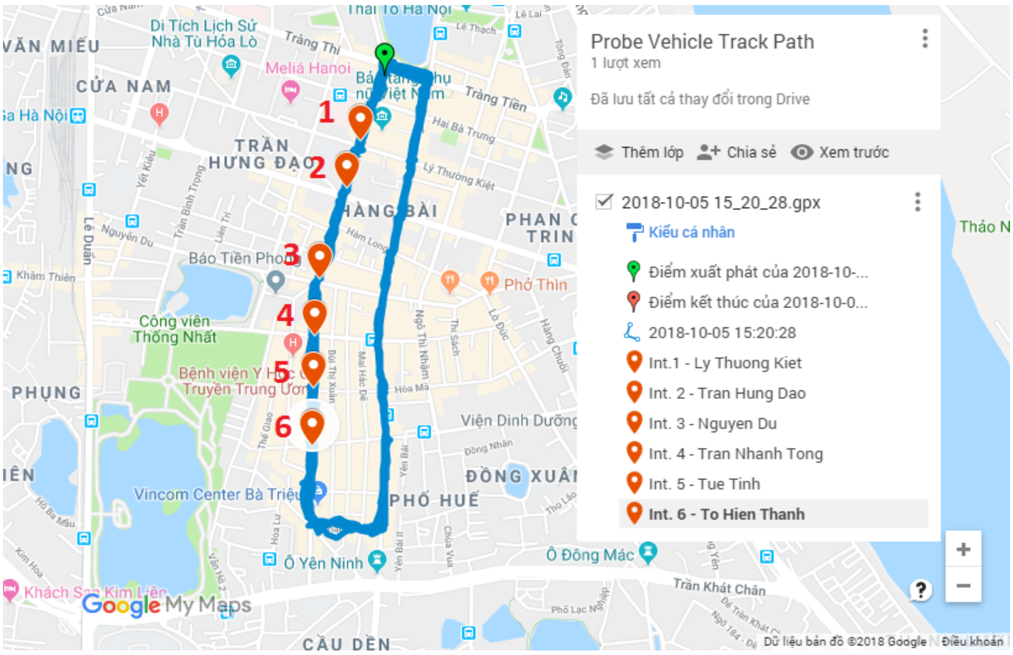

Figure 3. Experiment layout

In addition, seven probe vehicles were run along the arterial during two-hour survey period from 15:30 to 17:30. They include five motorcycles running normally and two motorcycles representing cars by chasing technique, which means the motor drivers follow one car during their path. If the car gets out of the corridor, the probe vehicle driver will chase another. Each driver carried GPS recording equipment to save position with a two-second interval, and run along Ba Trieu Street as a blue line in Figure 3. They were also requested to mark if they were stopped at the traffic signal. In total, there were 62 successfully recorded trips from probe vehicle drivers, and it will be used for data analysis in the next section.

4.2 Current Traffic Evaluation

From video camera data, the control delay per vehicle for each intersection could be calculated as table 2. It is clear from the table that if we consider these intersection isolatedly, LOS value is inside acceptable range which mean vehicle could run through each junction in Ba Trieu Street with delayed time in between 10 and 20 seconds per vehicle. It is a reasonable result since from the perspective of probe vehicle driver, stopped time at an individual intersection is not too much.

Table 2. LOS of six intersections in Ba Trieu Street

Int	Volume (pcu/h)	Lanes number	Saturation flow (pcu/h/lane)	Cycle length (s)	Green time(s)	Delayed time per vehicle (s/veh)	LOS
1	1646	3	2000	68	27	11.6	B
2	1489	3	2000	73	30	10.1	B
3	2128	3	2000	70	27	20.6	B
4	1533	2	2000	80	47	15.9	B
5	1250	2	2000	70	27	15.7	B
6	1475	2	2000	70	32	17.6	B

However, from probe vehicle track information, the negative view could be seen. There are only seven uninterrupted trips out of 62, account for 11.29 percent. Nearly half of probe vehicle (29 times) need to stop once during traveling, while the number of trips that has more than two stops is 26. Probe vehicles normally are stopped by signal at intersection three, four and five with 20, 25 and 33 times respectively.

In addition, travel speeds of probe vehicles were also calculated for the whole network as well as each segment. Results show that the highest speed of one route is 24.66 km/h, represents a non-stop path, while the slowest route is 12.88 km/h with three interrupted moments. Analyzing in larger scale, all seven trips with 0 stop rank in top 10 fastest routes and could reach LOS D while the others only have LOS E. There are only three trips could be classified as LOS D, the acceptable service rate for urban arterial road class III like Ba Trieu Street. 32 routes rank D, and the remaining samples (27 trips) have the velocity less than 16 km/h (LOS F).

When computing speed for each segment among six intersections, if the driver has to stop at Inti the signal waiting time will be subtracted from the total travel time to get the real time needed to accomplish this section. The average velocity in section 1-2 is highest (24.52 km/h) while another link 3-4 has the lowest speed (18.07 km/h). The value for link 2-3, 4-5, and 5-6 are 22.32, 20.73, and 19.32, respectively. The standard deviation of velocity between intersection 1 and 2 is also lowest (3 km/h), while other segments' value is larger than 4 km/h. The overall results from probe vehicle data are summarized as Table 3.

Table 3. Probe vehicle data

Segment	1-2	2-3	3-4	4-5	5-6	All route
Interrupt trips	2	20	25	33	11	91
Ave. Speed (km/h)	24.51	22.32	18.07	20.73	19.33	16.82
Std. Speed (km/h)	3.16	3.88	4.5	4.56	4.26	2.35
LOS C	9	3	2	0	0	0
LOS D	30	26	6	20	10	3
LOS E	21	30	35	32	42	32
LOS F	2	3	19	10	10	27

If we look closer to the experiment plan, it clear that the distance between intersection 1 and 2 is relatively short (200 m) and there is no special location (as defined above). As a result, traffic situation in this part is better, expressed by all criteria. On the other hand, this is the outbound one-way traffic flow in the evening time, the vehicle has trend to move out of the city center, and in the midblock between other segments, there are some big destination such as Central Eye Hospital between intersection 3 and 4, complicated junction at 3, many street coffee and small shops from 4 to 6. We can also see how unstable the traffic volume is in this arterial as Table 2 data. The flexibility of motorbike causes this fluctuated volume among links. As a result, traffic of the arterial road has to suffer higher impact followed outbound direction and travel speed reduced 2 to 6 km/h. Moreover, the direct merged flows from midblock section are unpredictable. Hence sections with higher i also have higher speed standard deviation.

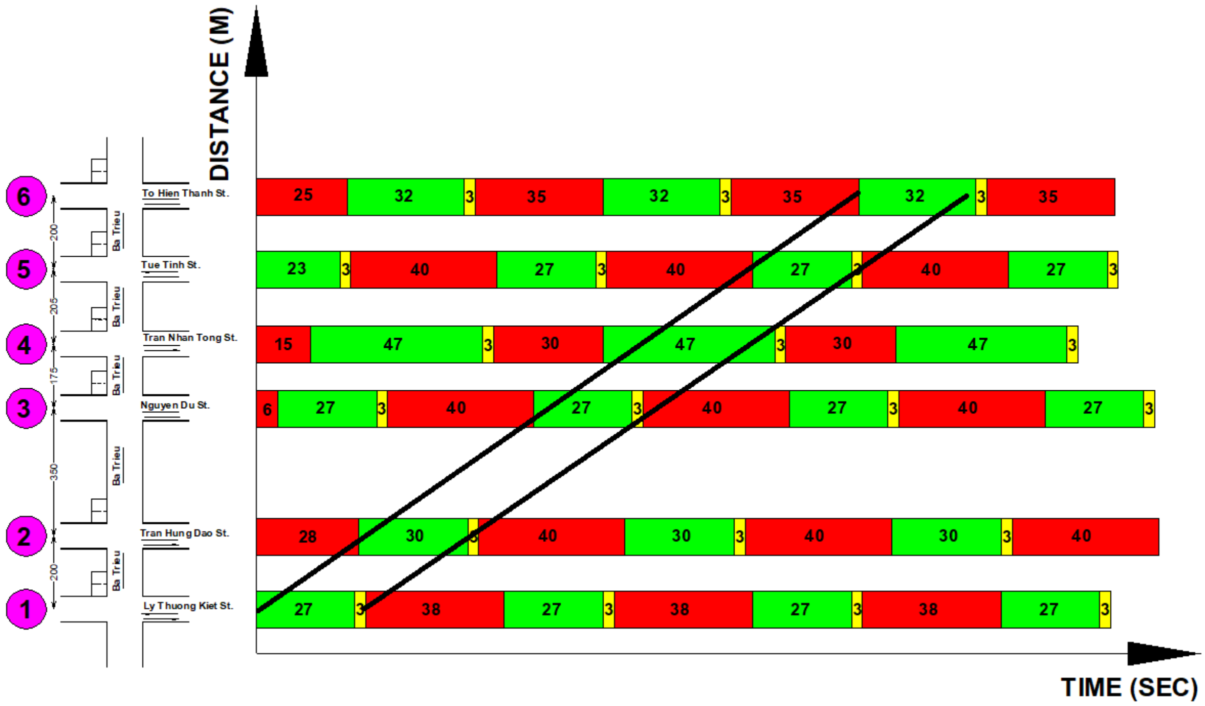

Figure 4. Current time splits of six intersection in Ba Trieu Corridor

These evaluations imply that the effectiveness of signal coordination in Ba Trieu arterial is bad and need to make some improvements. However, when investigating green splits in the arterial from video camera data during the survey, we could experience a good design of green-way, and the bandwidth efficiency should be high as Figure 4. As the optimum bandwidth in Figure 4, the network signal coronation is quite smooth with E value equals to 0.34 representing good coordination in term of theoretical. The problem in this situation is that when designing the signal coordination, traffic operators use the typical assumption that the velocity of vehicles unchanged during their movement. Therefore, even the coordinated traffic signal is well-designed, unexpected outcomes as the above analyzing section occur. As a result, the proposing methodology could make traffic in this corridor much better by modifying all variables including cycle time, green splits, offset and bandwidth of six intersections in Ba Trieu arterial road.

4.3 Time Splits Improvement

When investigating all six intersections in Ba Trieu Street, intersection two was chosen as a critical one due to the fact that it has average volume. In addition, traffic flow in 1-2 and 2-3 sections are stable, and currently, drivers could travel with high LOS. Base on the four input data including traffic volume, link length, travel speed, and road approaching capability, variables of each intersection have been modified following the proposed methodology in section 3 as table 4.

Table 4. Signal coordination improvement

Int.	Variable	Current	Adjust	Int.	Variable	Current	Adjust
1	Time cycle	68	71	4	Time cycle	80	80
	Green time	27	30		Green time	47	47
	Offset	---	---		Offset	19	40
2	Time cycle	73	73	5	Time cycle	70	78
	Green time	30	30		Green time	27	35
	Offset	28	30		Offset	41	35
3	Time cycle	70	78	6	Time cycle	70	78
	Green time	27	35		Green time	32	40
	Offset	48	56		Offset	29	35

After modification, the bandwidth efficiency E of the arterial is 0.375 which means great coordination in theoretical. Since this adjustment considers the speed variation as well as the flexibility of mixed traffic in Hanoi, other urban assessment criteria based on HCM could also be good. The green bandwidth of the improvement route is illustrated as Figure 5.

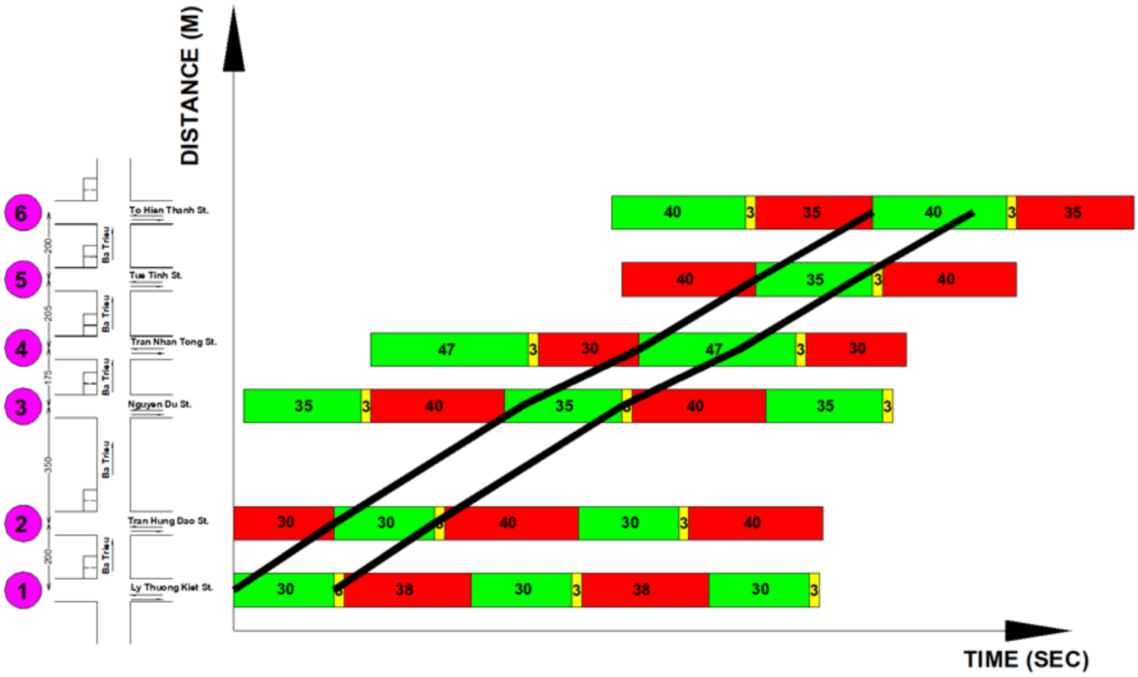

Figure 5. Signal coordination after adjustments

5. CONCLUSION

Mixed traffic in Vietnam is unlike anywhere in the world, so some typical traffic theories may not be applied directly. Further researches need to be made to modify well-known traffic algorithms and solve the congestion issue.

The study demonstrates the evaluation of signal coordination in a one-way arterial road in Hanoi, Vietnam. Follow some typical intersection evaluation criteria, the collaboration among signals is bad due to lack of considering speed variation between links as well as other feature of mixed traffic. The proposed methodology which introduces road approaching level could make the signal system along Ba Trieu road be better. However, there is a need to apply the modification to actual traffic and re-estimate the network to prove the effectiveness of this algorithm. In the next step, our research group will apply this principle to the two-way arterial road to verify the usage in more complicated circumstances.

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