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Quantifying the Benefits of Adaptive Split Feature on the Operation of Coordinated Actuated Traffic Signal System

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Abstract

Coordinated actuated traffic signal systems have been widely deployed in urban and suburban areas as they provide progression along the major corridors. However, it has been often observed that uncoordinated cross street movements experience higher delay under the coordinated actuated signal systems due to their inability to adjust maximum green times (or force-off points). A few studies mentioned the use of adaptive maximum or split to dynamically adjust maximum green on uncoordinated movements. However, no field implementation results were reported. The purpose of this study was to quantify the impacts of implementing an adaptive split feature on the operation of coordinated actuated traffic signal system through simulation, and then to validate such impacts through a field before-and-after study. The travel time on the coordinated arterials and the stopped delay on key approaches were selected as Measures of Effectiveness (MOEs) to assess the performance of adaptive split feature at the coordinated actuated signalized intersections. The field before-and-after study showed that adaptive split feature resulted in 18 to 38% reduction of stopped delay on cross street uncoordinated movements which is very similar as that estimated by simulation model. In addition, the travel time comparison of before-and-after study also showed that adaptive split feature would not have negative impact on the performance the coordinated approaches.
Keywords: *traffic signal, coordinated actuated signal control, adaptive splits, simulation, stopped delay*

1. Introduction

The first traffic signal control system in the world can be traced back to the manual traffic lights used in London as early as 1868 (Koonce *et al*., 2008). Traffic signals play an important role in the operation of traffic network. According to the 2009 Nationwide Personal Transportation Survey, an individual generally drives 40 miles per day and wastes about 36.1 hours on traffic delay annually (Schrank and Lomax, 2009). Obviously, the performance of the traffic network has great impact on the quality of life. Unfortunately, more than a half of the traffic signals in North America are in the need of repair, replacement or timing plan updates (Koonce *et al.*, 2008). Outdated and poor traffic signal timing accounts for a great portion of traffic delays on urban arterials. It is generally understood that updating the traffic signal system settings is relatively an easy and cost-effective way to improve traffic network performance when compared to adding new routes to the existing road network. In general, isolated actuated and coordinated actuated control systems are the two major traffic signal systems widely applied in the world.

Traffic engineers generally assume that the coordinated actuated traffic signal system performs better than the isolated actuated traffic signal system, because the performance of traffic signal system can be improved by providing progression along the major corridor (Skabardonis *et al.*, 1998; Buckholz, 1993; Bullock and Abbas, 2001). Ideally, the signal at an intersection should turn into green as soon as upstream traffic arrives. However, in practice, this is not always the case. There are several factors that could disrupt the progression on coordinated arterials including outdated offsets, early return to green and short-term variations in traffic patterns (Yun *et al.*, 2011; Mehran and Kuwahara, 2013). Under congested conditions large queues ahead of the stop line on a coordinated approach can disrupt progression, while vehicle actuation on uncoordinated phases may cause phase skip or phase gap-out that makes uncoordinated phases end earlier and the remaining green time would be allocated to coordinated phases under normal conditions. Then the coordinated phases would start earlier than planned, which may distort progression. In addition, coordinated actuated signal system may also cause more delay on cross street than isolated actuated signal system in certain conditions. For example, when there is no traffic demand on coordinated approach after the

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minimum green time, the coordinated phase can be gapped out in isolated actuated traffic signal system, but not in coordinated actuated traffic signal system.

On the contrary, experienced traffic engineers suggest that the adaptive split feature, which allows the traffic signal system to adjust the split time of the non-coordinated approaches in response to the variation in traffic demand, would improve the performance of coordinated actuated traffic signal systems on uncoordinated cross streets. This study intended to establish a simulation model to explore the potential benefits of implementation of adaptive split feature on the operation of coordinated traffic signal system and then make a field before-and-after study to verify the results from simulation model.

Adaptive split feature is a coordination feature which dynamically reallocates unused split time to heavier movements. It is technically different from the adaptive/dynamic maximum feature used at an isolated and fully actuated traffic control system. Under such an isolated and fully actuated signal control, the controllers with adaptive maximum feature can adjust the maximum green intervals for actuated phases within the upper and lower limits with a step size, according to the degree of traffic demands and their fluctuations (Yun *et al.*, 2007). There is no fixed cycle length under the isolated fully actuated signal control so that there is no problem in extending maximum green intervals for actuated phases using the adaptive maximum feature. However, under the coordinated actuated signal control, only unused split time of an unactuated phase can be reallocated to another unactuated phase whose traffic is heavy. There have been a few research efforts focusing on the impact of the adaptive/dynamic maximum green feature in the operation of actuated isolated traffic signal system, but the adaptive split feature have not received proper attention (Yun *et al.*, 2007; Park and Chen, 2010).

Traffic engineers implemented a base timing plan with the dynamic maximum green feature instead of generating an optimized timing plan for different time phase like off-peak and peak time. The research results showed that the base timing plan with the adaptive maximum feature provided equivalent performance as that of optimized timing plan in rural area (Click, 2008). This research was conducted via a software-in-the-loop-simulation. Obviously the results would be helpful for some rural traffic agencies that frequently struggle to provide reasonable traffic signal operation due to the lack of financial budget and the large variation in traffic demand.

The adaptive maximum green feature within actuated traffic signal operation was also evaluated via a microscopic simulation. Yun *et al*. (2007) evaluated an actuated traffic signal system with the adaptive maximum feature via a Hardware-In-The-Loop Simulation (HILS). VISSIM was used as a simulation model and the EPAC300 was used to control the traffic signal. This evaluation was conducted at an isolated actuated intersection. The results showed that the adaptive maximum feature outperformed the normal maximum green intervals. The average delay was reduced from 31.30 sec/veh to 28.07 sec/veh.

Currently, most 2070 NEMA controllers include the adaptive/dynamic maximum green feature, while the names vary by manufacturers. However, adaptive/dynamic split feature is only available at a few controllers. The Eagle controller implements the dynamic splits through the Coordination Adaptive Splits (CAS) feature while the Naztec controller provides it through the Critical Intersection Control (CIC) feature (Engelbrecht *et al.*, 2001). This may also be a reason that why adaptive split feature have not received proper attention among traffic engineers.

2. Background

According to the logic of the adaptive split feature, the goal of implementing it on the operation of coordinated traffic signal control system is to dynamically find and use the most advantageous splits. Because the split times for the coordinated phases are adjusted, the adaptive split feature only works for all uncoordinated phases. Adaptive split is achieved by monitoring the termination of each uncoordinated phase to determine whether the phase was gapped out or forced off. However, in order to make the adaptive split feature function adjust its splits, two conditions need to be occurred at the same time: (1) one phase is forced off by coordination for two consecutive cycles, and (2) the other phase is skipped or gapped out for two consecutive cycles. Otherwise, the adaptive split feature does not adjust its split. Fig. 1 shows an example of adaptive split feature operation.

As shown in Fig. 1, the total cycle length is 120 seconds with split times of 40:20:60 for phase 4, phase 1 and phase 2, respectively. The phase 2 is the coordinated phase where the split time is guaranteed – it could use additional green time if non-coordinated phases are skipped or gapped out. At the cycle number 1, the phase 4 forced off and the phase 1 gapped out (after 10 seconds of minimum green time). At the cycle number 3, with two consecutive gap-outs on the phase 1 and force-offs on the phase 4, the adaptive split feature moved two seconds of green time from the phase 1 to the phase 4. With continuation of gap-outs on the phase 1 and force-offs on the phase 4, two seconds of green times were moved at every two cycles. Finally,

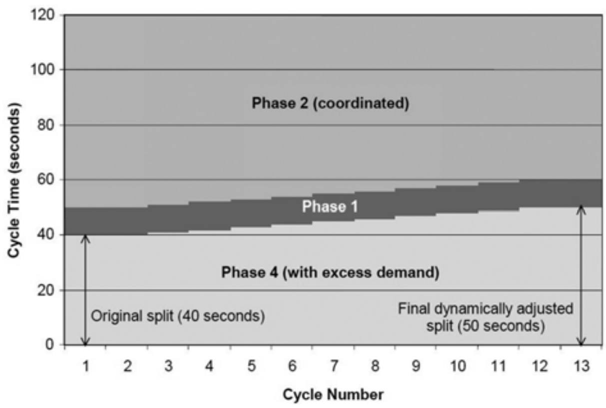

Fig. 1. An Example of Adaptive Split Feature Operation

at the cycle number 12, the phase 4 green was dynamically adjusted to 50 seconds while the phase 1's split time decreased to 10 seconds from 20 seconds, which was its original split time. It is noted that the actual split time of phase 1 is 20 seconds. However, due to light traffic demands, the phase was gaped out continuously. Because of the continuous gap-outs, the length of split time for phase 1 looks like 10 seconds in Fig. 1. It is noted that the performance of the phase 1 would not be impacted much, because it gapped out every cycle after 10 seconds. Of course, the phase 1 could gain green times if it does force-off and the phase 4 does gap-out or skip for two cycles in a row.

As noted, the adaptive split feature can only work with the coordinated actuated traffic signal system. In addition, the force off model has a huge impact on the operation of adaptive split feature because it decides when and how a phase is to be forced off. In general, there are two force-off models: one is the float force-off model and the other is the fixed force-off model. In case of the float force-off model that is commonly used in the coordinated actuated traffic control system, the unused split time from any uncoordinated phases can only be used by the coordinated phases. On the contrary, the fixed force-off model allows that the unused split time can be used by any following phase if necessary. Fig. 2 illustrates the difference between these two force-off models.

As shown in Fig. 2(a), the phase 2 is coordinated phase while the phase 3, 4, 1 are uncoordinated phases. Let us assume the phases 3 and 1 did gap-out and the phase 4 did force-off. As shown in Fig. 2(b), under the floating force-off model, once the phase 3 did gap-out, the force-off point of phase 4 moved to a new point which is earlier than scheduled. The unused green time from the phase 3 would not be used by the phase 4. This happens to the phase 1 as well. Thus, all unused split time from the phase 3 and the phase 1 are allocated to the phase 2. Thus, there is a possibility that the progression of the phase 2 would be disrupted due to the early return to green. On the contrary, as shown in Fig. 2(c), the unused split time from the phase 3 is to be used by the phase 4 under the fixed force-off model. In this case, the performance of the phase 4 could be improved by the extra green time and the likelihood of early return to green is reduced. Thus, when an adaptive split feature is implemented, the fixed force-off model is recommended.

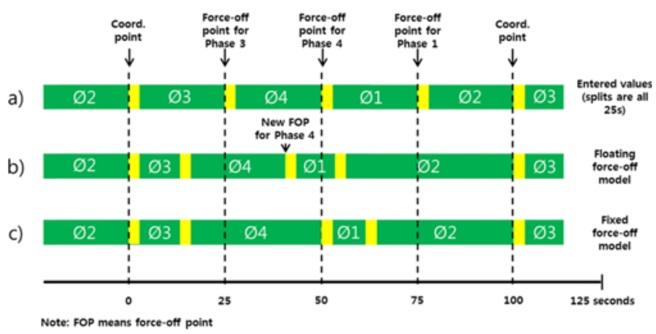

Fig. 2. Illustration of Different Force-off Models

3. Simulation Model Development

To understand the impact of the adaptive split feature and to develop an insight of implementing it in term of volume-to-capacity ratios, a simulation model calculating vehicular delays for with and without adaptive split feature under varying traffic volumes and cycle lengths was developed using a Visual Basic Application in the MS Excel program. The simulation model consists of two parts. The first part is MS Excel which generates randomly traffic demands for uncoordinated phases using 'rand' function. Based on the generated traffic demands, the second part, which is a Visual Basic code, calculates the inter-arrival times between consecutive vehicles, and then monitors the meet of conditions for the adaptive split features. During the development of the adaptive split feature, this study only focused on the delay impacts on cross streets. The decision was made in part to expedite the computation time. It is noted that the coordinated movements can be added into the simulation model if the adaptive split feature causes significant disruption on the coordinated approaches. This is to be determined from the field before-and-after study with and without adaptive split feature.

The arrival type of uncoordinated approaches was assumed to follow a Poisson distribution. Poisson distribution is a discrete probability distribution that expresses the probability of a number of events occurring within a fixed period of time if these events occur with a known average arrival rate and independence of the time since the last event (Kim and Lee, 2013). The equation is shown as follows:

$$P(x;\,\mu) = \frac{\mu^x e^{-\mu}}{x!} = \frac{(\lambda t)^x e^{-\lambda t}}{x!} \tag{1}$$

where,

$P(x)$ = Probability of x occurring in time interval t

t = Time interval over which x events occur

x = Exact number of events occurring during any time interval t

λ = Average number of events occurring per unit time

μ = λt, Average number of events occurring during time interval t

However, if no event occurs in time t (e.g., no vehicle arrives during time t), then:

$$P(x) = P(0) = e^{-\lambda t} \tag{2}$$

If no vehicle arrives during time t, there must have been a gap or time headway at least t seconds. This is the probability of a headway being equal to or greater than t, where h is the gap. So the probability that the gap may be less than t is:

$$P(h \le t) = 1 - e^{-\lambda t} \tag{3}$$

Thus, Eq. (3) was used to calculate the inter-arrival time between vehicles on non-coordinated approaches with a random number generated by a MS Excel function. Stopped delay was the only selected measure of effectiveness in this simulation study. Each vehicle's arrival and departure times were recorded to calculate the stopped delay. For the vehicles waiting at the stopped line at the end of each cycle, their delays are accumulated to the next cycle. The detailed simulation flow-chart is shown as follows:

As shown in Fig. 3, at the beginning, cycle length, volume-to-capacity ratio and green time was set. Once the simulation is started, the arriving vehicles for each phase were continuously generated until the end of the cycle. The arriving vehicles on uncoordinated phases wait until the coordinated phases terminate. If the phase 3 is skipped or gapped out, the entire or remaining the phase 3's green time is added to the phase 4. Otherwise, the phase 3 will force-off. If the phase 4 does force-off, green time from the phase 3 and the phase 4 green time are fully used. If the phase 4 does skip or gap-out, the remaining green time is added to the coordinated phase. At the end of each cycle, the simulation model calculates the phases 3 and 4 delays based on vehicle arrivals and departures, and adjusts the split time between the phases 3 and 4 based on the adaptive split logic. The remaining vehicles at the end of cycle are to be processed to the next cycle. To consider variability in vehicle arrivals, the simulation was repeated for 30 times with a new random seed at each run.

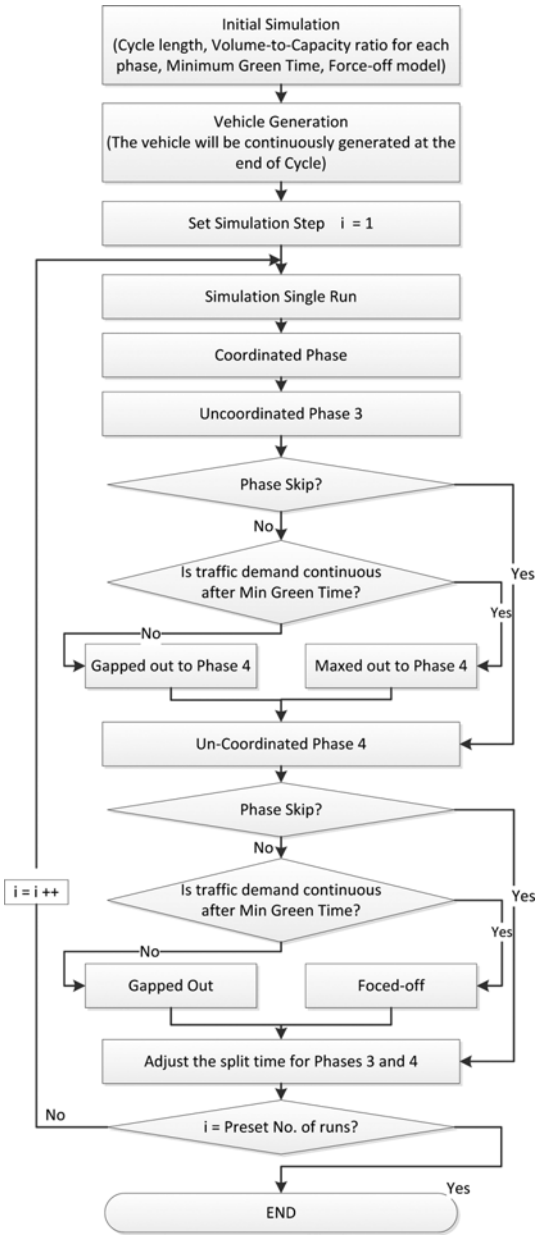

Fig. 3. Simulation Procedure of Adaptive Split Feature

4. Field Before-and-After Study

In order to validate the findings from the simulation model based evaluations, a field before-and-after study was conducted. Traffic volume, geometry and measures of effectiveness (i.e., stopped delay) data were collected from the selected study site. Stopped delay was used to validate the simulation model results and travel time were used to ensure the coordinated movements had similar delays during before-and-after study (i.e., with and without adaptive split feature).

The selected study site is located in Chesterfield County on US 60 as shown in Fig. 4. The total length of this site is about 3 miles, and the distance between adjacent intersections is in the range of 0.15 miles to 1.4 miles. An average traffic volume on the main corridor was around 750 vehicles per hour per lane. This site consists of six signalized intersections that had already been operated as coordinated actuated signal system (Park and Chen, 2010).

Two sets of data were collected; one for before case (i.e., coordinated actuated without adaptive split feature) and the other for after case (i.e., coordinated actuated with adaptive split

Fig. 4. Location and Geological Features of the Test Site

Table 1. Data Collection Time Plan of US 60

Types	Date	Control Mode	Off Peak	PM Peak
Coordination Timing Plan without adaptive split feature	8/5/2009	Actuated Coordination	1:30pm to 3:00 pm	4:30pm to 6:00 pm
Coordination Timing Plan with adaptive split feature	9/2/2009	Actuated Coordination	1:30pm to 3:00 pm	4:30pm to 6:00 pm

feature). Detailed data collection dates and times are shown in Table 1.

Both the Jamar traffic counters and Sony video cameras were used for collecting traffic volumes and stopped delays. In general, a person using a Jamar traffic counter counts the traffic volume for each approach at the intersection. However, when a person cannot cover all four approaches due to the high traffic volumes, the video camera was used to record the traffic volumes. The video cameras were also used to capture the stopped delay at the same time. In most cases, a person covered one major and one minor approach while the video camera covered the other major and minor streets and the stopped delay of the minor street. Data were later reduced to obtain traffic volumes and stopped delays by watching the recorded video. The data included the number of vehicles waiting at the intersection for each interval (in vehicles), vehicles-in-queue counts (in vehicle-seconds): Total number of traffic volume during the period (in vehicles).

In addition, two vehicles equipped with a Dell PDA with GPS feature were used for travel time data collection. In order to collect travel time in both directions at the same time, these two vehicles started at the two end points of the arterial and continued to travel through both directions during the data collection.

5. Evaluation Results

5.1 Simulation Based Results

To assess the benefits of adaptive split feature, a series of simulations were conducted within the MS Excel program by generating the movements of traffic stream of the cross street (uncoordinated) at the intersection. The cycle lengths and volume-to-capacity ratios were considered as two possible factors impacting the performance of adaptive split feature.

For coordinated actuated traffic signal system, the cycle lengths of all intersections should be same such that the system provides the progression along the coordinated approaches. In this study, the field implemented coordinated actuated timing plans were within the range of 100 and 120 seconds. Thus, both 120 seconds and 100 seconds were used to see whether the performance of adaptive split feature would vary under these two cycle lengths.

Considering the cycle length, the green time of uncoordinated phases were set as 20 seconds. In general, the green time for uncoordinated phases is smaller than that of coordinated phases. In addition, the effect of variance of green time can also be reflected by the volume-to-capacity ratio. The value of volume-to-capacity ratio for each uncoordinated phase was set in the range of 0.6 and 1.0. For each cycle length, the improvement realized by adaptive split feature was estimated for each volume-to-capacity ratio case. The results are shown in Table 2.

As shown in Table 2, it is apparent that cycle length does not affect the performance of adaptive split feature, while volume-to-capacity ratio does have significant impact. Thus, various volume-to-capacity ratio combinations of phase 3 and phase 4 were prepared and evaluated the performance of adaptive split feature. In this evaluation, the cycle length of 120 seconds was used. Table 3 presents statistical significance of implementing with and without adaptive split feature at a given phases 3 and 4 volume-to-capacity ratios. The cells with “N” indicate that the adaptive split feature does not have statistically significant benefits, while the cells with “Y” indicate that the implementation of adaptive split feature resulted in statistical significant benefits over typical coordinated actuated signal system (i.e., without adaptive split feature implemented). However, the results shown on Table 3 were not generated through in-depth and intensive

Table 2. Stopped Delay Comparison with and without Adaptive Split Feature

V/C	Phase no.	Cycle length = 100 sec.			Cycle length = 120 sec.		
		Delay of Coord. Without Adaptive (Secs)	Delay of Coord. With Adaptive (Secs)	Improvement	Delay of Coord. Without Adaptive (Secs)	Delay of Coord. With Adaptive (Secs)	Improvement
0.6	Phase 3	46	46	0%	56	55	1%
	Phase 4	43	43	2%	54	53	2%
	Total	45	44	1%	55	54	1%
0.7	Phase 3	47	46	1%	57	56	2%
	Phase 4	45	43	3%	56	54	4%
	Total	46	45	2%	57	55	3%
0.8	Phase 3	49	48	2%	63	60	4%
	Phase 4	49	45	7%	58	56	3%
	Total	49	46	5%	61	59	4%
0.9	Phase 3	57	53	7%	71	63	10%
	Phase 4	56	50	11%	71	64	11%
	Total	57	52	9%	72	64	11%
1.0	Phase 3	79	73	7%	107	99	8%
	Phase 4	79	72	9%	103	95	8%
	Total	79	72	9%	106	97	9%

Table 3. Guideline of Implementing Adaptive Split Feature

Phase 4 \ Phase 3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.5	N	N	N	N	N	N	Y	Y
0.6	Y	N	N	N	N	Y	Y	Y
0.7	Y	Y	Y	Y	Y	Y	Y	Y
0.8	Y	Y	Y	Y	Y	Y	Y	Y
0.9	Y	Y	Y	Y	Y	Y	Y	N
1.0	Y	Y	Y	Y	Y	Y	Y	N

experiments with diverse traffic and geometric conditions. Thus, there is a need for more studies in order to generate the guideline for the adaptive split feature in the future.

5.2 Field Before-and-After Study Based Results

The field stopped delay comparison between the coordinated actuated traffic signal system with and without adaptive split feature is shown in Table 4.

It is clear that significant improvements were made on stopped delay of non-coordinated approaches with the implementation of the adaptive split feature. The stopped delay improvements ranged from 18% to 34%. The volume to capacity ratio for each uncoordinated phases and improvement estimated by simulation was summarized in Table 5. Finally, the comparison between field and simulation improvements presented in Tables 4 and 5 was shown in Fig. 5.

As shown in Fig. 5, field improvements were quite similar to those of simulation based improvements. However, improvements estimated using simulation seem to underestimate consistently. This is the reason why both the simulation approach and the before-and-after study were applied together in this study. The simulation model consisting of MS Excel and the VBA code was not calibrated and validated to match the field traffic condition. Thus, the simulated delay based on the simulation model may not be sufficiently close to the actual delay measured from the field.

In addition, travel times along the corridor were also collected during the field before-and-after study. Table 6 shows the comparison summary of the before-and-after travel times. The corridor travel times were similar regardless of the use of the adaptive split feature. A statistical analysis showed that there was no significant difference between these two travel times. This confirms that the adaptive split feature does not affect the performance of the coordinated movements. It is noted that travel times between the off-peak and the peak are very similar mainly due to fairly low traffic volume during the peak period. In addition, it was found that the adaptive split feature slightly improved the average corridor travel time.

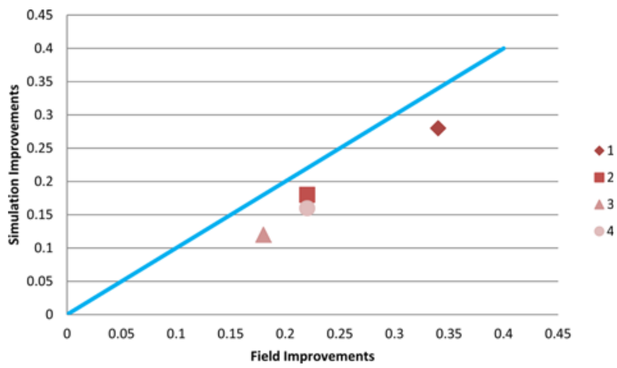

Fig. 5. Comparison of Field Measurement and Simulation Results

Table 4. Stopped Delay Comparison between the Coordinated System with and without Adaptive Split Feature

Periods	No.	Approaches	Coordinated with Adaptive Split (sec/veh)	Coordinated without Adaptive Split (sec/veh)	Adaptive Split Feature Improvement
Peak	1	US 60 & Crowder Rd. Minor South	38	58	34%
	2	US 60 & Winterfield Minor North	40	51	22%
Off-Peak	3	US 60 & Crowder Rd. Minor South	31	38	18%
	4	US 60 & Old Buckingham Rd. Minor South	40	51	22%

Table 5. Volume-to-Capacity Ratio and Improvements Estimated by Simulation Model

Periods	No.	Approaches	V/C Ratio of Phase 3	V/C Ratio of Phase 4	Improvement Estimated by Simulation
Peak	1	US 60 & Crowder Rd. Minor South	0.3	0.9	28%
	2	US 60 & Winterfield Minor North	0.6	0.9	18%
Off-Peak	3	US 60 & Crowder Rd. Minor South	0.7	0.9	12%
	4	US 60 & Old Buckingham Rd. Minor South	0.8	0.9	16%

Table 6. Summary of Field Travel Time Comparison during Before-and-After Study

Cases	Before Case Coordinated without Adaptive Split (sec)		After Case Coordinated with Adaptive Split (sec)		Results of t-test
Types	Average	STDEV	Average	STDEV	p-values
Off-Peak (Sec)	505	49	489	43	0.12
PM Peak (Sec)	505	63	498	65	0.70

Note: Results are based on 25 replications.

6. Conclusions

The concept of the adaptive split feature had been around for many years, but its importance has not received proper attention. The simulation model developed in this study demonstrated the performance improvement on the cross streets was achieved with the implementation of the adaptive split feature within the coordinated actuated traffic signal system. In addition, this study explored the guideline (i.e., combination of V/C ratio) for implementing the adaptive split feature.

The field implemented before-and-after study on the adaptive split feature illustrated that the developed simulation model properly represent field conditions, and that adaptive split feature can reduce stopped delays on uncoordinated approaches by 18% to 38%.

Although the simulation model did not explicitly consider the impact of adaptive split feature on the coordinated phases, the field before-and-after travel times comparison showed that the adaptive split feature did not make corridor travel time worse. Thus, when the coordinated actuated traffic signal control system is to be implemented in field, it is recommended that traffic engineers consider the use of the adaptive split feature to improve cross street performances.

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