A Monte Carlo Simulation Procedure to Search for the Most-likely Optimal Offsets on Arterials Using Cycle-by-Cycle Green Usage Reports

Pengfei, "Taylor", Li, Ph.D. (Corresponding Author)
Research Engineer, Kentucky Transportation Center
176 Raymond Hall, University of Kentucky
Kentucky, KY, 40506
Phone: (859) 257-4524
E-mail: pfli@engr.uky.edu

Peter Furth, Ph.D.
Professor, Department of Civil and Environmental Engineering
Northeastern University
431 Snell Engineering Center,
360 Huntington Ave.
Boston, MA 02115
Phone: (617) 373 - 2447
E-mail: pfurth@coe.neu.edu

Stephen S. Sawyer, Jr., P.E.
Vice President Transportation Services
Sebago Technics, Inc.
1 Chabot Street
Westbrook, ME, 04098
Phone: (207)856-0277
Email: ssawyer@sebagotechnics.com

Xiucheng Guo, Ph.D.,
Professor, Transportation College, Southeast University
Research room 328,
2 Sipailou, Nanjing, Jiangsu, 210096; P.R. China
Phone: +86-(25)83795427
Email: seuguo@163.com

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ABSTRACT

More and more towns in the states have installed central traffic managing software (ATMS) to manage their signal systems. ATMS's not only enable traffic engineers to remotely watch real-time traffic or access local controllers but also enable them to collect more data than ever. How to better utilize these data to improve the performance of traffic signals has been a topic receiving wide interest in the signal community. The data collected in ATMS's can be classified into two types, traffic counts/occupancies via detectors and green usage information via local actuated controllers. Unlike the previous researches and practices which mostly focused on how to better use the detector data, this paper is intended to explore how to use the green usage information in an ATMS to design optimal offsets of coordination. Although many factors could affect the effectiveness of offsets, the optimization of offsets usually starts with computing main-line link travel times. In actuated coordination, the main-line greens may start earlier than what are programmed because uncoordinated phases could gap out and return unused green back to the main-line. This phenomenon is referred to as "early-return-to-green". When it occurs, it makes the programmed coordination less effective.

In this paper, the authors considered the main-line greens random variants ranging from the programmed maximum greens to the whole cycle length. In this random scheme, the optimal offsets are also random and should vary cycle by cycle. Given that it is still uncommon to adjust the offsets cycle by cycle in major signal controllers, the objective of offset optimization in this paper is to find optimal values that can maximize bandwidth and therefore minimize delay with the largest likelihood. The authors first defined this new concept as *Most-likely Optimal Offsets*, then used cycle-by-cycle green usage reports and a Monte Carlo simulation model to determine the most-likely optimal offsets. The cycle-by-cycle green usage reports is a typical function of major ATMS systems to provide the distributions of random main-line greens. It serves as the basis to infer the optimal offset distributions and thus allow for identifying the most likely optimal offsets.

Three intersections on Payne Road in Scarborough, Maine were selected to test a set of new offsets inferred with this method. A before-and-after comparison in simulation revealed that the new offsets could significantly reduce the travel times on arterials with 95% confidence level compared to the offsets optimized with SYNCHRO 7 when the early-return-to-green frequently occurs. The implementation in the field also supports the speculations from simulation.

Key words: Traffic signal control, Traffic signal coordination, Arterial Management, Monte Carlo Simulation, Traffic simulation, ATMS, ITS, VISSIM

1. Introduction

Queues discharging at signalized intersections will form platoons and it is desired to allow these platoons to cross downstream intersections without stopping. As such, coordinating signalized intersections on arterials with proper offsets is a common signal operational practice. Offsets refer to the time difference between the local controllers' clock and a system's background clock. They are calculated according to local controllers' reference points. The reference points define where the coordination is referred to with each cycle. In general, there are two types of reference points: beginning-of-green (BOG) and ending-of-green (EOG) of coordinated phase(s). Taking the simplest one-way coordination as an example, the BOG coordination is to ensure that the first discharged vehicle on an arterial will encounter green at next intersection whereas the EOG coordination ensures that the last discharged vehicle in the queue will encounter green at next intersection. These two types of reference points can be simplified as in Figure 1. From Figure 1, it is clear that a portion of the green time is uncoordinated at the intersection with longer main-line green. More specifically, on the left side of Figure 1, the tail end of the main-line green at INT 2 is uncoordinated. On the right side of Figure 2, the beginning portion of the main-line green at INT 2 is uncoordinated.

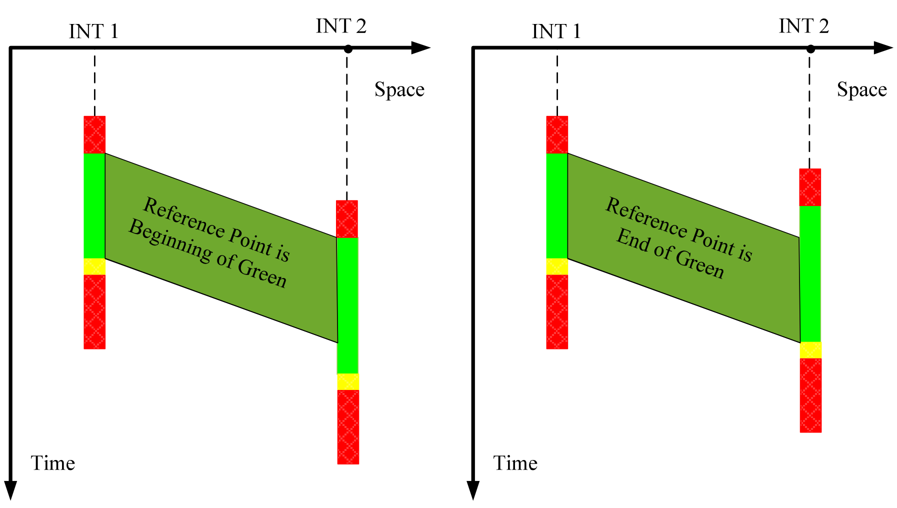


Figure 1 Two types of reference points in coordination

The offset optimizing procedure in software tools usually starts with computing link travel times, takes into account other factors such as existing queues and then fine tunes the offsets to either maximize the green band or minimize delays. Although this method implicitly takes into account the early-return-to-green phenomenon in actuated coordination, the optimized offsets are often unsatisfactory and need significant fine-tuning in practice. One possible reason is that the objective models in the offset optimization were originally developed for fixed-timing control strategies and therefore lack the capabilities of fully addressing the inherent randomness in actuated controllers. In signal timing software, a common method to address the early-return-to-green is to compute offsets in multiple scenarios (from high volume to low volume) and then use the average. Although it is an improvement compared to one single scenario, it is still insufficient to reflect the traffic dynamics and complex interaction with actuated controllers.

A goal of signal coordination is to minimize delays and stops on arterials. The number of vehicles that can cross without stopping is determined by two factors, the main-line greens and the offsets. The main-line greens are determined by traffic volumes at individual intersections whereas the offsets are computed based on link travel times plus existing queues downstream and vehicles coming out of side streets during main-line red. Although this method is proved effective, in many instances the traffic is so dynamic that the offsets optimized with software tools often need extra fine tuning to avoid failing the coordination in the field. To address this issue, some real-time offset optimizing systems were developed using real-time detector data to fine-tune the offsets periodically (e.g., every 15 minutes).

Instead of using detector data, the authors in this paper used the cycle-by-cycle green usage information collected via an ATMS to design offsets. The authors considered the theoretical offsets as random variants. Since the main-line greens vary from cycle to cycle, so are the theoretical offsets. However, given that only one single set of offsets are allowed for each coordination timing plan in signal controllers, the task of this paper is to provide a method to seek the optimal offsets that most likely occur.

This paper is organized as follows: after the introduction, the authors stated a common problem in actuated coordination and pointed out that since the main-line greens are random, optimal offsets in theory should also be random. After a review of relevant literature, the authors described how actuated controllers work in a coordination mode and then developed a procedure to quickly determine the most-likely optimal offsets using a Monte Carlo simulation. Finally, a case study was conducted to evaluate the effectiveness of the new procedure.

2. Problem Statement

Nowadays, the detector data (e.g., vehicle counts) are the primary input in signal operations and researches. However, today's major central traffic management systems or ATMS's can collect more types of data than detector data. These "additional" data have been underused in the researches. For example, the cycle-by-cycle green usage report has become a standard function in major ATMS systems but only a limited number of pertinent researches used it. The authors in this paper presented a procedure to explore how to utilize the cycle-by-cycle usage report to better design offsets in actuated coordination.

Both BOG and EOG reference points are being used in signal coordination practice today. As shown in Figure 2, in an ideal one-way coordination, the BOG reference can ensure that all the vehicles are able to be coordinated as long as the main-line greens are sufficient (Part A of Figure 2). However, with the EOG reference, the first several vehicles in a platoon are possibly uncoordinated and may have to stop (Part C of Figure 2) even though the offsets are appropriate. Therefore, the BOG reference is more effective than the EOG reference under certain conditions. In actuated coordination, when the BOG reference is used and the main-line green starts earlier at Intersection 1, the vehicles will also be released earlier and have stop at Intersection 2 (Part B of Figure 2). For the EOG reference, vehicles will have to wait longer at Intersection 2 (Part D of Figure 2). The negative impact brought about by the early-return-to-green is particularly severe when the traffic on the side streets is moderate. When side-street traffic is light, the main-line green will stay green most of time, making the early-return-to-green issue and offsets less important. When traffic on the side street is heavy, all uncoordinated phases will be driven to maximum greens and consequently there are few early-returns-to-green. In that case, the randomness on the controllers' side is less and offsets optimized in software are more effective.

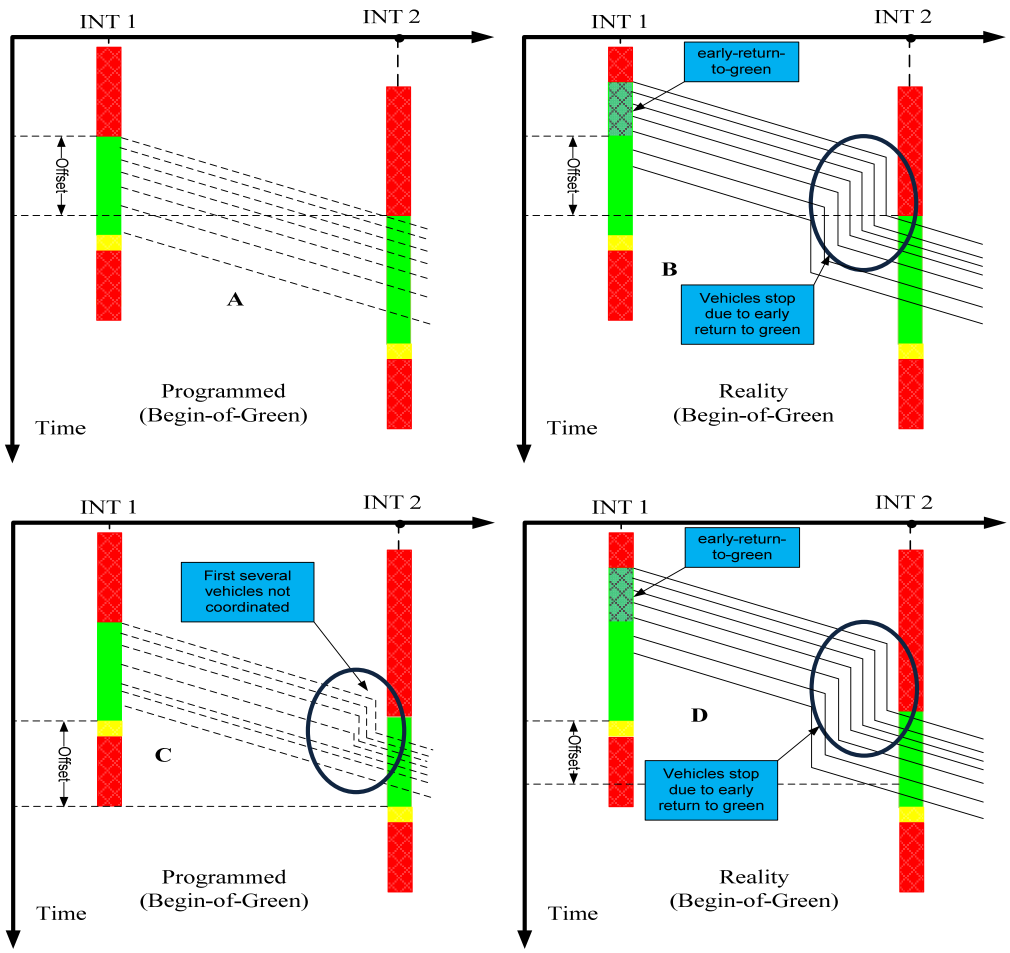


Figure 2 Coordination fails due to early-return-to-green phenomenon

Gap outs on the side streets make the main-line green starts random, and the starting time ranges from the programmed begin of main-line green to the end of main-line green in last cycle. As such, the offsets based on a pre-timed control strategy (i.e., fixed reference points) cannot guarantee effective coordination all the time. The optimal offsets will also be random when the main-line greens become random. Therefore, it is necessary to investigate the random features of the main-line greens and optimal offsets and then optimize the offsets from a random perspective. Since the optimal offsets are random, it is necessary to seek those optimal offset values which are most likely to occur.

3. Literature Review

Previous research on the topic of optimizing offsets can be divided into two types, off-line optimization and on-line optimization. On the side of off-line optimization, Gartner et al. developed a link performance function to express the loss incurred by platoons traveling through a signalized intersection. Gartner et al. considered the loss as a function of offsets and so formulated the offset optimization as a mixed-integer linear program(1). Improta proposed a binary integer programming model to compute optimal traffic signal offsets for an urban road network aiming to minimize delay(2). Al-Khalili evaluated several criteria to optimize offsets in simulation and concluded the best criterion is to minimize the fuel consumption(3). Yamada and Lan developed coordination plans for the situations when the traffic volumes on side streets become significant(4). Chaudhary et al. developed the bandwidth-based signal optimization software, PASSER V (5). Similar to PASSER V, another software package, MAXBAND, also aims to optimize offsets to maximize green bandwidth(6). Stamatiadis and Gartner attempted to maximize the green bandwidth on each link rather than create a uniform bandwidth at the arterial level, and developed a bandwidth optimization software, MULTBAND(7). Yin et al. considered the main-line greens as random and optimized the offsets based on mean values of actual main-line greens rather than the greens calculated based on historical data(8). With the objective to minimize delays, Trafficware Inc. provided a delay-based offset optimization module in its SYNCHRO STUDIO(9). In Europe, Robertson developed a platoon dispersion model as a function of distance from the upstream stop bar(10). Robertson's model was later used to calculate the offsets in TRANSYT-7F software package(11) and the SCOOT adaptive signal control system(12).

All of the above optimization efforts are based on analytical objective functions and thus cannot cover individual vehicle behaviors in detail. As such, the solutions derived with those methods may not be reflecting reality with high fidelity. By connecting microscopic simulation optimization algorithms, recent research efforts optimized offsets using microscopic-simulation-based optimization. This approach seeks the optimal offsets in conjunction with other variables, such as green splits and phasing sequence, to maximize the travel speeds on arterials, minimize overall vehicle delay or fuel consumptions. The genetic algorithm (GA) is most commonly used to optimize traffic signal systems in simulation-based optimization (13-16). Nevertheless, there are also other relevant research efforts using different optimization algorithms for specific problems(17). While simulation-based optimization is intuitively more accurate than analytical-model-based optimization, the computing time is usually too long to be implemented in a real-time manner.

Given that traffic on arterials could be affected by many factors, platoons formed with each cycle could be highly dynamic in terms of a platoon's releasing time and link travel time. Therefore, offsets should be fine-tuned periodically. On-line offset optimization utilizes incoming detector data to recognize real-time traffic conditions and fine-tune the offsets accordingly. Abbas et al. assumed that effective offsets should be able to generate similar volumes profile and occupancy profile(18). The algorithm developed by Abbas et al. is able to fine tune offsets on arterials by comparing the difference between volume and occupancy profiles, which is collected via mid-block system detectors. More recently, ACS-LITE software, a cost-effective version of adaptive signal systems sponsored by FHWA, optimizes the offsets both at individual intersections and on arterials using real-time detector data (19, 20).

Most of the above research efforts addressed the early-return-to-green somehow. For instances, SYNCHRO optimizes offsets with multiple scenarios from slightly heavier traffic to lighter traffic and uses the average optimal offsets. This method can mitigate the negative impact of early-return-to-green brought by traffic fluctuation. The simulation-based offset optimization could address the early-return-to-green issue in nature as long as the signal emulators in simulation are set as "actuated". The ACS Lite can predict the green durations of future cycles according to the green usage of recent cycles. This method enables ACS Lite to predict when the main-line actually starts and computes the offsets accordingly. In the latest Naztec's adaptive signal control system, or Adaptive.NOW, the offsets are also fine-tuned periodically according to the main-line green durations (21). Day et al. used a similar idea with the ACS Lite to conduct an off-line analysis (22).

4. Model Description

In coordination mode, actuated signal controllers return all the unused green on the side streets (i.e., the side streets gap out) to the main-line, and the main-line green always ends at the same point with each cycle. As illustrated in Figure 3, uncoordinated phase 2 and 3 gap out and result in earlier start of main-line phase 1.

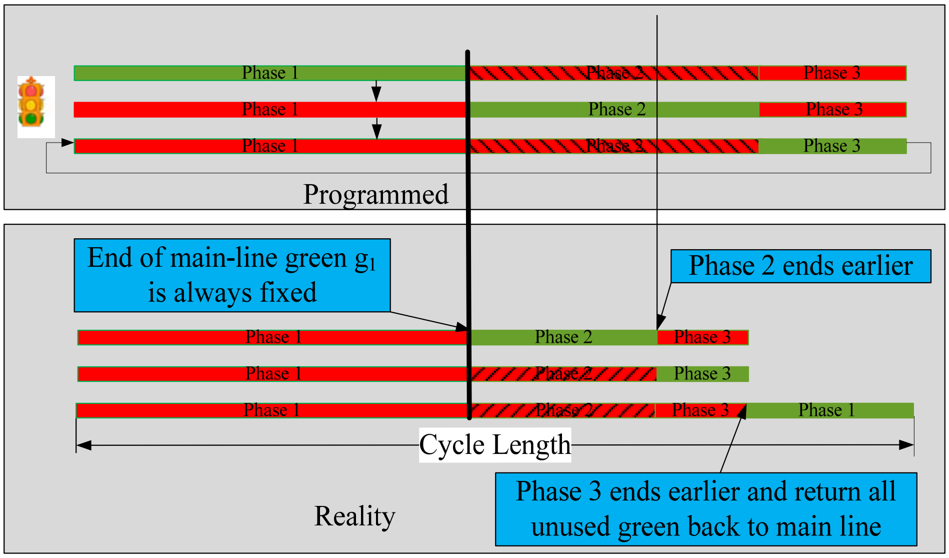


Figure 3 Actuated coordination and early return to green

Using the example in Figure 3, the lengths of phase 2 and 3 are determined by controller settings (e.g. min/max green) and queue lengths. Eq. [1] is a generic form to describe the lengths of green time on side streets. On the other hand, the length of phase 1 is independent of the main-line traffic and could be formulated as Eq. [2].

$$g_s = \min(Maxgreen_s, \max(Mingreen_s, T_q)) \qquad \text{Eq. [1]}$$

Where:

- g_s: Actual green time on side streets;
- $Maxgreen_s$: Programmed maximum green on side street;
- $Mingreen_s$: Programmed minimum green on side street;
- T_q: needed green time to clear queue;

$$g_m = Maxgreen_m + \sum_i (Maxgreen_{si} - g_{si}) \qquad \text{Eq. [2]}$$

Where:

- g_m: Actual green time on main line;
- $Maxgreen_m$: Programmed maximum green on main line;
- $Mingreen_m$: Programmed minimum green on main line;

- g_{si}: Actual green time on side street *i*;

Fixed force-off and floating force-off

There are two force-off modes in actuated coordination, fixed force-off and floating force-off. Under the fixed force-off mode, if a previous non-coordinated phase ends earlier, any unused green may be used by its following phase up to the following phase's force-off point. In other words, the following phase green could be longer than its programmed maximum green. By contrast, the floating force-off mode does not allow the green of uncoordinated phases to exceed their maximum greens and thus any unused green time on side streets will be eventually returned to the main-line. As shown in Figure 4, assume phase 2 gaps out and more-than-average vehicles arrive on phase 3 and phase 4 with current cycle. Under floating force-off, phase 3 and phase 4 will max out when the maximum green timers expire. However, under fixed force-off, phase 3 could utilize the unused green by phase 2 to clear vehicles. As a result, the green length of phase 3 would exceed the programmed maximum green.

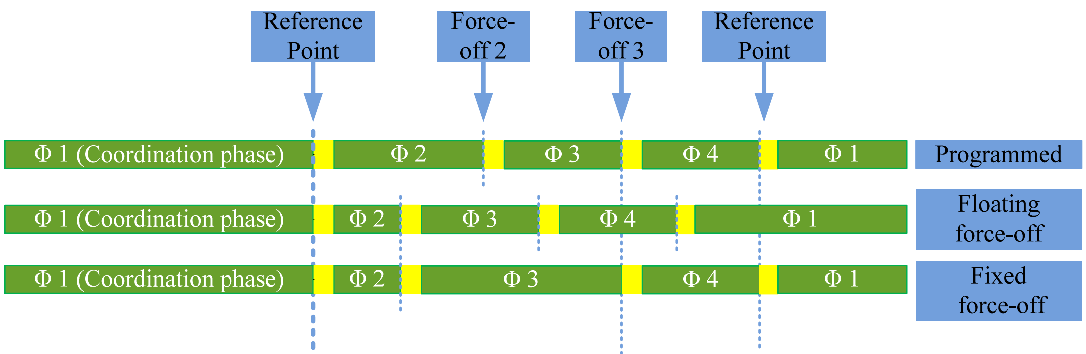


Figure 4 Illustration of floating force-off and fixed force-off

Therefore, floating force-off is more restrictive on side streets. Whereas fixed force-off may be beneficial to side streets when their traffic demand fluctuates and the side streets need more green. The item, $Maxgreen_{si} - g_{si}$, in Eq. [2] is positive under the floating force-off mode. Whereas it could be either positive or negative if fixed force-off applies.

Random analysis of early-return-to-green

The early-return-to-green phenomenon often occurs when side streets have light or moderate traffic. Vehicle arrivals could be approximated as a Poisson process when traffic is light or moderate(23). The needed green on a particular side street with each cycle is determined by the green time to clear the queue formed during red and the additional time associated with any phase extensions. Figure 5 illustrates how the random arrivals of vehicles on side streets affect the main-line green. The phasing sequence in Figure 5 has a single ring structure with three phases. Phase 1 is coordinated while Phase 2 and 3 are uncoordinated. When the Phase 2 is red, a queue will be formed by randomly arriving vehicles. The queue length will keep increasing until Phase 2 turns to green (Point A). While the queue 2 is discharging, newly arriving vehicles will join the end of the moving queue. Obviously, the total queue length cleared in the end will be longer than the queue length at the green onset. After the queue is cleared (Point B), the controller will typically extend the green for certain seconds (extension time). If a new vehicle arrives before the extension timer expires, the extension timers will be reset and the controller will extend the green for another several seconds. If the extension timer expires before it is reset by next arriving vehicle, Phase 2 will gap out and turn over the green to Phase 3 (Point C). If the extension timer does not expire before Phase 2 reaches maximum green, Phase 2 will max out and turn over the green to the Phase 3 regardless of the extension timer. Phase 3 will go through exactly the same process as Phase 2 and eventually any unused green to be returned back to the coordinated Phase 1.

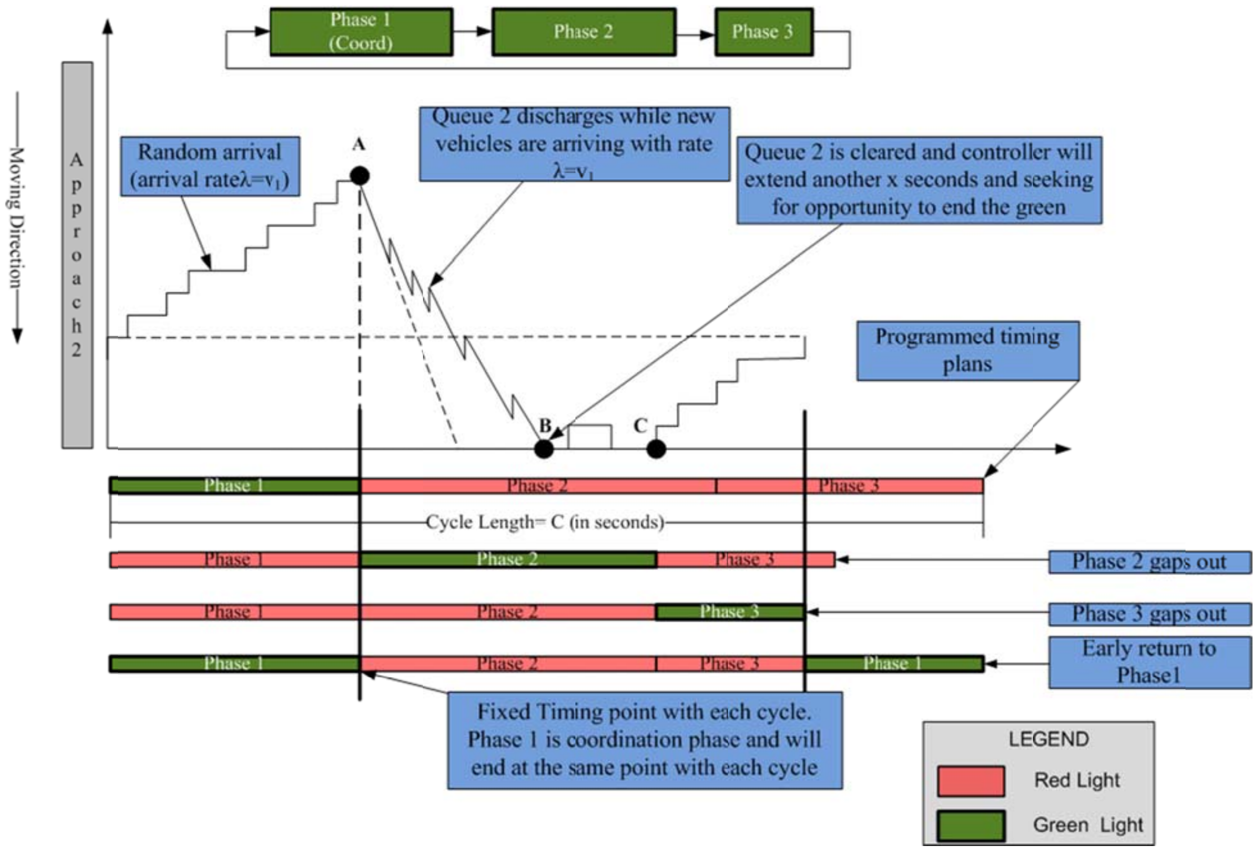


Figure 5 Random analysis of early return to green

Random optimal offsets in actuated coordination

Obviously, an early-return-to-green will make the optimal offsets based on fixed reference points less effective. As illustrated in Figure 6, if intersection 1 and 2 return to main-line green Δg_1 and Δg_2 seconds earlier respectively, the optimal offset for that cycle should be:

$$offset_o = T + \Delta g_1 - \Delta g_2 \qquad \text{Eq. [3]}$$

Where T is the optimal offset based on fixed reference points. Besides the one-way coordination shown in Figure 6, T could also be the optimal offset for two-way coordination.

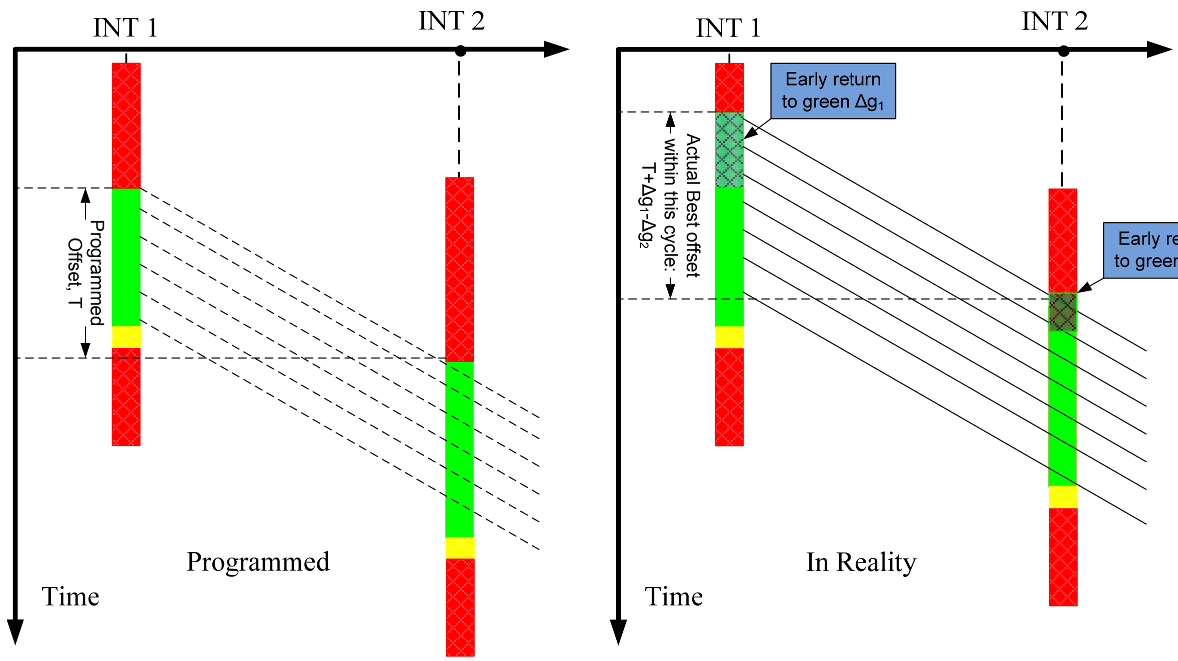


Figure 6 Dynamic offsets in actuated coordination

Since Δg_1 and Δg_2 are random, so is $offset_o$. As such, if we could infer the distributions of Δg_1 and Δg_2 based on the cycle-by-cycle green usage reports, we could also infer the distribution of the optimal offsets. The optimal offsets should be located where they are most likely to occur. See Figure 7 for conceptual illustration.

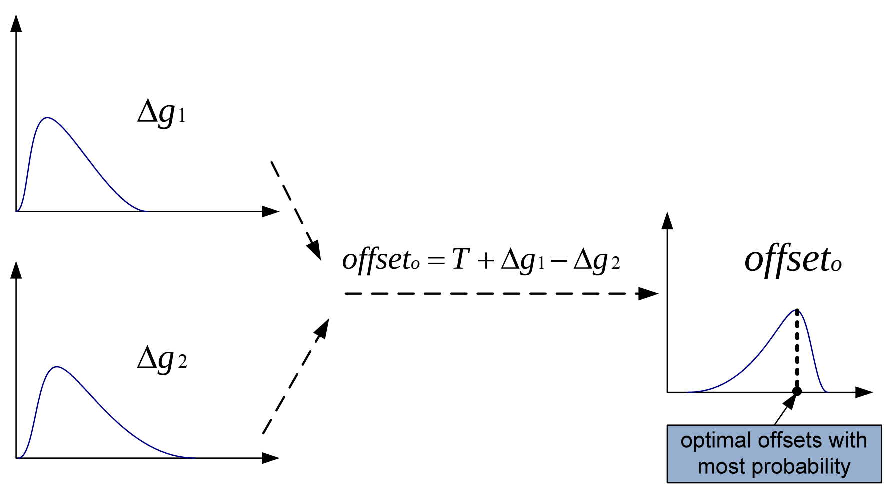
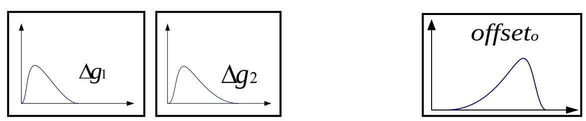


Figure 7 Illustration how to seek optimal offsets

Identify most-likely optimal offsets using Monte Carlo simulation

Given the complexity of the early-return-to-green phenomenon, there is not a well-defined random process able to describe this mechanism. Therefore, the authors designed a Monte Carlo simulation model. First, we empirically inferred the distributions of Δg_1 and Δg_2 using the green usage reports. Secondly, random numbers were generated according to theses distributions. With each pair of random numbers of Δg_1 and Δg_2, an optimal offset was computed with Eq. [3]. Please note that Eq. [3] just represents the simplest expression of optimal offsets and they may or may not need changing in practice. Each simulation run will generate a new pair of Δg_1, Δg_2 and a calculated optimal offset value (each row of Figure 8-A). The Monte Carlo simulation generated 10,000 optimal offset samples with which the distribution and probability density function of the optimal offsets were inferred according to the calculated offset values. The whole process is illustrated in Figure 8-A.



38	22	46
41	47	24
36	4	62
4	2	32
31	25	36
47	36	41
49	22	57
41	49	22
26	19	37
45	13	62
48	16	62
7	40	-3
17	13	34
30	18	42
34	31	33
…	…	…

$$offset_o = T + \Delta g_1 - \Delta g_2$$

* : Number is for illustration only

Figure 8-A Estimate the distribution of optimal offsets using Monte Carlo Simulation

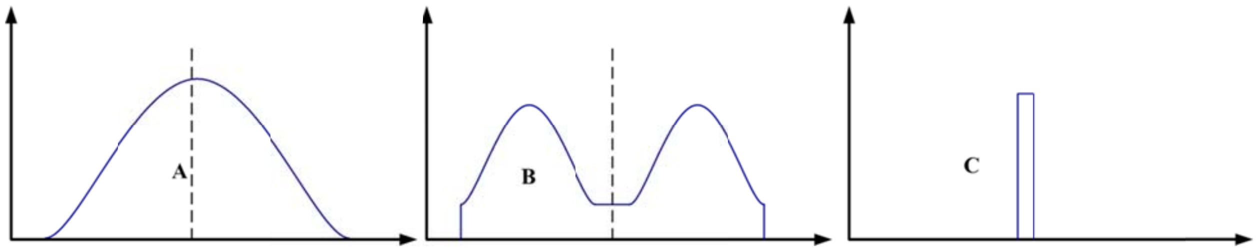


Figure 8-B Three possible pdf curve shapes of optimal offsets

The empirical pdf curves of optimal offsets derived from a Monte Carlo simulation could be any shape. Nevertheless, the pdf curves could be classified into three types. As in Figure 8-B, in Case A, the pdf curve is unimodal with the highest probability in the center. In Case A, if the skewness is not exceptionally large, the most-likely optimal offset is around the mean of the optimal offset's distribution and the most-likely optimal offsets could be approximately simplified as in Eq. [4].

$$offset_o = T + (\bar{g}_1 - g_{1p}) - (\bar{g}_2 - g_{2p}) \qquad \text{Eq. [4]}$$

Where:

- $\bar{g}_i$ is actual average main-line green
- g_{ip} is programmed main-line green

In Case B, the most-likely optimal offset should approximate either of the two peaks and the most-likely optimal offset will not be close to the mean value.

In Case C, if the range of an optimal offset is very tight, it implies the optimal offset is almost deterministic. This situation most likely occurs when the traffic on side streets is heavy and literally converts actuated coordination to pre-timed (i.e., deterministic) coordination.

5. Case Study

Three closely spaced intersections on the Payne Road in Scarborough, Maine were selected as a test site to evaluate the new offset optimizing method. The posted speed on Payne Road is 35 MPH, and the three intersections were are all controlled with Naztec NTCIP controllers connected to Streetwise®, a Naztec ATMS system, which allows collection of main-line green usage cycle-by-cycle. The traffic on the Payne Road is very directional and therefore one-way coordination was adopted.

The coordination timings at the three intersections are regularly updated with SYNCHRO 7 according to the newly incoming traffic counts. There are three Time-Of-Day one-way coordination timing plans for the weekdays, including AM peak, Midday and PM peak. The reference points are all begin-of-green. Two hours during the Midday (from 11:00 AM to 1:00 PM) were selected to test the new offsets because traffic on the side streets during this period is moderate and thus gap-outs and early-turn-to-greens occur more frequently than at other times of the day. As such, the potential benefit from new offsets should be more significant and more easily observed. Figure 9 and Figure 10 show the traffic volumes, midday timing plans and other relevant information.

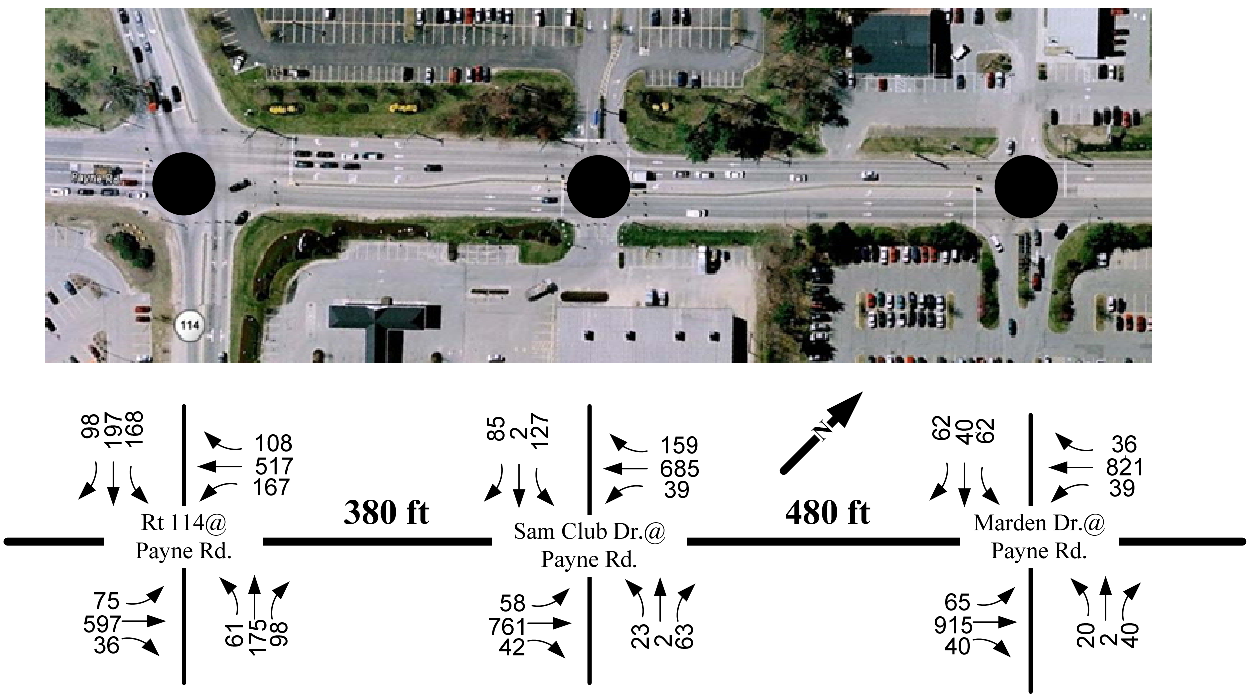


Figure 9 Traffic movement counts at three test intersections

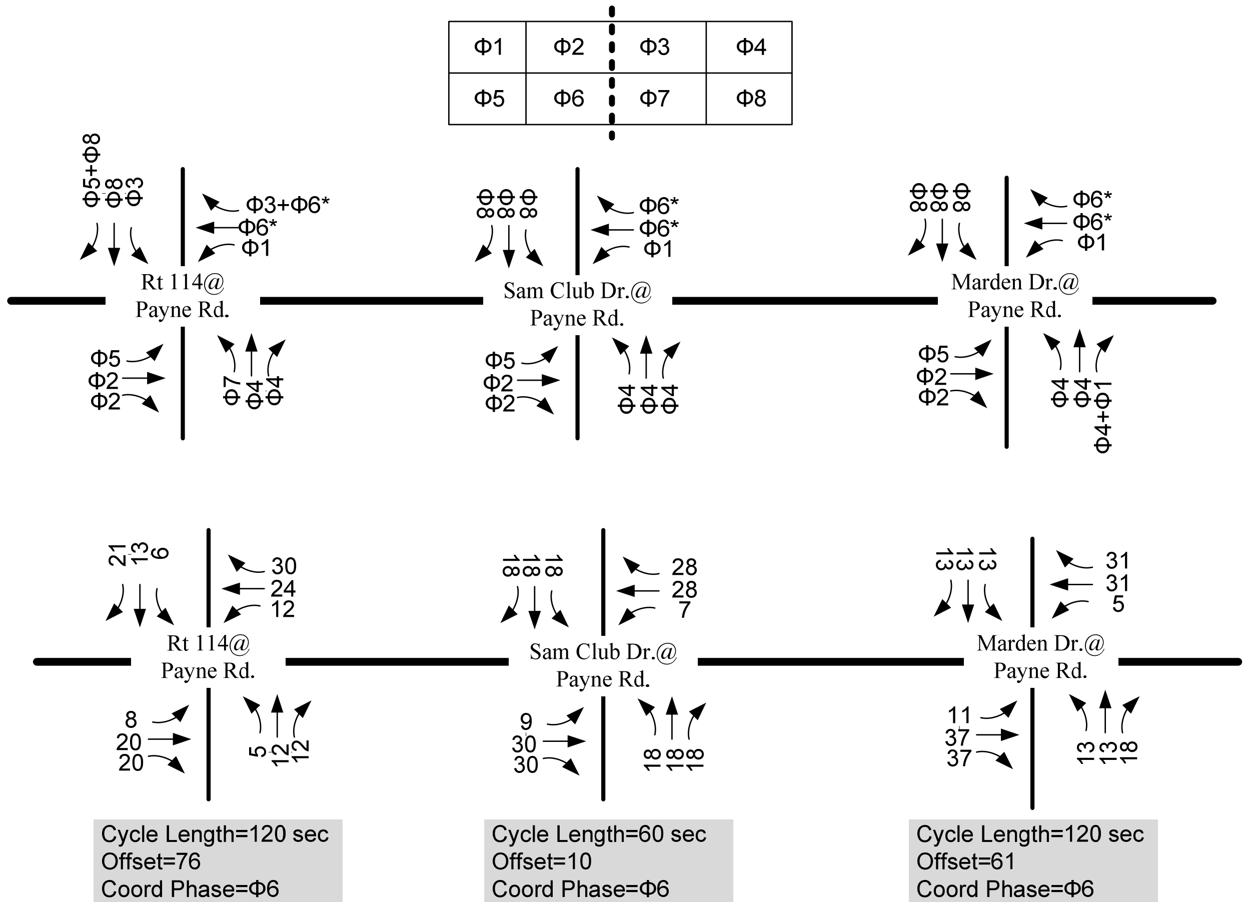


Figure 10 Ring structure, phasing sequence and green times at three test intersections

Main-line green usage and distribution

Two weeks of green split reports at these three intersections were retrieved to determine the distributions of Δg_1, Δg_2, and Δg_3. From the histograms in Figure 11, it appears that there are no well-defined distributions able to represent Δg_1, Δg_2 and Δg_3. As such, a numerical method, namely *Acceptance-Rejection Method* (21), was used to indirectly generate samples of Δg_1, Δg_2, Δg_3 to estimate the optimal offsets in the Monte Carlo Simulation. The concept behind the Acceptance-Rejection method is to generate random numbers using a known distribution similar to the desired distribution first and then reject those numbers which are out of the empirical probability density function curve. The remaining random numbers then will have the desired distribution. For details of the Acceptance-Rejection Method, please refer to the listed reference.

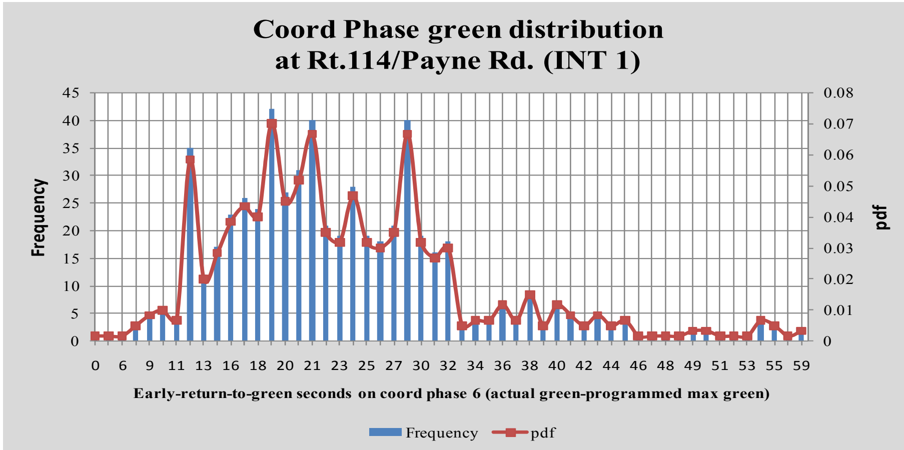


Figure 11-A Early-return-to-green distribution (Δg_1) at Rt.114 /Payne Rd.

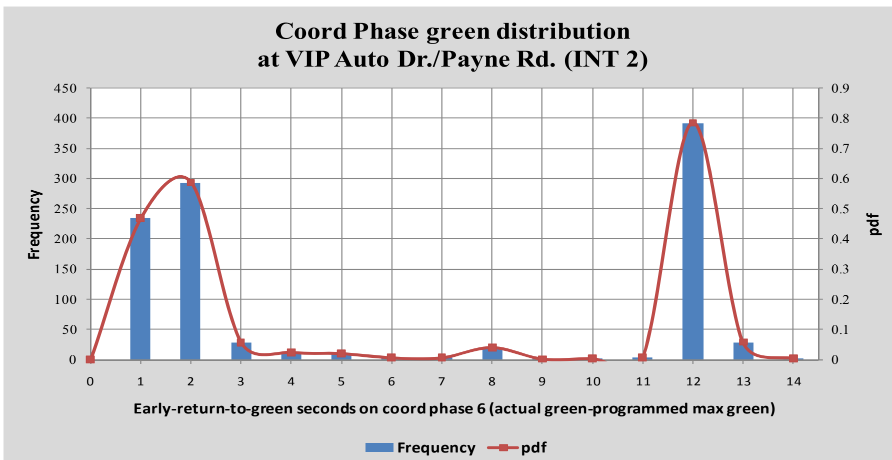


Figure 11-B Early-return-to-green distribution (Δg_2) at Sam Club Dr. /Payne Rd.

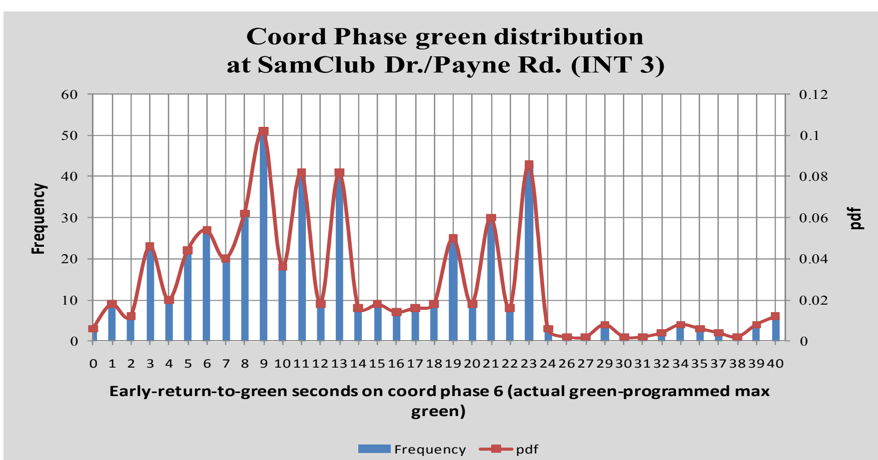


Figure 11-C Early-return-to-green distribution (Δg_3) at Marden's Dr. /Payne Rd.

Optimal offset distribution inferred with Monte Carlo Simulation

10,000 samples of Δg_1, Δg_2, and Δg_3 were generated and each sample of the optimal offsets was computed with the sample values of Δg_1, Δg_2, Δg_3 and Eq.[3]. The offsets were optimized with SYNCHRO 7 and the values are 8 seconds (T_1) between Rt. 114/Payne Rd. and Sam Club Dr./Payne Rd. and 10 seconds (T_2) between Sam Club Dr./Payne Rd. and Marden's Dr./Payne Rd. The generated optimal offsets samples are divided by seconds and Figure 12 shows the histogram.

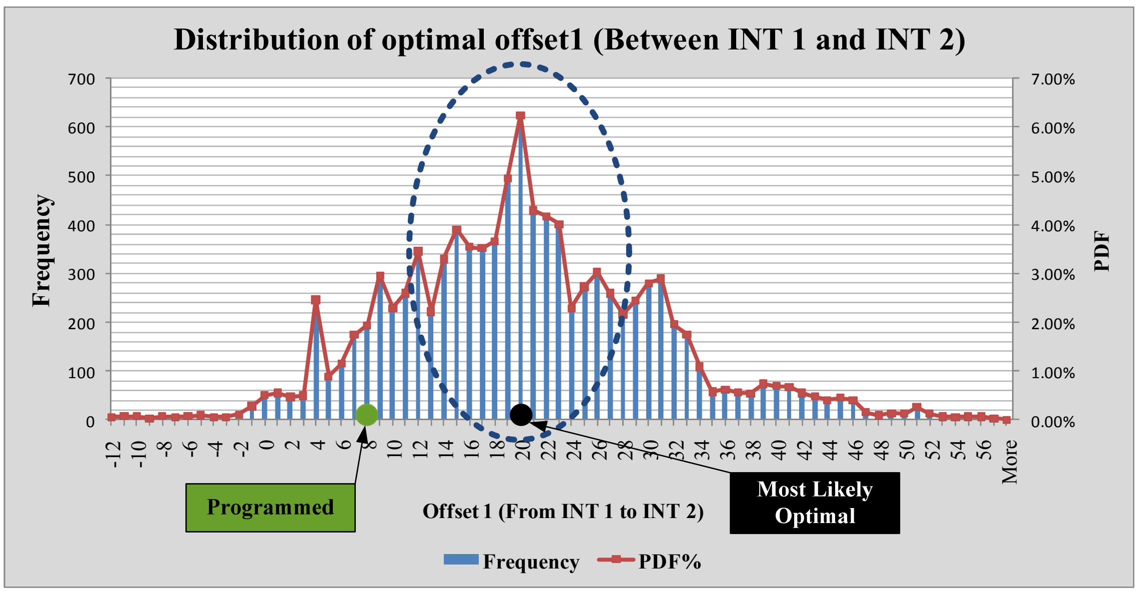


Figure 12-A Distribution of Offset 1

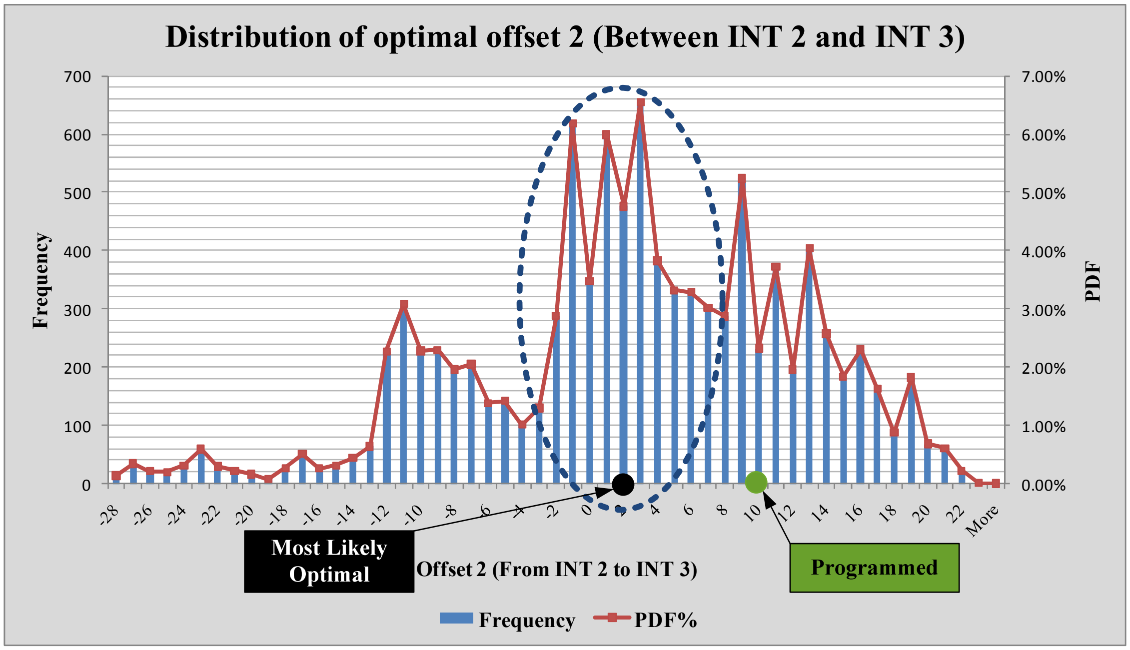


Figure 12-B Distribution of Offset 2

From Figure 12-A and Figure 12-B, it appears that the optimal offset 1 most likely occurs around 22 seconds and the optimal offset 2 most likely occurs around 2 seconds. By comparison, the probability of optimal offsets computed in SYNCHRO 7 is much less than that around the most likely optimal offsets. Therefore, 22 seconds and 2 seconds were selected as the new offsets for these three intersections.

Before and After Comparison in Simulation with paired T-test

Before deployed in the field, the new offsets were first evaluated in simulation. PTV's VISSIM (24, 25) was selected because its signal emulator can simulate most of functions in actual controllers. Two scenarios were compared: the baseline scenario with existing offsets optimized by SYNCHRO 7, and the testing scenario with the above new offsets. The settings in the two scenarios were exactly the same except for the offsets. Each scenario was simulated 1,000 times with a common set of random seeds.

A paired t-test for means was performed to determine if the travel time (μ_1) under the new offsets was shorter than that (μ_2) under the existing offsets. The following hypotheses were formulated as:

Null Hypothesis, H_0: $\mu_1 = \mu_1$, Alternative hypothesis, H_1: $\mu_1 < \mu_1$

Paired T-test results: From Table 1 and Table 2, it is clear that both northbound traffic and southbound travel times under the new offsets were shorter than those under the existing offsets with more than 0.95 confidence since the p values are much less than 0.05.

Table 1 Paired T-test for northbound traffic on the mainline

Northbound

	New offsets	*Existing Offsets*
Mean	42.31	44.60
Variance	4.64	5.03
Observations	1000	1000
Hypothesized Mean Difference	0	
Degree of freedom	999	
t Stat	- 28.27323086	
P(T<=t) one-tail	5.5814E-130	
t Critical one-tail	1.646380345	

	New offsets	*Existing Offsets*
Mean	42.31	44.60
Variance	4.64	5.03
Observations	1000	1000
Hypothesized Mean Difference	0	
Degree of freedom	999	
t Stat	-28.27323086	
P(T<=t) one-tail	5.5814E-130	
t Critical one-tail	1.646380345	

Table 2 Pared T-test for southbound traffic on the mainline

Southbound

	New offsets	*Existing Offsets*
Mean	44.82	49.45
Variance	8.06	12.59
Observations	1000	1000
Hypothesized Mean Difference	0	

Degree of freedom	999
t Stat	- 41.98554922
P(T<=t) one-tail	4.0438E-223
t Critical one-tail	1.646380345

	New offsets	*Existing Offsets*
Mean	44.82	49.45
Variance	8.06	12.59
Observations	1000	1000
Hypothesized Mean Difference	0	
Degree of freedom	999	
t Stat	-41.98554922	
P(T<=t) one-tail	4.0438E-223	
t Critical one-tail	1.646380345	

Before and After Comparison in the field

The new offsets were also evaluated in the field. The travel time and stops between these three intersections were measured under both existing and new offsets. Ten travel time runs on Payne Road were conducted under existing and new offsets respectively. Table 3 indicates the results.

Table 3 Measured travel times and stops under existing and new offsets

	North Bound		South Bound	
	Travel Time	Average Stops	Travel Time	Average Stops
Under Existing Offsets	44.3	0.75	44.8	0.76
Under New Offsets	41.4	0.5	45.1	0.75
Improve %	**6.55%**	**33.33%**	**-0.67%**	**1.32%**

From Table 3, the travel times and stops under the new offsets were less than those under the existing offsets, which supports the conclusion drawn from the simulation. It appears that there is more benefit for the northbound traffic than the southbound, but the overall benefits are limited. This is because the baseline coordination has been optimized with SYNCHRO 7 and the coordination is only for northbound traffic (phase 6) from 11:00 AM to 1:00 PM. As a result, the most-likely optimal offset estimation based on the green usage reports of phase 6 give more priority to the northbound traffic than the southbound traffic.

6. Conclusion and Future Work

Due to the early-return-to-green phenomenon in actuated coordination, main-line greens are random rather than deterministic. As such, optimal offsets in theory between intersections should also be random and determined not only by the main-line travel time but also the traffic demand on the side streets. However, given that only one set of offsets is allowed for each timing plan in signal controllers, optimizing offsets becomes a process of not only seeking optimal values to maximize green band or minimize delays, but also seeking optimal values that most likely occur. The authors utilized the green usage reports generated by the Naztec ATMS system, or Streetwise, to infer the distributions of main-line greens. Based on the main-line green distributions, the authors derived the distribution of optimal offsets using a Monte Carlo simulation method and then identified the most-likely optimal offsets accordingly. The before-and-after comparison in simulation shows that the travel time and stops measured in the field were significantly reduced under the new offsets. The same evaluation conducted in the field also supports this conclusion.

Further work for this new method will include:

When we calculated the optimal offsets with Eq. [3], we appreciated that many factors other than link travel time would affect the "T". In reality, there may be stop-bar queues at downstream intersections formed either by the turning vehicles from the side streets or vehicles that were not cleared during the previous cycle. The existence of stop-bar queues will affect the calculation of optimal offsets in Eq. [3]. As such, the stop-bar queues will be considered when we further refine this method in future.

In addition, the travel time was simply calculated as the link distance divided by the posted speed in the case study. This may be true when traffic is light or moderate. However, there are still more complicated situations in reality. The link travel speed could be rather dynamic given it is affected by traffic volumes, drivers' aggressiveness, weather, etc. Additional investigation will be needed to identify the time-dependent link travel speeds when we calculate the link travel times. For instance, the newly emerging travel time measurement using Bluetooth technology seems a promising solution to measure travel time more precisely.

The authors are planning to introduce more realistic traffic models (e.g., an offset-dependent traffic control delay model) into this procedure in the future, more analysis (e.g., offsets' sensitivity analysis) will be done with the Monte Carlo model presented in this paper.

Finally, the authors also plan to utilize this new method in conjunction with real-time link travel speeds and queue detectors to design an on-line version of the most-likely optimal offsets searching algorithm. Multiple real-time inputs will help better estimate queue lengths and the “T” in Eq. [3] and the mostly-likely optimal offsets will be updated periodically.

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