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An ATMS data-driven method for signalized arterial coordination

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Abstract: In order to minimize the delays and stops caused by the early started coordinated green phase of the vehicle-actuated signal systems, a stochastic offsets calculation method based on the new types of advanced traffic management system (ATMS) data is proposed. As the mainline green starts randomly in vehicle-actuated signal systems, the random theory is applied to obtain the distribution of the unused green time at side streets based on the green gap-out mechanism. Then, the green start time of the mainline can be selected at the point with maximum probability to minimize the delays or stops caused by the randomly started mainline green. A case study in Maine, USA, whose traffic conditions are similar to those of the middle-size Chinese cities, proves that the proposed method can significantly reduce the travel time and delays.

Key words: traffic signal control; random theory; traffic simulation; advanced traffic management system (ATMS); intelligent transportation system

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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. The reference points of offsets 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 phases. The offset optimizing procedure in software tools usually starts with computing link travel times and takes into account other factors 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.

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. [1] developed a link performance function to express the loss incurred by platoons traveling through a signalized intersection. They considered the loss as a function of offsets and so formulated the offset optimization as a mixed-integer linear program. Chaudhary et al. [2] developed the bandwidth-based signal optimization software, PASSER V. Stamatiadis and Gartner[3] 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. In Europe, Robertson developed a platoon dispersion model as a function of distance from the upstream stop bar. Robertson's model was later used to calculate the offsets in the TRANSYT-7F software package[4] and the SCOOT adaptive signal control system[5]. More recently, the related research efforts focused on how to conduct stochastic simulation-based optimization (SSO). The concept of SSO is to use a microscopic simulation tool to evaluate feasible timings and search the optimal timing accordingly. The advantage of SSO is that the microscopic simulation can precisely replicate many traffic conditions which cannot be easily replicated by the analytical models, such as those that involve over congestions. Park et al. [6] conducted a series of SSO research based on the VISSIM and the genetic algorithm. Stevanovic et al. [7-11] also conducted similar research on optimizing timings with SSO techniques. Most of the above research efforts addressed the early-return-to-green somehow. For instance, 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 on by traffic fluctuations. The simulation-based offset optimization can address the early-return-to-green issue in nature as long as the signal emulators in the simulation are set as "actuated".

The authors in this paper used the cycle-by-cycle green usage information collected via the ATMS to design offsets. The authors considered the theoretical offsets as random variants. The mainline greens vary from cycle to cycle, so are the theoretical offsets. However, given that only one single set of offsets is 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.

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1 Problem Statement

Both the BOG and the EOG reference points are used in signal coordination practice today. As shown in Fig. 1, in an ideal one-way coordination, the BOG reference can ensure that all the vehicles are able to be coordinated as long as the mainline greens are sufficient (see Fig. 1(a)).

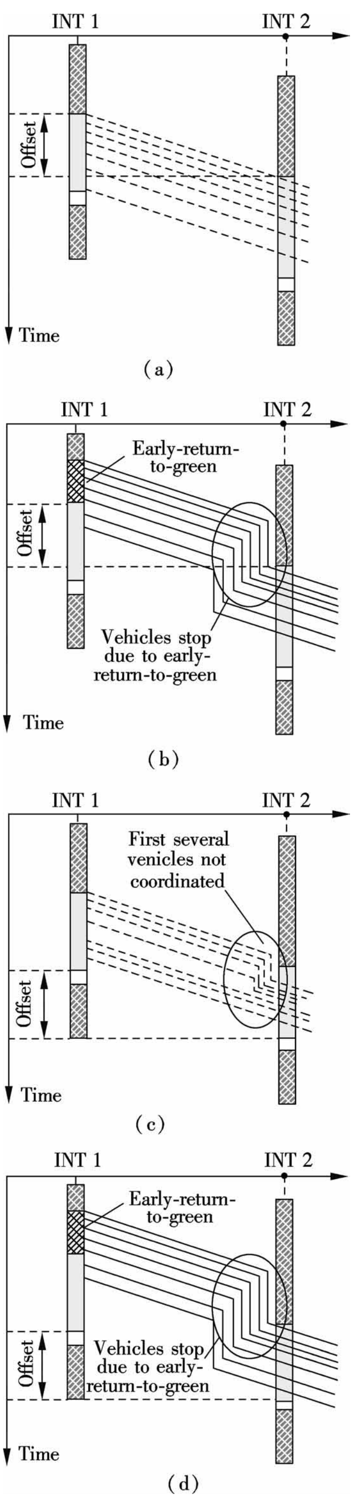

Fig. 1 Coordination fails due to early-return-to-green phenomenon. (a) Programmed begin-of-green; (b) Begin-of-green in reality; (c) Programmed end-of-green; (d) End-of-green in reality

However, with the EOG reference, the first several vehicles in a platoon are possibly uncoordinated and have to stop (see Fig. 1(c)) 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 mainline green starts earlier at intersection 1, the vehicles will also be released earlier and have to stop at intersection 2 (see Fig. 1(b)). For the EOG reference, vehicles will have to wait longer at intersection 2 (see Fig. 1(d)). The negative impact brought about by the early-return-to-green is particularly severe when the traffic on the side streets is moderate (e. g. 300 to 600 vphpl) (vehicle per hour per lane). When side-street traffic is very light (e. g., less than 100 vphpl), the mainline 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 the 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 the offsets optimized in the software are more effective.

Gap-outs on the side streets make the mainline green starts random, and the starting time ranges from the programmed beginning of mainline green to the end of mainline green in the 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 mainline greens become random. Therefore, it is necessary to investigate the random features of the mainline greens and the 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.

2 Model Description

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

Using the example in Fig. 2, the lengths of phases 2 and 3 are determined by controller settings (e. g. min/max green) and queue lengths. A generic form describing the lengths of the green time on side streets is

$$g_s = \min(G_s^{\max}, \max(G_s^{\min}, T_q)) \tag{1}$$

where g_s is the actual green time on side streets; $G_s^{\max}$ is the programmed maximum green time on side streets; $G_s^{\min}$ is the programmed minimum green time on side streets; T_q is the required green time to clear queue.

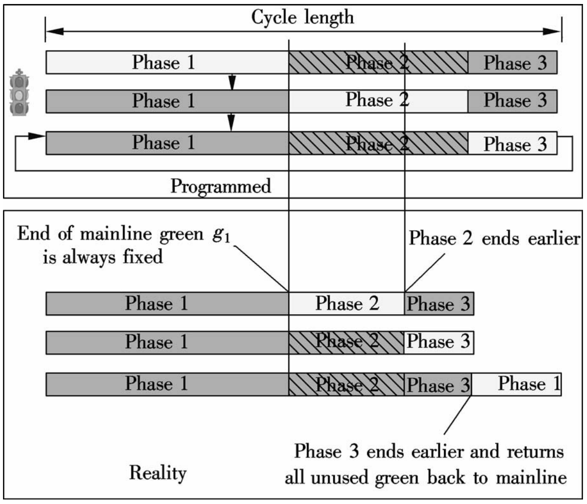

Fig. 2 Actuated coordination and early return to green

On the other hand, the length of phase 1 is independent of the mainline traffic and it can be formulated as

$$g_{\mathrm{m}} = G_{\mathrm{m}}^{\max} + \sum_{i}^{n} (G_{\mathrm{s}_i}^{\max} - g_{\mathrm{s}_i}) \tag{2}$$

where g_{m} is the actual green time on the mainline; $G_{\mathrm{m}}^{\max}$ is the programmed maximum green time on the mainline; g_{s_i} is the actual green time on side street i.

2.1 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 time may be used by its following phase up to the following phase force-off point. In other words, the following green phase can be longer than its programmed maximum green time. By contrast, the floating force-off mode does not allow the green time of uncoordinated phases to exceed their maximum green times and thus any unused green time on side streets will be eventually returned to the mainline. Assume that phase 2 gaps out and more-than-average vehicles arrive on phase 3 and phase 4 with the current cycle. Under floating force-off, phase 3 and phase 4 will max out when the maximum green times expire. However, under fixed force-off, phase 3 can utilize the unused green time by phase 2 to clear vehicles. As a result, the green length of phase 3 can exceed the programmed maximum green time.

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 time. The early-return-to-green, i. e., $G_{\mathrm{s}_i}^{\max} - g_{\mathrm{s}_i}$ in Eq. (2), is positive under the floating force-off mode. Whereas it can be either positive or negative if fixed force-off applies.

2.2 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 can be approximated as a Poisson process when traffic is light or moderate. The needed green time 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. Fig. 3 illustrates how the random arrivals of vehicles on side streets affect the mainline green. The phasing sequence in

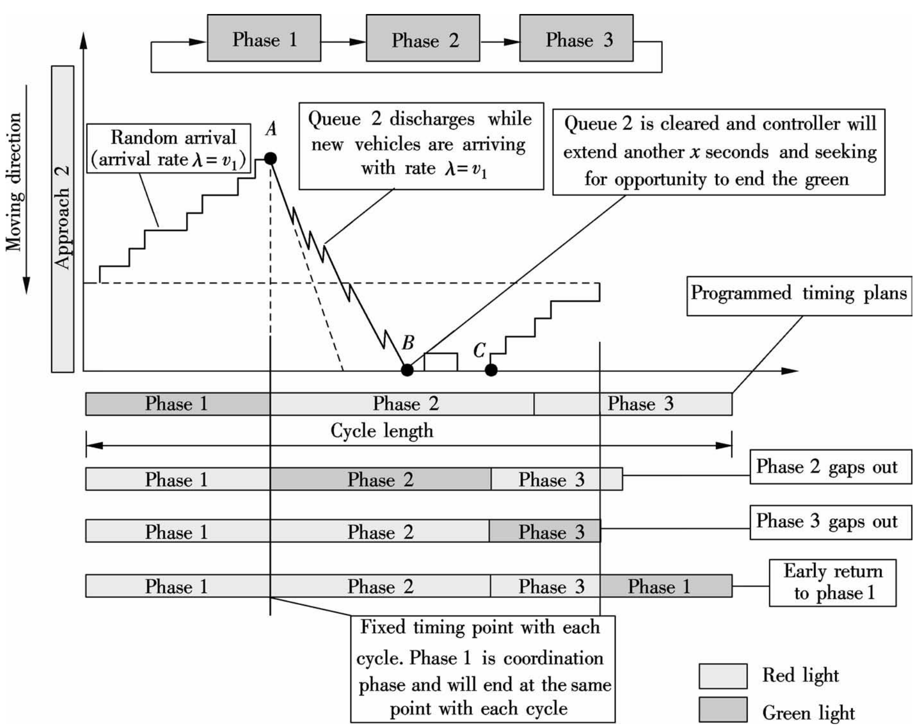

Fig. 3 Random analysis of early return to green

Fig. 3 has a single ring structure with three phases. Phase 1 is coordinated while phases 2 and 3 are uncoordinated. When 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 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 a certain number of 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 the 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 the maximum green time, phase 2 will max out and turn over the green phase to 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.

2.3 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 Fig. 4, if intersections 1 and 2 return to the mainline green Δg_1 and Δg_2 seconds earlier respectively, the optimal offset for that cycle should be shown as

$$O_o = T + \Delta g_1 - \Delta g_2 \tag{3}$$

where T is the optimal offset based on fixed reference points. O_o is the optimal offset.

Besides the one-way coordination shown in Fig. 4, T can also be the optimal offset for the two-way coordination.

Δg_1 and Δg_2 are random; so is offset. As such, if we can infer the distributions of Δg_1 and Δg_2 based on the cycle-by-cycle green usage reports, we can also infer the distribution of the optimal offsets. The optimal offsets should be located where they are most likely to occur.

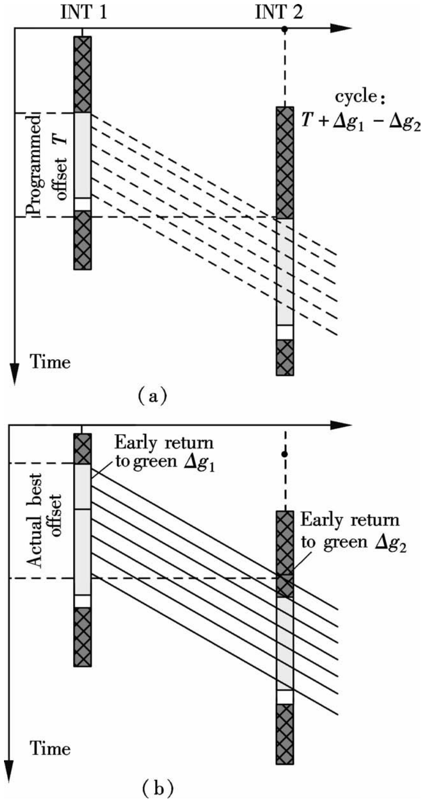

Fig. 4 Dynamic offsets in actuated coordination. (a) Programmed offset; (b) Offset in reality

3 Case Study

Three closely spaced intersections on the Payne Road in Scarborough, Maine are selected as a test site to evaluate the new offset optimizing method. The posted speed on the Payne Road is 56.3 km/h, and the three intersections are all controlled with Naztec NTCIP controllers connected to Streetwise®, a Naztec ATMS system, which allows collection of mainline green usage cycle-by-cycle. The traffic on the Payne Road is very directional and, therefore, one-way coordination is 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 to 13:00) are 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. Fig. 5 shows the traffic volumes, midday timing plans and other relevant information.

3.1 Mainline green usage and distribution

Two weeks of green split reports at these three intersections are retrieved to determine the distributions of Δg_1, Δg_2 and Δg_3. From the histograms in Fig. 6, 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 the acceptance-rejection method, is 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.

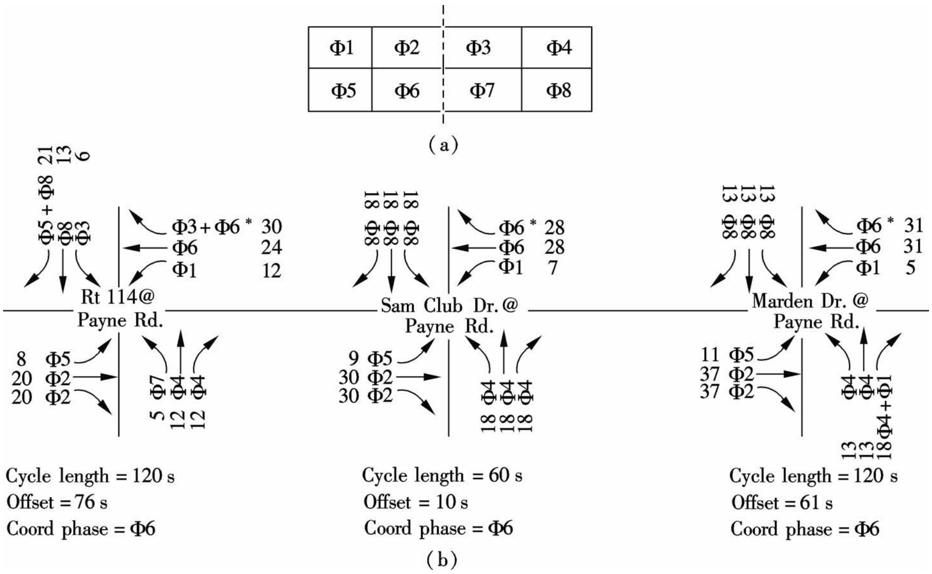

Fig. 5 Ring structure, phasing sequence and green times at three test intersections. (a) Ring structure; (b) Phasing sequence and corresponding green times

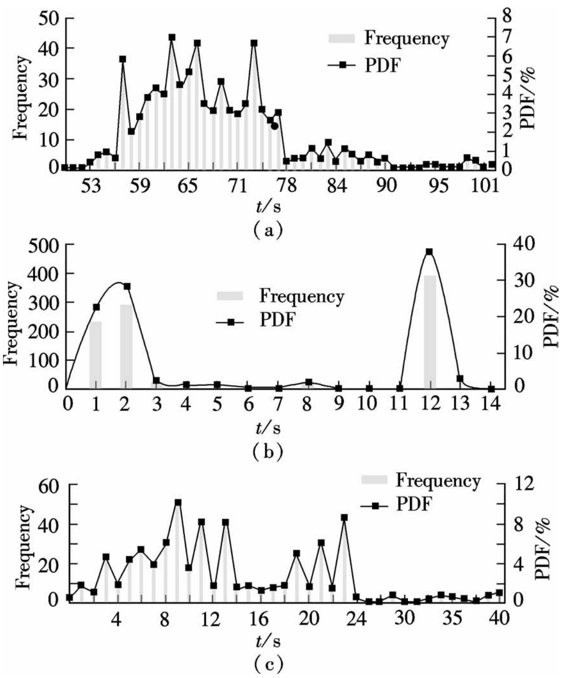

Fig. 6 Early-return-to-green distributions. (a) At Rt. 114/Payne Rd (INT 1); (b) At VIP Auto Dr./Payne Rd (INT 2); (c) At Sam Club Dr./Payne Rd (INT 3

3.2 Optimal offset distribution inferred with Monte Carlo simulation

10^4 samples of Δg_1, Δg_2, and Δg_3 are generated and each sample of the optimal offsets is computed with the sample values of Δg_1, Δg_2, Δg_3 and Eq. (3). The offsets are optimized with SYNCHRO 7 and the values are 8 s between Rt. 114/Payne Rd. and Sam Club Dr./Payne Rd. and 10 s between Sam Club Dr./Payne Rd. and Marden's Dr./Payne Rd. The generated optimal offsets samples are divided by seconds and Fig. 7 shows the histogram. From Fig. 7, it appears that the optimal offset 1 most likely occurs around 20 s and the optimal offset 2 most likely occurs around 2 s. By comparison, the probability of optimal offsets computed in SYNCHRO 7 is much less than that around the most likely optimal offsets. Therefore, 20 and 2 s are selected as the new offsets for these three intersections.

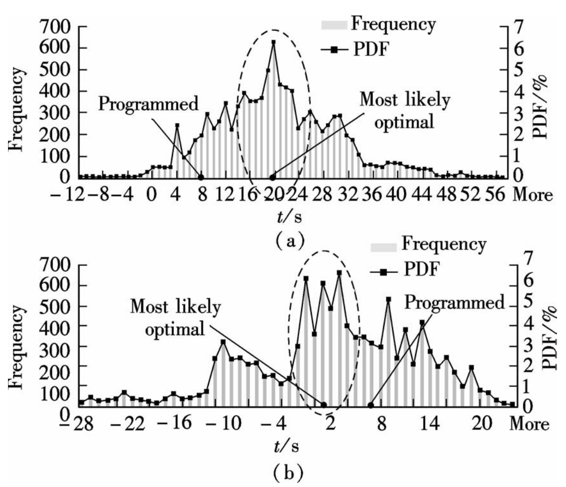

Fig. 7 Distribution. (a) Offset 1; (b) Offset 2

3.3 Comparison in simulation with paired T-test

Before being deployed in the field, the new offsets are first evaluated in simulation. The microscopic simulation software VISSIM is selected because its signal emulator can simulate most of the functions in actual controllers. Two scenarios are 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 are exactly the same except for the offsets. Each scenario is simulated 1 000 times with a common set of random speeds.

A paired T-test for means is performed to determine if the travel time μ_1 under the new offsets is shorter than μ_2 under the existing offsets. The following hypotheses are formulated:

Null hypothesis $H_0: \mu_1 = \mu_2$;

Alternative hypothesis $H_1: \mu_1 < \mu_2$.

From Tab. 1 and Tab. 2, it is clear that both northbound traffic and southbound travel times under the new offsets are shorter than those under the existing offsets with more than 0.95 confidence since the p values are much less than 0.05.

Tab. 1 Paired T-test for northbound traffic on the mainline

Variables	New offsets	Existing offsets
Mean offset/s	42.3	44.6
Variance/s	4.6	5
Observations/counts	1 000	1 000
Hypothesized mean difference	0	
Degree of freedom	999	
t statistic	−28.3	
$p(T \leqslant t)$ one-tail	0	
t critical one-tail	1.6	

Tab. 2 Paired T-test for southbound traffic on the mainline

Variables	New offsets	Existing offsets
Mean offset/s	44.8	49.5
Variance/s	8.1	12.6
Observations/counts	1 000	1 000
Hypothesized mean difference	0	
Degree of freedom	999	
t statistic	−42	
$p(T \leqslant t)$ one-tail	0	
t critical one-tail	1.6	

3.4 Before-and-after comparison in the field

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

Tab. 3 Measured travel time and stops under existing and new offsets s

Compared variables	Northbound		Southbound	
	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
Improvement/%	6.55	33.33	−0.67	1.32

From Tab. 3, the travel time and stops under the new offsets are 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 for the southbound traffic, 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 to 13:00. As a result, the most-likely optimal offset estimation based on the green usage reports of phase 6 gives more priority to the northbound traffic than to the southbound traffic.

4 Conclusion and Future Work

Due to the early-return-to-green phenomenon in actuated coordination, mainline greens are random rather than deterministic. As such, optimal offsets in theory between intersections should also be random and determined not only by the mainline travel time but also the traffic demand on the side streets. The authors utilize the green usage reports generated by the Naztec ATMS system, or Streetwise, to infer the distributions of mainline greens. Based on the mainline green distributions, the authors derive the distribution of optimal offsets using the Monte Carlo simulation method and then identify the most-likely optimal offsets accordingly. The before-and-after comparison in simulation shows that the travel time and stops measured in the field are significantly reduced under the new offsets. The same evaluation conducted in the field also supports this conclusion.

Further works for this method are listed as follows: When we calculate the optimal offsets with Eq. (3), we appreciate that many factors, such as the stop-bar queues, will affect the optimal offset based on fixed reference points. All these factors should be considered when we further refine this method in future. In addition, the travel time is simply calculated as the link distance divided by the posted speed in the case study. Additional investigation should be added to identify the time-dependent link travel speeds. The authors are planning to introduce more realistic traffic models (e. g., an offset-dependent traffic control delay model) into this procedure in future, and more analysis (e. g., offsets' sensitivity analysis) will be done with the Monte Carlo model presented in this paper.

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基于高级交通管理系统数据的城市干道协调控制方法

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摘要:为使感应式交通信号控制系统中由于协调控制方案调整造成的额外延误和停车次数最小,基于先进交通管理系统数据设计了基于随机理论的相位差计算方法. 在感应式信号控制系统中,干线的绿灯启动时间是随机的. 基于支线绿灯时间中断机理,应用随机理论分析支线未使用绿灯时间的分布. 最佳干线绿灯启动时间可选取在绿灯时间返还概率最大处,以保证因干线绿灯启动时间变化而引起的停车和延误最小. 所提方法通过在交通状况接近于中国中小城市的美国缅因州的一个实例研究得到了进一步的论证,证实了新计算方法能够显著减低干线车辆行驶时间和延误.

关键词:交通信号控制;随机理论;交通仿真;高级交通管理系统;智能交通系统
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