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Improving method of real-time offset tuning for arterial signal coordination using probe trajectory data

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Abstract
In the environment of intelligent transportation systems, traffic condition data would have higher resolution in time and space, which is especially valuable for managing the interrupted traffic at signalized intersections. There exist a lot of algorithms for offset tuning, but few of them take the advantage of modern traffic detection methods such as probe vehicle data. This study proposes a method using probe trajectory data to optimize and adjust offsets in real time. The critical point, representing the changing vehicle dynamics, is first defined as the basis of this approach. Using the critical points related to different states of traffic conditions, such as free flow, queue formation, and dissipation, various traffic status parameters can be estimated, including actual travel speed, queue dissipation rate, and standing queue length. The offset can then be adjusted on a cycle-by-cycle basis. The performance of this approach is evaluated using a simulation network. The results show that the trajectory-based approach can reduce travel time of the coordinated traffic flow when compared with using well-defined offline offset.

Keywords
Improving method, signalized intersections, offset tuning, probe trajectory data

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Introduction

Traffic signal control is one of the major traffic control methods for urban streets. It is of little doubt that improving traffic signal operations has potentially enormous payoffs for the quality of travel experience. Among all the aspects of traffic signal control, traffic signal coordination is one of the most important concepts. It aims to make motorists able to travel through multiple intersections along a corridor with minimal stops and short delays. In fact, the 2011 Urban Mobility Report notes that in its reporting areas, more than half of the city street miles have traffic signal coordination because the technology has been proven, the cost is relatively low, and the government institutions are familiar with the implementation methods.

The performance of signal coordination is determined by the signal timing parameters: the cycle length,

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the split, and the offset. To maintain continuous coordination, a common cycle length is usually predefined for the corridor. The split is intersection specific and determined by traffic demand of approaches. The offset, which is defined as the time difference from a system reference point to the beginning or ending point of a complete green phase at certain intersection, determines the arrival type, should be set to let traffic flow go through signals without stopping.

Offsets are very important to achieve satisfying progression in a coordinated signal systems. The delay of a coordinated corridor is very sensitive to offsets; an unsuitable offset at one intersection in the corridor can significantly increase the delay.[1] On the basis of the concept of coordination, the offset can be simply determined by the link travel time between the adjacent traffic signals, which is a function of the link length and the free flow speed (FFS). However, actual traffic conditions fluctuate significantly and usually quite different from the design conditions. In addition, when actuated controllers are installed, the fluctuation of the traffic from side streets would cause the so-called early return to green problem.[2] That is, when the demand is insufficient to extend phases to the force-off point, the extra green time is relocated to the coordinated phase. Because all the intersections do not have the same degree of saturation on all phases, the amount of extra green time relocated to the coordinated phase is different. As a result, the design offset is not kept and the progression is degenerated. The standing queue is another problem. The arrival during the red forms the standing queue. When the upstream traffic arrives, the standing queue would force the arrival traffic to slow down or stop if it has not already dissipated, which increases the travel time significantly. Other factors such as the variable arrival traffic speed and queue dissipation rate would also affect the actual optimal offset.

Lots of offset tuning methods have been proposed to achieve better progression. Most of them are offline methods. One way to mitigate the "early return to green" problem is using the average lengths of the non-coordinated phases to calculate the offset. Wu et al.[3] used Global Positioning System (GPS) data to obtain actual travel speeds and later adjusted the offset to maximize green bandwidth. This method can provide more suitable offsets but still not address the real-time traffic fluctuation. Recent studies are about dynamic or online methods. The Split-Cycle Offset Optimization Technique (SCOOT) has been installed worldwide.[4] Abbas et al.[1] proposed an offset transition algorithm using second-by-second approach loop detector data. Offsets are adjusted based on a procedure of tabulating volume and occupancy profiles. Li et al.[5] used the cycle-by-cycle green usage reports to search for most-likely optimal offsets. Lee et al.[6] developed a real-time estimation approach for lane-based queue lengths, using upstream and downstream detectors. Most existing methods rely on loop detector data to improve coordination. Studies of using modem traffic detection technologies are limited. The trajectory data, as a new data source, can provide detailed information about traffic conditions at the individual vehicle level. There are studies indicating the potential of such data source by estimating queue length.[7–9] The main challenge of developing a trajectory-based model is how to convert the microscopic detection into usable measures for offset tuning.

This study is an attempt to use probe trajectory data for real-time offset tuning. Using the concept of critical points (CPs) on trajectories,[8] which are the boundary points of different states of vehicle movements, the dynamics of the vehicular movement can be captured in a space-time diagram. Different traffic conditions can then be revealed. The free flow segment of the trajectories can be used to calculate the actual travel speed of upstream arrival traffic, and the CPs related to the queue dissipation process can be used to estimate the clear time of the standing queue. The length of standing queue can also be estimated. In the later sections of this article, this approach is presented in detail. The performance of this approach is then evaluated with a simulation network and the results are demonstrated. It indicates that this trajectory-based approach can adjust offset on the cycle-by-cycle basis and help improve progression in a signal coordination system.

Methodology

We assume that a set of signal timing parameters, the common cycle length, the splits, and offsets, has been determined offline based on the prevailing traffic conditions. The intent is to tune the offset to address the real-time traffic fluctuation. Major factors including the arrival traffic FFS, queue dissipation rate, and the standing queue length would be considered in tuning offsets. Figure 1 shows the overall flowchart of the approach. When there is a probe vehicle available in the target link, the trajectory is divided to segments based on the extracted CPs. The FFS is updated and the queue dissipation rate is updated. The standing queue length is also estimated. All the three factors are then used to adjust the offset. Note that the probe is tracked for individual link instead of the entire corridor for the purpose of privacy protection.[10]

Critical points on trajectories

The trajectory of a vehicle can be represented as a series of points, $\{x_t\}$, where x_t is a record of the vehicle's

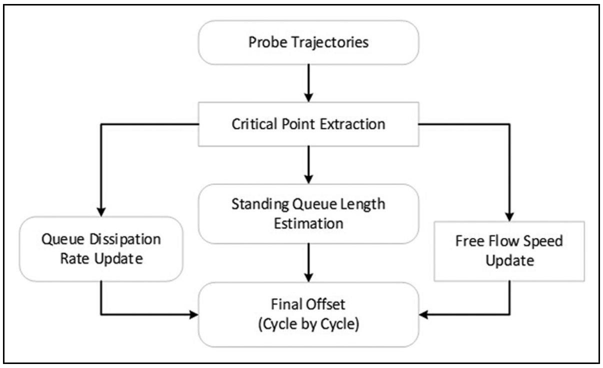

Figure 1. Methodology flowchart.

dynamics at time t. x_t is a vector where $x_t = [l, v]$, where l is the location and v is the speed. In some cases, the acceleration rate, a, is also included. In this case, $x_t = [l, v, a]$. The trajectory of a vehicle can be divided into several segments, in which the vehicle is either in uniform motion or in uniform acceleration motion.[8] Critical points (CPs), $\{x_t^c\}$, a subset of $\{x_t\}$, are defined as the boundary points of these segments.

Consider an online application case when the probe vehicle reports its trajectory point by point. If the newly available point of the trajectory indicates the same movement as its previous ones, this point is not a CP; otherwise, this is a new CP. In this study, a classification algorithm based on the location and speed differences is used.[11] The main idea of the CP extraction algorithm is to use the previous trajectory to predict the current one in terms of speed and location. Assuming the prediction errors for its previous points follow a normal distribution, if the error for this point is statistically significantly larger, it would be considered as a new CP since the large error indicates the change of motion. After a new CP has been found, the beginning point is updated as the new CP until reaching the last available point.

Note that CPs are related to the changes in traffic conditions, either significant (e.g. queue formation) or trivial (local traffic disturbance). After getting all the CPs, the problem now is to identify the CPs which should be considered in the offset tuning algorithm; CPs resulting from local disturbances should be removed. Figure 2 demonstrates three types of shockwaves and three types of CPs for a typical signal cycle. Shockwave 1 is the queue formation shockwave; shockwave 2 is the queue discharging shockwave; shockwave 3 is the forward propagating shockwave generated after shockwave 1 and shockwave 2 intersect. Type I CPs indicate segments when the vehicle is at the FFS. A Type II CP is the point when and where the vehicle stops and joins the queue. A Type III CP is the beginning point of acceleration when the signal turns green.

Based on the definitions, the three types of CPs can be separated from the CPs extracted from one trajectory using a rule-based CP procedure:

1. Find all the uniform motion segments which cover a significant length of the link (e.g. 100 feet) and calculate the speed for each of them. The one with the highest speed is selected. Compare this speed with historical FFS, if the difference is within a range (e.g. 10%), this boundary points of the segment are Type I CPs.
2. Find the segment where the vehicle speed is less than the stopping speed (e.g. 3 mph). Type II CP is the first point and Type III CP is the last one.

Online calibration of FFS

As discussed, segments defined by Type II CPs are used to estimate the actual FFS, which can be calculated as

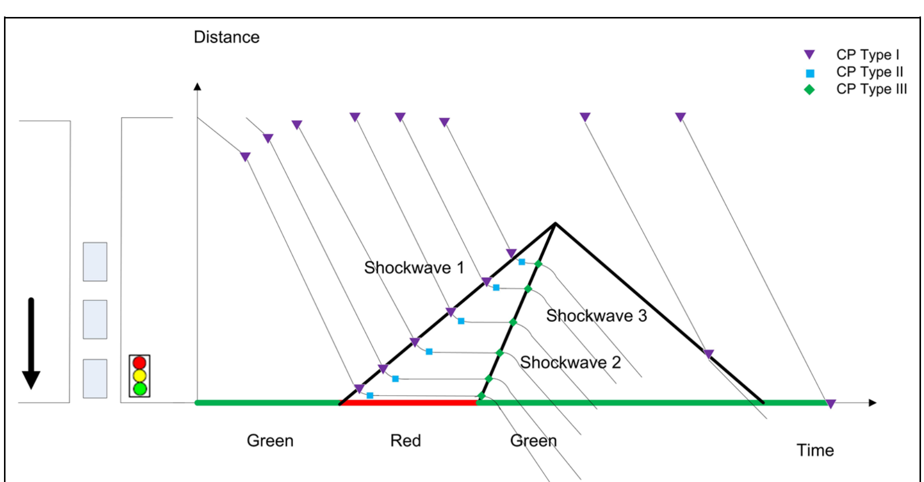

Figure 2. Circuital points related to the queue.

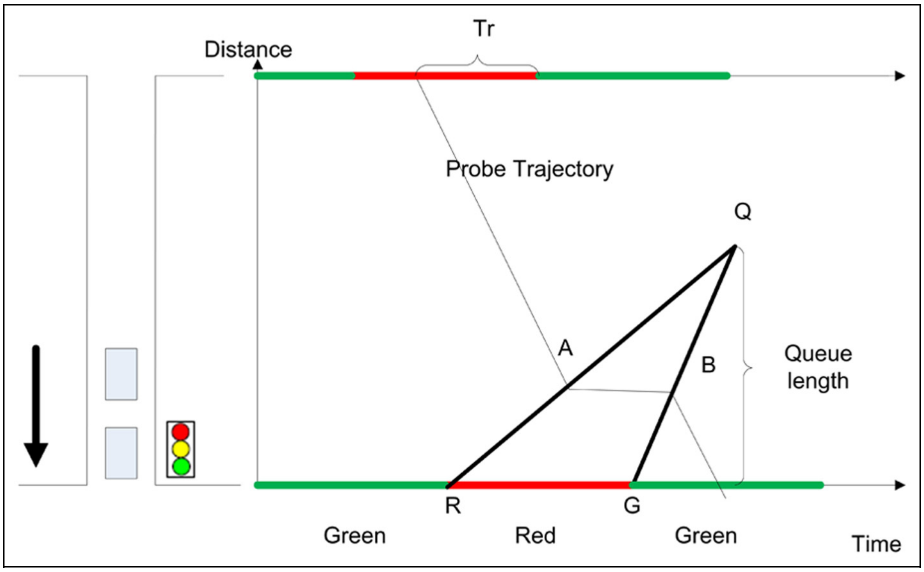

Figure 3. Standing queue length estimation.

$$\text{FFS} = \frac{1}{n}\sum_{p \in n} v_p \tag{1}$$

where v_p is the average speed of the segment defined by two Type I CPs from trajectory p, and n is number of trajectories in the last time period. A moving time window is used to update FFS; this study uses 15 min.

Online calibration of queue discharging shockwave speed

Using Type III CP and the start time of green from the controller, the shockwave speed can be calculated as

$$v_{3,i} = \frac{L_{CP\,\text{III},\iota}}{T_{CP\,III,i} - T_{g,i}} \tag{2}$$

where $T_{CP\,\text{III},\iota}$ is the time stamp of the Type III CP from cycle i, and $L_{CP\,\text{III},\iota}$ is the distance from the Type III CP to the stop-bar from cycle i.

Similar to the calibration of FFS, a moving time window is also used to update this shockwave speed

$$v_3 = \frac{\sum_{i=0}^{n} v_{3,i}}{n} \tag{3}$$

Standing queue length estimation

For each cycle, the length of standing queue is calculated to tune the offset. The queue length estimation consists of two parts, the lower bound of the queue and the upper bound of the queue. The lower bound is the distance from the last available Type II CP to the stop-bar. The upper bound needs a more complex analysis.

As shown in Figure 3, when a probe enters the link and stops at the queue end, it indicates the queue length at that moment. The upper bound of the queue length is

$$Q_{\max} = Max(Q_A + \int_{T_r} q(t)dt) = Q_A + T_r\left(\sum_{m \in \{M\}} I(m)c(m)\right) \tag{4}$$

where $\int_{T_r} q(t)dt$ is the total arrival after the probe and before the queue release at the upstream intersection, $\{M\}$ is the set of all the movements that enter this link, $I(m) = \begin{cases} 0 & \textit{when this movement is not protected} \\ 1 & \textit{this movement is protected movement} \end{cases}$, $c(m)$ is the capacity flow rate of the movement, and $\sum_{\mathrm{m} \in \{M\}} I(m)c(m)$ is the sum of the capacity flow rate of all protected movements which enter this link.

Offset calculation

The suitable offset should not only provide enough time to allow the accumulated queue to clear before the upstream traffic arrives but also not too early to waste of the green time. Therefore, the optimal offset (OO) can be calculated as

$$OO_i = \frac{FFS_i}{L_j} - \frac{q_i}{v_i} \tag{5}$$

where q_i is the standing queue length of cycle i; FFS_i is the latest FFS for vehicles traveling from the upstream intersection to the downstream intersection for cycle i; v_i is the queue discharging shockwave speed cycle i,

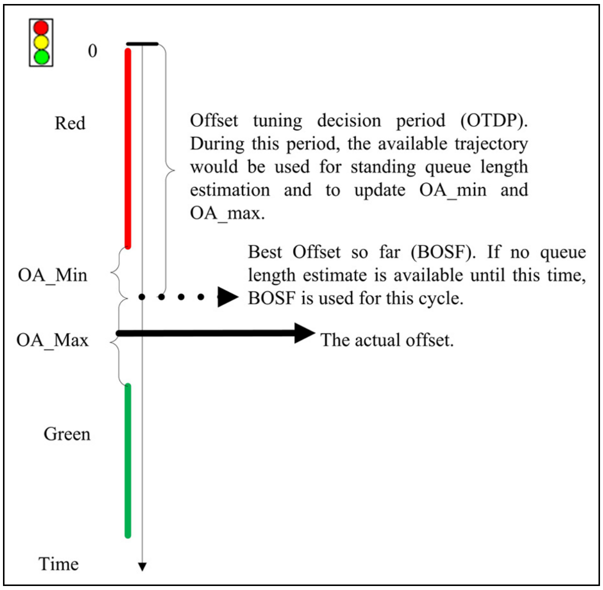

Figure 4. Offset tuning decision in a cycle.

which is equivalent to the queue dissipation rate if normalized; and L_j is the length of link j.

Offset tuning logic

Because the standing queue length estimate is given in terms of lower and upper bounds, offset adjustment is provided as

$$\begin{aligned} OA_{\min,i} &= BO - OO_{Q\max,i} \\ OA_{\max,i} &= BO - OO_{Q\min,i} \end{aligned} \tag{6}$$

where BO is the predetermined offset in the base condition, and $OO_{Q\max,i}$ and $OO_{Q\min,i}$ are the optimal offset using max standing queue length and min standing queue length, respectively.

Figure 4 shows how the offset tuning decision is made in a cycle. For each cycle, if there is probe trajectory available during the offset tuning decision period (OTDP), the range of tuning the offset, defined by $OA_{\min}$ and $OA_{\max}$, would be updated based on the queue length estimate. The best offset so far (BOSF) is either the BO or the OO based on the last probe. This consideration is to address the case when more than one probe is available in the cycle. If there is no probe available, the predetermined BO is used for this cycle.

The offset tuning follows the logic shown in Figure 5.

In Figure 5, the range of OA is short if

$$OA\_\max - OA\_\min < \alpha \tag{7}$$

where α is a constant. In this study, $\alpha = 3$ s.

The final offset (FO) is set as

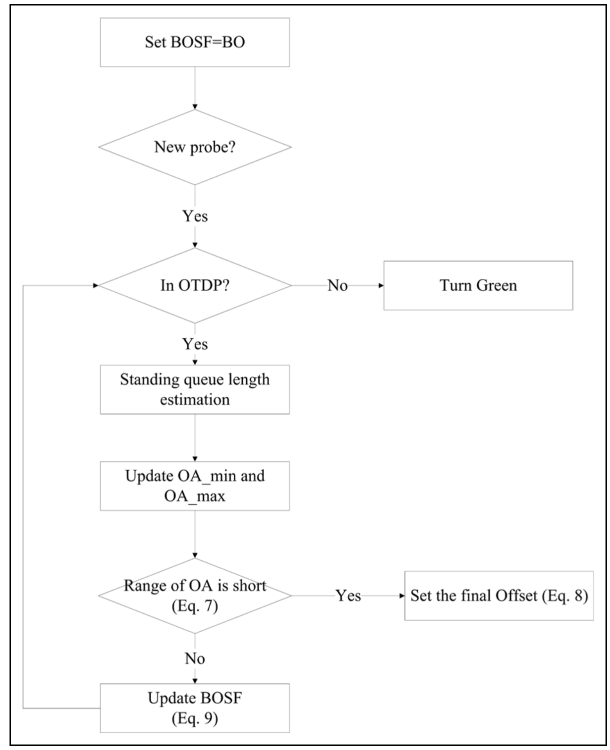

Figure 5. Offset tuning logic.

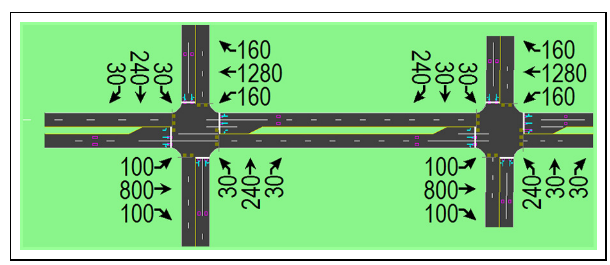

Figure 6. Simulation network.

$$FO = BO + \frac{OA\_\max - OA\_\min}{2} \tag{8}$$

The BOSF is updated using

$$BOSF = BO + \theta OA\_\max \tag{9}$$

where θ is a constant, $0 < \theta < 1$. In this study, $\theta = 0.75$.

Experimental design

A simple network consisting of two intersections is selected to evaluate the proposed offset tuning algorithm. The network and average traffic volumes are shown in Figure 6. All the approaches have two lanes, and the EB and WB have left turn bays. The WB approach is chosen as the coordinated phase.

Table 1. Delays for the coordinated approach (WB).

	Delay in P Case (s)		Delay in V Case (s)	
	Mean	SD	Mean	SD
No offset tuning	3827	173.3	4341	258.1
Offset tuning	3879	185.6	3932	194.8

SYNCHRO, as an offline signal tool, was used to determine the signal timing parameters for the two intersections as the benchmark. The common cycle length is 80 s, the green time for the *EB* and *WB* approaches are 59 s, and the green time for *NB* and *SB* are 21 s. The offset is 10 s. This offset is selected as the *BO*.

VISSIM was then used to build a replica network with the same geometric and signal timing. The traffic volumes were also set the same as the ones in SYNCHRO. This scenario is referred as the prevailing traffic condition case (P Case). A total of 20 independent simulation runs were conducted to produce the delay.

Another replica network was created in VISSIM with the same geometric and signal timing. The traffic volumes were set to have a 10% increase or decrease for consecutive 5-min interval. In this way, traffic fluctuation was simulated, but the averages are kept the same as the P Case. This scenario is referred as the variance traffic condition case (V Case). A total of 20 independent simulation runs were conducted to produce the delay.

The proposed algorithm was implemented both in the P and V cases. For each cycle, one vehicle was randomly picked as the probe and the trajectory was used for offset tuning. A total of 10 runs of simulation were conducted for both cases, and the delays of the coordinated approach were recorded.

Numerical experiment results

The total delays of the *WB* approach on the link between the two intersections are shown in Table 1. It is easy to find that, in the P case, the mean and SD delays of No offset Tuning are 3827 and 173.3 s, respectively, and of the Offset Tuning are 3879 and 185.6 s. In the V case, the mean delays of these two situations are 4341 and 3932 s, and the SD delays are 258.1 and 194.8 s.

Comparing the V Case with the P Case without offset tuning, it shows that traffic demand fluctuation would affect the effectiveness of progression and increase delay if the offset is not adjusted online. When the proposed offset tuning algorithm is implemented, the delay in V Case is decreased. The proposed method is also stable so that the delay in P Case remains the same.

Conclusion and future works

Lots of offset tuning methods have been proposed to achieve better progression, but few of them take the advantage of modern traffic detection methods such as probe vehicle data. The trajectory data, as a new data source, can provide detailed information about traffic conditions at the individual vehicle level. This study proposes a method using probe trajectory data to adjust offsets in real time. The CP, representing the changing vehicle dynamics, is first defined as the basis of the approach. Using the CPs related to different states of traffic conditions, such as free flow, queue formation, and dissipation, the actual travel speed, the queue dissipation rate, and the standing queue length can be estimated. The offset can then be adjusted on the cycle-by-cycle basis. The performance of this approach is evaluated with a simulation network. The results indicate that this trajectory-based approach can reduce travel time of the coordinated traffic compared with using well-defined offline offset. This study is the proof of concept. However, this method has not been tested using field data in the case of multiple intersections or even an urban network, which is the limitation of this study. So far as we know, coincident with the development of Internet of Vehicles, the vehicle to infrastructure (V2I) technologies application is not far from now; thus, integration with the current adaptive signal control logic and further testing using data in the environment of V2I will be studied in the future.

Declaration of conflicting interests

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