Offline Offset Refiner for Coordinated Actuated Signal Control Systems[1]

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Abstract: This paper presents the concept and implementation of an offline offset refiner, which addresses the problem of uncertain (not fixed) starts/ends of green in the determination of offsets for coordinated actuated signal control. Making use of a large amount of archived signal status data available from real-time signal operations, the refiner may fine tune the signal offsets to provide smoother progression in either one-way or two-way coordination. The proposed offset refiner is easy to implement and can work readily with current closed-loop signal control systems to improve their system performance.

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Introduction

An increasing number of traffic signal controllers in use in the United States are traffic actuated. It has been a common practice to operate these controllers in coordinated systems to provide progression for major traffic movements along arterials and networks. Compared with fixed-time coordinated systems, these semiactuated coordinated systems offer additional flexibility in responding to fluctuations in traffic demand. Under signal coordination, traffic actuated signals operate on a common background cycle length. Coordination is provided through offset with respect to a fixed reference point (FHwA 1996). This reference point defines the start of the controller local clock, and it can be set to the start of green, end of green (yield point), or other time interval for the sync phases (e.g., beginning of the flashing don't walk, FDW, interval). Note that the controller local clock definition varies among signal controller manufacturers. The rest of the phases are actuated and their duration varies between a minimum and a maximum green time. These phases may terminate at fixed force-off points in the background cycle, terminate early (gap out), or terminate when they reach their maximum green (max out) (Skabardonis 1988). Typically, when the actuated phases terminate early, the spare green time in the cycle is received by the sync phases (note that the NTCIP ASC specification allows the user to control the spare time going to either the next phase in the sequence or the sync phases).

To ensure operation efficiency of coordinated actuated systems, attention should be paid to determining appropriate signal settings, particularly offsets due to the fact that the start of green of the sync phases (typically Phases 2 and 6) is not fixed. Several approaches have been proposed in the literature to address such a so-called "early return to green" problem in the determination of offsets. Jovanis and Gregor (1986) suggested adjusting the end of green of the sync phase to the end of the through band for noncritical signals. Skabardonis (1996) proposed three methods for determining offsets from the optimal fixed-time splits and offsets. Although the three methods differ in the procedure and applicable situation, the concepts are essentially the same: making a best estimate on average starting point of the sync phase and then optimizing the offset based on the estimate. Chang (1996) offered a similar suggestion for obtaining the offsets from a second optimization run that uses the *anticipated* green times on the noncoordinated phases, as constraints on their maximum green times.

The above prior studies have focused on determination of appropriate offsets in the stage of design of the signal timing plans. Certainly after implementing the timing plans in the field, there are still opportunities for fine tuning. Shoup and Bullock (1999) examined a concept of using the link travel times observed for the first vehicle in a platoon to adjust offsets. The concept could lead to an online offset refiner, if vehicle identification technologies had been deployed in arterial corridors. Abbas et al. (2001) developed an online real-time offset transitioning algorithm that continually adjusts the offsets with the objective of providing smooth progression of a platoon through an intersection. More specifically, the objective was achieved by moving the green window so that more of the current occupancy actuation histogram is included in the new window. A greedy search approach was used to determine the optimal shift of the green window. In the ACS-Lite system developed by FHwA (Luyanda et al. 2003), a run-time refiner can modify in an incremental way the cycle, splits, and offsets of the plan that is currently running based on observation of traffic conditions.

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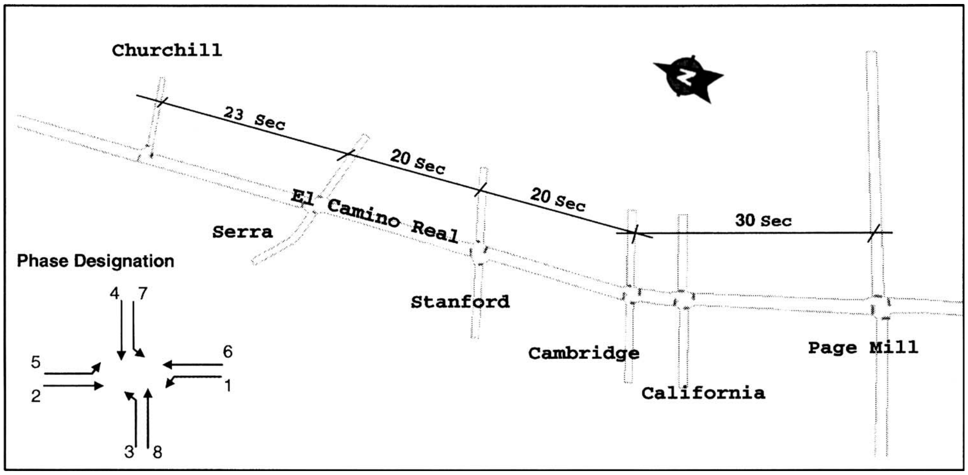

Fig. 1. Study corridor, El Camino Real, Palo Alto, Calif.

ITS technologies make high-resolution signal operation data more readily available. For example, in California, second by second returns of signal status can be obtained for all phases via using AB3418. (The California legislature passed legislation, Assembly Bill 3418, requiring all signal controllers purchased in the state after January 1, 1996, to be compliant with a standardized protocol.) These data do offer tremendous opportunities for us to further improve the efficiency of closed-loop signal control systems.

This paper presents the basic concept of an offline offset refiner for coordinated actuated control systems. The tool is not intended for taking the place of traditional signal optimization methodologies or software. Presumably the signal settings are optimized by using these methodologies or programs, probably following the guidelines set up in Skabardonis (1996), Chang (1996), and Nichols and Bullock (2001) among others. The refiner is supposed to be used after implementing the resulting timings for a certain period of time (say, 2 weeks or longer). Making use of a large amount of signal status data obtained from the field operation, it refines the offsets to provide smoother progression by remaximizing the bandwidth and minimizing the red-meeting probability.

The remainder of the paper is organized as follows. Next, we present the premise of the offset refiner and its justification by examining the signal status data from a real-world network. The third section discusses maximization of expected bandwidth in determination of optimal offsets when starts of green for actuated phases are uncertain. The fourth section introduces a new metric as the probability of the lead vehicle from the first intersection in coordination to meet a red light at any of the downstream intersections, which may serve as another objective function in determination of optimal offsets in order to provide better perceived progression. Conclusions and recommendations for further research are offered in the last section.

Premise of Offset Refiner

The premise of the offset refiner is that day-to-day traffic and pedestrian flows are realization of uncertain traffic and pedestrian demands, which are certain types of stochastic processes. As a consequence, the resulting responses of actuated signals, such as phase durations or starts/ends of green phases, would follow certain types of stochastic distributions. These distributions can be estimated based on a large amount of signal status data from the field operation, thereby providing a better knowledge about the uncertainty of starts/ends of green for coordinated phases. The refiner will then apply the knowledge to adjust the offsets to improve the coordination. In real-world implementation, the refiner may be applied periodically to fine tune the system until a satisfactory performance has been achieved. Note that the concept presented in this paper uses signal status data only. Our experience with field signal operation data reveals that signal status data are often far more accurate and robust than loop detector data (count and occupancy). The latter are prone to be inaccurate or missing due to inappropriate setting of loop sensitivity, loop malfunction, communication conflict, weather conditions, etc. Certainly if high-quality loop data can be made available, the information would definitely help refine the system, as suggested later in this paper. Our ongoing research is looking into the opportunities.

To facilitate the presentation of the concept, we use the field data from a real-world network illustrated in Fig. 1 [the figure is a snapshot of the simulation using Paramics produced by Quadstone (2003)]. The network is a segment of El Camino Real, a major arterial in the San Francisco Bay Area. The study section is located in the city of Palo Alto, Calif., consisting of five signalized intersections whose cross streets are Churchill, Serra, Stanford, Cambridge, and Page Mill from north to south, respectively (there is another signalized intersection named California between Cambridge and Page Mill where the field master is located. We were not able to obtain its signal status data since a special program was needed. We ignore this intersection in this paper, without impairing the validity of the concept presented herein.) The average travel times between intersections are also given in Fig. 1. The signal status data are pulled by the field master every 2 s and are stored in a roadside computer, and are further retrieved regularly via a dial-up connection. The data used in this paper were collected from 11:00 a.m.–3:00 p.m., during the period of February 6–March 7, 2005, for a total of 14 weekdays with more than 1,600 cycles. Moreover, the corridor is in two-way coordination, and the signal settings were recently optimized by using the Synchro software (Trafficware 2003). The signal settings for the time period of analysis are given in Table 1.

The premise of the offset refiner can be justified by examining the signal status data. Fig. 2 presents the empirical cumulative distribution functions for starting points of Phase 2 at the El

Table 1. Signal Settings for Each Intersection

Intersection	Cycle length (s)	Force-off 1	2	3	4	5	6	7	8	Offset (s)
Churchill	120	N/A[a]	0	33	N/A[a]	63	0	N/A[a]	33	84
Serra	120	59	0	N/A[a]	30	51	0	N/A[a]	N/A[a]	72
Stanford	120	81	25	N/A[a]	58	25	0	N/A[a]	N/A[a]	62
Cambridge	120	21	0	N/A[a]	57	82	21	N/A[a]	57	1
Page Mill	120	106	19	43	83	19	0	43	83	108

[a]N/A=not available.

Camino/Page Mill intersection. Visually, it can be observed that the more days of data we used, the closer to each other the resulting distributions would be, which suggests that the empirical distributions tend to be stable.

We performed a Kolmogorov–Smirnov test to examine the null hypothesis that 10 and 14 days of data have the same distribution. The observed Kolmogorov–Smirnov statistic is 0.033 and p value is 0.4711. Clearly the difference between their distributions is not significant at the 5% level, and thus we cannot reject the null hypothesis. The statistical test verifies the above observation that the empirical distributions would eventually become stable, and 14 days of data may be sufficient to estimate the distribution. Be aware that the conclusion is only valid for this specific site and the time period (11:00 a.m.–3:00 p.m.), and separate tests would be necessary for other implementation sites or different times of day.

To illustrate how prevailing the problem of "early return to green" is, Fig. 3 depicts the histograms for starts of green of Phases 2 and 6 at two selected intersections along El Camino: Page Mill and Stanford. Page Mill is a critical intersection for the corridor with almost equal amounts of mainline and cross-street traffic. Still, the probabilities of "early return to green" are 61% for Phase 2 and 39% for Phase 6. Stanford has low volume of minor-phase traffic, thus the probabilities are as high as 92% for Phase 2 and 94% for Phase 6, respectively. The histograms confirm the assertion made in the previous studies that the problem of "early return to green" should be recognized and explicitly addressed in the timing of coordinated actuated control.

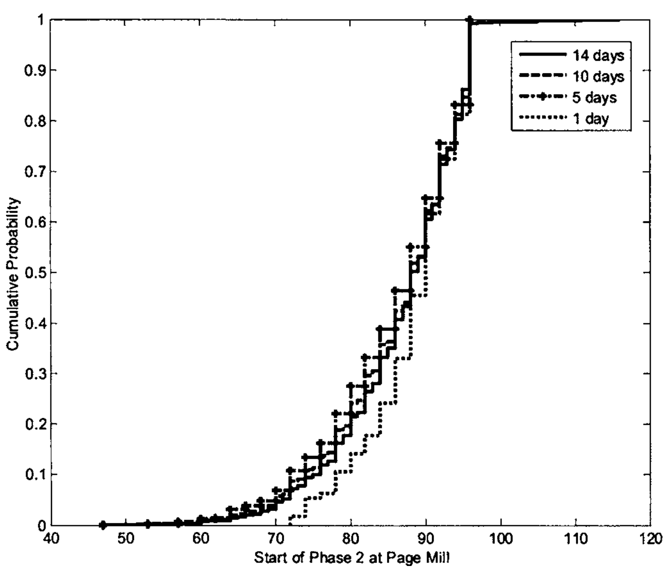

Fig. 2. Empirical cumulative distributions for start of green of Phase 2 at Page Mill

Note that in addition to uncertainty of start of green, end of green is also uncertain, especially under a lead-lag phase sequence, due to skip or gap out of the left-turn phase. Fig. 4 presents the histograms for green terminations of Phases 2 and 6 at Page Mill and Stanford. It can be seen that compared with starts of green, terminations of green have much narrower spans. Under many circumstances, the termination is the force-off point. In addition, the starts of Phases 2 and 6 are typically affected by traffic actuations on the cross streets, while the terminations of green often result from traffic actuations on main street left turns. Since traffic flows of these two streams can be viewed independently, the start and termination of green are likely independent, and thus can be treated separately.

Maximization of Expected Bandwidth

Maximizing bandwidth is often one of the objectives in determination of optimal offsets, especially for two-way coordination. Therefore the refiner aims to marginally adjust offsets to maximize the bandwidth or the sum of the bandwidths in the two arterial directions.

Since the start and end of major green are random variables, the bandwidth will also be random. Therefore, the objective is then to maximize the expected bandwidth. Before proceeding to discuss the bandwidth maximization, we conduct a coordinate transformation in order to facilitate the calculation. The coordinate transformation is to simply shift forward/backward the local clocks (coordinates) of the downstream/upstream intersections by a "distance" of the corresponding average travel time from the reference intersection. After the transformation, the vehicle trajectories will become vertical (Newell 1989). Consequently, the expected one-way bandwidth can be calculated as follows

$$W=E[\min(e_1, \ldots, e_i, \ldots, e_n)]-E[\max(s_1, \ldots, s_i, \ldots, s_n)] \tag{1}$$

where W=expected one-way bandwidth; $E(\cdot)$=expected value; e_i=end of green in the transformed coordinate at intersection i; and s_i=start of green in the transformed coordinate at intersection i.

The start and end of green, s_i and e_i, are discrete and independent random variables, whose distributions are estimated from the empirical data. However, analytical derivation of the expected bandwidth using Eq. (1) based on the estimated distributions is quite tedious. In view of that the minimum/maximum operation is a concave/convex function, we have

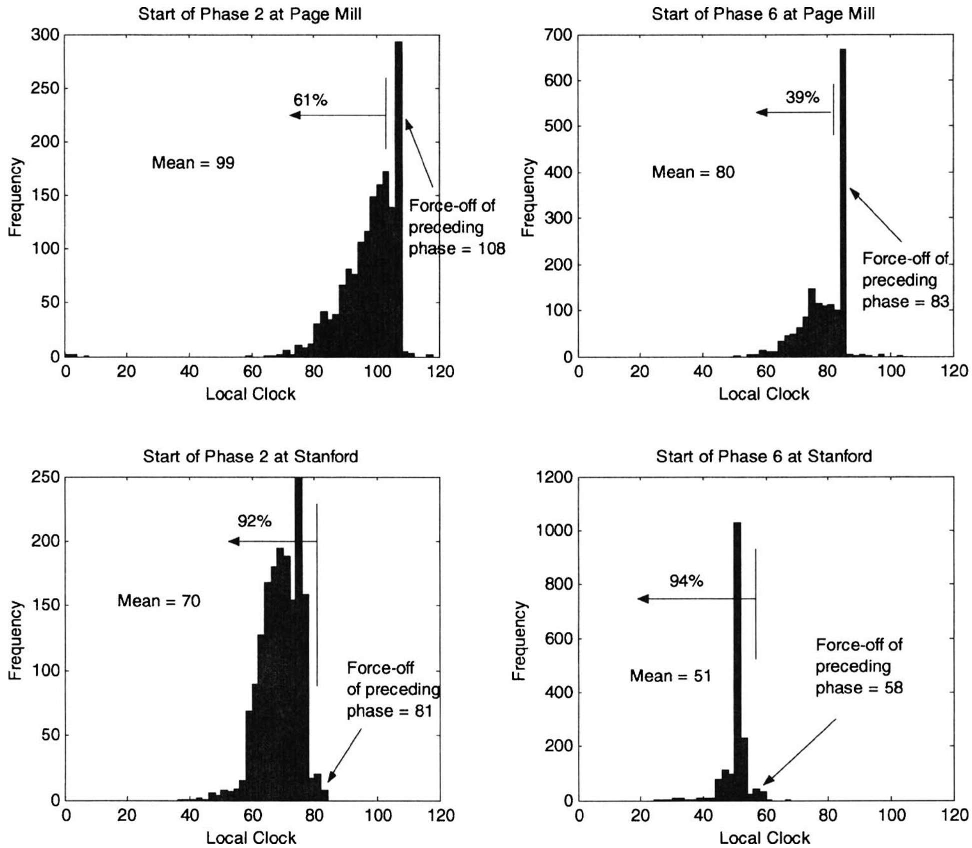

Fig. 3. Probability of early return to green at selected intersections

$$W = E[\min(e_1, \ldots, e_i, \ldots, e_n)] - E[\max(s_1, \ldots, s_i, \ldots, s_n)] \leq \min[E(e_1), \ldots, E(e_i), \ldots, E(e_n)] - \max[E(s_1), \ldots, E(s_i), \ldots, E(s_n)] = \hat{W} \quad (2)$$

The interpretation of Eq. (2) is straightforward: the expected values of starts and ends of green may be used to roughly estimate the bandwidth, and the estimator $\hat{W}$ is actually an upper bound of the expected bandwidth. The tightness of this upper bound depends on the difference among the distributions of start/end of green of each intersection.

It is easy to see that the variables s_i and e_i are function of the offset o_i, and thus the bandwidth W ($\hat{W}$) is affected by a set of offsets $\{o_i\}$. Changing offsets is like doing another coordinate transformation to shift ends and starts of arterial green, therefore changing the value of the bandwidth. The objective here is to determine a set of offsets to maximize the one-way bandwidth or the sum of the bandwidths in the two arterial directions, which is a constrained optimization problem whose constraints are $-C \leq o_i \leq C$, $i=1,2,\ldots,n$, where C=cycle length. This optimization problem can be readily solved by a suite of efficient algorithms.

We demonstrate the concept in the El Camino Real study corridor. A sequential quadratic programming (SQP) subroutine with finite-differencing derivatives in Matlab was adopted to solve for the optimal offsets for maximum two-way bandwidth. The SQP algorithm is one of the most efficient solution approaches for constrained nonlinear programming problems. It mimics Newton's method for unconstrained optimization in that it finds a step away from the current point by minimizing a quadratic model of the problem. Applying the refiner, we obtained the optimal marginal offsets (in addition to the current offsets) as $\{5,0,0,0,4\}$ s, respectively, for the intersections from north to south. The resulting through bands are shown in Figs. 5 and 6. The refiner increased the expected two-way bandwidth from 72 to 76 s, and all of the improvements were obtained from Phase 2. The reason for achieving such a limited improvement (5%) is that the corridor is constrained by one critical intersection, Page Mill, whose green intervals of Phases 2 and 6 are very small compared with those of other intersections, and thus the largest bandwidth we can possibly obtain is the sum of these two green intervals. If the corridor had multiple critical intersections where the situation is more complicated and the tradeoff is trickier, it is expected that the resulting improvement would be more significant.

Note that the optimal set of offsets is not unique. For example, the set of marginal offsets of $\{2.5,0,-3.5,0,1\}$ is another optimal solution. If the loop detector data can be made available, the count and occupancy information could be used to choose the set of offsets that also minimizes the total delay of traffic.

In summary, the procedure described above is to first obtain the empirical signal status data to estimate the average starts/ends of green, and then use an optimization module or existing bandwidth programs to further optimize the offsets. The concept is exactly the same as what Skabardonis (1996) and Chang (1996) have previously suggested, but this paper further notes that:

1. A large amount of empirical signal data is able to provide a more realistic estimate of starts/ends of green for the coordinated phases; and
2. The expected values of starts/ends of green may be used as reference points to optimize the bandwidth. The resulting

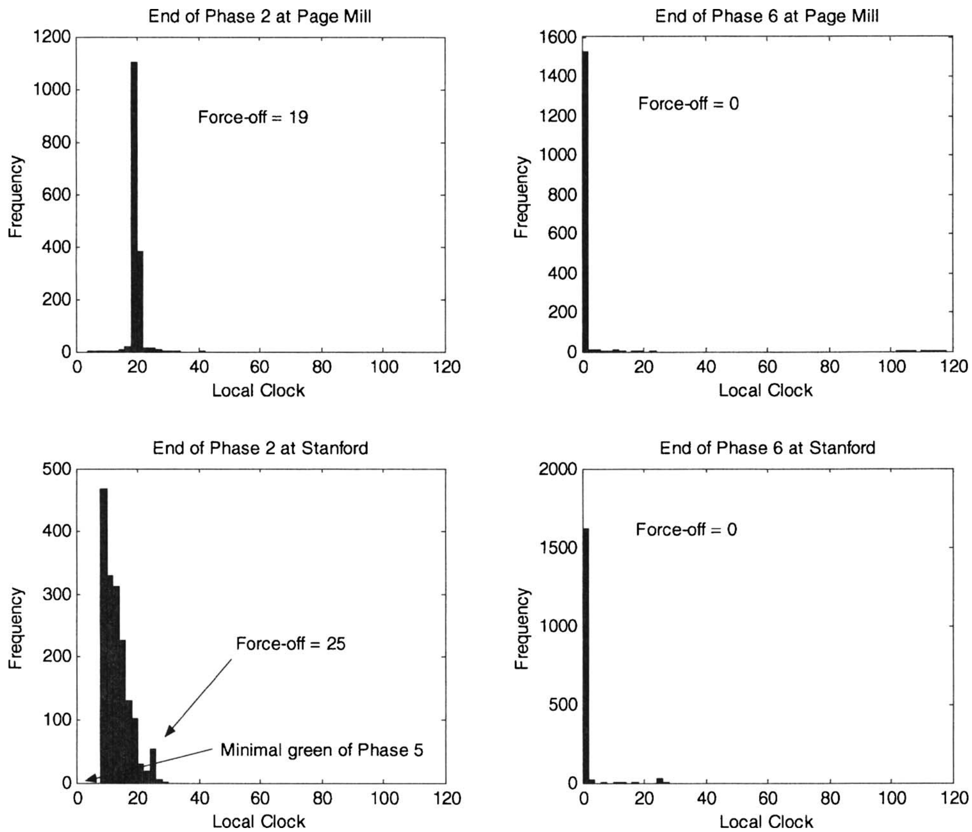

Fig. 4. Uncertain termination of green at selected intersections

bandwidth is the upper bound of the actual expected bandwidth.

Minimization of Red-Meeting Probability

Maximum bandwidth does not necessarily provide a better progression perceived by drivers. It has been pointed out that the two-way bandwidth maximization in no way guarantees perceived driver progression even for fixed-time signal controls (Wallace and Courage 1982). However, it remains feasible to change the offsets to reduce the probability of a vehicle departing from an intersection to stop at another downstream intersection. As previously noted, Abbas et al. (2001) and Luyanda et al. (2003) have used a cyclic platoon pattern from detector data to dynamically adjust offsets for a smoother progression.

For one-way coordination, it has been known for a long time that the last vehicle in a platoon should be guaranteed to clear all intersections in the coordination such that the total traffic delay can be minimized (Newell 1989). However, this way the lead vehicles released from one intersection may have to stop on red at downstream intersections, giving drivers a perception of bad progression. In view of this, traffic engineers still tend to do the coordination for the lead vehicle, more specifically with reference to starts of green, even when confronted with the problem of "early return to green."

Once the reference points are determined, one-way coordination is generally straightforward and the bandwidth is the minimal green interval along the corridor. However, the uncertainty of starts of green in an actuated signal makes the task tricky, because the vehicles released earlier than those reference points may stop at the red again at the downstream signals. One way to mitigate or even eliminate this adverse effect is to set the offsets so that the earliest starting point of green at the first intersection is later than the latest starting point of green at any of the downstream intersections (all these points are in the transformed coordinates). However, in this case the effective bandwidth could be significantly reduced. Therefore, there are actually two objectives among others in designing one-way or two-way progression for actuated signals. One is to provide enough bandwidth, and the other is to make sure early-released vehicles do not meet red lights at the downstream intersections. These two objectives are conflicting to a certain extent, and both need to be addressed in offset settings.

To represent the second objective, we define a new metric as the probability of the lead vehicle from the first intersection in coordination to meet a red light at any of the downstream intersections. Note that if the information of average queue length can be made available, the metric could be the lead vehicle from the first intersection in coordination not to s*top* at any of the downstream intersections. The calculation of the probability would be the same as that presented in the paper, except adding additional queue clearance times to the starts of green. Let $P^t_{i\to i+1}$ denote the probability for a vehicle departing at time t from intersection i to meet a red light at the next intersection $i+1$ or any of further downstream intersections, we have

$$P^t_{i\to i+1} = \Pr(s_{i+1} > t) + \Pr(s_{i+1} \leqslant t \leqslant e_{i+1}) \cdot P^t_{i+1\to i+2} \qquad (3)$$

Note that Eq. (3) is recursive. It means that the probability $P_{i\to i+1}$ consists of two components: the first is the probability of the vehicle meeting a red light at intersection $i+1$, and the second is for the case that the vehicle passes through intersection $i+1$ with a green light but meets a red light at a further downstream inter-

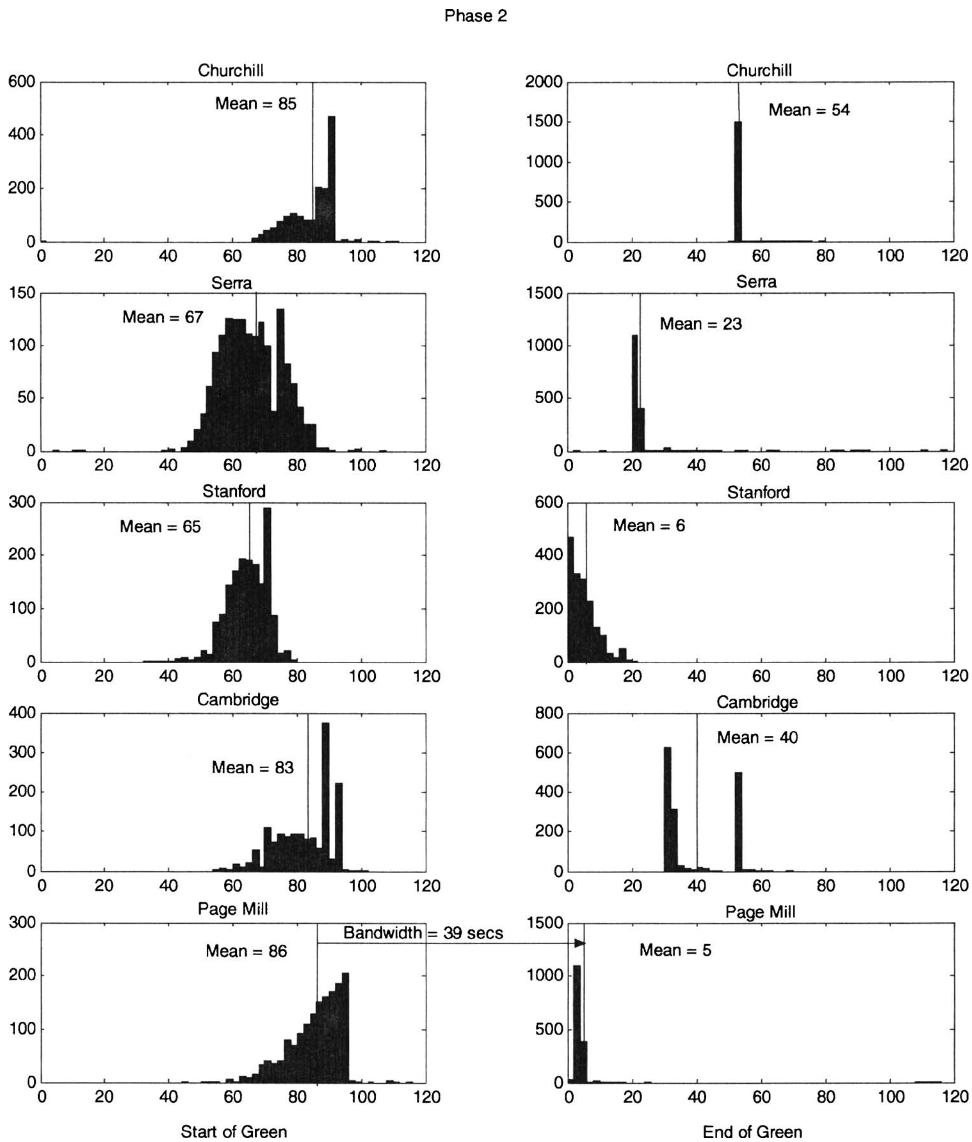

Fig. 5. Optimized through band for Phase 2—two-way coordination

section; the probability for the occurrence of this case is the probability of that vehicle meeting a green light at intersection $i+1$ *times* the probability of meeting a red light at intersection $i+2$ or any further downstream intersections. The concept is illustrated by a time–space diagram in Fig. 7.

The boundary condition for the last intersection is

$$P^t_{n-1\to n} = \Pr(s_n > t) \tag{4}$$

which implies that the probability for a vehicle departing at time t from intersection $n-1$ of meeting a red light at the last intersection is equal to the probability that the start of green is greater than the time t.

Consequently, summing up the probability for all discrete departure times t from the beginning of the cycle to the end of the cycle yields the probability for the first vehicle released from intersection 1 to meet a red light at any of the downstream intersections. Therefore the new metric defined can be mathematically expressed as

$$P = \sum_{t=1}^{C} \Pr(s_1 = t) P^t_{1\to 2} \tag{5}$$

To illustrate the proposed metric, we applied it to Phase 6 of the study corridor. The full mathematical expression of the probability for the corridor is

$$\begin{aligned} P = \sum_{t=1}^{C} & \Pr(s_{\text{Page Mill}} = t) \cdot [\Pr(s_{\text{Cambridge}} > t) \\ & + \Pr(s_{\text{Cambridge}} \leqslant t \leqslant e_{\text{Cambridge}}) \cdot [\Pr(s_{\text{Stanford}} > t) \\ & + \Pr(s_{\text{Stanford}} \leqslant t \leqslant e_{\text{Stanford}}) \cdot [\Pr(s_{\text{Serra}} > t) \\ & + \Pr(s_{\text{Serra}} \leqslant t \leqslant e_{\text{Serra}}) \cdot \Pr(s_{\text{Churchill}} > t)]]] \end{aligned} \tag{6}$$

With the current setting of offsets, the probability for the first vehicle departing from Page Mill of meeting a red light at any of the four downstream signals is 21.8% while the expected bandwidth for Phase 6 is 37 s. The probability is quite high. However,

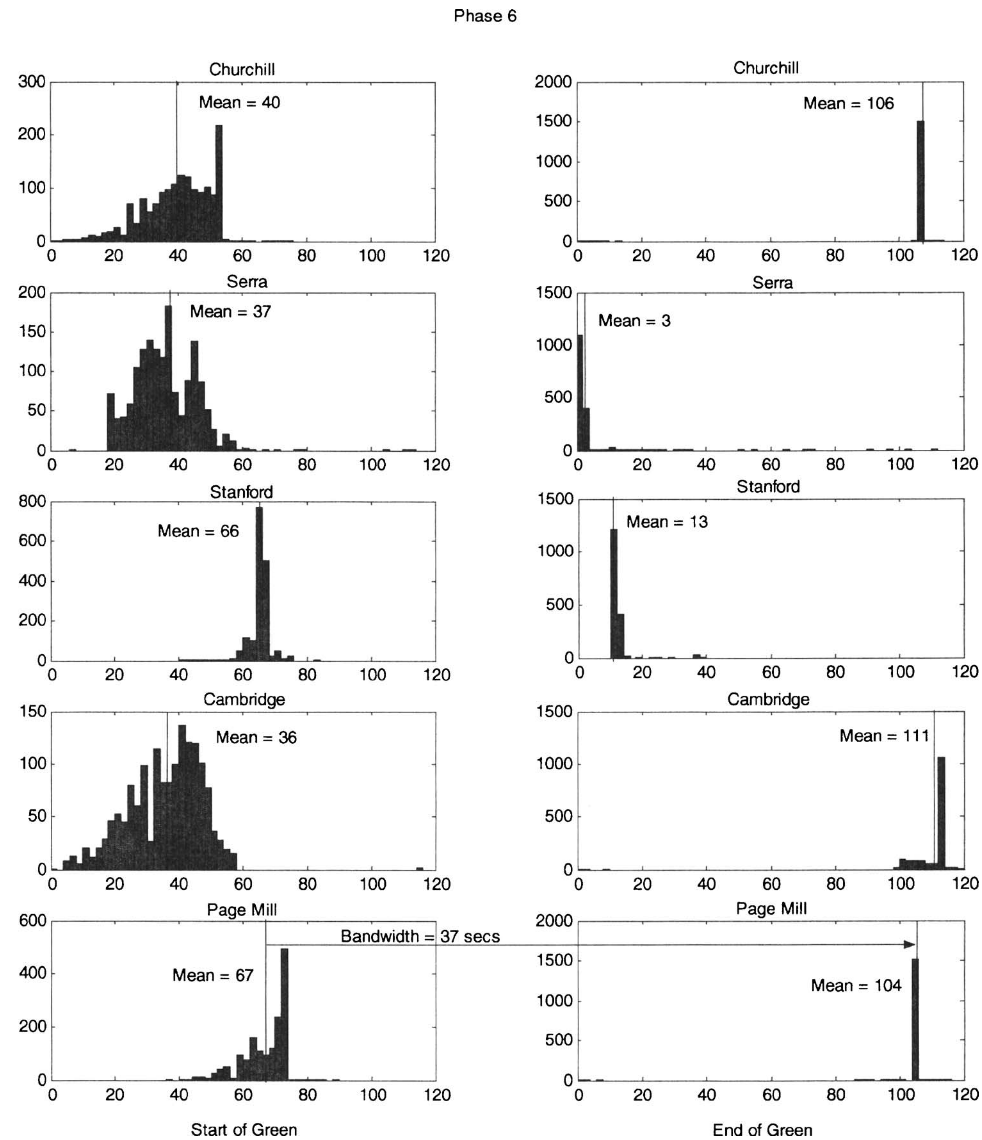

Fig. 6. Optimized through band for Phase 6—two-way coordination

had the one-way coordination been made with reference to the expected values of starts of green for those five intersections, the probability would be 83.4% and the bandwidth would remain the same. On the other extreme, if the sole objective is to minimize the red-meeting probability, then the set of marginal offsets of $\{0,0,6,0,-26\}$ provides a minimum value of the probability of 0.3%, but the bandwidth is significantly reduced to 14 s. This is because to minimize the probability, the earliest starting point of green at the first intersection could be moved to be time point later than the latest starting point of green at any of downstream intersections, which obviously reduces the effective bandwidth.

Clearly we now have a biobjective optimization problem whose two objectives are conflicting with each other. We thus are not able to find an unambiguous optimal solution. Rather, we will seek Pareto optimal or nondominated solutions, which are optimal in the sense that no improvement can be achieved in any objective without degradation in others. Several methods, such as the weighted sum method and the ε-constraint method, have been proposed in the literature to solve the multiobjective optimization problem for the Pareto optimal solutions.

A subroutine of the goal attainment method for multiobjective optimization in Matlab was adopted for the case study. Applying the refiner to the example corridor, we obtained Pareto optimal marginal offsets as $\{0,0,24,0,0\}$ s, respectively, which result in a probability of 2.3% and a bandwidth of 37 s. The resulting through band is shown in Fig. 8. The solution of $\{0,0,6,0,-26\}$ with a resulting probability of 0.3% and a bandwidth of 14 s and that of {0,0,24,0,0} with a probability of 2.3% and a bandwidth of 37 s are both Pareto optimal and nondominated. Since the difference of the red-meeting probability is quite trivial, it is expected that the latter solution will be favored by the practitioners. This offset setting successfully reduces the red-meeting probability from 21.8 to 2.3% with the bandwidth unchanged. Again, if a corridor has multiple critical intersections, the trade-off between the two objective functions would become more complex and profound. In this case, it would be necessary to produce a set of Pareto optimal solutions that forms an efficient frontier for traffic engineers to make the final selection based upon their preferences over these two objectives.

Note that the refiner presented in this paper uses signal status data only in view of inaccuracy or frequent loss of loop detector data that we have experienced. Consequently, the refiner is con-

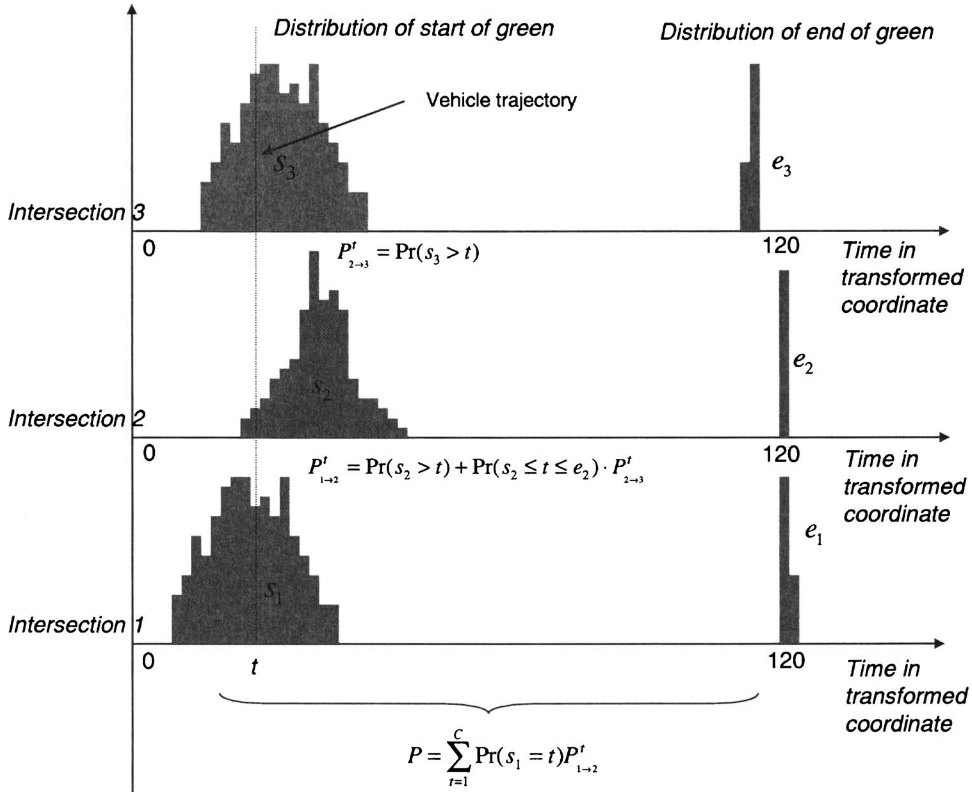

Fig. 7. Red-meeting probability

cerned with bandwidth maximization and red-meeting probability minimization, without accounting for delays or travel times. However, since the refinement is often marginal, we expect the impacts on these measures of performances will be also marginal. To verify this, we conducted a simulation study using Paramics (Quadstone 2003) to evaluate each of the following scenarios: baseline scenario with current offsets and the two scenarios with refined offsets for two-way coordination and one-way coordination, respectively. Vehicle intersection delay in the simulation was defined as the travel time for a vehicle departing from an arrival loop detector to a departure loop detector minus its free-flow travel time. During the simulation period, all vehicles moving through intersections were traced by a tool developed through Paramics application programming interface. Table 2 compares resulting average corridor delays for the three scenarios. To test the significance of the changes in delay, two-sided t-tests were performed. The null hypothesis is that the means of corridor delays with refined offsets are different from those in the baseline scenario. Given the size of the population, the critical value with 95% confidence level is ± 1.68. As shown in Table 2, all of the t-statistics are smaller than 1.68. Therefore, both null hypotheses are rejected, implying that changes in delay incurred by the refiner are statistically insignificant. In summary, the simulation study has verified our expectation that the refiner may impose statistically insignificant impact on travel time or delay.

Concluding Remarks

We have presented the basic concept of an offline offset refiner, which attempts to address the problem of uncertain starts/ends of green in determination of offsets for coordinated actuated signal control. It has been shown that a large amount of archived signal status data is able to provide a more realistic estimate of distributions of starts/ends of green of the coordinated phases. The refiner will take advantage of this knowledge to fine tune the implemented offsets in the field to provide smoother progression.

We have discussed two objectives in determination of offsets for coordinated actuated signal control. The first one is maximization of expected bandwidth. For this purpose, it is acceptable to use means of starts/ends of green to do the bandwidth optimization. We have shown that the estimated bandwidth is the upper bound of the expected bandwidth.

We have defined a new metric to represent the smoothness of the progression, the probability of the lead vehicle departing from the first intersection in the coordination to meet a red light at any of downstream intersections. Minimization of this probability can serve as one of the objectives in designing signal coordination plans in addition to maximization of the bandwidth. Because these two objectives are often conflicting with each other, a biobjective optimization procedure has to be adopted to seek the Pareto optimal offsets.

The offset refiner presented in this paper readily works with the current signal control system, and is easy to implement. It can also serve as a standalone tool available at the Traffic Management Center, built upon commercial optimization software, or using self-programmed codes to solve the resulting optimization problems. The refiner could be run periodically or together with an online progression monitor. If the signal performance degrades, then the refiner can be called to fine tune the offsets for better coordination.

The development of the offset refiner described in this paper is part of a signal performance monitoring system being developed at California PATH. An arterial lab has been established that receives real-time high-resolution loop and signal status data from the El Camino Real and other arterial corridors. Ongoing research

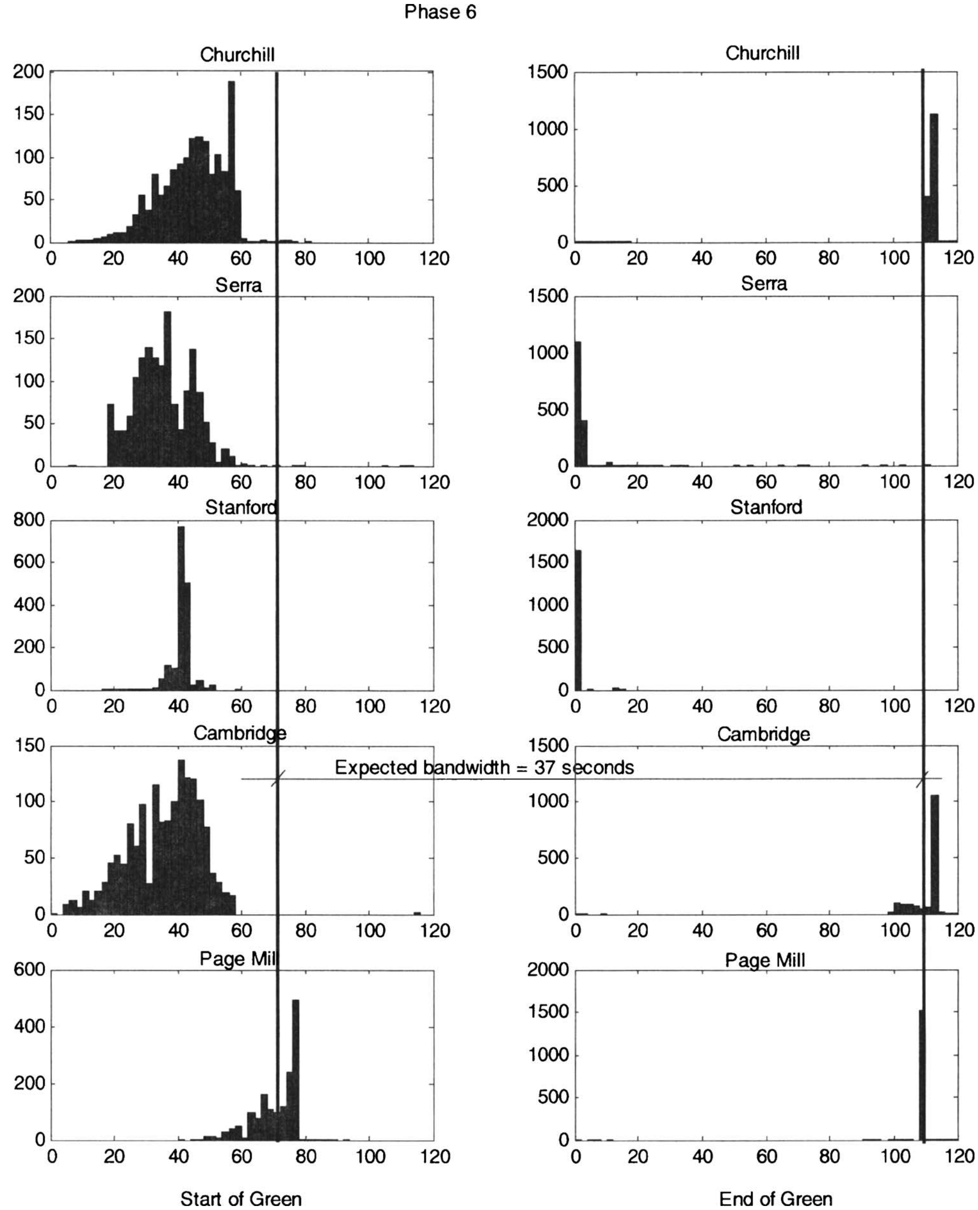

Fig. 8. Optimized through band for Phase 6—one-way coordination

Table 2. Simulation Analysis of Traffic Corridor Delay

		Baseline		After		Change	
		Mean (s)	Standard deviation (s)	Mean (s)	Standard deviation (s)	Mean (s)	t-stat
Two-way	Major	37.805	27.864	39.348	28.440	1.544	1.385
	Minor	55.329	37.362	53.971	39.549	−1.358	−1.161
One-way	Major northbound	38.532	30.784	35.950	46.493	−2.581	−0.902
	Major southbound	37.385	25.888	35.087	26.943	−2.298	−1.630
	Minor	55.329	37.362	54.029	36.943	−1.300	−1.150

Note: The delay for major phases is the average corridor delay while the delay for minor phases is the average delay of each intersection.

includes how the real-time data can be used to measure arterial performance and to improve the signal timing plans.

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Notation

The following symbols are used in this paper:

C = cycle length;
$E(\cdot)$ = expected value;
e_i = end of green in transformed coordinate at intersection i;
o_i = offset at intersection i;
P = probability for first vehicle released from intersection 1 to meet red light at any of downstream intersections;
$P^t_{i\rightarrow i+1}$ = probability for vehicle departing at time t from intersection i to meet red light at next intersection $i+1$ or any of further downstream intersections;
s_i = start of green in transformed coordinate at intersection i;
W = expected one-way bandwidth; and
$\hat{W}$ = upper bound of the expected bandwidth.

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