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Visualization and Assessment of Arterial Progression Quality Using High Resolution Signal Event Data and Measured Travel Time

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ABSTRACT

Signal offsets are a signal timing parameter that have a substantial impact on arterial travel times. The traditional technique is to optimize offsets using an offline software package, implement the settings, and then possibly observe field operations. It is not uncommon for a traffic engineer to fine tune the settings by observing the arrivals of platoons at an intersection and make adjustments to the offset based on this qualitative visual analysis.

In this paper, we discuss two tools to assist the engineer in the task of managing arterial offsets. First, we introduce the Purdue Coordination Diagram (PCD) as a means of visualizing a large amount of controller and detector event data that allows investigation of the time varying arrival patterns of coordinated movements. The second technique is arterial travel time measurement by vehicle reidentification using Bluetooth MAC address matching. This is used to evaluate existing offsets and assess the impact of implemented offset changes.

These tools are demonstrated with a case study involving a before/after comparison of an offset tuning project. PCDs were used to identify causes of poor progression in the before case, as well as visualize both the predicted and actual arrival patterns associated with the optimized offsets. Over 300 Bluetooth probe travel time measurements were used to statistical assess before and after travel time. The statistical comparison showed a significant (at 99% level) 1-minute reduction (~20%) in mean travel time for the northbound direction, and a significant (at 90% level) 0.5-minute (~10%) reduction in mean southbound travel time.

INTRODUCTION

Arterial signal timing plans have three fundamental components: a cycle length, the splits at each intersection, and a set of offsets that control the start times of movements relative to other signals in the system. Performance evaluation of offset changes is a vital aspect of managing arterial operations. A variety of methods exist for designing and evaluating signal offsets, but few of these rely on field data specifying how vehicles actually behave in the network. In this paper, a series of tools are presented that extend signal offset analysis methods by introducing information from the field:

- The Purdue Coordination Diagram (PCD) is introduced as a tool to visualize arrival patterns at signalized intersections before an offset change was made; predict the impact of changes to the offsets; and observe the impact of their implementation.
- A large, statistically significant comparison of before/after travel time changes is performed using a vehicle re-identification technique (Bluetooth MAC address matching).

REVIEW OF COORDINATION STRATEGIES

The practice of signal coordination is nearly 100 years old, and no fully comprehensive review of its history has yet been written. In the past century, there have been two major strategies for developing signal coordination timing plans: bandwidth maximization and flow profile methods.

In the 1920s, coordinated timing plans for automatic signals were developed by manipulating cycles in time space diagrams (*1, 2, 3*). The green band was modeled using pins and thread on a drawing board, and cycles were represented by strips of paper. This technique sufficiently coordinated fixed time signals during an era when digital computers were either nonexistent or prohibitively expensive.

From the 1960s, a variety of approaches emerged for developing coordinated signal timing plans in a more systematic manner. In 1964, Morgan and Little developed a geometric analysis and an algorithm for maximizing bandwidth (*4*), allowing a more accurate approach than existing analog methods. In the next 20 years, a series of software packages were developed using this strategy, including MAXBAND (*4, 5*), PASSER and its descendants (*6,7,8,9*), and MULTIBAND (*10*).

The flow profile approach emerged in the in the UK, starting in the 1960s. A 1956 paper by Pacey (*11*) describing the evolution of vehicle platoons as they departed a traffic signal was among the first to describe vehicle flow profiles. Several years later, Hillier and Rothery (*12*) utilized vehicle flow profiles to develop arrival curves; assuming a departure curve from a theoretical signal operation plan, the resulting delay could be estimated. This led to a delay-offset relationship that could be used to seek a delay-minimizing offset. The Combination Method (*13, 14*) and TRANSYT (*16*) emerged from this research, using delay-offset relationships to design offsets a signal networks.

The above methods were developed for fixed-time controllers. In actuated coordinated systems, variations in green time due to phase actuation can lead to the "early return to green" problem (*17, 18*). Over the years, a number of researchers have attempted various approaches to this problem, including the use of average green times in place of the fixed green times in optimization software (*19,20*); an iterative process using bandwidth maximization software to first design offsets, then refine them by feeding the observed green back into the software (*21*); construction of time space diagrams with average greens (*23*); and use of estimated vehicle travel times to determine ideal offsets (*24*). Hale and Courage (*25*) proposed several additional improvements aimed at improving the accuracy of models for determining signal timings for actuated coordinated systems. A recent paper by Yin *et al*. (*26*) reported on an offline offset refiner with a bandwidth-maximizing approach that addressed the problems of uncertainty in the start and end of green.

In 2001, Abbas *et al*. (*27, 28*) developed a real-time offset tuning algorithm that sought to increase vehicle occupancy during the green band, by considering incremental changes to the offset at a local signal. The algorithm was developed for one direction on an arterial. The concept of green occupancy maximization was used in ACS-Lite (*29, 30*), which considers the local and downstream impacts of incremental changes to offsets for all coordinated phases in the system.

TRAVEL TIME MEASUREMENT

Various methods exist to measure travel time, including the use of floating car with GPS (*31*) to vehicle reidentification techniques (*32*). The basic concept behind these technologies are the same; a unique identifier moving through the traffic system needs to be time stamped at a minimum of two known places within the system in order to determine the travel time. Floating car studies provide a detailed picture of travel speeds for one vehicle in the system, but provide a low number of data points (one travel time measurement per floating car transit). Vehicle reidentification techniques can become expensive if many observation points are needed. Unlike freeways, arterial systems contain many more entrances and exits. A large number of data points are required to quantify the impact of signal timing changes with statistical significance.

In recent years, the tracking of probe vehicles using the media access control (MAC) address of discoverable Bluetooth enabled devices has become a low cost means of calculating travel time (*33,34,35,36*). Such devices have become very common and are observed in 5% to 10% of vehicles on the roadway. By capturing MAC addresses at multiple locations, travel times can be obtained by comparing the time that it took for the MAC address to travel from one point to the other.

ARTERIAL TRAVEL TIME ANALYSIS

Figure 1 shows a map of SR 37 in Noblesville, Indiana as of July 2009. This is an actuated coordinated system. A portion of the coordinated phases are also actuated, as described extensively elsewhere (*38*). Each intersection in the arterial features stop bar detectors on the minor movements, and advance detectors on coordinated movements. Advance detectors are located 405 ft upstream of the stop bar at each coordinated approach. Intersections 1001, 1002, 1003, and 1004 have the capability of logging high-resolution controller data (phase and detector status changes) at a resolution of 0.1 seconds. This data was acquired through scheduled downloads via FTP through a virtual private network (VPN) connection over the internet.

Several sensors for collecting MAC addresses were also deployed along the arterial:

- Permanent sensors were established at intersections 1001, 1002, 1003, and 1004. These made use of power and communications available in traffic signal cabinets.
- Temporary sensors were deployed at midblock locations (MB01, MB02, MB03, MB04, MB05) along the arterial. These ran off of battery power and had no communication. Data was read from flash memory after retrieving the devices from the field.

Figure 2 shows plots of travel time measurements of vehicles traveling between Int. 1004 and Int. 1001 (northbound). Two weeks of travel times are displayed from before (Figure 2a) and after (Figure 2b) an offset adjustment. For each two-week period, approximately 5000 MAC address matches were obtained. Subsequent sections of this paper describe an optimization technique and visualization tools for validating optimal offsets prior to implementation, and ultimately allow an assessment of the implemented offsets that resulted in the improved Saturday travel time shown in Figure 2b.

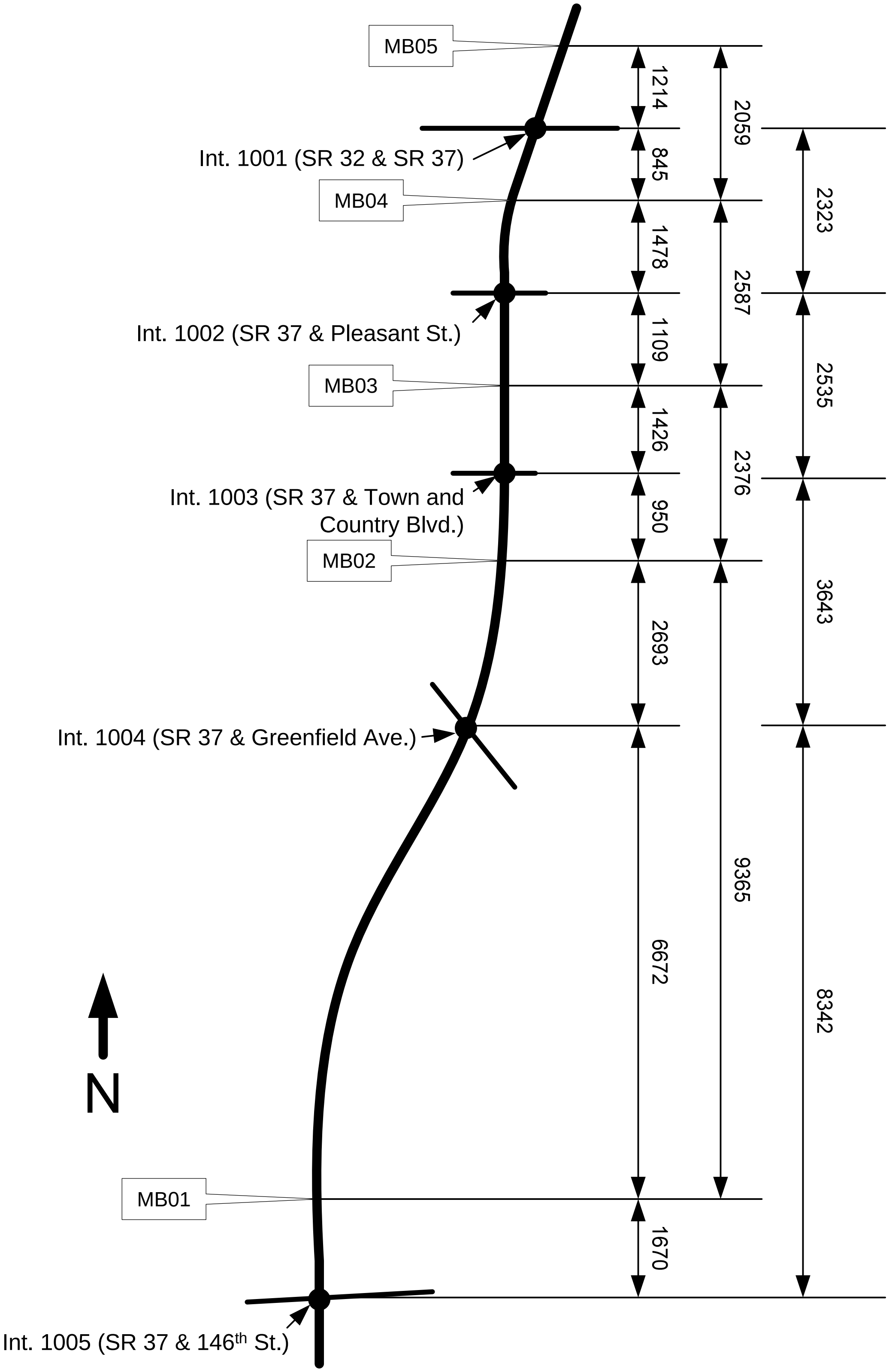
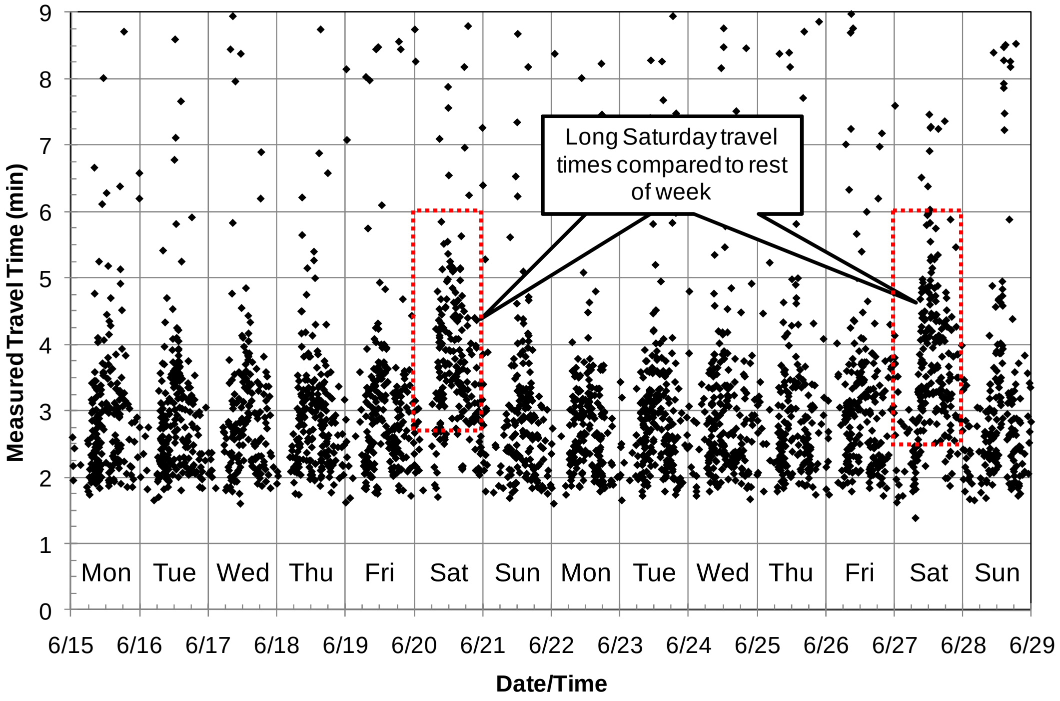
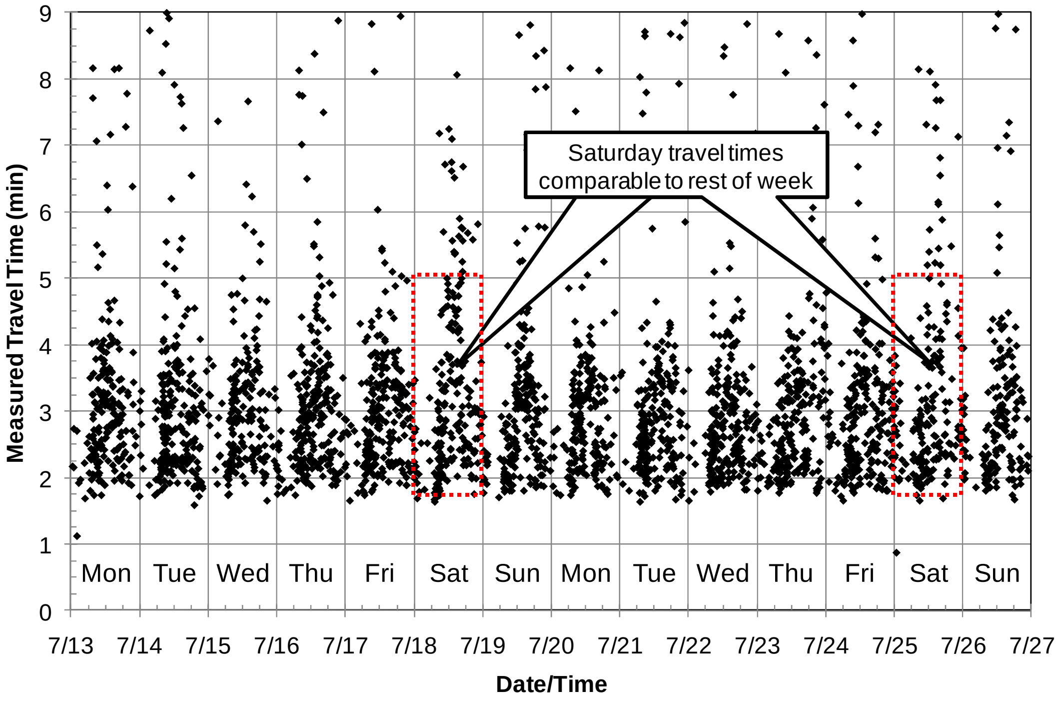


Figure 1. Map of instrumented arterial corridor showing intersections and midblock Bluetooth stations (distances are in feet).



(a) Before offset adjustment (N = 4797).



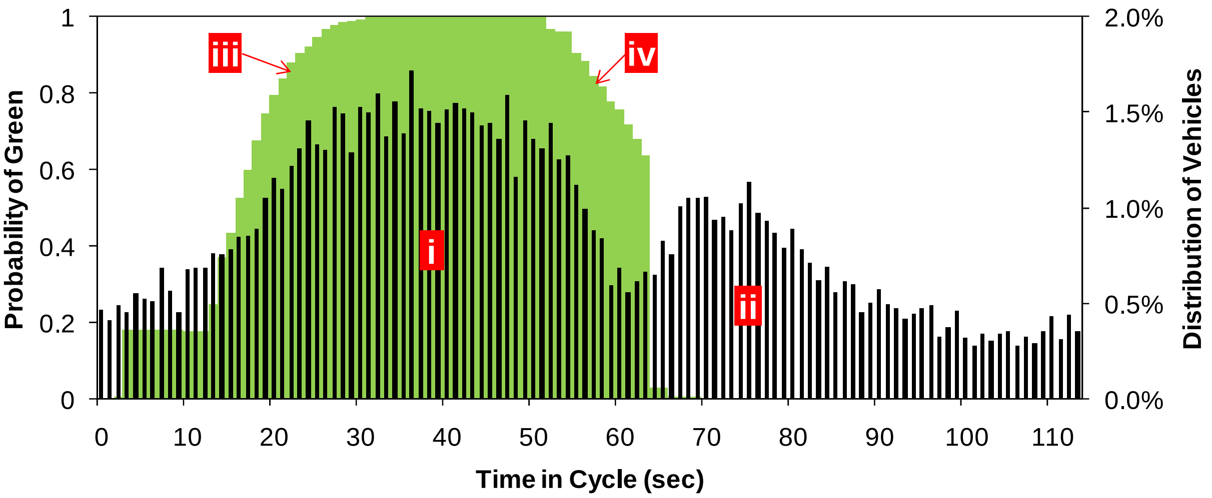
(b) After offset adjustment (N = 5401).

Figure 2. Northbound Travel times along SR 37 (from Int. 1004 to Int. 1001).

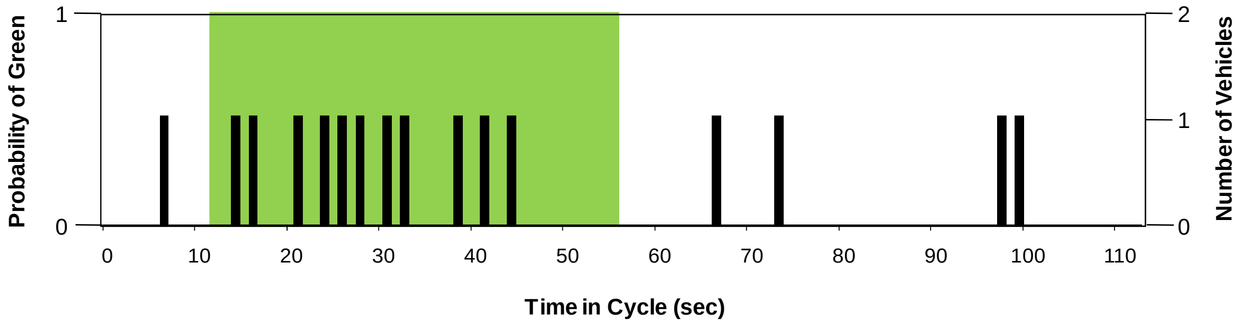
COORDINATION VISUALIZATION TOOL

The Purdue Coordination Diagram (PCD) was recently developed (*37*) as a tool for visualizing and evaluating the quality of progression and possible opportunities for improvement. The PCD builds on concepts established in the literature, but takes a disaggregate approach using high resolution signal event data.

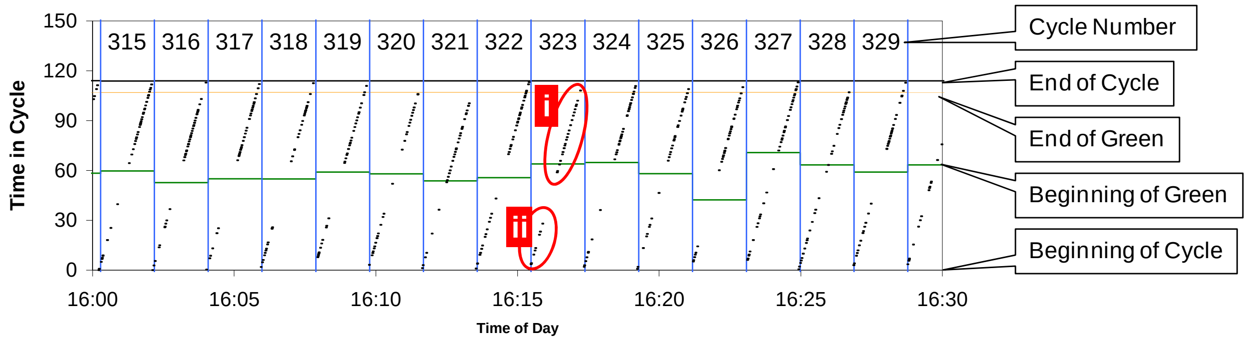
Figure 3a presents a combined flow profile (black bars) and probability of green distribution (green shaded region) for the southbound movement at Intersection 1004 for the Saturday coordinated pattern (0600–2200, 504 cycles). This is essentially the same type of flow profile data that would be generated by TRANSYT (*16*), and the same green time and vehicle arrival data that could be measured by an adaptive system such as ACS-Lite (*29, 30*). The combine plot of the two distributions might be accurately called a coordination profile. It is possible to observe the existence of a primary (Figure 3a, i) and secondary (Figure 3a, ii) platoon in the flow profile, as well as the distribution of start and end green times (Figure 3a, iii and iv). While this diagram illustrates the quality of progression well, it presents a picture of an average cycle, and thus obscures the impact of stochastic variation from cycle to cycle, as well as temporal shifts over a day.



(a) Coordination profile for 504 cycles.



(b) Coordination profile for one cycle.



(c) PCDs depiction of arrivals over several cycles.

Figure 3. Components of the PCD introduced as an extension of coordination profiles.

It is possible to reduce the number of cycles used to construct a coordination profile (e.g., to 30-60 min). However, it would be necessary to generate a large number of profiles to track changes throughout the day. Figure 3b reduces the time scale of the coordination profile to one cycle. In this case, the green shaded region reflects the actual provided green, and the vehicle arrivals reflect the particular arrivals that took place in this cycle. If this diagram is rotated and plotted for several consecutive cycles (Figure 3c), it is possible to obtain the disaggregate picture, while also capturing patterns that repeat. Conceptually, this adds a second “time” axis to a coordination profile. This is the central concept of the PCD.

Figure 3c shows the PCDs for several cycles after 1600 on Saturday. The plot facilitate comparison between adjacent cycles. The horizontal axis of the plot is time of day, while the vertical axis is time in cycle. Vehicle arrivals are represented by dots that reflect both time of day and time in cycle; phase events are shown as bars that span the duration of the cycle. Starting from the horizontal axis (time in cycle = 0), the beginning of cycle is defined as the previous start of red; the second line marks the beginning of green; the third line shows the end of green, and the uppermost line shows the end of cycle (beginning of red). Primary (Figure 3c, i) and secondary (Figure 3c, ii) platoons can be observed, corresponding to the coordination profile (Figure 3a, i and ii). This view provides the same overall picture as the flow profile, but also provides a means of viewing a large amount of signal event data.

When the PCD is extended to a 24-hour period, macroscopic trends become apparent, as shown in Figure 4. The upper plot shows cycle-by-cycle calculations of percent on green (POG); the lower plot is a 24-hour PCD using the same data. The time period associated with the Saturday coordinated pattern is shown, extending from 0600 to 2200. The slight variation in cycle end times in the PCD is due to the use of actuated coordinated phases (*38*).

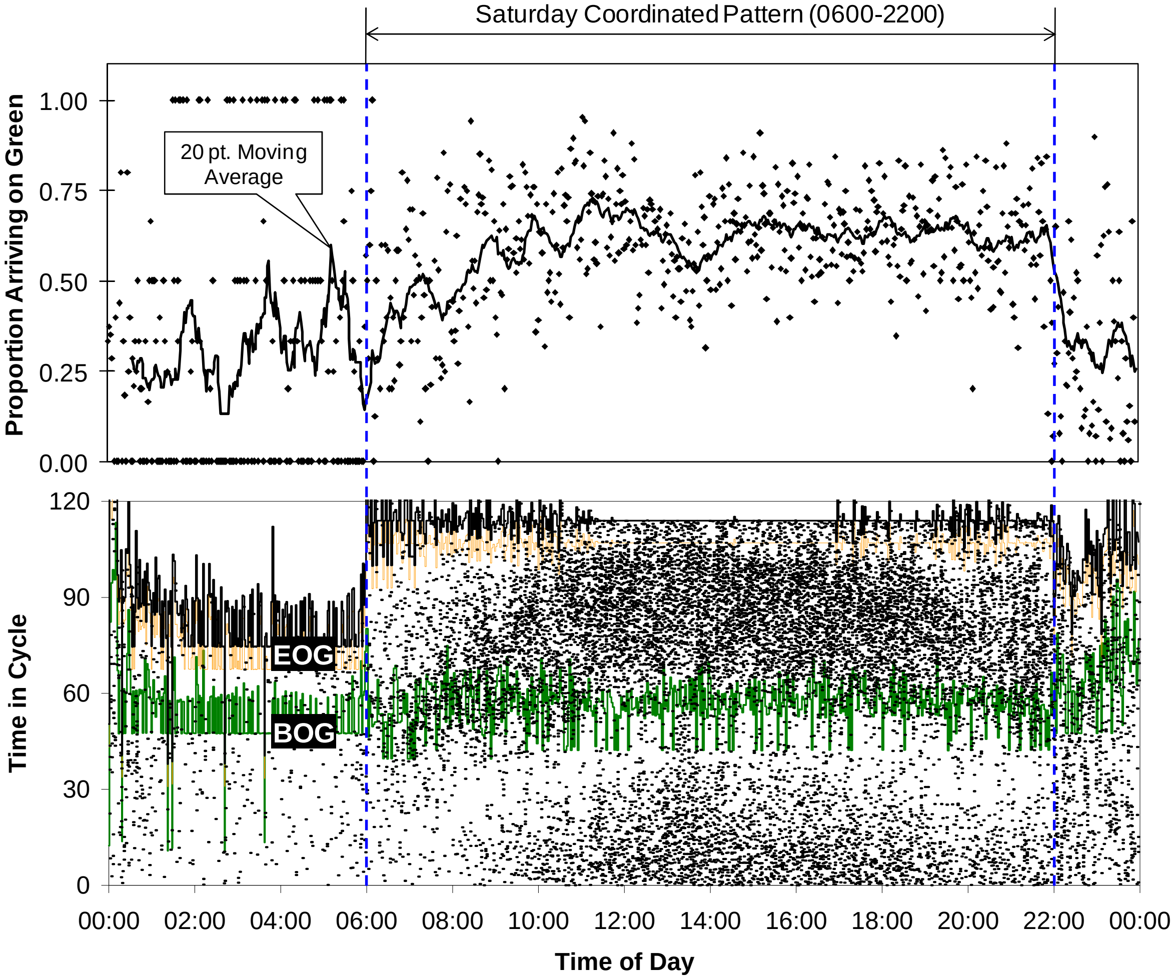


Figure 4. 24-hour Purdue Coordination Diagram for the southbound movement at Intersection 1004 on Saturday, July 25, 2009.

While POG provides an excellent measure of the quality of progression, it does not explain by itself why POG is low or high during any given time period. For most of the day, POG hovers around 60%, decreasing to 50% around 1300-1400. This information tells us that the progression quality tends to decrease at that time, but we are unable to determine the reason from the POG plot. The distribution of vehicles in the PCD reveals that the primary coordinated platoon continues to be served during green, while the secondary platoon increases in size during this time period, contributing more arrivals on red and thereby lowering POG. An alternative explanation might have been that the upstream signal fell out of sync, but the PCD illustrates that this was not the case.

Figure 5 shows PCDs for the coordinated time periods (0600-2200) for all eight coordinated approaches in the arterial testbed on Saturday, June 6, 2009. One timing plan is used for the entire coordinated period on Saturdays, with a cycle length of 114 seconds. Southbound PCDs are shown on the left while northbound PCDs are shown on the right.

A visual inspection of the PCDs suggests that poor progression occurs in the northbound direction at Intersections 1002 (a) and 1004 (b). This would be a reasonable explanation for the rather poor travel times in the northbound direction on Saturdays (Figure 2a). The other approaches perform rather well, although there is opportunity for improvement in the southbound direction at Int. 1004 (c). The different levels of dispersion of the platoons are also notable:

- Northbound platoons at Int. 1002 (a) are rather tight, because of the short distance (2500 ft) from the upstream intersection.
- Northbound platoons at Int. 1004 (b) are slightly more dispersed. This approach is 8352 ft from the upstream signal, which is also coordinated.
- Southbound vehicles at Int. 1001 (d) appear random. This approach is 7450 ft from the upstream signal, but it is not coordinated and the upstream signal runs free.

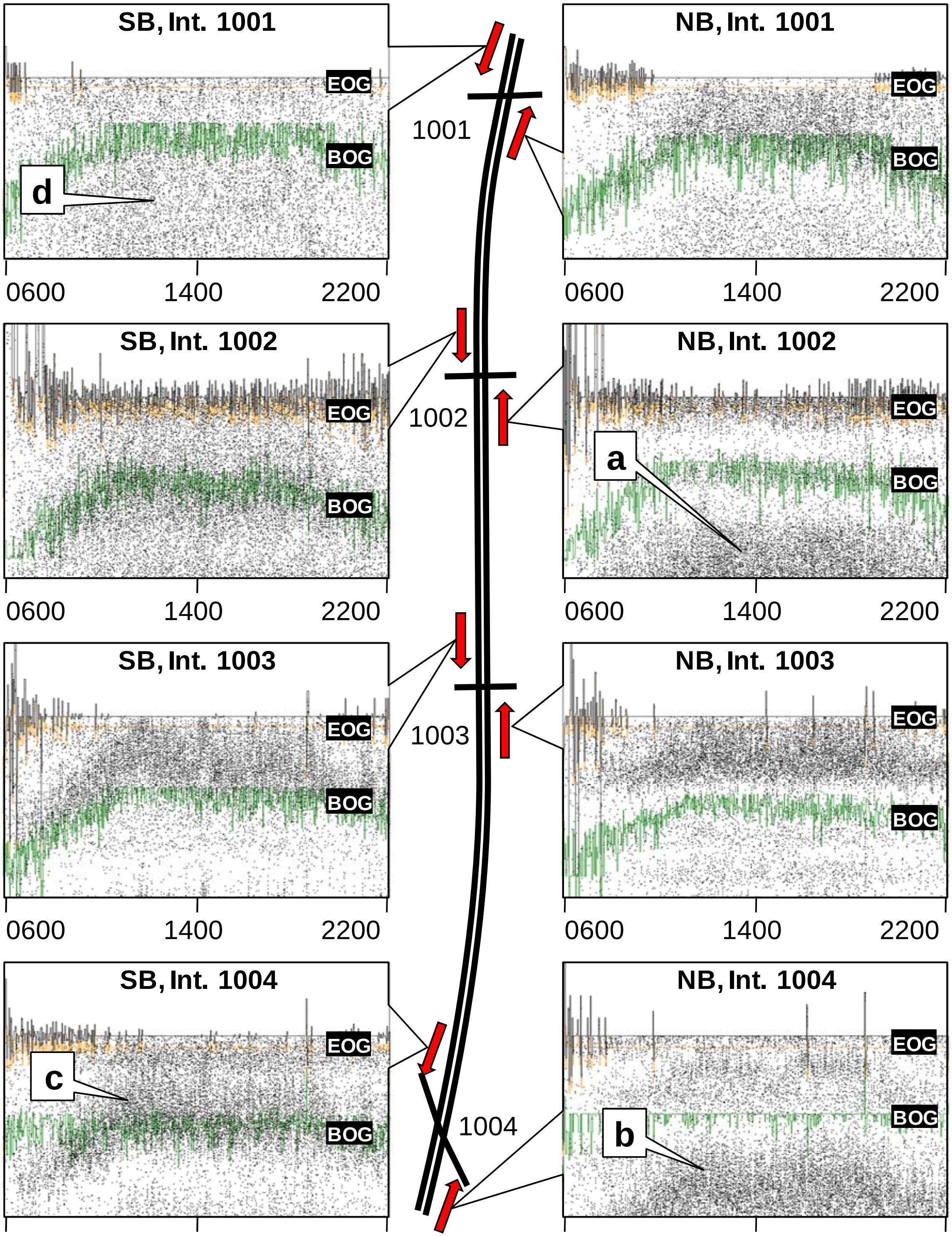


Figure 5. Observed PCDs for eight coordinated phases on SR 37 from June 6, 2009.

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These plots demonstrate the utility of the PCD for viewing arterial coordination performance at a glance and providing a qualitative picture. Because data from advance detectors are used to construct the plots, the PCDs reflect actual vehicle behavior on the corridor, compared to methods that model the behavior based on parameters such as speed and distance. The PCD would include changes in driver behavior that actually took place (e.g., due to weather and incidents) without having to update model parameters.

These plots also contain the necessary data to calculate the quantitative measure, percent on green (POG):

$$POG = \frac{N_g}{N} = \frac{\sum\limits_{t_k \in [t_g + \varepsilon_g, t_{r,i} + \varepsilon_r]} 1}{\sum\limits_{t_k \in [t_{r,i-1} + \varepsilon_r, t_{r,i} + \varepsilon_r]} 1}, \qquad \text{Equation 1}$$

where:

N_g = the number of vehicles on green;
N = the total number of vehicles;
t_k = the arrival time of the k^{th} vehicle;
$t_{g,i}$ = the beginning of green time for the i^{th} cycle;
$t_{r,i}$ = the beginning of red time for the i^{th} cycle;
ε_g = start-up lost time; and
ε_r = amount of clearance used by vehicles.

The summation terms indicate that one vehicle is counted for each t_k that satisfies the conditions. In addition, the performance of the network may be characterized by the summation of N_g over all coordinated approaches at all intersections, yielding the total system arrivals on green, $\sum N_g$. This quantity provides a system-level performance measure that can serve as the objective function for an optimization algorithm.

PREDICTING THE OPERATION OF NEW OFFSETS

The text explaining Figure 2a discussed the means of identifying operational deficiencies in an arterial network and the preceding section used the PCD to qualitatively understand problems with arrival flow profiles. To remedy such problems, agencies typically rely on optimization software to suggest improvements to the system. While these procedures are well established, they typically necessitate a set of assumptions about vehicle behavior such as travel speed and platoon dispersion. With the raw PCD data, it is possible to model the impact of proposed offset changes using a superposition principles.

Figure 6 illustrates how an offset adjustment can be modeled by showing an example of a three-intersection system. The red shaded regions represent effective red for the arterial movements in both directions; the trajectory of the first vehicle is shown. An adjustment (ΔO_2) is implemented, causing cycles at Int. 2 to be moved forward in time by about 25% of the cycle length. This has two impacts on the system:

- Coordinated phase transitions at Int. 2 are shifted in time by $+\Delta O_2$. This may be modeled by adjusting local vehicle arrival times being shifted by $-\Delta O_2$.
- Vehicle arrival times at the downstream intersections (1 and 3) are shifted by ΔO_2.

This is similar to the modeling of offset adjustments proposed by Abbas (*28*) and extended to both directions in ACS-Lite (*30*), except that the local controller effects are modeled as local vehicle arrival shifts rather than green time shifts. This facilitates the use of PCDs to visualize the impact, because the green bands are static while the vehicle arrivals move relative to them.

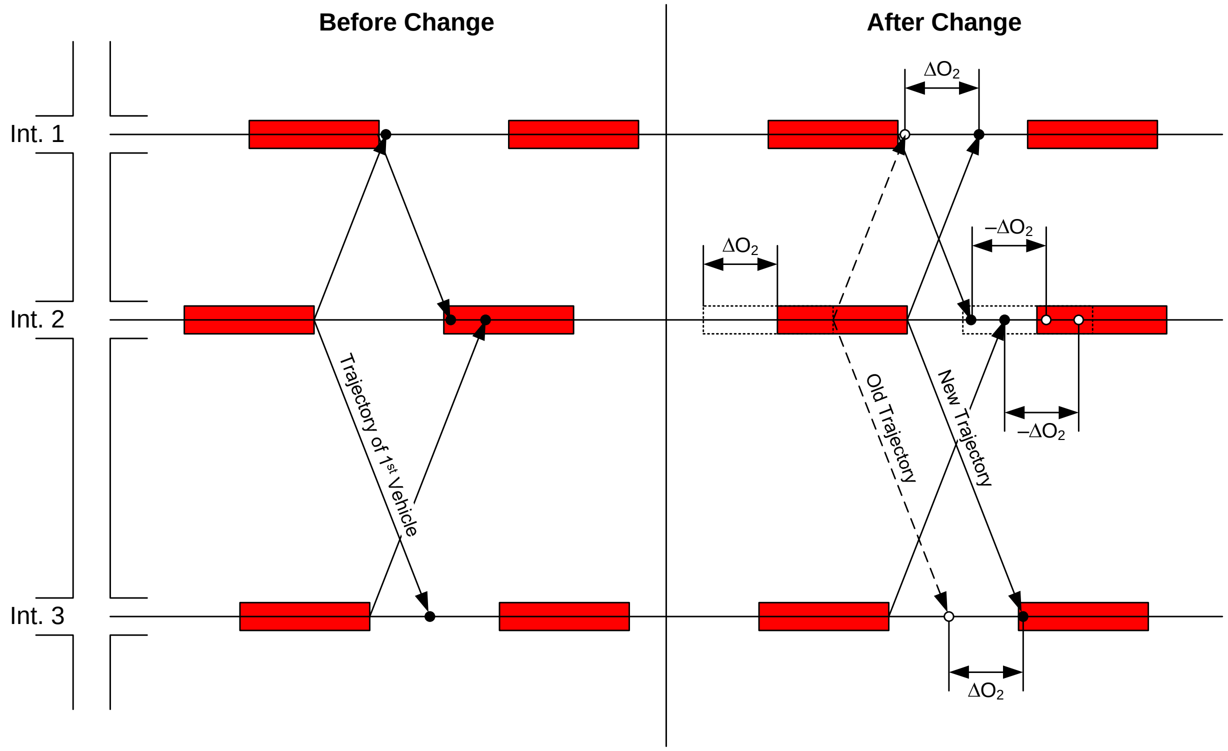


Figure 6. Model for predicting impact of offset changes.

The data used to construct the PCD also contains a quantitative measure, $\sum N_g$ (see Equation 1), that allows a relationship between offset and coordination performance to be established. This value may be recalculated for any set of offset adjustments by using the above modeling procedures, allowing a prediction of the impacts.

This concept was applied to Saturday offsets on SR 37. The results of an optimization program were approximated by a two-stage manipulation of offsets using the PCDs. Because it intersected another coordinated system (SR 32), the offset of Int. 1001 (O_{1001}) was held constant (e.g., $\Delta O_{1001} = 0$). Potential adjustments to O_{1002}, O_{1003}, and O_{1004} were evaluated by calculating $\sum N_g$ over the range of possible combinations using a low-resolution search that evaluated possible combinations of $\Delta O_j = \{-40, -20, 0, +20, +40, +60\}$. This required $6^3 = 216$ scenarios to be calculated. The result with the greatest value of $\sum N_g$ was identified for second optimization step with a finer resolution adjustments to O_{1001}, O_{1003}, and O_{1004} in turn. This approximated the action of online offset refining algorithms (*28, 30*). Finally, an adjustment for the system to the south of the testbed (O_{1005}) was calculated independently, since it only affected the northbound movement at Int. 1004.

The collection of offset adjustments are summarized in Table 1 for all of the intersections on SR 37, including the four non-instrumented intersections comprising the system to the south.

Table 1. Summary of offset changes.

Intersection	Cycle Length (sec)	Intersection Offsets (sec)		
		Before	After	Adjustment
1001: SR 37 & SR 32*†	114	0	0	+0
1002: SR 37 & Pleasant St.*	114	62	44	–18
1003: SR 37 & Town and Country Blvd. *	114	74	38	–36
1004: SR 37 & Greenfield Ave.*	114	29	89	+60
1005: SR 37 & 146th St.	114	83	102	+19
1006: SR 37 & 141st St.	114	97	2	+19
1007: SR 37 & 131st St.	114	26	45	+19
1008: SR 37 & 126th St.	114	89	108	+19

*instrumented intersection.
†master intersection.

Figure 7 PCDs show predicted vehicle arrival patterns for offset adjustments in Table 1, assuming that phase and vehicle activity remains similar to that on June 6, 2009. Compared to Figure 5, overall progression performance is expected to improve, particularly for the northbound direction at Int. 1002 (Figure 7, a) and Int. 1004 (Figure 7, b). Progression was also projected to improve slightly for SB at Int. 1004 (Figure 7, c). Other phases were projected to degrade (NB at Int. 1001) due to the platoon arriving earlier in the cycle (Figure 7, e). However, this approach had the lowest volume in the system. Additionally, SB at Int. 1003 was expected to have some platoons truncated by the end of green (Figure 7, f). There was no change for SB at Int. 1001 (Figure 7, d).

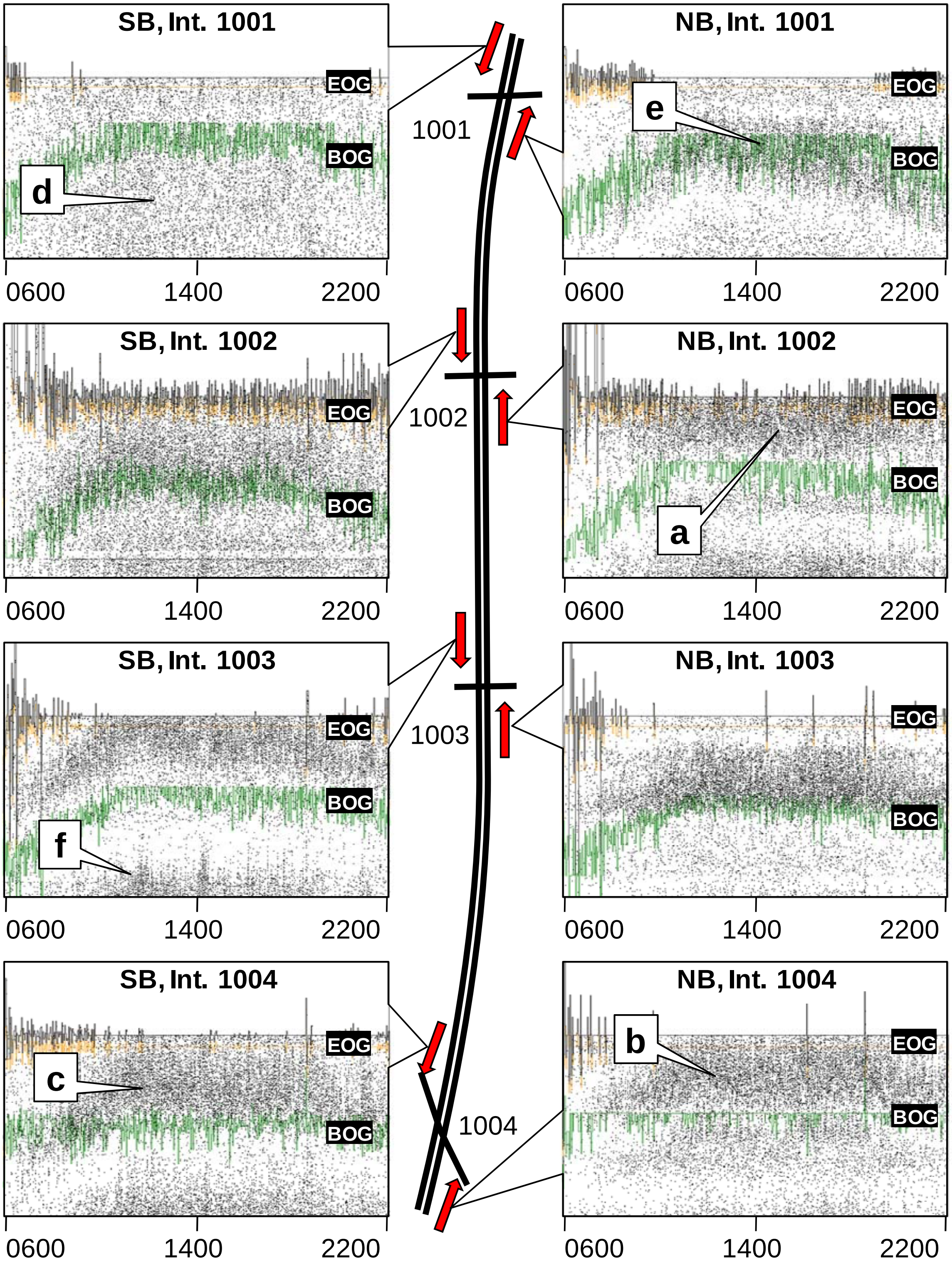


Figure 7. PCDs for eight coordinated phases on SR 37 using data from June 6, 2009 to predict the impacts of offset adjustments.

IMPLEMENTATION AND ASSESSMENT

Offset Implementation

The Saturday offset adjustments in Table 1 were programmed into the controllers and allowed to operate on July 18 and July 25, 2009. Data collected on July 25 were used to construct the PCDs shown in Figure 8. Generally, the observed vehicle arrival patterns followed the predicted patterns shown in Figure 7. The three approaches expected to show improved performance (Figure 7, a, b, c) met these expectations (Figure 8, a, b, c) The two approaches whose performance was forecast to slightly worsen (Figure 7, e, f) also exhibited the anticipated behavior (Figure 8, e, f). The random arrivals at Int. 1001 were not affected by the offset change (Figure 8, d). The empty vertical stripe on both approaches at Int. 1002 (Figure 8, z) represents a 30-minute period in which detector data was not logged due to equipment problems.

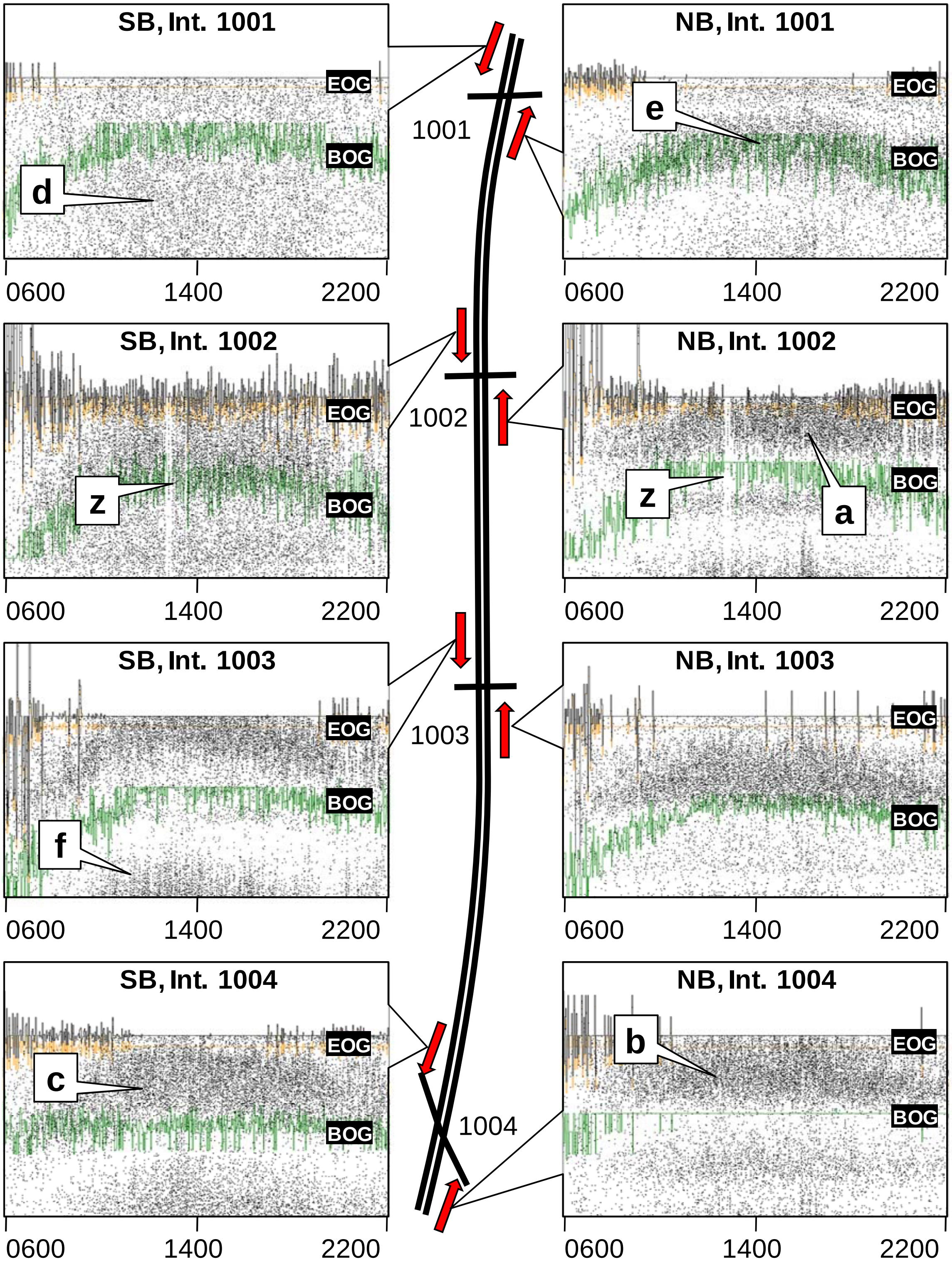


Figure 8. Observed PCDs for eight coordinated phases on SR 37 from July 25, 2009, after implementation of offsets.

Table 2 provides a summary of POG and N_g for the arterial observed with old offsets on June 6 (Figure 5), as predicted with new offsets using data from June 6 (Figure 7), and observed with new offsets on July 25 (Figure 8). On June 6, a total of 50,449 out of 91,540 vehicles detected on the coordinated movements of the system were served during green, or 55.1%. It was predicted that the offset adjustment would increase this proportion to 61.5%. The observed performance exceeded expectations, achieving an overall POG of 64.9%.

Table 2. Summary of MOEs from before and after the offset adjustment.

Intersection	Movement	MOE	June 06, Actual	June 06, Predicted After Offset Adjustment	July 25, Actual	July 18, Actual*
1001: SR 37 & SR 32	Northbound	N_g	5401	4924	4770	5555
		POG	57.8%	45.9%	53.1%	55.9%
	Southbound	N_g	3541	3541	3437	3508
		POG	38.2%	38.2%	38.4%	37.3%
1002: SR 37 & Pleasant St.	Northbound	N_g	4628	7455	7818	7282
		POG	39.5%	63.6%	73.3%	70.8%
	Southbound	N_g	7732	8785	8072	7526
		POG	52.6%	59.8%	59.9%	58.0%
1003: SR 37 & Town and Country Blvd.	Northbound	N_g	8603	8320	8132	8715
		POG	79.6%	77.1%	79.5%	78.4%
	Southbound	N_g	8312	7465	7527	7415
		POG	79.6%	70.4%	72.0%	69.4%
1004: SR 37 & Greenfield Ave.	Northbound	N_g	4379	8044	8255	8739
		POG	35.8%	65.7%	69.6%	67.5%
	Southbound	N_g	7853	8389	8580	9085
		POG	61.0%	65.1%	68.0%	68.5%
Overall Northbound		$\sum_{NB} N_g$	23,011	28,113	28,975	30,291
		POG	52.2%	63.7%	69.4%	68.4%
Overall Southbound		$\sum_{SB} N_g$	27,438	28,180	27,616	27,534
		POG	57.8%	59.4%	60.7%	59.4%
4-Intersection Network Total		$\sum N_g$	50,449	56,293	56,591	57,825
		$\sum N$	91,540	91,562	87,242	90,614
		Overall POG	55.1%	61.5%	64.9%	63.8%

* missing ~ 2 hours data at SR 37 & Pleasant St. on July 18, 2009.

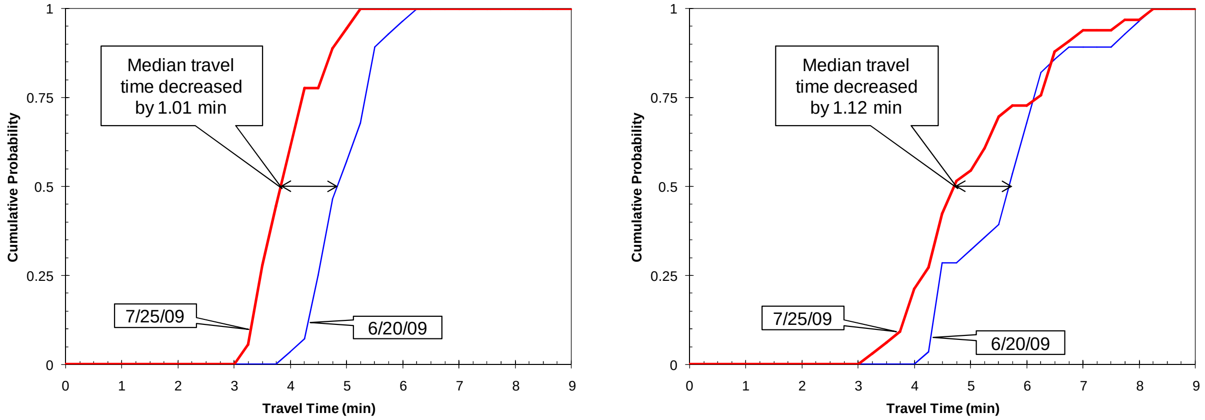
In general, the observed changes in POG for individual phases were similar to the predicted changes. Notably, the NB movement at Int. 1002 had a substantially higher POG (73.3%) than was predicted (63.6%). This is likely due to there being smaller secondary platoons on July 25 than on June 6. A similar trend was also seen for the NB movement at Int. 1003. These trends were also observed on July 18. Another interesting disparity was in the NB movement at Int. 1001. Here, the July 25 POG (53.1%) exceeded predictions (45.9%) by a substantial margin. This suggests that the offset performance on the northbound approach at Int. 1002 influenced the northbound arrival pattern at Int. 1001 in a way that was not predicted by the model discussed in the previous section, which limited the estimation of offset adjustment impacts to adjacent intersections.

Travel Time Evaluation

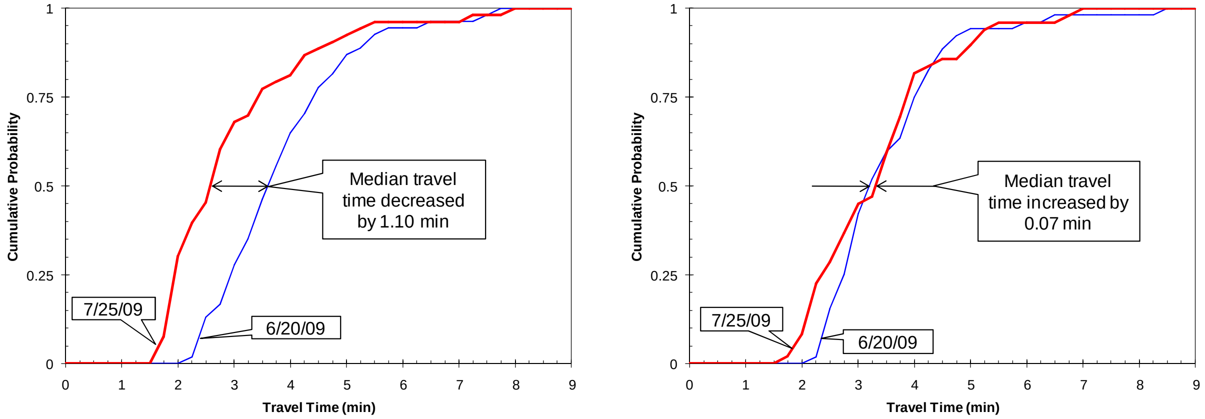
Although PCD's allow visualization of vehicle arrivals, probe vehicle travel times are one of the most widely used signal timing assessment tools due to their simplicity and wide understanding. Figure 9 shows cumulative distribution functions (CDFs) of travel times for a midday time period (0900-1300) on Saturdays before and after the offset adjustment:

- Figure 9a shows northbound travel times measured from midblock sensors (Figure 1, MB01 to MB05).
- Figure 9b shows southbound travel times measured from midblock sensors (Figure 1, MB05 to MB01).
- Figure 9c shows northbound travel times measured from intersection sensors (Figure 1, Int. 1004 to 1001).
- Figure 9d shows southbound travel times measured from intersection sensors (Figure 1, Int. 1001 to 1004).

The midblock Bluetooth probe sensors are the most desirable because they are not influenced by stop vehicle traffic. However, the intersection mounted Bluetooth probe sensors are more practical for long term monitoring due to the convenient access to power and communication.



(a) Northbound on SR 37 (Midblock)   (b) Southbound on SR 37 (Midblock)



(c) Northbound on SR 37 (Intersection)   (d) Southbound on SR 37 (Intersection)

Figure 9. Saturday (0900-1300) travel time cumulative distribution functions.

Table 3 provides summary statistics for midblock (Table 3a) and intersection (Table 3b) sensors describing the data used to construct the CDFs in Figure 9. Travel times were significantly different for the northbound direction, with greater than 99% confidence ($P < 0.001$). For the southbound direction, there was no significant change in travel time. With a total of 315 points from both midblock and intersection sensors in the before and after periods, this represents perhaps the largest travel time sample size that has been reported to date for a before/after study focused on a signal timing change. Mean northbound travel times improved by 0.97 min ($P < 0.001$), as measured from midblock sensors.

Table 3. Statistics for Saturday travel times between 0900 and 1300.

	a) Midblock Stations (MB01 and MB05)				b) Intersection Stations (Int. 1001 and Int. 1004)			
	Northbound		Southbound		Northbound		Southbound	
	June 20 (Before)	July 25 (After)	June 20 (Before)	July 25 (After)	June 20 (Before)	July 25 (After)	June 20 (Before)	July 25 (After)
Mean Travel Time, min	5.16	4.19	5.86	5.32	4.08	3.18	3.77	3.60
Standard Deviation of Travel Time, min	0.55	0.58	1.08	1.28	1.19	1.35	1.14	1.18
Minimum Travel Time, min	4.07	3.27	4.27	3.38	2.50	1.83	2.50	2.00
Median Travel Time, min	5.08	4.07	5.97	4.85	3.92	2.82	3.48	3.55
Number of Samples	28	18	28	33	54	53	52	49
T-value (mean)	-5.736		-1.804		–3.645		–0.724	
P-value (mean)	< 0.001		0.076		< 0.001		0.471	

The intersection mounted probe sensors (Table 3b) measured this improvement as decreasing by 0.9 min ($P < 0.001$); the value is slightly smaller because the intersection sensors measure travel time across a shorter distance. Additionally, the change in travel time at the endpoints of the arterial segment was excluded. Southbound travel time did not increase by a substantial amount; very slight improvement was observed with intersection sensors, while midblock sensors saw a 0.54 min decrease in mean travel times that would be significant at the 90% level.

CONCLUSIONS

This paper demonstrated the utility of two tools to assist in arterial offset management:

1. The PCD was used to visually identify satisfactory and poor progression conditions, predict the impacts of offset adjustments, and assess the effects of implementation.
2. The data used to construct the PCD also was capable of yielding quantitative performance measures (Equation 1, POG and $\sum N_g$) that could serve as an objective function in an offset optimization formulation.
3. Bluetooth probe travel times were used to independently compare the before and after operations associated with an offset change.

These two tools were applied to a case study in which arterial offsets were tuned for a weekend (Saturday) coordinated timing plan. Calculation of $\sum N_g$ and *POG* from the PCD data was used in to identify a set of offset adjustments to improve progression. PCDs were used to predict the impact of the adjustments, and verify the changes after implementation. It was predicted that overall network POG would improve from 55% to 62%. Actual improvements were in the range of 64–65%. The impact of these changes on travel time was evaluated using MAC address matching. A large travel time sample size, showed an improvement of approximately 1 min (~20%) in the northbound direction and 0.5 min (~10%) in the southbound direction.

The performance of midblock sensors was compared to signal cabinet mounted sensors at intersections. Although midblock sensors provided a superior travel time estimate because they were not influenced by vehicle wait times at intersections, cabinet mounted sensors nevertheless performed reasonably well and are generally easier to deploy due to convenient access to power and communication.

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