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ABSTRACT

Decisions on whether to coordinate adjacent intersections are currently made by rules of thumb, coupling indices based on ratios of volume to distance, and modeled traffic flows. As high resolution event data from signalized intersections becomes more readily available, it becomes possible to analyze actual link vehicle flows to better characterize whether (and when) signal coordination is desirable. This paper proposes and demonstrates a methodology to assess opportunities to improve arterial progression if a non-coordinated system is coordinated, using peer data obtained from adjacent intersections. The beginning of green from the upstream intersection is combined with vehicle arrival times from a downstream intersection to characterize whether vehicles are likely to arrive in consistent platoons at the downstream signal. The peer data based methodology is used to investigate the benefits of extending a coordination plan to system running without coordination during a late night time period. A case study of a fully-actuated late evening timing plan on an arterial identified opportunities for potential benefits from coordination; the implementation of a timing plan for an adjacent time period reduced travel times by approximately 1 minute in both directions on the arterial.

INTRODUCTION

Whether two adjacent signals should be coordinated (and at what times of day the plans should operate) depends on the amount of benefit that can be obtained. Most traffic engineers have an opinion based on experience about when to coordinate signals; rules of thumb that are sometimes applied include there being no benefit to coordinating links longer than one mile, or perhaps after 9 PM. Several numerical heuristic techniques have been proposed over the years for determining when to develop a coordination plan. Some of these have been relatively simple, such as using the ratios of the link volume (*V*) to the distance (*D*) to determine a "coupling index" (CI) (*1*):

$$CI = \frac{V}{D}, \qquad \text{Equation 1}$$

A variant of this idea is the so-called "gravity" model, which considers the weight of the distance *squared* (*2*):

$$CI = \frac{V}{D^2}. \qquad \text{Equation 2}$$

Besides numerical indices of coordination opportunity, a more sophisticated approach is to model platoon formation and dispersion on links through a network. Empirical observations of platoon dispersion were first reported by Pacey (*3*), and expanded by others (*4*,*5*,*6*,*7*). Hillier and Rothery (*8*) later combined the concept of a cyclic platoon profile with a delay model. Robertson (*9*,*10*) integrated the delay minimization concept with a formalized platoon dispersion model, forming the basis of TRANSYT. Numerous researchers have subsequently investigated platoon dispersion (*11*,*12*,*13*,*14*,*15*,*16*,*17*,*18*,*19*,*21*,*21*,*22*,*23*,*24*), investing a considerable amount of effort in calibrating or refining the Robertson model (*15*,*16*,*17*,*20*,*22*). In general, as traffic flow becomes more dispersed and random, coordination becomes less beneficial (*25*). Beyond determining when and where to coordinate, a closely related problem is determining how to partition signal systems into subsystems (*1*,*25*,*26*,*27*).

Conventionally, arterial coordination plans are developed for the times of day when volumes are known to be high. At other times of day a common strategy is to drop coordination and run signals in fully-actuated mode with recall to the mainline. It is not often known whether this an effective strategy. Analyzing arterial performance under non-coordinated operations is particularly challenging because cyclic flow profile-based techniques cannot be used when the signals do not operate with a regular cycle length.

This paper proposes a framework for evaluating operations on links between pairs of fully-actuated signalized intersection. This concept is based upon relating vehicle arrivals at the downstream intersection to the beginning of green at the upstream intersection, incorporating data from the two "peer" intersections. The results are dramatically different from measuring vehicle arrivals relative to downstream signal phase events. We demonstrate that the methodology can identify when benefits are likely to be obtained from signal coordination.

METHODOLOGY

Analyzing Link Flows

Figure 1 shows the hypothetical trajectory of a vehicle traveling on a link between two non-coordinated intersections, with an advance detector situated ahead of the downstream signal that measures arrivals for the purpose of operating the downstream signal. In most currently deployed systems, such vehicle detectors only provide information to the *downstream* signal. In Figure 1, the following quantities are defined:

- d_D, Distance from the detector from the upstream intersection;
- d_U, Distance from the detector to the downstream intersection;
- t_{DET} , time of the detection;
- t_{BOG}^{U}, time of the upstream beginning of green;
- t_{EOG}^{D}, time of the downstream end of green;
- T_A^D , vehicle arrival time relative to downstream intersection;

- T_A^U, vehicle arrival time relative to upstream intersection; and
- *S*, the assumed speed on the link.

Under fully-actuated, non-coordinated operation, the signal phases at each intersection are determined by phase actuation, minimum and maximum timing intervals, and the volume-density controller settings (*e.g.*, vehicle extension). Without implementing a coordination plan, or otherwise fundamentally altering the fully-actuated signal logic, there is no inherent provision for influencing the local signal states to provide a progressive pattern. Because the permissive periods for the minor phases are active essentially all of the time, coordination of green phases for arterial movements happens only by chance. Links with distances and volumes that do not return satisfactory results to formulas such as Equation 1 and Equation 2 are assumed to have no need for coordination. In particular, under low-volume conditions (*e.g*., late-night plans) it is often assumed that minor street phases will be served infrequently enough that the arterial through movements will be green most of the time, provided the signals rest in green on those phases. However, these assumptions are rarely evaluated or confirmed with actual data.

It is difficult to analyze incoming arrivals based on downstream signal events, but this is typically the only data available to a local controller. Under coordinated operations, it is possible to construct an arrival flow profile based on the time in cycle when vehicles arrive (*8*). The time after the downstream end of green (Figure 1) occurs periodically under coordination, and platoons generally arrive at the same time in cycle, with variations due to minor phase actuation (*e.g.* early return). The arrival time of a vehicle with respect to the downstream signal (T_A^D) is given by

$$T_A^D = t_{DET} - t_{EOG}^D \, . \qquad \text{Equation 3}$$

The downstream end of green is selected as the reference point because it is a periodically recurring event in actuated-coordinated operation. It is used, for example, as the reference point for constructing arrival profiles in ACS-Lite (*28*,*29*).

If the upstream signal is not coordinated, flow profiles constructed relative to the downstream green will appear random. Figure 2 shows a distribution of vehicle arrival times obtained by applying Equation 3 to raw data from a fully-actuated intersection. The average "cycle length" (time between successive ends of green) was 98 seconds. The arrival pattern is random, with minor perturbations around 98 seconds that reflect fluctuations in the cycle length. While it is highly desirable to use advance detector data in conjunction with the downstream detector phase state to calculate a percentage on green (POG) or arrival type (AT) to evaluate the quality of progression (*30*, *31*), this perspective is inadequate for determining whether arrivals occurring during non-coordinated operations would benefit from coordination. While more sophisticated systems could incorporate data from multiple intersections, this type of data is unavailable at the intersection level within currently available commercial systems.

Figure 1 illustrates a method for relating vehicle arrivals at a downstream detector to the upstream signal state. The travel time between the upstream intersection and the detector is calculated from an assumed travel speed *S*, which projects the upstream phase events to the detector position. The downstream arrival time of each vehicle at the advance detectors relative to the upstream signal (T_A^U) is given by

$$T_A^U = t_{DET} - \left(t_{BOG}^U + \frac{d_U}{S} \right). \qquad \text{Equation 4}$$

Note that by measuring downstream arrivals instead of upstream departures, the need for modeling platoon dispersion along the link is avoided. The location of the detector in the example data is 405 ft upstream of the stop bar, as discussed in more detail later.

Figure 3 shows a distribution of vehicle arrival times calculated from the upstream beginning of green (Equation 4). This plot represents the same data shown in Figure 2 (Equation 3), excluding the travel time from the intersection to the detector. It is obvious from this graph that most vehicles arrive at the detector approximately 15 seconds after the beginning of green at the upstream intersection. The peak in the distribution results from frequent cycling of the upstream signal, leading to the downstream detection of the released vehicles at around the same time relative to the beginning of upstream green. If the upstream signal rested in green most of the time, the tail of the distribution would extend well beyond the range of the plot because the time after upstream green will be an increasingly large number, and the peak would be diminished. The prominence of the peak (72% of vehicles arrived between 0 and 25 seconds) suggests that a substantial proportion of arriving vehicles could potentially be captured by a coordinated green band.

The outcome of Figure 3 is unsurprising, because vehicles travel on the link at approximately the same speed, and consequently arrive at the detector at approximately the same time after they depart the upstream intersection. To demonstrate how the peak attenuates as minor phase activity decreases at the upstream signal, we repeat the procedure for several separate analysis periods at the example location during the overnight period. The results are illustrated in Figure 4, with vehicle arrival distributions representing the two-hour intervals 2200-2400 (the time period of the example in Figures 2 and 3), 2400-0200, 0200-0400, and 0400-0600 respectively shown by Figure 4(a), Figure 4(b), Figure 4(c), and Figure 4(d). In Figure 3 and Figure 4(a), we observe 72% of vehicles arriving in the peak from 2200-2400. From 2400-0200, this decreases to 53% [Figure 4(b)], and from 0200-0400 it is reduced even further, to 38%. The 0200-0400 is an example of a time period where there is not enough evidence of platoon formation to recommend coordination. The increasing granularity of the distributions corresponds to decreasing vehicle volume. Finally, in the early morning hours 0400-0600, activity starts to increase again and the proportion of vehicles in the peak increases to 62%.

Deciding Whether to Coordinate Adjacent Intersections

The methodology described in the previous section offers a potential framework for inferring whether arterial stops could be reduced by coordinating signals during a particular time period. Further work is needed to solidify these concepts into a practitioner-ready methodology. Two specific topics are identified for refinement:

- A performance measure is needed for assessing if coordination is warranted. The presence of prominent peaks in vehicle arrival distributions is expected to correspond to a strong potential benefit from coordination. The percentage of vehicles occurring within a certain time range of the distribution (e.g., 73% in Figure 3) is a candidate metric for this purpose. Because successful realization of the benefit is contingent upon selection of appropriate control parameters, this metric would likely represent a “best case” scenario.

- The tradeoff in implementing a coordination plan is the increase in delay experienced by non-coordinated phases. Coordination patterns enforce a schedule for coordinated greens, which limits the available time for minor phase permissive periods and tend to increase cycle length. Vehicles arriving on a minor phase consequently have to wait longer before being served.

Subsequent sections of this paper present a case study where the methodology was applied to an 8-intersection arterial. Operations from fully-actuated and coordinated modes are compared, and the above mentioned issues are explored further.

Data Schemes in Currently Deployed Systems

Closed-loop signal systems communicate with other cabinet devices to operate the signal, receive dial-up connections to synchronize clocks and occasionally receive new timing plans, and talk to a master controller to ensure that they are operating the appropriate cycle length and offsets in coordination. However, with the exception of a few isolated research efforts, signal controllers do not presently communicate with *each other* to share information. The existing model is a client-server system in which the controller receives or sends information in a well defined vertical hierarchy. Alternative paths for information that have not been utilized in closed-loop signal systems are horizontal channels of communication between peer devices. These concepts are employed in adaptive systems (*32,33,34*), which vary in complexity from the use of detectors information from upstream intersections to model downstream arrivals (*32*) to monitoring of platoons and conflicts between platoons in a network (*34*). The methodology described in this paper demonstrates a potential application for information shared between adjacent controllers in closed-loop systems.

The subsequent sections of this paper report the application of this methodology to examine fully-actuated operations during the 2200-2400 time period on an eight-intersection arterial, use that data to make a decision regarding extending the coordination time, and compare the quality of arterial progression before and after the implementation of a coordinated plan during that time period.

INSTRUMENTED ARTERIAL

Figure 5 shows a map of SR 37 in Noblesville, Indiana. SR 37 is a 5.2-mi (8.3 km) corridor consisting of eight intersections. The posted speed limit on the corridor is 55 mph (88 km/h). Each intersection runs a common cycle length every day from 0600-2200, then operate fully-actuated from 2200-0600. Signal controllers capable of logging high resolution event data were deployed at each intersection to collect event phase and detector event data (*35*). Probe vehicle travel time measurements were collected with Bluetooth (BT) device MAC address matching (*36*, *37*). Sensor cases were stationed at the entry points to the arterial, and at a midpoint location. This configuration was used to measure travel time for the entire arterial (Case A to Case C) and for two subsystems marked in Figure 5 as System 1 (Case A to Case B) and System 2 (Case B to Case C). Data was collected during fully-actuated operations on Wednesday, June 30, 2010, 2200-2400, and during coordinated operations on Wednesday, July 14, 2010, 2200-2400. To implement coordination, the existing coordination plan operating from 1900-2200 was extended to run an additional two hours on Wednesday, July 14, 2010 from 2200-2400.

For reference, Figure 6 shows the typical layout of an intersection on the test arterial. Each minor phase lane group is actuated by use of stop bar loop detection zones. The arterial through movements, coordinated throughout most of the day, are operated using advance detectors located 405 ft upstream from the stop bar. Dedicated left and right turn lanes exist on the arterial at each intersection; at all intersections, the turning lanes extend back further than 405 ft, meaning that most traffic passing over the advance detectors consists of through vehicles.

Figure 7 shows the average effective cycle lengths that operated with the controllers in fully-actuated mode on June 30, 2010. The error bars are based on the standard deviation. This paper defines the effective cycle length as the time between successive ends of green for the northbound through phase. Most effective cycle lengths ranged between 50–70 seconds. These rather low average values suggest that from 2200-2400, the arterial through movements did not rest in green for long periods of time as expected based on the assumption of low minor phase activity. At Int. 5, an effective cycle length of 98 seconds was maintained throughout the 2200-2400 interval. This was caused by a minor phase detector in recall. Although unintentional, this phenomenon helped facilitate the comparisons in the previous section between upstream and downstream phase events as alternative perspectives. It seems more likely that the quality of progression on the arterial was more substantially affected by the lack of coordination between adjacent signals on the seven arterial links than by a side street phase being in recall at Int. 5.

APPLICATION OF THE METHODOLOGY

Figure 8 shows plots of vehicle profiles related to the downstream end of green (Equation 3) for the fourteen coordinated links on the test arterial. The profiles are labeled with the intersection number and direction of the arrival approach. The average cycle length at the downstream intersection is indicated by a vertical line on each graph. The shape of the vehicle arrival distributions is influenced by the variations in effective cycle length at the downstream intersection. There is little evidence of platoon formation in these arrival profiles.

Using the same arrival data, but using the upstream beginning of green as the reference point (Equation 4), a set of arrival flow profiles using the proposed analysis methodology are shown in Figure 9. Next to each distribution is the percentage of vehicles arriving within the first 25 seconds of the profile. This percentage is greater than 50% for each link. The flow profiles all exhibit prominent and clear peaks, indicating considerable upstream phase cycling (as opposed to extended periods of resting in green). Another interesting artifact is the existence of minor peaks at 4/NB and 6/SB, which may be attributed to vehicles making turns from side street phases at Int. 5. The crossing street, 146th St. is a busy east-west road and the intersection features protected double left turn lanes for both eastbound and westbound traffic (i.e., there are no permitted left turns). Entries from the side streets do not seem to create arterial platoons on other links, perhaps because of lower volumes or more randomly dispersed inflows of traffic.

Figure 9 qualitatively demonstrates that a potential benefit from coordination was available during the 2200-2400 time period. The percentage of vehicles belonging to the peak, as estimated by the percentages of vehicles arriving in the first 25 seconds as indicated in Figure 9, is an optimistic estimate for the percentage of vehicles that could be captured by coordinated green bands. In reality, the choice of cycle length and offsets largely determines the performance of the coordination plan, and it may not be possible to provide two-way coordination throughout the entire system. However, if platoons are consistently formed on the links and are observed arriving at the downstream intersections, it seems likely that a signal coordination will provide less delay for arterial movements than a series of independently cycling fully-actuated controllers.

RESULTS

Impact on Progression Quality (Percent Arrivals on Green)

Coordination was implemented for the 2200-2400 time period by simply extending the latest coordination plan of the day (1900-2200) two hours later. This was an expedient way of creating a late evening coordinated scenario that could be compared with fully-actuated operations to verify whether any benefits are obtained from coordination. Likely, better results would be obtained by designing a timing plan specifically for traffic in the 2200-2400 time period, perhaps with a shorter cycle length.

Figure 10 shows the percentage of vehicles arriving on green, the “percent on green” (POG), by approach, under fully-actuated and coordinated operations. With the exception of two approaches, the percent on green increased substantially. This could be attributed in part to increased green times for the northbound and southbound phases related to the fact that the 114 second cycle length is longer than any of the average effective cycle lengths under fully-actuated operations. For example, the two entry points to the arterial (Northbound at Int. 8, Southbound at Int. 1) both experienced considerable increases in POG. The decrease in POG for the northbound at Int. 2 is attributed to a poor offset at that intersection, a possibility that was mentioned earlier.

Impact on Arterial Travel Times

While POG gives a sense of the independent performance of each signal, a better independent verification of arterial progression can be obtained by looking at the travel time along the arterial. Figure 11 shows six cumulative frequency diagrams (CFDs) of travel time under fully-actuated and coordinated operation on the following sections of SR 37:

- Figure 11(a) and Figure 11(b) respectively show CFDs of southbound and northbound travel times along the entire length of the arterial (Figure 5, between Case A and Case C).
- Figure 11(c) and Figure 11(d) respectively show CFDs of southbound and northbound travel times for System 1 (Figure 5, between Case A and Case B).
- Figure 11(c) and Figure 11(d) respectively show CFDs of southbound and northbound travel times for System 2 (Figure 5, between Case B and Case C).

The center horizontal gridline in these charts intersects the median values of the two CFDs. For the entire arterial, and for each subsystem, coordination was found to lower the amount of travel time through the system. A reduction of approximately 1.1 minutes in the southbound travel time [Figure 11(a)] and 1.0 minutes in northbound travel time [Figure 11(b)] were measured from travelers moving along the entire arterial. In System 1, both northbound and southbound travel times were reduced by about 0.3 minutes [Figure 11(c), Figure 11(d)], while in System 2, the reductions were 0.8 and 0.9 minutes for northbound [Figure 11(e)] and southbound [Figure 11(f)] travel times respectively.

Impact on Minor (Non-Coordinated) Phase Delay

Different agencies have different performance objectives for intersection operations. The two most common objectives are minimizing overall intersection delay, or minimizing the number of stops along an arterial. In general, short cycles are most effective at minimizing system delay, and longer cycles make it easier to create large green bands for minimizing stops. This paper has focused on identifying opportunities to minimize stops by imposing a coordinated plan, but it is important to remember that changes in cycle length can significantly influence delay. There are necessary tradeoffs to be made between delay for non-coordinated movements, and the performance of progressive arterial movements.

For example, let us consider Int. 6, which has an average cycle length of 57 s under fully-actuated control (Figure 7), and upon which a 114 s cycle is imposed by the coordination plan. Doubling the cycle length is certainly expected to increase delay for non-coordinated movements. If one applies the *Highway Capacity Manual* (HCM) (38) signalized intersection methodology and analyzes the two-hour period (2200-2400) using observed volumes and green times and approximated minor movement arrival patterns, Figure 12 illustrates how the delay distribution by movement shifts with this new cycle. Figure 12a shows the average delay, while Figure 12b shows the total delay by movement. In this example, activating the coordination plan increased the estimated overall intersection delay by approximately 30%, while the proportion of vehicles arriving on green at the coordinated movements increased from 52% to 87% (Figure 10) and arterial travel times improved as discussed in the previous section.

Potential ways to mitigate side street delay would be to develop a plan using a shorter cycle length, if feasible, or consider using controller features such as alternative permissive periods or phase reservice (*39*). The use of fully actuated-coordinated phases, which allow the coordinated phases to terminate early after the flow of through vehicles drops off, could also help mitigate the increase in minor phase delay due to coordination (*40*).

CONCLUSIONS

A method was proposed for analyzing the quality of progression between adjacent traffic signals based on information shared between devices at the same status in the control hierarchy, otherwise known as peer data. Peer data is envisioned as a basis for link-based performance measurement of signal systems independent of local intersection cycle/offset/split paradigms. An example application that used peer data to analyze non-coordinated adjacent signal operations was presented. By examining the arrivals of vehicles at a downstream detector relative to upstream phase events, it was possible to determine whether vehicles form platoons and hence whether a benefit from coordination is likely. This methodology better integrates arterial progression concepts normally associated with coordinated operations into the analysis of fully-actuated operations.

A case study was presented consisting of fully-actuated arterial operations in the late evening, a time period where operations had not previously been substantiated by field study. In the case study, platoons were clearly identified using peer data during a time period when coordination was not in use and was presumed to be unnecessary. The implementation of an existing coordination plan in the late evening time period was found to improve arterial travel times by one minute over a 5.2-mi segment, a modest improvement that would possibly be improved further by optimizing the timing plan for late evening traffic volumes. For the case study, it is recommended that coordination be implemented for the 2200 to 2400 time period. Future research should focus on developing a decision framework to guide agencies in deciding what time periods to coordinate that considers both stops and delays.

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List of Figures

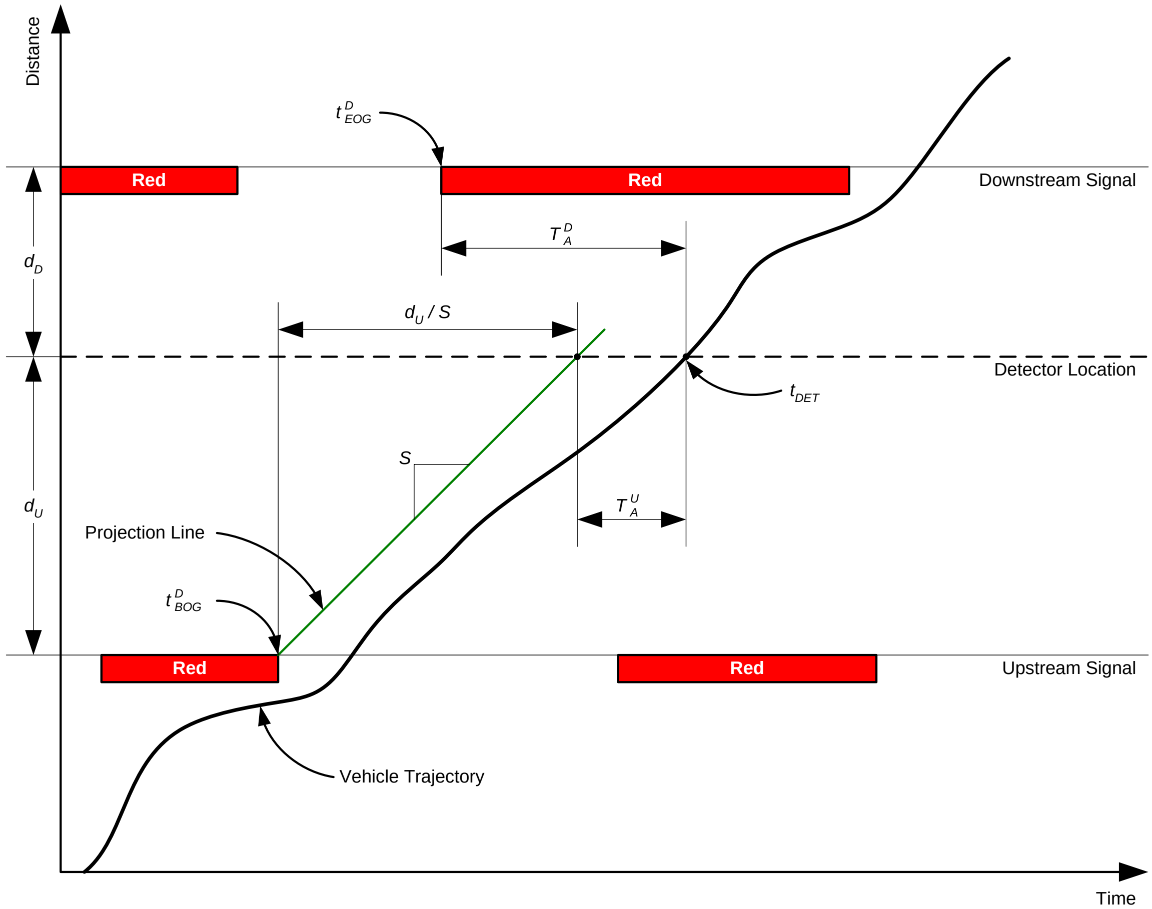


Figure 1: Vehicle movement on a link between two non-coordinated intersections.

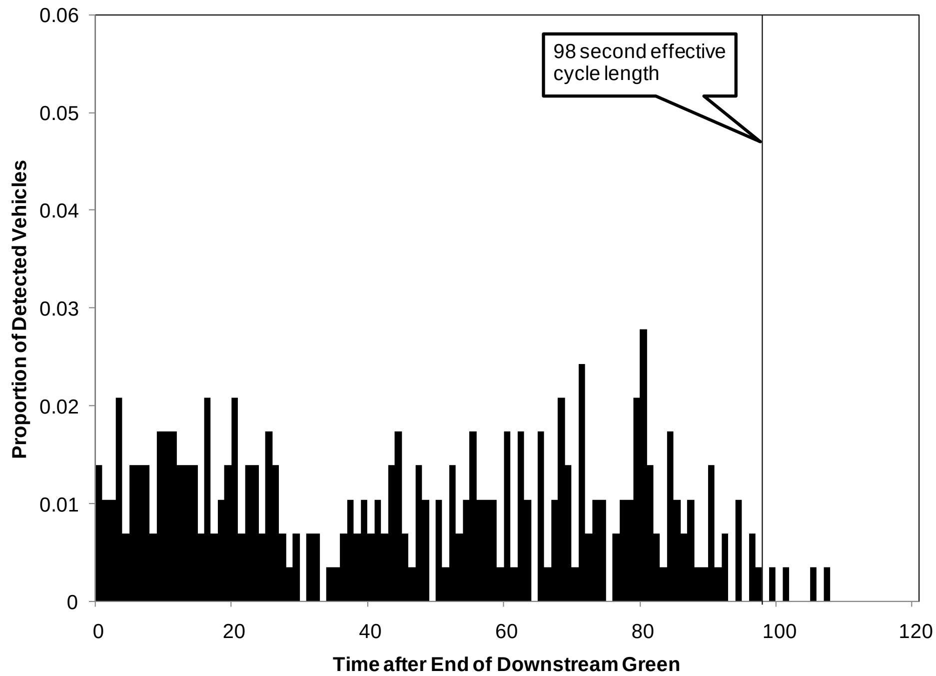


Figure 2: Vehicle detection times measured relative to signal events at a downstream intersection (T_A^D) on a non-coordinated link (based on same raw data as Figure 3).

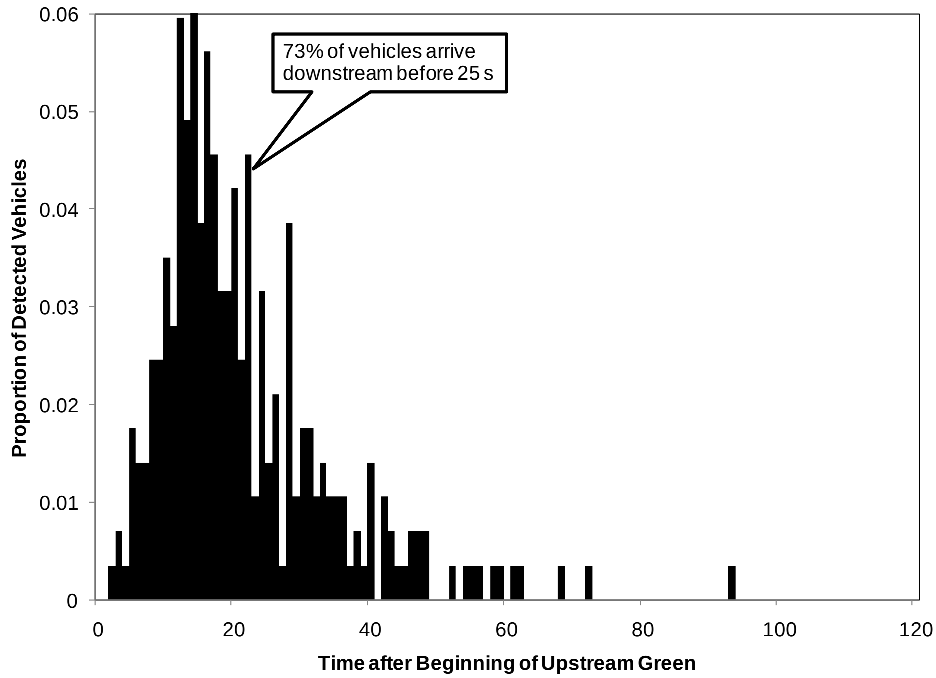
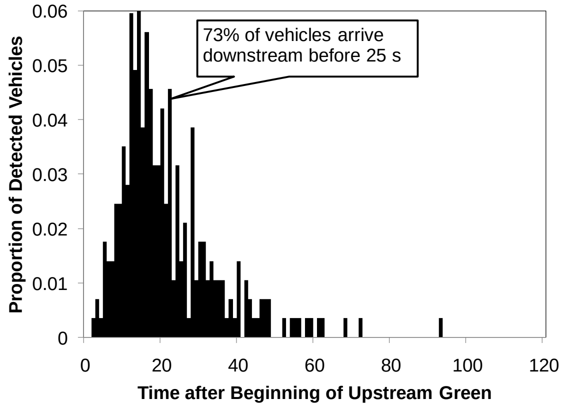
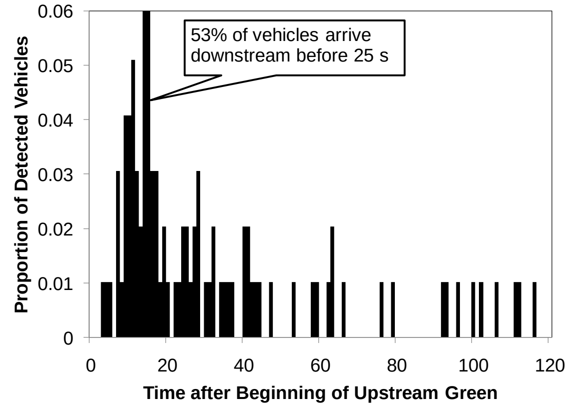


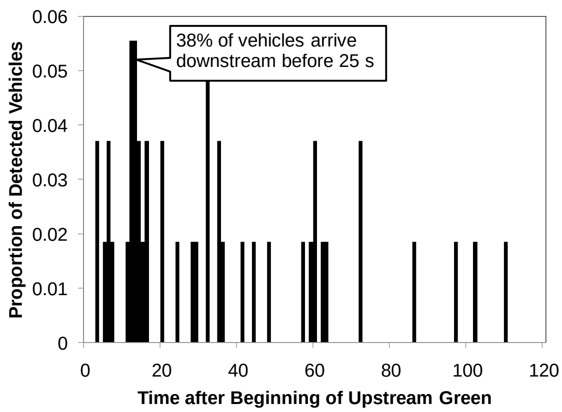
Figure 3: Vehicle detection times measured relative to signal events at an upstream intersection (T_A^U) on a non-coordinated link (based on same data as Figure 2).



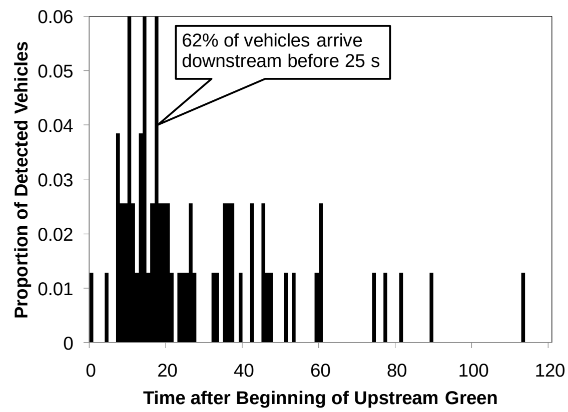
(a) 2200-2400.



(b) 2400-0200.



(c) 0200-0400.



(d) 0400-0600.

Figure 4: Vehicle flow profile referenced to upstream green, .

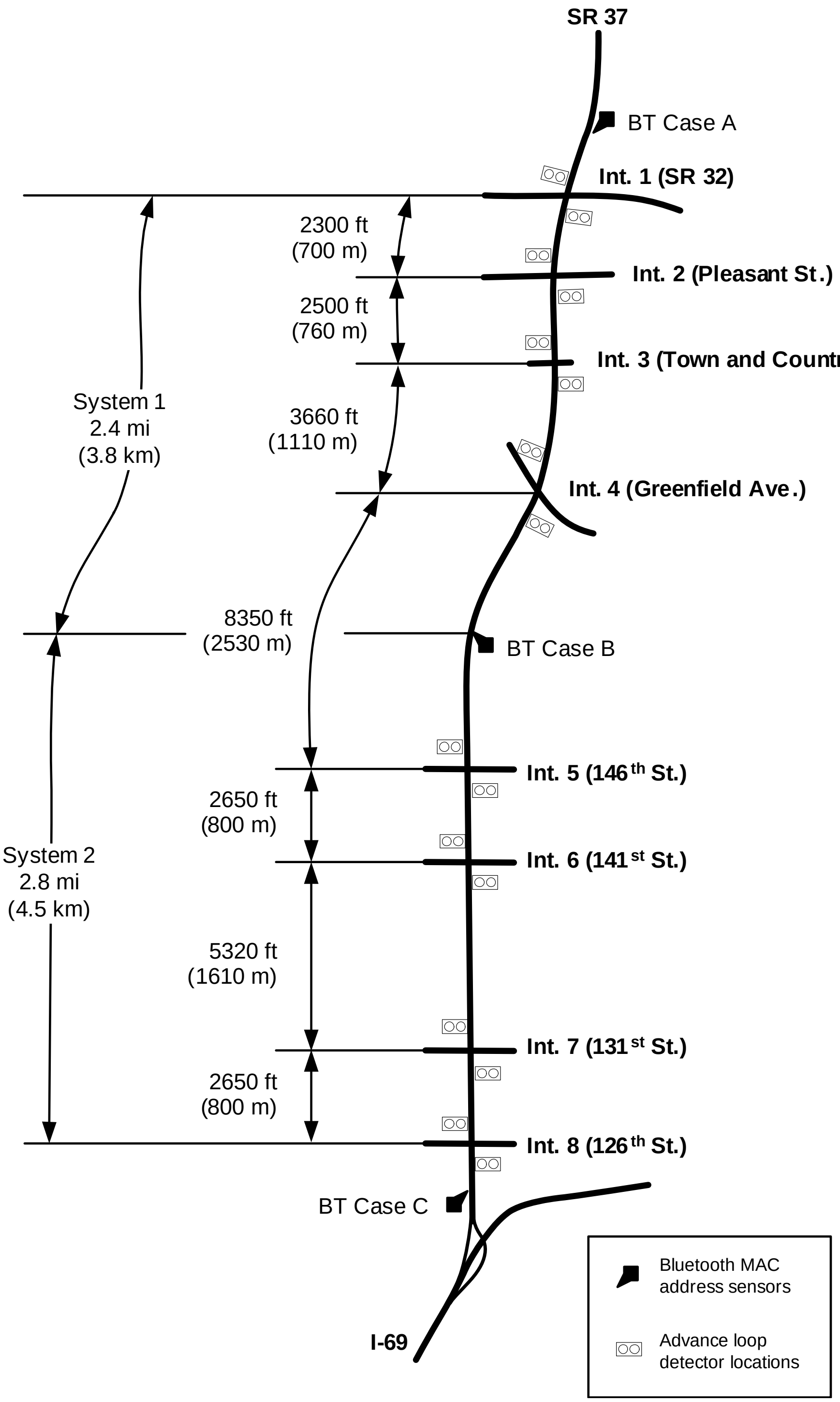


Figure 5: Map of the SR 37 Corridor.

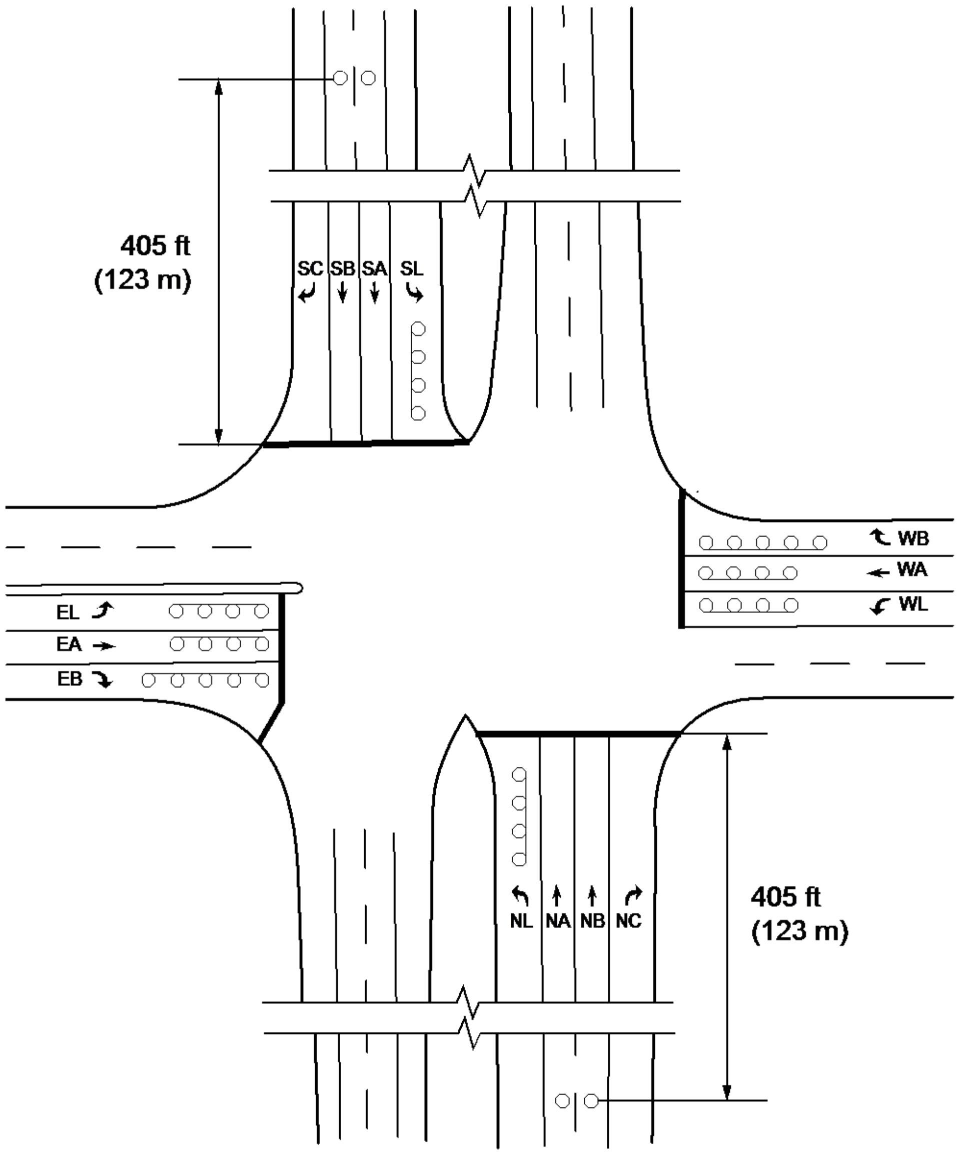


Figure 6: Detector configuration of a typical intersection on SR 37.

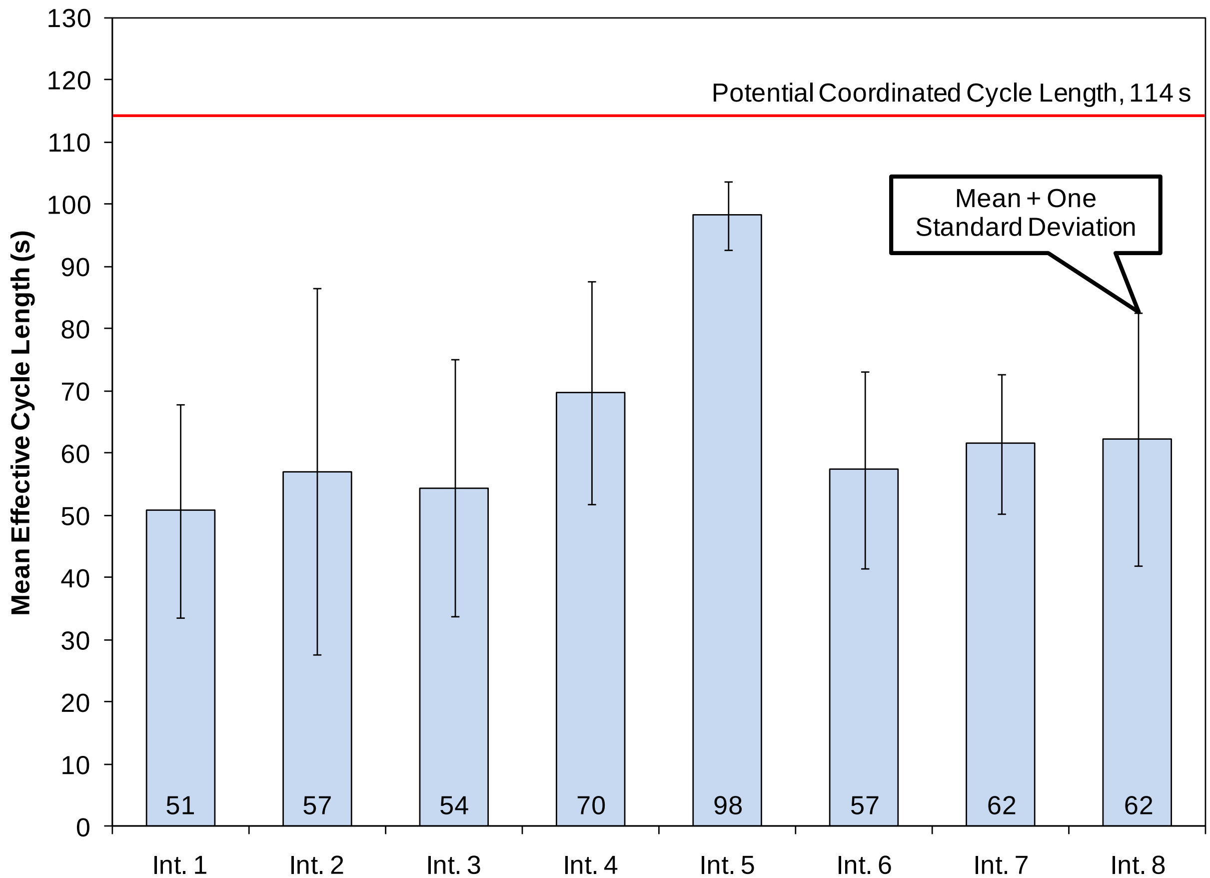


Figure 7: Effective cycle lengths under fully-actuated operation, June 30, 2010, 2200-2400.

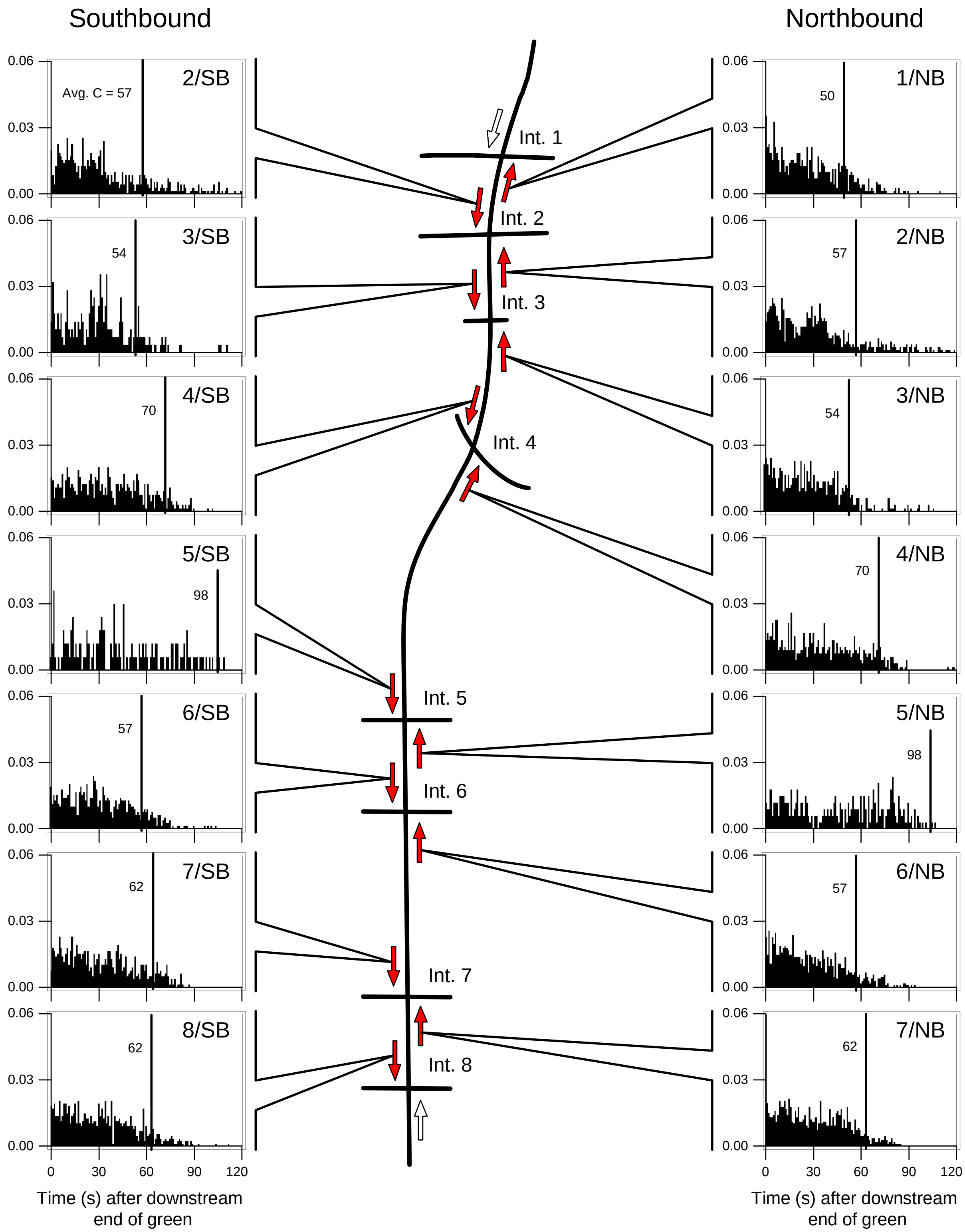


Figure 8: Arrival profiles based on downstream end of green for fully-actuated operation, June 30, 2010, 2200-2400. Effective cycle lengths are shown.

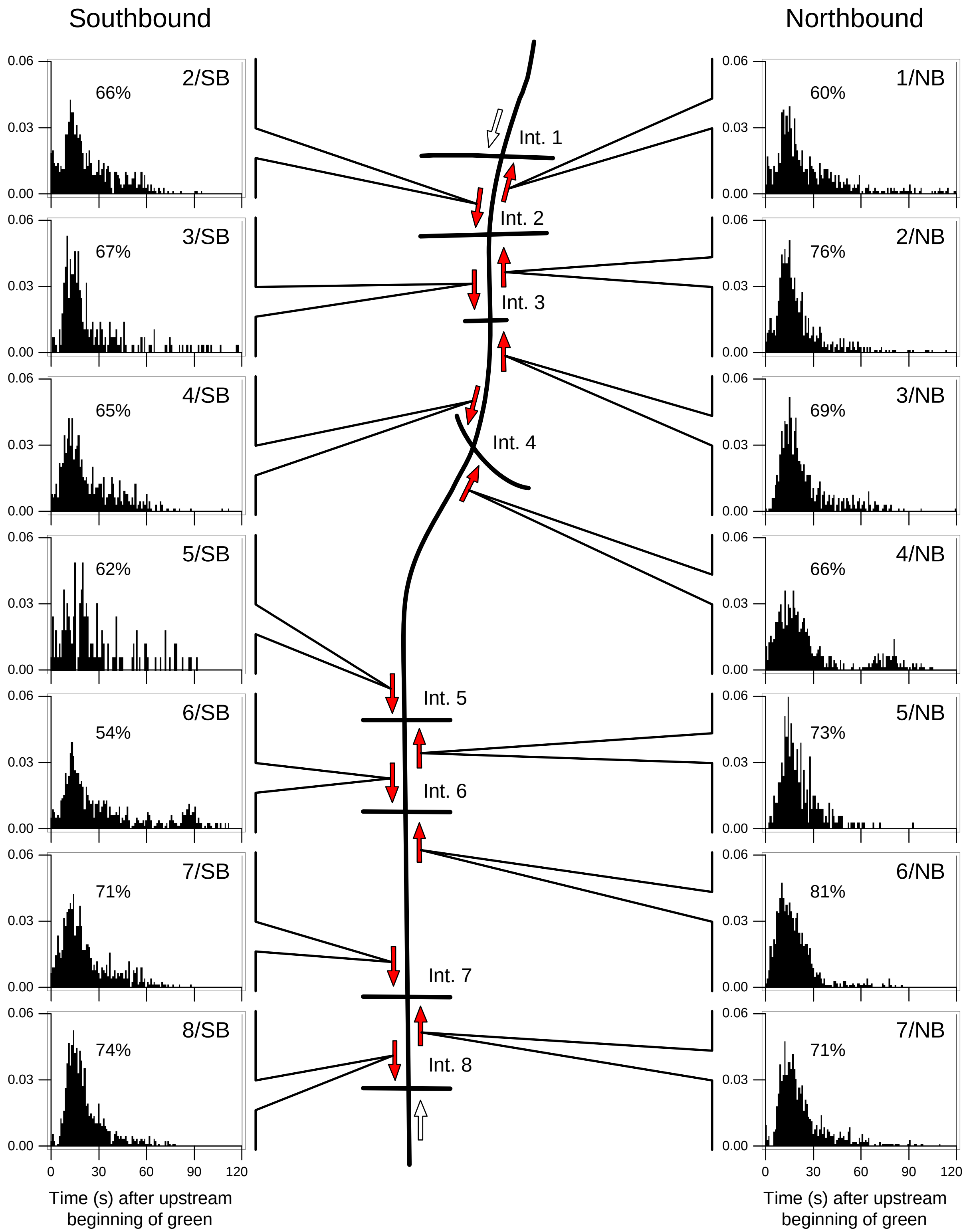
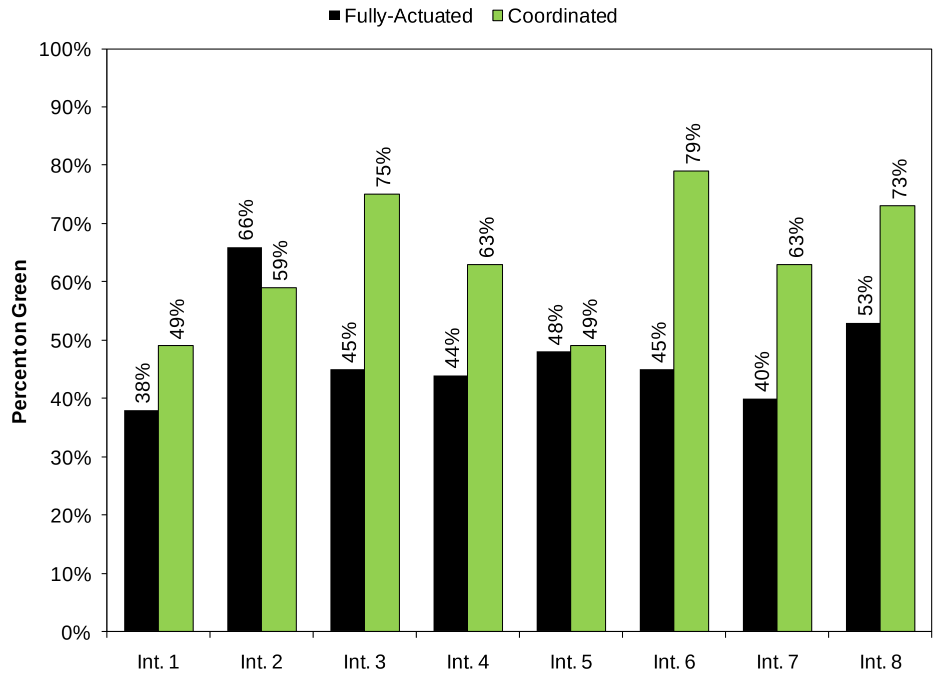
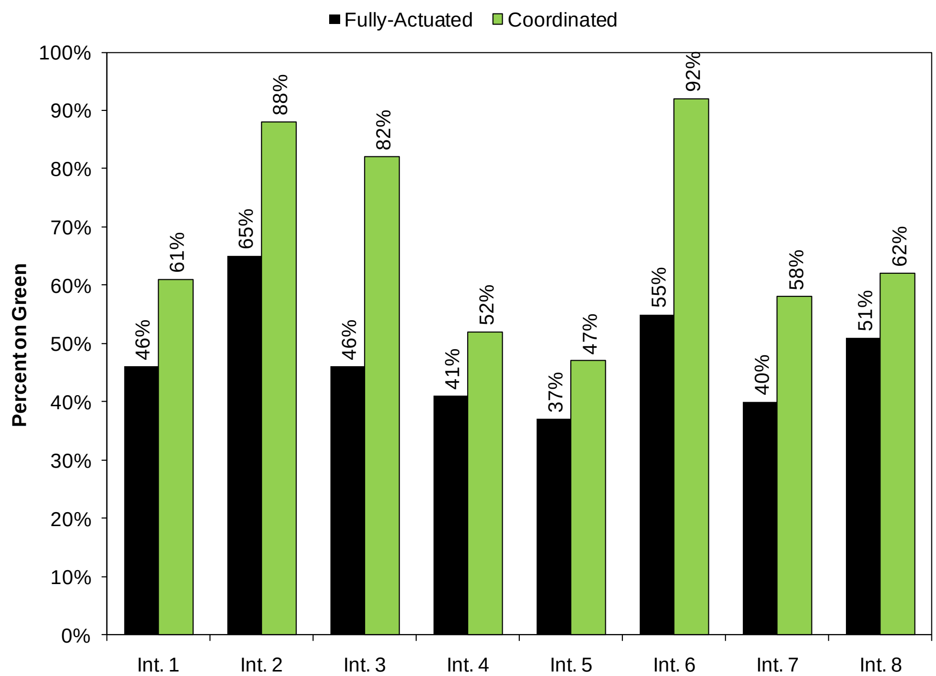


Figure 9: Arrival profiles based on upstream beginning of green for fully-actuated operation, June 30, 2010, 2200-2400.

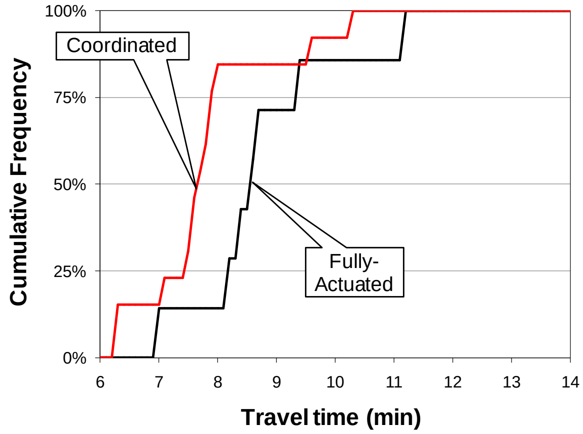


(a) Northbound.

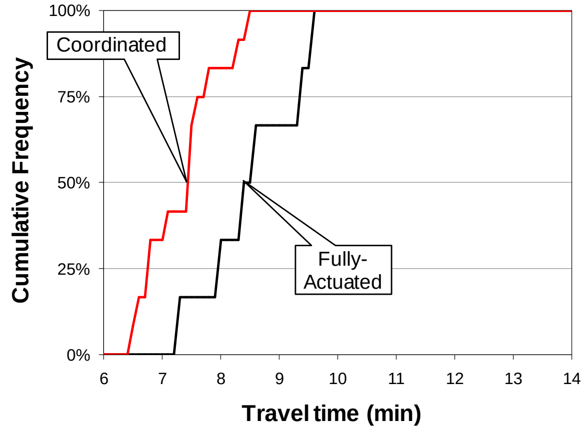


(b) Southbound.

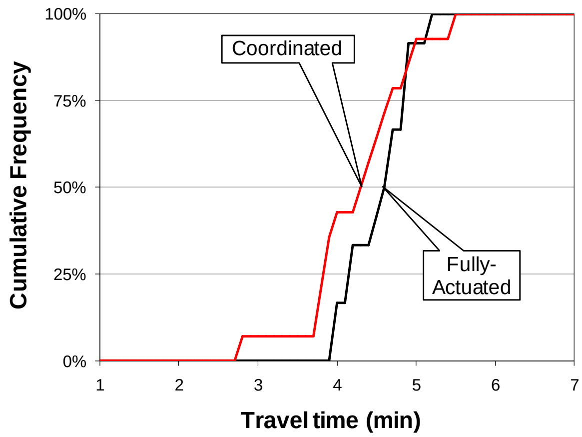
Figure 10: Percentage on green by intersection.



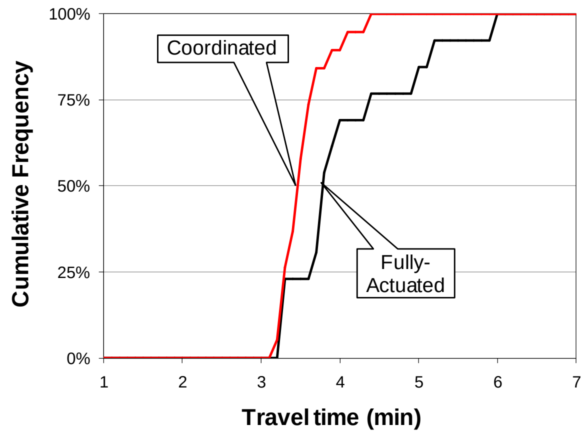
(a) Southbound, Case A to Case C.



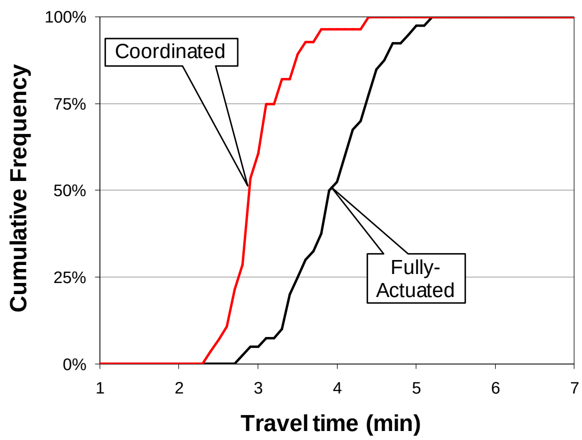
(b) Northbound, Case C to Case A.



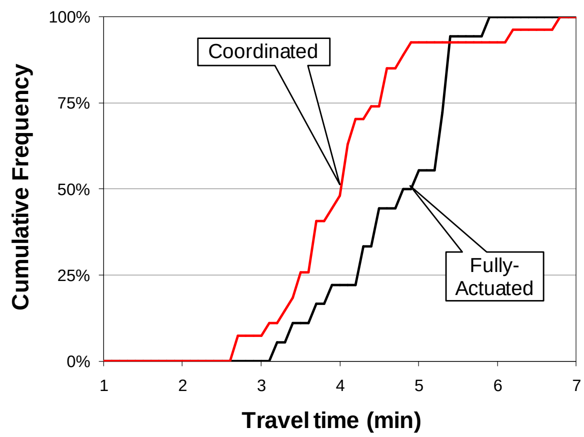
(c) Southbound, Case A to Case B.



(d) Northbound, Case B to Case A.

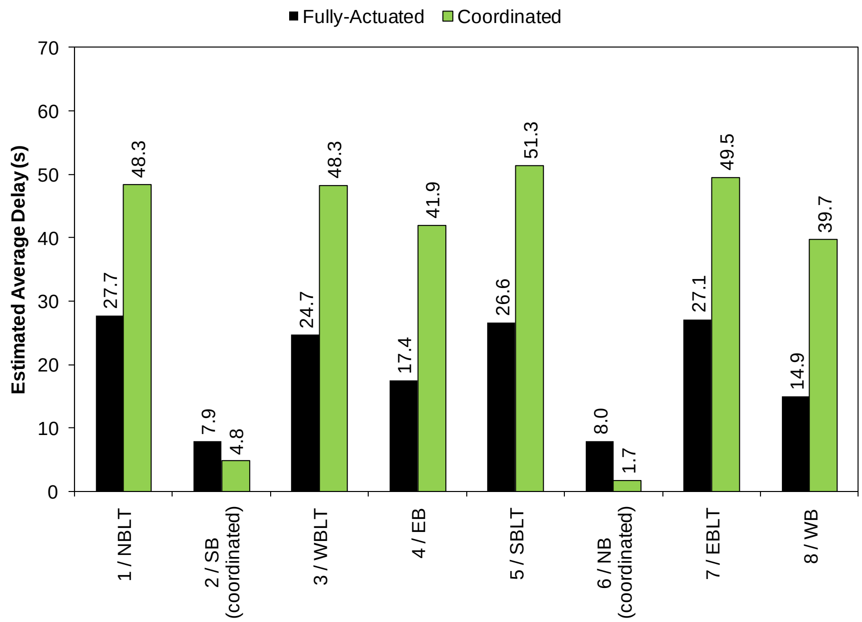


(e) Southbound, Case B to Case C.

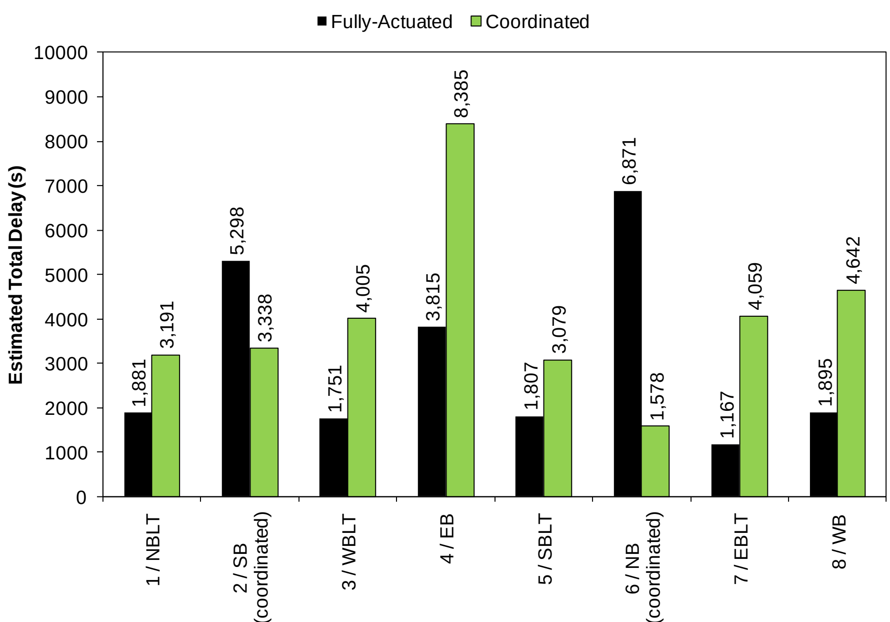


(f) Northbound, Case C to Case B.

Figure 11: Cumulative frequency diagrams of probe vehicle travel time (minutes).



(a) Average Delay



(b) Total Delay

Figure 12: Estimated HCM delay by movement at Int. 6.