Lyles School of Civil Engineering Faculty Publications

Lyles School of Civil Engineering

11-15-2016

Investigation of Self-Organizing Traffic Signal Control with Graphical Signal Performance Measures

Christopher M. Day

Darcy M. Bullock

Investigation of Self-Organizing Traffic Signal Control with Graphical Signal Performance Measures

Christopher M. Day*
Purdue University
550 Stadium Mall Drive
West Lafayette, IN 47906
(765) 494-9601
cmday@purdue.edu

Darcy M. Bullock
Purdue University
550 Stadium Mall Drive
West Lafayette, IN 47906
(765) 494-2226
darcy@purdue.edu

*Corresponding author.

Word Count: 4746 words + 11 * 250 words/(figure-table) = **7496** words

November 15, 2016

ABSTRACT

Adaptive signal control is the subject of an increasing amount of research, as well as development and implementation. Most existing adaptive control systems achieve coordination by applying system control as a constraining layer on top of local control. Some researchers have suggested that, with the right local-control logic, coordination might be achieved as an dynamically emergent phenomenon without the need for a management layer. This paper explores the potential of a self-organizing signal control algorithm using a variety of performance measures. First, the initially reported algorithm performance is reproduced in an idealized environment; next, the algorithm is applied in a realistic road network to compare its performance against actuated-coordinated control, with and without pedestrian phases. Comparisons are made under (1) the same base volumes used to design the actuated-coordinated timing plan; and (2) a variant volume. Self-organizing control is found to be more flexible than coordinated control, and induces a tradeoff in performance among different movement types. Delay reductions of 38–56% are seen in an environment without pedestrian phases. However, with pedestrian phases in recall, self-organizing control performs worse (39% increase in delay) under base volumes, and achieves a weak benefit (6% reduction in delay) under the variant volume. Because of the large total delay reductions in some scenarios, the results show promise for future development.

keywords: *traffic signals, adaptive control, self-organization, performance measures*

INTRODUCTION

Over the years, numerous methods have been proposed to make traffic signal operation more responsive to dynamically changing traffic conditions. Some early efforts were made with analog computing (*1*). The first "computer control" method was proposed in 1963 (*2*). Early methods sought to base phase-switching decisions on traffic engineering variables such as delay, rather than detector occupancy or passage timers; most of these studies focused on isolated intersections. In the UK, a system called Microprocessor Optimized Vehicle Actuation (MOVA) (*3*) has seen numerous deployments.

These isolated-intersection algorithms react to the real-time traffic conditions without imposing patterns by design. However, coordinated control of multiple intersections is more complex. Most adaptive control systems employ some mechanism that constrains local intersection control to create a progressive pattern.

- *Urban Traffic Control System (UTCS) Project.* This 1960s-1970s project explored real-time control under a variety of traffic schemes (*4*): SOLIS (Signal Optimization using Link Signatures) for low-volume traffic, CYRANO (Cycle-Free Responsive Algorithm for Network Optimization) CYRANO for moderate-volume traffic, and CIC (Critical Intersection Control) for high-volume traffic. The initial results generally did not exhibit marked improvement against conventional control.
- *Cycle/Offset/Split-Adaptive systems.* SCOOT (Split, Cycle, and Offset Optimization Technique) and SCATS (Sydney Coordinated Adaptive Traffic System) retain the Cycle/Offset/Split (COS) paradigm, with adaptive adjustments of pattern settings, and other dynamic decisions such as determining when to coordinate intersections. ACS-Lite operates in a similar manner (*5*).
- *Real-Time adaptive systems.* OPAC (Optimization Policies for Adaptive Control), RHODES (Real-Time Hierarchical Optimized Distributed Effective System), and InSync eliminate the COS scheme with real-time optimization of phase times. In OPAC, a "virtual cycle length" is used to coordinate multiple intersections, while RHODES tracks platoons and mitigates conflicts. InSync achieves coordination with "tunnels" that repeat within a "period length" (*5*).

In recent years, some studies have shown that coordination is possible *without* system-level control. Instead, given an appropriate local control algorithm, intersections can *self-organize*, and achieve coordination as a natural, dynamic consequence of local control. Gershenson published a paper in 2005 that was the first to suggest this possibility (*6*), and demonstrated it with a proposed algorithm. A similar control philosophy was proposed by Lammer and Helbing (*7*). More recently, Cesme and Furth examined whether self-organizing control could be implemented by adding new methods of phase extension to fully-actuated control (*8,9*), while Xie et al. proposed a self-scheduling method based on identifying inbound platoons (*10*).

This paper explores self-organizing control through application of both simulation metrics such as delay, and signal performance measures (SPMs) based on high-resolution data (*11,12*). The algorithm of Gershenson is investigated in this study because it has received considerable attention. First, the initial results are reproduced in an idealized network. Next, the algorithm is implemented in a more realistic scenario to compare its performance with actuated-coordinated control. This study offers an example of how SPMs can be used to better understand how novel signal control algorithms operate.

SELF-ORGANIZING CONTROL LOGIC

Original Description of the Algorithm

The initial report of “self-organizing traffic lights” (SOTL) achieved much improved performance as compared to methods that approximated conventional signal timing (*6*). Animations of SOTL showed that traffic patterns would tend to converge, forming vehicles into platoons that would almost always be progressed on every approach in the network.

The SOTL algorithm consists of the following steps, which are paraphrased as follows:

1. Measure the number of vehicles (N_ϕ) approaching the intersection for each phase ϕ, within two defined distances: a longer distance d, and a shorter distance r.
2. Do not terminate the current phase if its green time is less than the minimum green.
3. If there are vehicles within r on the current phase (*i.e.*, if there are vehicles crossing the intersection), do not terminate the current phase.
4. If N_ϕ exceeds a threshold value n on a phase that is red, terminate the current phase and begin serving the other phase.
5. If no vehicles are approaching the current phase (within d), and there are any vehicles on an approach controlled by another phase (within d), terminate the current phase.
6. If there is a downstream blockage on the current phase, then terminate it.
7. If every downstream approach is blocked, rest in red until one opens.

Interestingly, most of these steps have parallels in existing signal control logic. The minimum green requirement of step two is universal. The third step is roughly equivalent to vehicle extension with stop bar detection. The fifth step is similar to the operation of SOLIS (*4*). Termination in event of downstream blockage was explored during NCHRP 3-66 (*13*). The fourth step introduces a decision for phase-switching that does not have immediate parallels. Although added initial timing accumulates green time based on an upstream detector, the counter value itself does not play a role in the termination of another phase in service.

It should be noted that the initial results published by Gershenson (*6*) may have largely resulted from the idealized test environment, as subsequent researchers have observed (*8,9*). The initial study network had equally spaced intersections, a single lane on every approach, no turning traffic, and a grid of streets that “wrapped around” so that traffic disappearing off of the left side of the screen re-appeared on the right side, enabling traffic patterns to converge. Readers who have played the classic video game *Asteroids* would recognize this toroidal world shape. However, positive results were reported under somewhat more realistic tests (*14,15*).

Implementation in a VISSIM Environment

To test the effectiveness of self-organizing control, the algorithm was coded in VISSIM using the external controller API.

Several interpretations of the original algorithm were necessary. First, detector distances d and r had to be defined. The original study used a cellular automata simulation with units of “cells”. In VISSIM, physical distances are needed, so feasible real-world detector distances were adopted. A typical setback detector distance for dilemma zone detection (5 seconds travel time from the stop bar) served as d. A distance of 100 ft (30 m) was used for r. This was intended to roughly approximate a 50-60 ft (15–18 m) stop bar with a 3-second passage time.

Borrowing MOVA’s nomenclature (*3*), the detectors at d and r were respectively named the “IN” and “X” detectors. Each phase was given a corresponding count, $N_{\phi,\mathrm{IN}}$ and $N_{\phi,\mathrm{X}}$, for approaching and crossing traffic. The counters were incremented when vehicles crossed the relevant detector, and decremented when vehicles departed from a third “exit” detector at the stop bar. A fourth detector was added beyond the intersection to measure downstream blockages at distance e. The detector layout is shown in Figure 1. Note that the vehicles are counted on a per-approach basis rather than a per-lane basis, so the left-turn lane does not require a separate IN detector.

This configuration was intended to faithfully reproduce the original algorithm’s vehicle counting philosophy. Real-world field detection may vary considerably. The simple increment and decrement of counters might not be sufficient in a real-world scenario, because of driveways, detector errors, and other considerations. These are topics for further research that would need to precede actual field deployment.

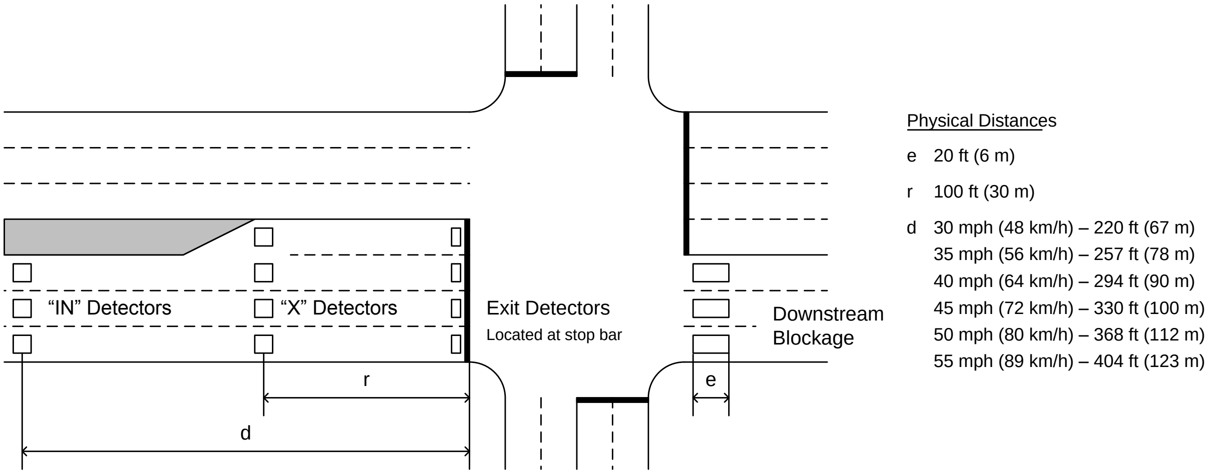


Figure 1. Detector layout used for self-organizing control in VISSIM.

Next, the phase-switching logic was coded. First, it was imperative that minimum greens would be served. Pedestrian walk and clearance phases were also added. After the end of all minimum green and pedestrian intervals, the controller would enter a green extension state for the current phase, with the termination decision controlled by the self-organizing logic.

During green extension, five test conditions were continually checked based on the counter values. The following description references the current phase ($\phi = \mathrm{G}$) and the conflicting phase, currently red ($\phi = \mathrm{R}$).

1. Are there *m* or fewer vehicles crossing the intersection ($N_{\mathrm{G,X}} \leq m$)?
2. Is the number of vehicles approaching the conflict phase greater than the number of vehicles approaching the current phase, beyond a threshold ($N_{\mathrm{R,IN}} > N_{\mathrm{G,IN}} \times h$)?
3. Are there *no* vehicles approaching the current phase, but *any* vehicles approaching the conflict phase ($N_{\mathrm{G,IN}} = 0$ and $N_{\mathrm{R,IN}} > 0$)?
4. Is the current phase exit path blocked, but the other phase is not blocked (have all downstream detectors each been continuously occupied for longer than 10 seconds)?
5. Has the green been extended beyond a maximum value while vehicles are waiting on the conflict phase?

The current phase would be terminated if condition 1 and 2 were both true, or if any of conditions 3, 4, or 5 were true.

When $m = 0$, the first condition is largely equivalent to simple gap-out logic—if *any* vehicles are “crossing” the intersection, the phase will be extended.

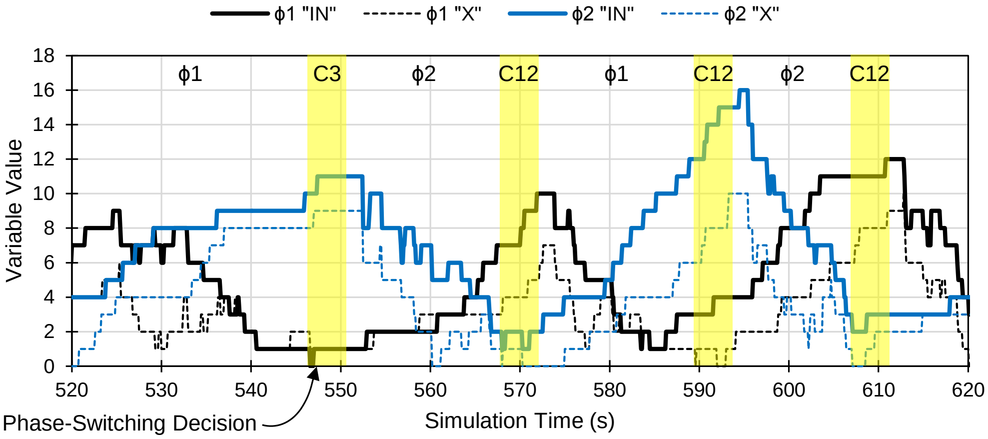
The second condition is slightly modified from step 4 of the original logic. Rather than a static switching threshold value *n*, the switching decision examines whether there is more traffic approaching the conflicting phase than the current phase in service—plus a hysteresis value *h* to avoid excessive switching if the demand for both phases is similar.

The fifth condition was added because no real-world implementation would be complete without it—it is unconscionable to design an algorithm that could potentially leave a single vehicle or pedestrian waiting indefinitely. This is equivalent to the maximum timer in fully-actuated control.

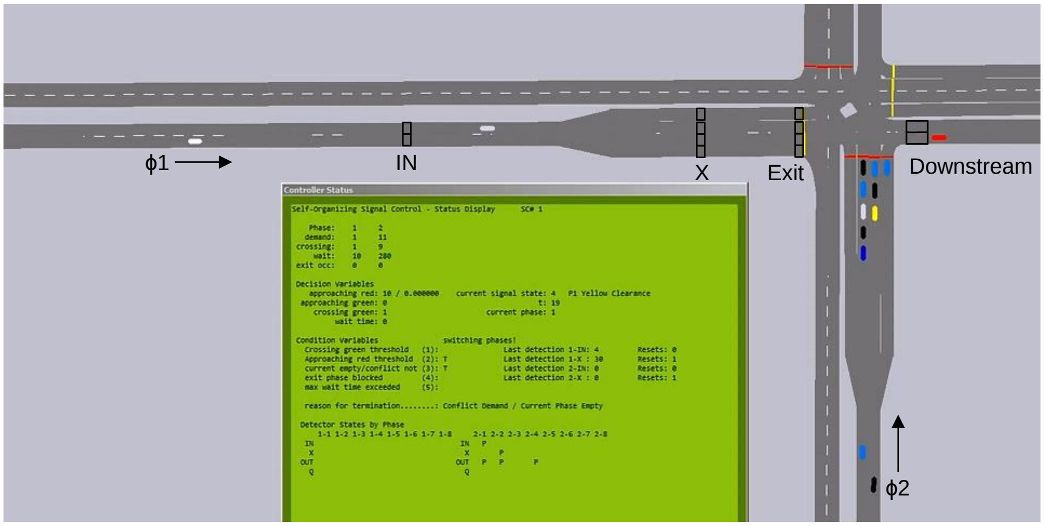
Although the above logic is written for a two-phase scenario, others have applied the algorithm to multiple phases in a single ring (*15*). Extension to a multiple-*ring* decision (*i.e.*, with asynchronous opposing left turns) is another topic for future development.

Figure 2 illustrates the operation of self-organizing logic, showing the states of the “IN” and “X” counter variables for two phases (Figure 2a) along with the phase currently in service and phase-switching transitions. The change periods are labeled as “C3” indicating that condition 3 was true, and “C12” indicating that condition 1 and 2 were both true. Figure 2b and Figure 2c respectively show simulation screenshots corresponding to the first and second phase-switching decisions.

(a) Internal Variables and Phase States Over Time

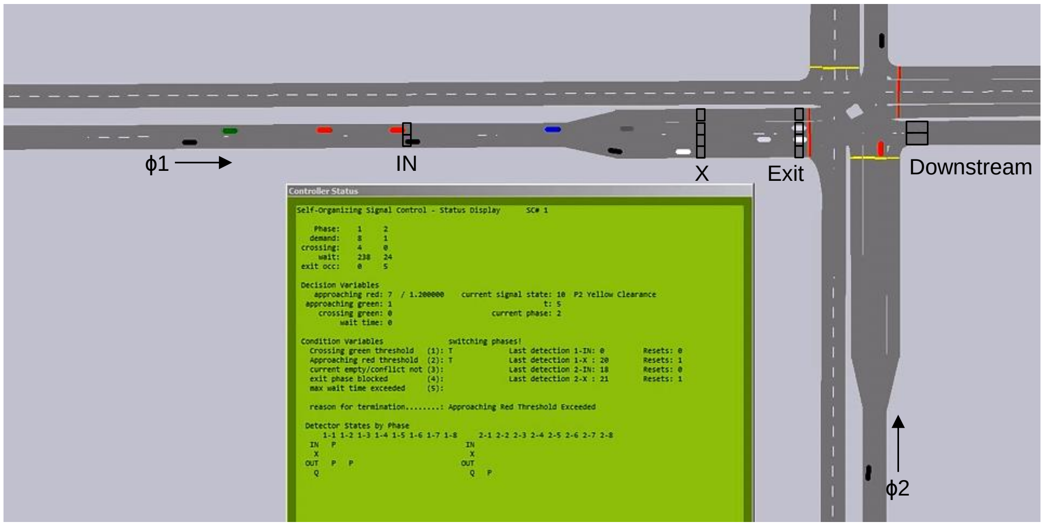


(b) View of System at 547 Seconds



```
Self-Organizing Signal Control - Status Display      SC# 1

   Phase:    1     2
  demand:    1     11
crossing:    1     9
    wait:    10    280
exit occ:    0     0

Decision Variables
   approaching red: 10 / 0.000000    current signal state: 4   P1 Yellow Clearance
 approaching green: 0                                   t: 19
    crossing green: 1                       current phase: 1
         wait time: 0

Condition Variables                switching phases!
  Crossing green threshold   (1):              Last detection 1-IN: 4        Resets: 0
  Approaching red threshold  (2): T            Last detection 1-X : 30       Resets: 1
  current empty/conflict not (3): T            Last detection 2-IN: 0        Resets: 0
  exit phase blocked         (4):              Last detection 2-X : 0        Resets: 1
  max wait time exceeded     (5):

  reason for termination........: Conflict Demand / Current Phase Empty

 Detector States by Phase
    1-1 1-2 1-3 1-4 1-5 1-6 1-7 1-8     2-1 2-2 2-3 2-4 2-5 2-6 2-7 2-8
  IN                                 IN  P
   X                                  X      P
 OUT                                OUT  P   P       P
   Q                                  Q
```

(c) View of System at 568 Seconds



```
Self-Organizing Signal Control - Status Display      SC# 1

   Phase:    1     2
  demand:    8     1
crossing:    4     0
    wait:    238   24
exit occ:    0     5

Decision Variables
   approaching red: 7  / 1.200000    current signal state: 10  P2 Yellow Clearance
 approaching green: 1                                   t: 5
    crossing green: 0                       current phase: 2
         wait time: 0

Condition Variables                switching phases!
  Crossing green threshold   (1): T            Last detection 1-IN: 0        Resets: 0
  Approaching red threshold  (2): T            Last detection 1-X : 20       Resets: 1
  current empty/conflict not (3):              Last detection 2-IN: 18       Resets: 0
  exit phase blocked         (4):              Last detection 2-X : 21       Resets: 1
  max wait time exceeded     (5):

  reason for termination........: Approaching Red Threshold Exceeded

 Detector States by Phase
    1-1 1-2 1-3 1-4 1-5 1-6 1-7 1-8     2-1 2-2 2-3 2-4 2-5 2-6 2-7 2-8
  IN P                               IN
   X                                  X
 OUT P   P                          OUT
   Q                                  Q  P
```

Figure 2. View of the internal logic of self-organizing control in operation. Detector locations are displayed on the eastbound approach for Phase 1.

REPRODUCING THE ORIGINAL RESULTS

Gershenson's initial study of self-organizing control used a highly idealized network, as well as a custom-built simulator. To determine the degree to which the simulation contributed to the results, this study first attempted to reproduce those results in VISSIM. To create a network where platoons are recycled into the system, a "pseudo-toroidal" network was created, as illustrated in Figure 3.

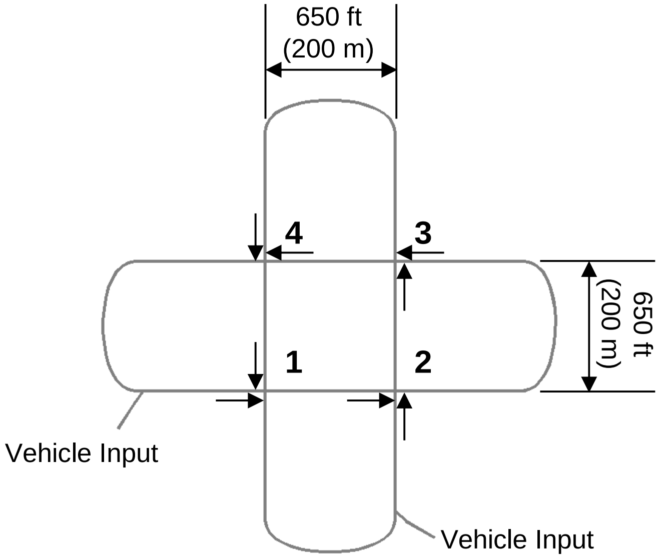


Figure 3. Pseudo-toroidal network.

Two vehicle inputs generated 400 veh/h during the first 400 seconds of simulation time, placing approximately 44 vehicles on each roadway. Vehicle speeds were uniformly distributed between 27–33 mph (43–53 km/h), and the vehicle stream consisted entirely of passenger cars. The vehicles could not exit the network and there were no turns at the intersections. This was intended to approximate the reported test conditions of the initial study (*6*).

In addition to self-organizing control, fully-actuated (non-coordinated) control was tested for comparison. For this, virtual Econolite ASC/3 controllers were used. Advance detectors were placed at 220 ft (67 m), and applied a 5-second extension. Additionally, 50 ft (16 m) stop bar detectors were used, with a 3-second extension.

For self-organizing control, the parameters $m = 0$ and $h = 1.2$ were used. For both self-organizing and fully-actuated control, a yellow clearance of 3 seconds, red clearance of 1 second, minimum green of 5 seconds, and maximum green of 35 seconds were used.

During simulation, after an initial warm-up period, traffic patterns tended to become similar to those reported by Gershenson (*6*). Interestingly, a similar pattern (albeit with poorer arrival characteristics) was observed using fully-actuated control. Figure 4 illustrates these conditions using a combination of time-space diagrams and a visualization called the Purdue Coordination Diagram (PCD) (*16*). The PCD visually indicates the quality of progression by displaying individual vehicle arrival times (dots) relative to green (shaded region). Platoons are indicated by clusters of dots. Ideal progression is typified by clusters of dots in the green shaded region.

Figure 4 illustrates conditions the horizontal loop roadway for self-organizing control (Figure 4a–e) and fully-actuated control (Figure 4f–j). After 300 seconds, traffic patterns converge to a mostly stable pattern.

- Under self-organizing control, the vehicles are nearly always progressed on every approach. The trajectory lines become mostly straight in the time space diagram (Figure 4a), while in the PCDs, the dots lie within the green-shaded region (Figure 4b–e).
- Under fully-actuated control, a stable pattern forms, but the time space diagram exhibits recurring bends (Figure 4b) and the PCDs show platoons arriving on red at Int. 2 and Int. 4 (Figure 4i, Figure 4g), indicated by dots in the unshaded region below the green line.

Although self-organizing control achieves better coordination, a recurring pattern occurs under both types of control. This convergence likely results from channeling outflowing traffic back into the network. These results demonstrate that Gershenson's results can be produced in VISSIM, and also that they might be closely tied to the network topology. In the next section, the algorithm is applied to a more realistic scenario with non-recycling traffic.

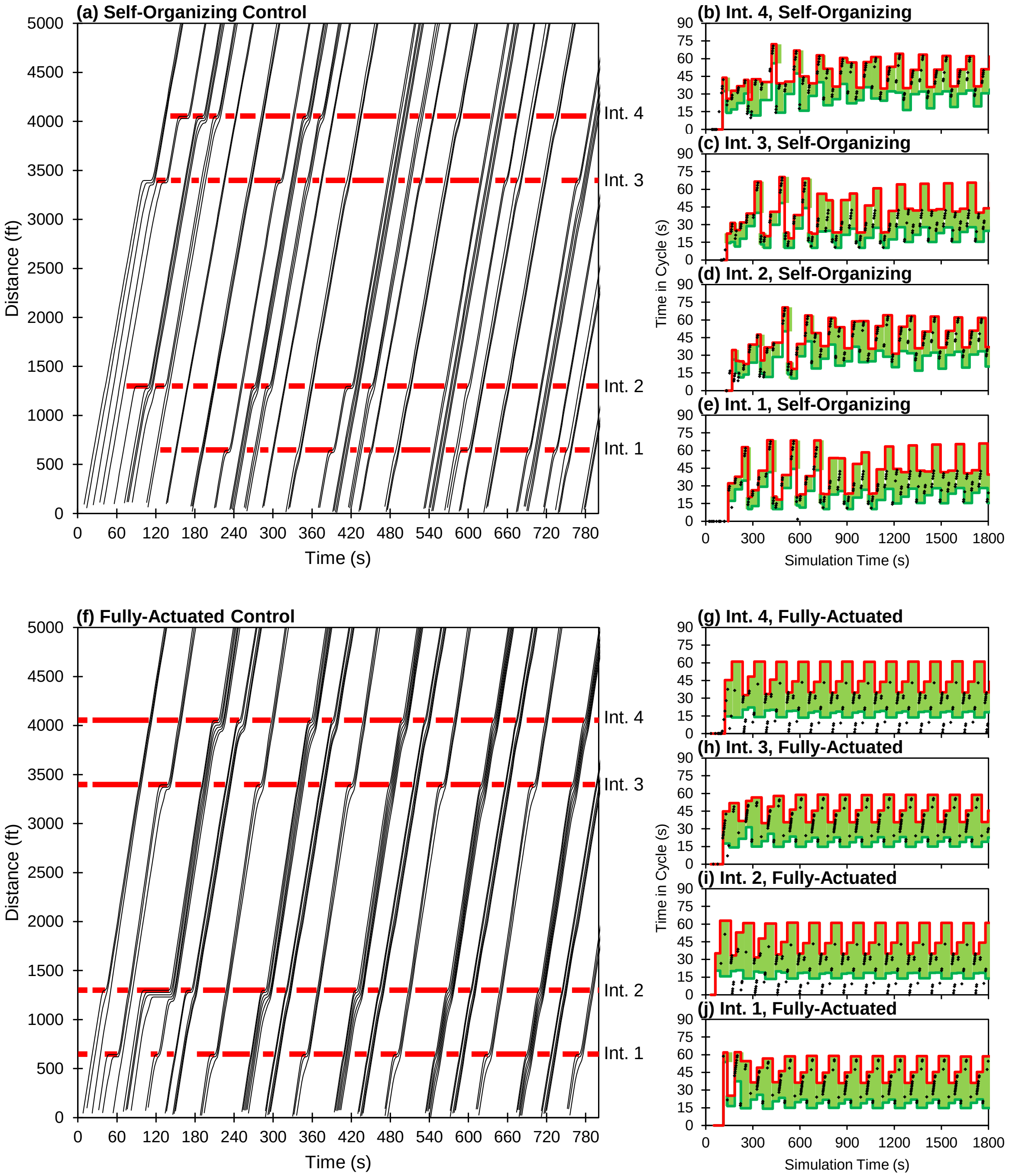


Figure 4. Time-space diagrams and Purdue Coordination Diagrams (PCDs) comparing operation of self-organizing and fully-actuated control in a pseudo-toroidal network.

IMPLEMENTATION IN A MORE REALISTIC NETWORK

Many different test conditions can be imagined for signal control. This study presents a grid-type network in a central business district (CBD) area because it is more congruent with two-phase operation than a high-speed arterial with left-turn phases.

Figure 5 shows a map of the test network, with two different volume scenarios: base volumes (Figure 5a) and variant volumes (Figure 5b). All intersections are two phase. The east-west streets are two-way, while the north-south streets are mostly one-way. The geometry is based on a portion of the CBD of Anderson, Indiana. The grid is semi-regular, but traffic includes many turning vehicles and lane configurations are diverse.

Traffic consisted of 98% passenger cars and 2% trucks. Vehicle speeds were uniformly distributed between 29–35 mph (47–56 km/h). Pedestrian times included a 4-second walk time and pedestrian clearance times were set using a crossing speed of 3.5 ft/s (1.07 m/s).

Two coordinated timing plans were developed in Synchro using initial volumes (Figure 5a), for actuated-coordinated control with and without pedestrians, as shown in Table 1. Phases were actuated using 50-ft stop bar detection on all phases, with 2-second times. Lane-by-lane detection and early yield (*17*) were both used. East-west phases were coordinated. Self-organizing control used the same parameters and detector layout as described earlier.

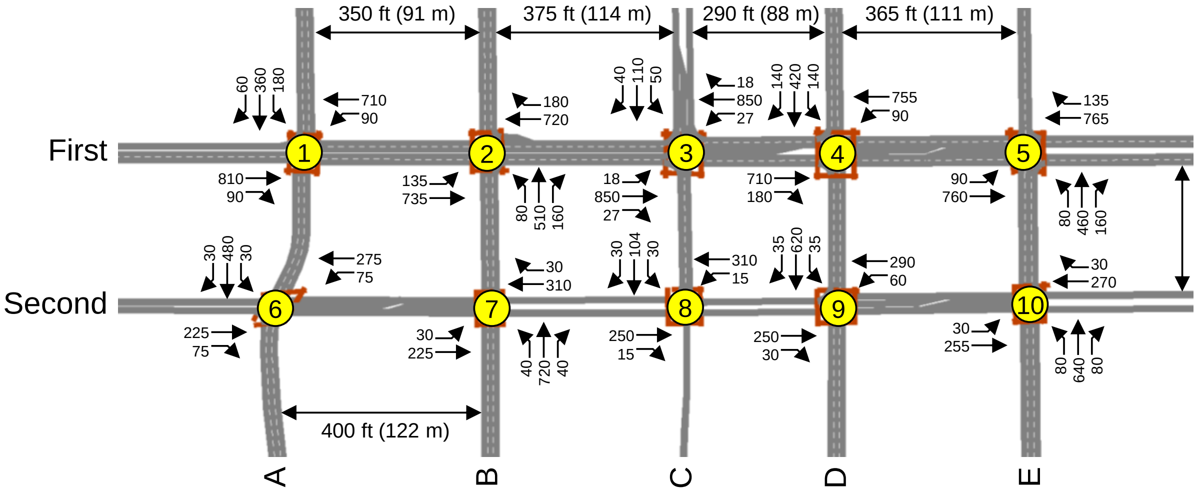
Eight scenarios were simulated:

1-A. Base volumes, actuated-coordinated, no pedestrians
1-S. Base volumes, self-organizing, no pedestrians
2-A. Base volumes, actuated-coordinated, ped recall
2-S. Base volumes, self-organizing, ped recall
3-A. Variant volumes, actuated-coordinated, no pedestrians
3-S. Variant volumes, self-organizing, no pedestrians
4-A. Variant volumes, actuated-coordinated, ped recall
4-S. Variant volumes, self-organizing, ped recall

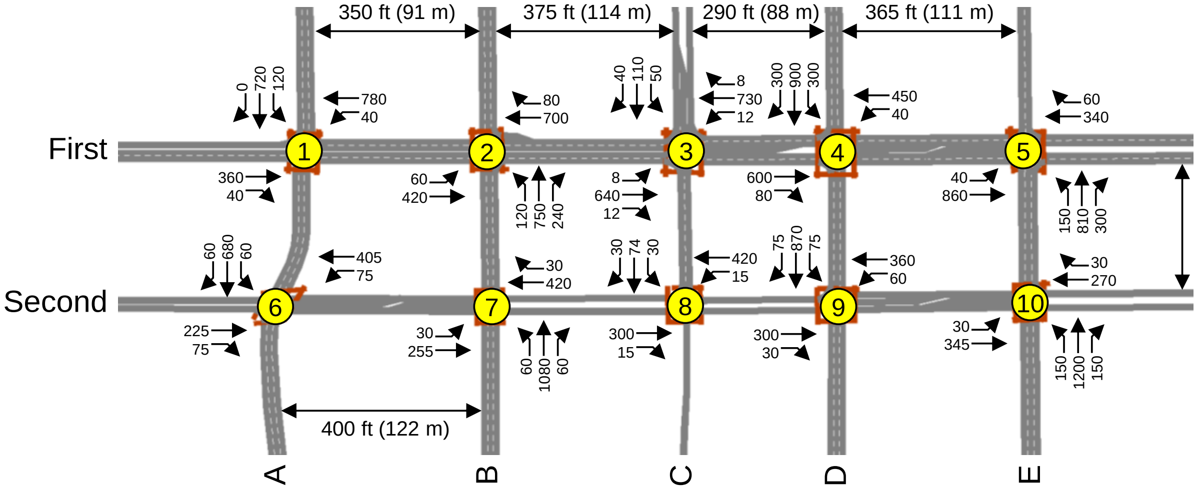
The no-pedestrian scenarios were intended to provide a comparison in a similar spirit to previous studies, while the ped recall scenarios were intended to give an upper-level boundary case for showing the impact of pedestrians. Ped recall is common in CBD areas during business hours in particular, and pedestrian performance is commonly prioritized over vehicular progression. For self-organizing control with pedestrian recall, each green interval was accompanied by walk and ped clearance intervals, effectively increasing the minimum green. The phase control logic was otherwise unchanged.

The base volume scenarios directly compared self-organizing control with an optimized signal timing plan. However, perhaps the main reason to use adaptive control is to handle unexpected conditions. The variant volume scenarios were tested to explore this. These were created by generally reducing east-west volumes and increasing north-south volumes.

Ten simulation runs were executed for each scenario. Each lasted for 1 hour of simulation time, with a 10-minute seeding period.



(a) Base volumes.



(b) Variant volumes.

Figure 5. Central business district network showing distances and turning movement counts in veh/h.

Table 1. Actuated-coordinated timing plans.

	Intersection	Cycle Length (s)	Offset (s)	North-South Split (s)	East-West Split (s)
(a) No pedestrian phases (Scenarios 1-A, 3-A)	1	62	58	42	20
	2	62	0	42	20
	3	62	55	40	22
	4	62	59	41	21
	5	62	1	41	21
	6	62	58	36	26
	7	62	2	34	28
	8	62	58	37	25
	9	62	60	35	27
	10	62	2	42	20
(b) Pedestrian phases in recall (Scenarios 2-A, 4-A)	1	70	65	46	24
	2	70	68	46	24
	3	70	65	43	27
	4	70	66	45	25
	5	70	68	45	25
	6	70	68	39	31
	7	70	0	38	32
	8	70	64	41	29
	9	70	0	38	32
	10	70	0	37	33

RESULTS

Total Delay

Figure 6 shows the amount of total system delay for all eight scenarios. Delay is segmented by movement type, while numbers indicate the total values and the change induced by implementing self-organizing control.

Actuated-coordinated control favored east-west progression. Self-organizing control consistently increased delay on the east-west movements, while decreasing it for the north-south movements. The net benefit was very different depending on whether pedestrian phases were in use. Without pedestrian phases, self-organizing control reduced overall total delay by 38% under the baseline volumes (scenario 1-S), and 56% under variant volumes (scenario 3-S). However, with pedestrian phases are in recall, total delay *increased* by 39% under the baseline volumes (scenario 2-S), while it decreased only 6% with variant volumes (scenario 4-S).

Without pedestrians, delay reductions likely resulted from the flexibility arising from removal of the cycle length constraint. That flexibility was reduced by the lengthening of phase durations with pedestrian phases in recall.

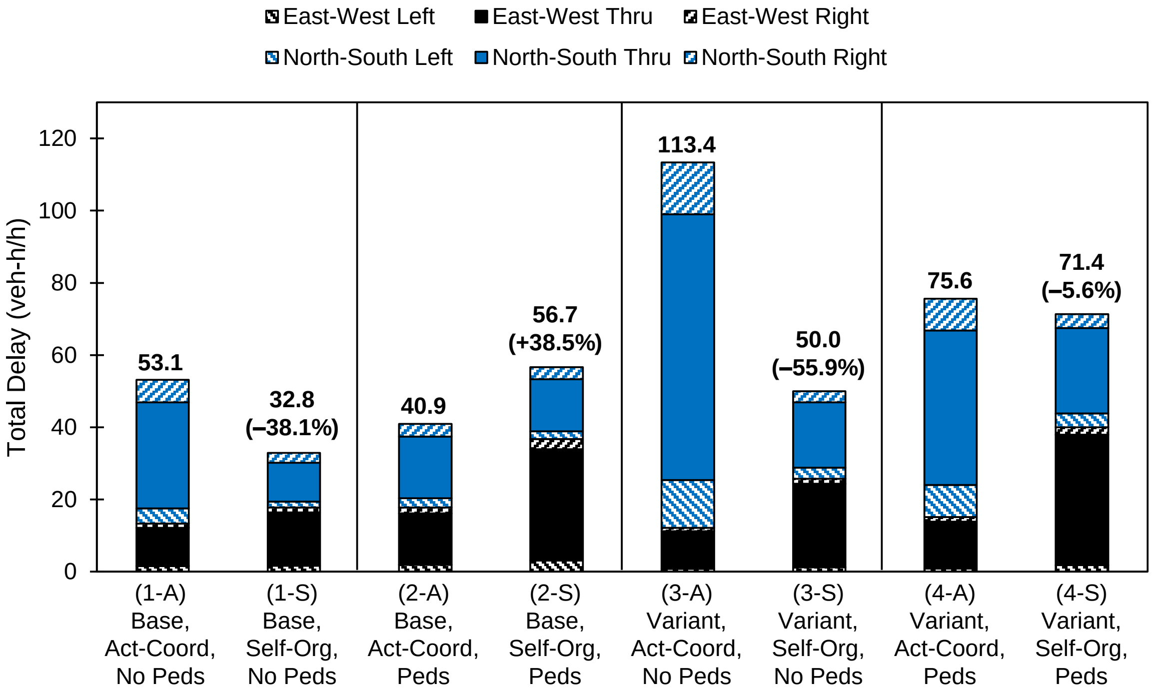


Figure 6. Total delay (veh/h) by scenario and movement type, with percent changes shown for each Actuated-Coordinated (Act-Coord) versus Self-Organizing (Self-Org) comparison pair.

Travel Time for Selected Routes

Travel times along the east-west and north-south routes were examined by tabulating the distributions of travel time for each. Figure 7 shows cumulative frequency diagrams (CFDs) for the four comparison pairs for two representative routes: eastbound traffic on “First” St. (Figure 7a) and southbound traffic on “D” St (Figure 7b). The CFDs compare travel time distributions under self-organizing with actuated-coordinated control. The change in median travel times are indicated by the arrows.

Travel time CFDs on signalized roadways tend to have plateaus that result from stopping at traffic signals. Vehicles that are stopped generally remain stopped for the duration of red. If red times are consistent, and a substantial amount of traffic is stopped, the distribution can take on an additional mode for each location where vehicles are stopped. In all eight CFDs, these plateaus disappeared under self-organizing control, because there was no longer a fixed cycle length.

Eastbound travel times always increased (Figure 7c,e,g,i), with a greater increase occurring with pedestrian phases. However, some of the southbound travel time CFDs (Figure 7d,f,h,j) exhibit strong improvements. Without pedestrians, the median southbound travel time is reduced from approximately 90 to 20 seconds (Figure 7d,h). With pedestrian phases in recall (Figure 7f,j), the median is not changed but the distribution has lost its plateau because the red times are no longer all about the same duration.

These changes correspond to the reductions in north-south through movement total delay observed in Figure 6, and its increase for the east-west movements. Self-organizing control serves traffic according to real-time demand levels rather than predetermined priority. Those phases that were prioritized under actuated-coordinated control tend to experience worse performance while non-priority phases see an improvement. However, the degree of improvement is substantially less when pedestrian phase are in recall.

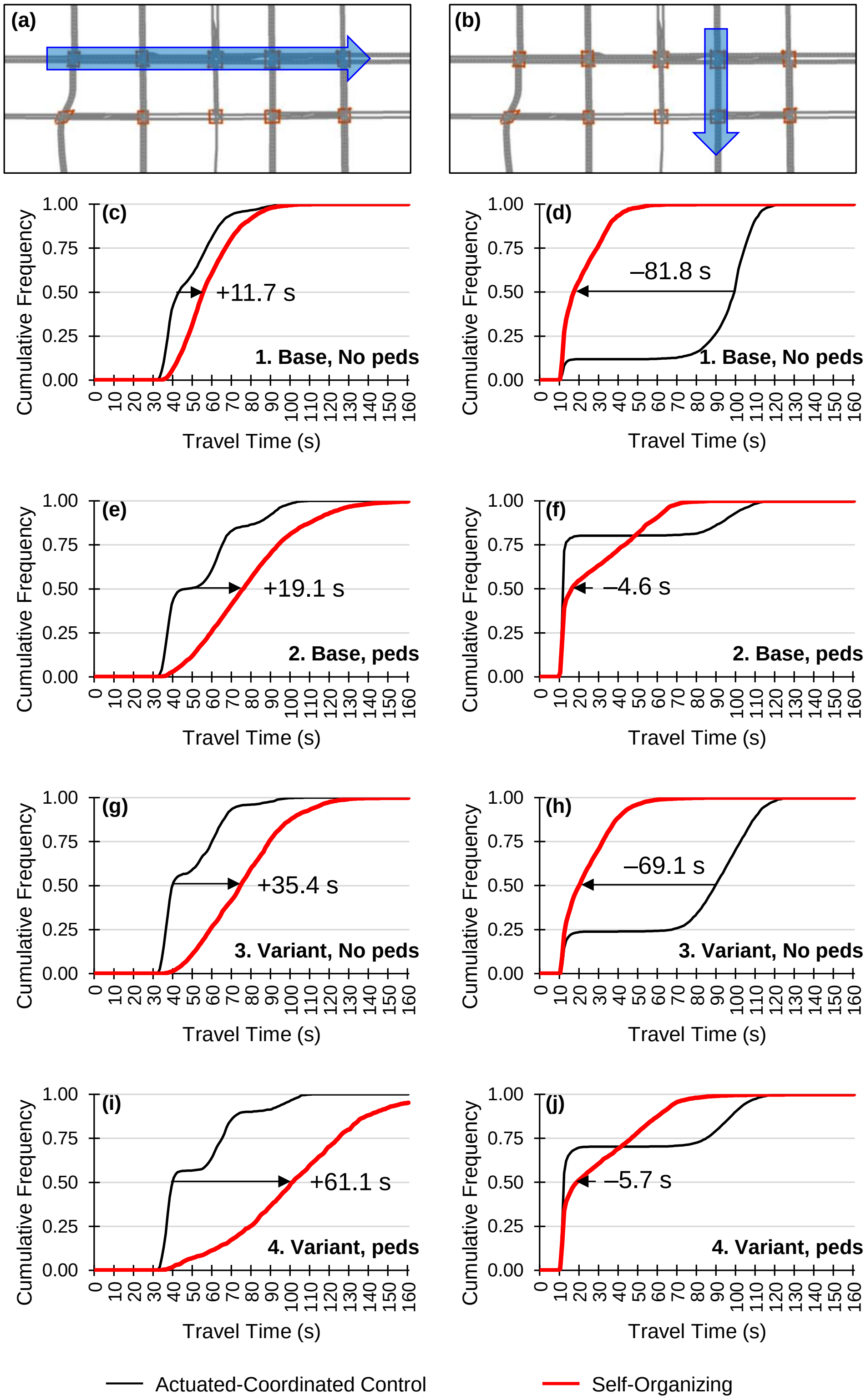


Figure 7. Cumulative frequency diagrams (CFDs) of travel times on two representative routes, comparing actuated-coordinated to self-organizing control for four comparison pairs.

Quality of Progression

The delay and travel time analysis showed that east-west traffic had higher delay and longer travel times while the north-south traffic saw improvements. To understand why, this section examines details of progression using graphical performance measures. There is not enough space in this paper to highlight the performance of every approach in detail, but similar trends were observed on the streets parallel to those movements selected for a close-up look.

The quality of signal progression can be measured by the number of vehicles that arrive on green. Figure 8 repeats the visual analysis in Figure 4 for eastbound traffic on First St, comparing actuated-coordinated control (Figure 8a–e) with self-organizing control (Figure 4f–j). These are shown for base volumes with no pedestrians. The PCDs include the average effective cycle length (C_E), measured as the duration between consecutive ends of green.

- Actuated-coordinated control exhibits cyclic patterns of reds and greens in the time-space diagram (Figure 8a), and roughly equal red and green times in the PCDs (Figure 8b–e). The starts and ends of green vary because of actuation and early yield. Most of the time, good eastbound progression is achieved, as shown by the coincidence of dots with the green bands in the PCDs. In addition to platoons of coordinated traffic, there are also many turning vehicles in the mix.
- Self-organizing control is acyclic and the signals switch more frequently. Cycle lengths are reduced by nearly half. The time-space diagram shows more, shorter red intervals (Figure 8f) while the PCDs show rapid cycling (Figure 8g–j). Despite the lack of a fixed cycle length, many of the eastbound greens capture platoons, such as Int. 3 (Figure 8i) and Int. 4 (Figure 8h), but other are less successful, such as Int. 2 (Figure 8j).

Figure 9 shows the same performance measures for base volumes with pedestrian phases in recall.

- Actuated-coordinated control (Figure 9a–e) exhibits similar characteristics as before. The cycle length is slightly longer, but most eastbound platoons are coincident with green, as indicated by the PCDs (Figure 9b–e). As before, there is a substantial amount of turning traffic joining the platoons.
- Self-organizing control (Figure 9f–j) is again acyclic, but the red and green intervals are much longer with pedestrian phases. Effective cycle lengths are still a few seconds smaller than under actuated-coordinated control. The time-space diagram shows evidence of substantial queuing (Figure 9f), and progression is somewhat haphazard. The PCDs show that during some cycles, platoons are captured in green, while in others they are not. For example, Figure 9g shows just about as many platoons coincident with green (clusters of dots in the green shaded region) as coincident with red (in the unshaded region).

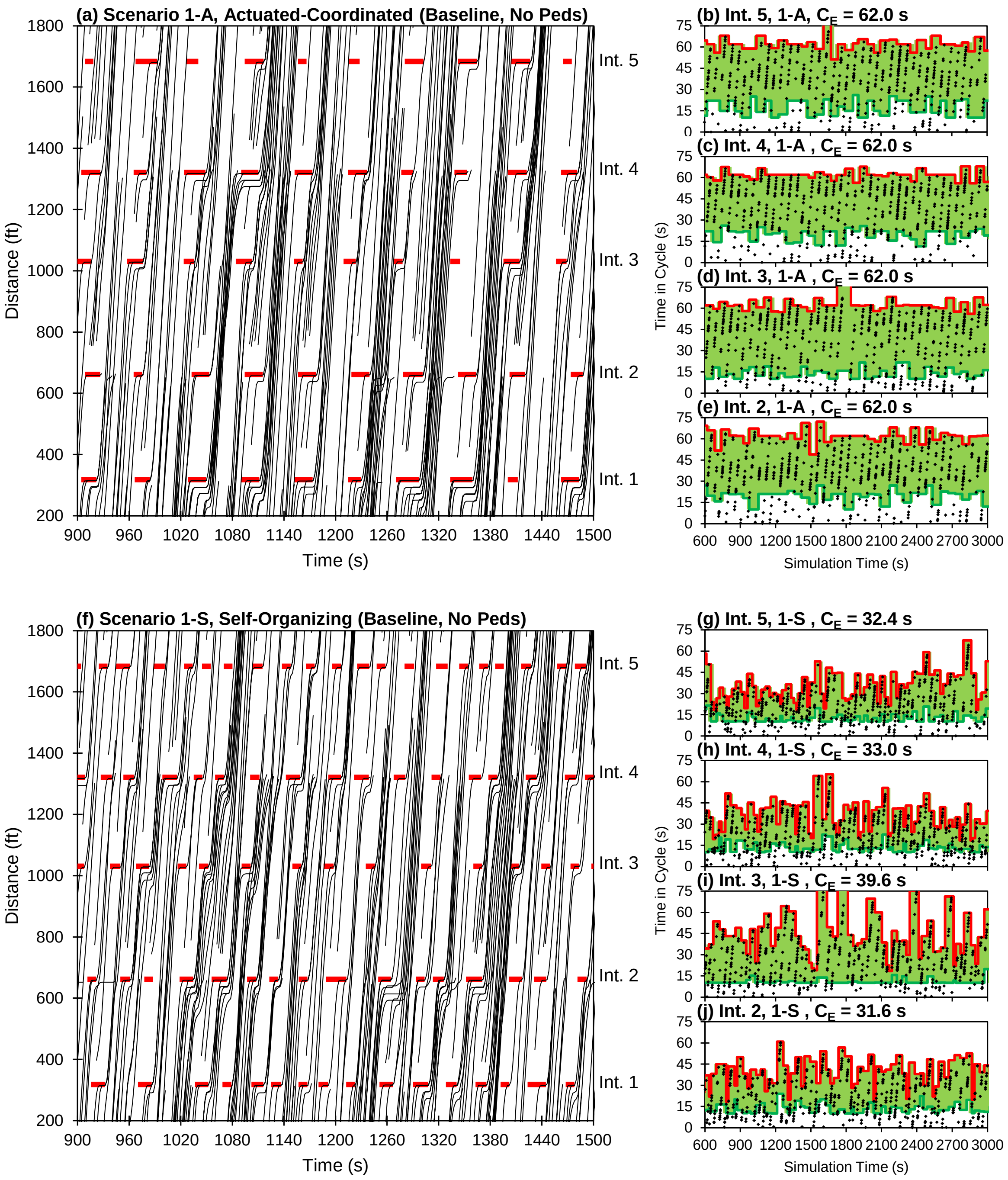


Figure 8. Time-space diagrams and PCDs comparing operation of actuated-coordinated and self-organizing control in a CBD-type network, for eastbound traffic on First St. under Test 1 (Actuated-coordinated versus Self-organizing without pedestrians).
The average effective cycle length in each scenario, C_E, is indicated.

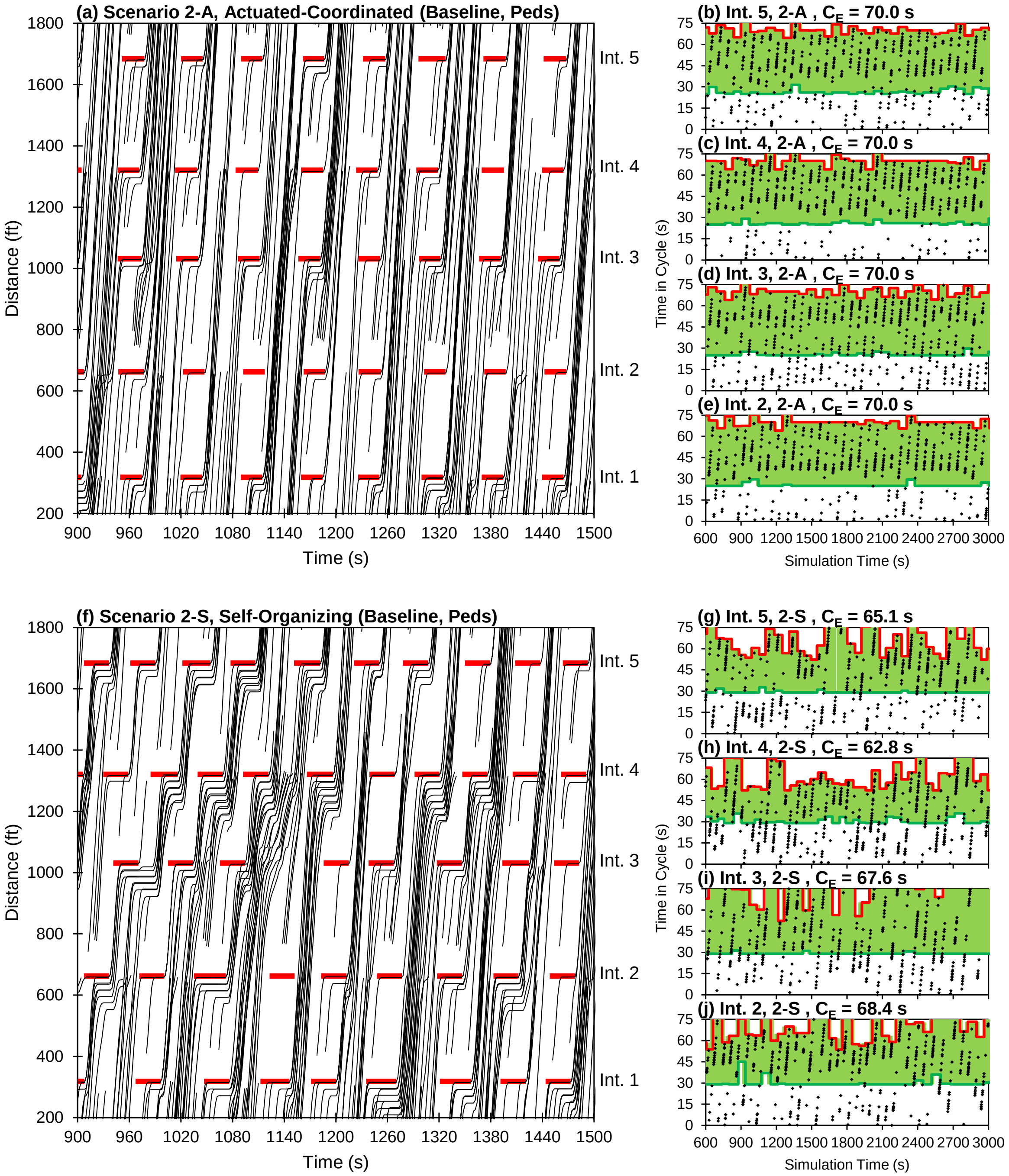
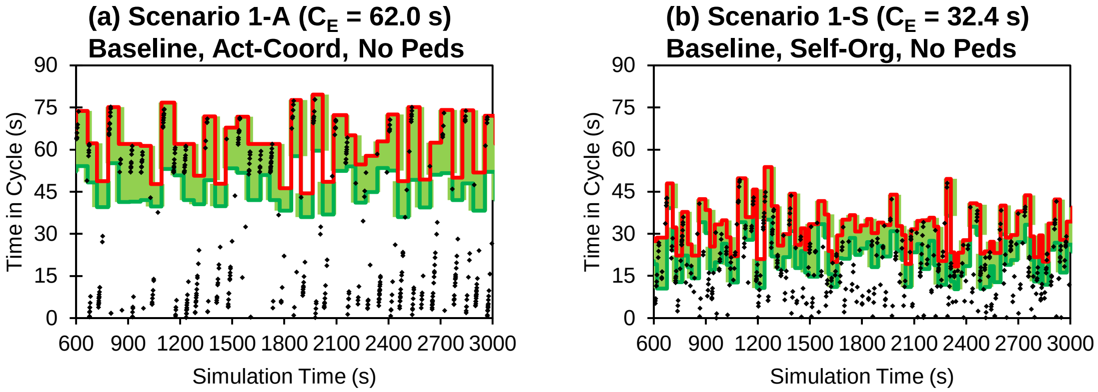


Figure 9. Time-space diagrams and PCDs comparing operation of actuated-coordinated and self-organizing control in a CBD-type network, for eastbound traffic on First St. under Test 2 (Actuated-coordinated versus Self-organizing with pedestrians).
The average effective cycle length in each scenario, C_E, is indicated.

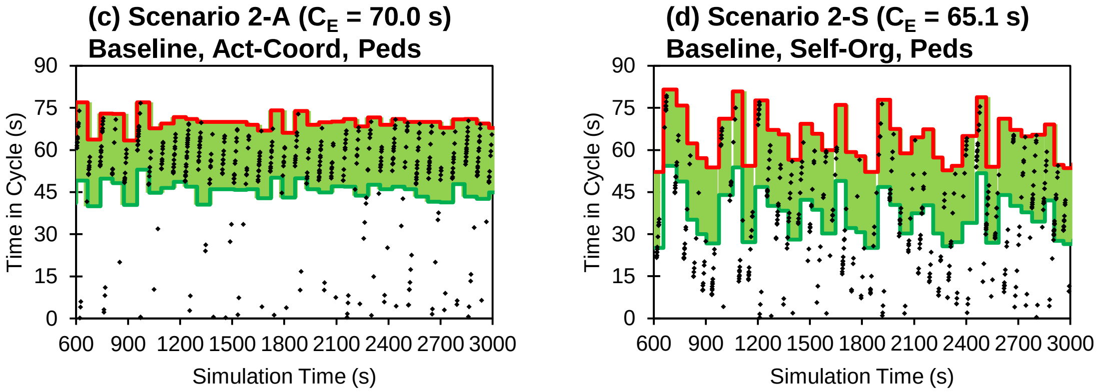
Figure 10 shows PCDs for the northbound approach at Int. 5, to examine the performance of a non-coordinated phase. These are shown for all eight scenarios.

Scenarios 1-A and 3-A (Figure 10a,e) show actuated-coordinated operation without ped phases. The platoons are completely “missed” by the green, which usually gaps out before it can be extended. However, with ped recall, as in scenarios 2-A and 4-A (Figure 10c,g), the green is automatically extended long enough for platoons to arrive. Thus, northbound progression is successful under the base volumes (2-A, Figure 10c), whereas the variant volumes are much higher in the northbound direction and a substantial amount of the platoons are cut off by the end of green (Figure 10g).

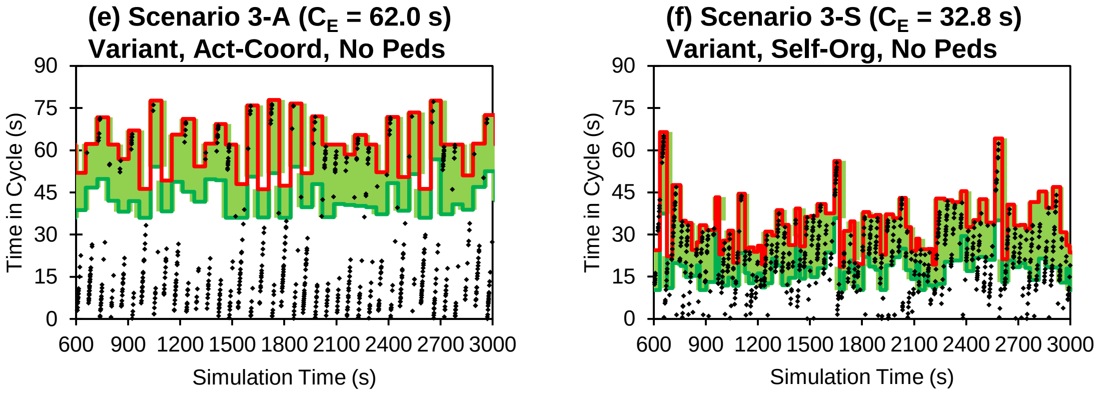
Self-organizing control exhibits improved results for the northbound direction in absence of pedestrian phases. With base volumes (1-S, Figure 10b), there are still many vehicles arriving in red, but the reduced cycle length means they are not delayed as long as under coordination. With variant volumes (3-S, Figure 10f), the higher demand for the northbound movement gives it greater weight in the phase-switching decision, and the algorithm provides excellent progression without a cycle length. With ped recall, the cycle lengths are much higher (similar to actuated-coordinated control, in fact), so the algorithm is unable to provide similar benefits for the lower-volume northbound movement under the base volumes (2-S Figure 10d). This corresponds to the overall increase in total delay seen for the overall network: the loss of coordination increased east-west delay, with few benefits for north-south traffic. However, with the variant volumes, good progression is still achieved during most cycles (4-S, Figure 10h), demonstrating that the arrival-weighted phase-switching logic can still achieve some benefit even under added minimum green constraints.


(a) Scenario 1-A (C_E = 62.0 s)
Baseline, Act-Coord, No Peds

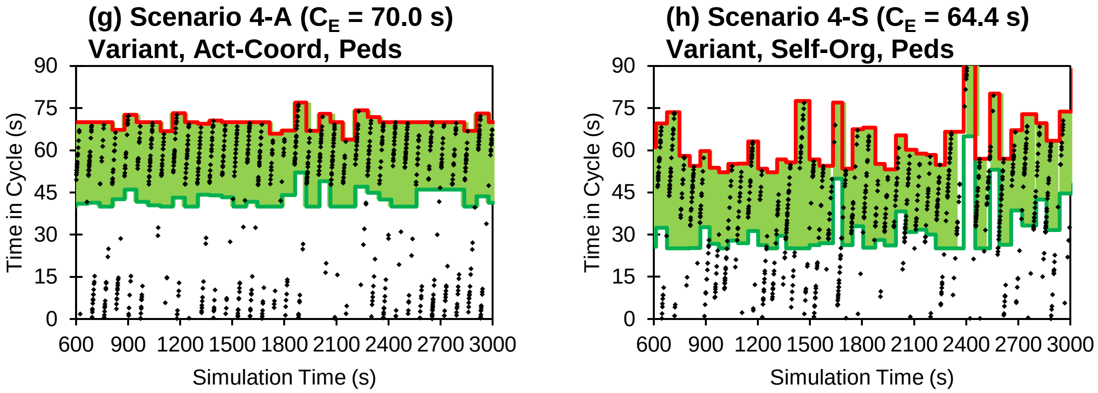
(b) Scenario 1-S (C_E = 32.4 s)
Baseline, Self-Org, No Peds


(c) Scenario 2-A (C_E = 70.0 s)
Baseline, Act-Coord, Peds

(d) Scenario 2-S (C_E = 65.1 s)
Baseline, Self-Org, Peds


(e) Scenario 3-A (C_E = 62.0 s)
Variant, Act-Coord, No Peds

(f) Scenario 3-S (C_E = 32.8 s)
Variant, Self-Org, No Peds


(g) Scenario 4-A (C_E = 70.0 s)
Variant, Act-Coord, Peds

(h) Scenario 4-S (C_E = 64.4 s)
Variant, Self-Org, Peds

Figure 10. PCDs showing operation for the northbound movement at Int. 5. The average effective cycle length in each scenario, C_E, is indicated.

CONCLUSIONS

This paper investigated the potential performance of self-organizing control through a variety of test scenarios. First, the initial results obtained in a cellular automata simulation with recycling traffic were reproduced in VISSIM. Next, the algorithm was tested in a more realistic network under different volume and pedestrian phase conditions, and compared with actuated-coordinated control.

Self-organizing control was found to improve performance of non-coordinated movements, generally decreasing their delay and improving their travel times, while degrading that of coordinated movements. In general, the amount of tradeoff was such that a net benefit was obtained for the network in three out of four test scenarios (Figure 6). Self-organizing control yielded a much greater benefit when no pedestrian phases were included. With pedestrian phases in recall (representing the opposite extreme), total delay increased when compared to an optimized timing plan (base volumes), and only slight improvement occurred when compared to a suboptimal timing plan (variant volumes). Average effective cycle lengths were consistently reduced by self-organizing control, which would generally tend to reduce delays for all modes.

Graphical performance measures (time space diagrams and PCDs) were employed to determine the reasons for these changes. These showed that self-organizing control provided less reliable progression as actuated-coordinated operation along the prioritized routes. This is a consequence of relaxing the timing requirements required by traditional coordination. However, the tradeoff was improved performance for non-coordinated movements. Self-organizing control successfully progressed traffic on those movements (Figure 10d), especially when the volumes on those movements increased (Figure 10h).

These initial results show that the algorithm can yield delay reductions under some scenarios, and would likely be improved by better handling of pedestrian demands. Additional future work might also include incorporating person-based or priority-based weighting of detected vehicles as a means of incorporating transit or freight priority. Future work should explore implementation on signalized arterials, and compare performance against fully-actuated control under a variety of traffic scenarios. For arterials, it would be necessary to extend the algorithm to handle multiple phases in multiple rings.

In closing, a note on the potential for implementation is warranted. The logic for self-organizing control is relatively simple and could easily be incorporated into existing fully-actuated logic. Some others have suggested the use of external units to achieve this with legacy controller models (*18*). However, more recent controller models that feature user-programmable logic could begin running such an algorithm today, by implementing counting variables with setback detection to monitor approach counts, and perhaps by approximating the monitoring of crossing vehicles with passage timers activated by stop bar detection.

ACKNOWLEDGMENTS

This work was supported in part by Joint Transportation Research Program and the Pooled Fund Study (TPF-5(258)) led by the Indiana Department of Transportation (INDOT) and supported by the state transportation agencies of California, Georgia, Kansas, Minnesota, Mississippi, New Hampshire, Pennsylvania, Texas, Utah, and Wisconsin, the Federal Highway Administration Arterial Management Program, and the Chicago Department of Transportation. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation.

REFERENCES

1. Tyack, F.G. “Street Traffic Signals, with Particular Reference to Vehicle Actuation.” IEE Journal, 82, 1938, 125-154.
2. Miller, A.J. “A Computer Control System for Traffic Networks.” Proc., 2nd International Symposium on Traffic Flow Theory and Transportation, 1963, 200-220.
3. Vincent, R.A. and J.R. Pierce. ‘MOVA’: *Traffic Responsive, Self-Optimising Signal Control for Isolated Intersections*. Research Report 170. Crowthorne, Berkshire, UK: Transport and Road Research Laboratory, 1988.
4. Lieberman, E.B. et al. *Variable Cycle Signal Timing Program, Volume 1: Development of Third-Generation Control Policies for the UTCS.* Report FHWA-RD-74, Federal Highway Administration, Washington, D.C., 1974.
5. Stevanovic, A. *Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*. NCHRP Synthesis 403. Transportation Research Board of the National Academies, Washington, D.C., 2010.
6. Gershenson, C. “Self-Organizing Traffic Lights.” Complex Systems, 16, 2005, 29-53.
7. Lämmer, S. and D. Helbing. “Self-Control of Traffic Lights and Vehicle Flows in Urban Road Networks.” Journal of Statistical Mechanics: Theory and Experiment, P04019, 2008.
8. Cesme, B. and P.G. Furth. “Self-Organizing Traffic Signals using Secondary Extension and Dynamic Coordination.” Transportation Research Part C, 48, 2014, 1-15.
9. Cesme, B. and P.G. Furth. “Self-Organizing Control Logic for Oversaturated Arterials.” Transportation Research Record No. 2356, 2013, 92-99.
10. Xie, X.-F., G.J. Barlow, S.F. Smith, and Z.B. Rubinstein. “Platoon-Based Self-Scheduling for Real-Time Traffic Signal Control.” Proceedings, IEEE ITS Conference 2011, 879-884.
11. Day, C.M., D.M. Bullock, H. Li, S.M. Remias, A.M. Hainen, R.S. Freije, A.L. Stevens, J.R. Sturdevant, and T.M. Brennan. *Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach.* West Lafayette, Indiana: Purdue University, 2014. Available online at http://docs.lib.purdue.edu/jtrpaffdocs/3/
12. Day, C.M., D.M. Bullock, H. Li, S.M. Lavrenz, W.B. Smith, and J.R. Sturdevant. *Integrating Traffic Signal Performance Measures into Agency Business Processes.* West Lafayette, Indiana: Purdue University, 2016. Available online at http://docs.lib.purdue.edu/jtrpaffdocs/24/
13. Smaglik, E.J., D.M. Bullock, T. Urbanik, and D. Bryant. “Evaluation of Flow-Based Traffic Signal Control Using Advanced Detection Concepts.” Transportation Research Record No. 1978, 2006, 25-33.
14. Cools, S.B. *A Realistic Simulation for Self-Organizing Traffic Lights.* MS Thesis, Vrije Universiteit Brussel, 2006.
15. de Gier, J., T.M. Garoni, and O. Rojas. “Traffic Flow on Realistic Road Networks with Adaptive Traffic Lights.” Journal of Statistical Mechanics: Theory and Experiment, P04008, 2011.
16. Day, C.M., R. Haseman, H. Premachandra, T.M. Brennan, J.S. Wasson, J.R. Sturdevant, and D.M. Bullock. Evaluation of Arterial Signal Coordination: Methodologies for Visualizing High-Resolution Event Data and Measuring Travel Time. Transportation Research Record No. 2192, 2010, 37-49.
17. Day, C.M. and D.M. Bullock. Design Guidelines and Conditions that Warrant Deploying Fully Actuated Coordination. Transportation Research Record No. 2439, 2014, 1-11.
18. Goel, S., E. Dincelli, A. Parker, and E. Sprissler. “Enabling a Self-Organized Traffic System in Existing Legacy Hardware.” Proc., IEEE International Conference on Connected Vehicles and Expo, 2014.