Benefits of Coordinated Actuated Traffic Signal Control: A Before-and-After Case Study

Yin CHEN[a,b], Jeehyung PARK[c], Ilsoo YUN[d] and Byungkyu Brian PARK[a,e]

[a] *University of Virginia, Charlottesville, VA 2204, USA*
[b] *E-mail: yc9k@virginia.edu*
[c] *Korea Transport Institute, S. Korea; E-mail: jhpark@koti.re.kr*
[d] *Ajou University, Suwon, S. Korea; Email: ilsooyun@ajou.ac.kr*
[e] *E-mail: bpark@virginia.edu*

Abstract: While widely implemented, little field efforts have quantified benefits of coordinated actuated traffic signal controls. The purpose of this study was to quantify benefits of coordinated actuated traffic signal controls by conducting a before-and-after case study. The travel times along the coordinated arterials and the stopped delay on selected key approaches were used as measures of effectiveness (MOEs). In addition, traffic signal timing optimization program Synchro was evaluated whether it can properly reflect the delta changes occurring during before and after study. The field study showed that the coordinated actuated traffic signal controls resulted in a 30 percent reduction in travel times on the coordinated corridor and a 15 percent increase in stopped delay on non-coordinated movements over the actuated isolated control. In addition, Synchro evaluation indicated that the delta changes estimated from the Synchro program were in line with those from field measurements.

Keywords: Traffic Signal Timing Optimization, Coordinated Actuated Traffic Signal Control, Before-and-After Study, Synchro

1. INTRODUCTION

Since the first traffic signal system in the US was deployed in 1912 to improve traffic operations and safety by assigning right of ways (Koonce et.al, 2008), currently, there are about 311,000 traffic signals being operated in the US (NTOC, 2012). According to the nationwide personal transportation survey, an individual generally drives 40 miles per day and wastes about 36.1 hours due to traffic delay annually (Schrank et al., 2009). Obviously the performance of the transportation system has great impact on the quality of life. It is estimated that more than a half of the traffic signals in North America are in need of repair, replacement or updating of the timing plan (Koonce et.al, 2008). Outdated and inadequate traffic signal timing accounts for a significant portion of traffic delay on urban arterials. The traffic signal system optimization is one of the most cost-effective ways to improve transportation system performance when compared to adding additional lanes or new routes. For example, the Denver region traffic signal system improvement program resulted in total delay reduction of nearly 36,000 vehicle hours per day and reduction in fuel consumption of 15,000 gallons per day between 2003 and 2008 (FHWA, 2009).

Traffic engineers generally assume that the coordinated actuated signal systems perform better than the isolated traffic signal systems. This is primarily due to the belief that the performance of the signal system can be improved by providing better progression along the major corridors. When intersections are closely spaced and volumes on the coordinated arterials are large, the coordinated signal system is preferred to the isolated signal system.

However, little field evaluations were conducted regarding the benefits that can be achieved from coordinated systems over isolated systems. In addition, Buckholz (1993) indicated that coordinated signal systems do not perform well in certain conditions, including skipped phases that cause early return to green on the coordinated phases resulting in a disruption of the arterial's progression. Ideally, the traffic signal at an intersection should turn to green as soon as upstream traffic arrives. However, in practice, this is not always the case. There exist many factors that could cause improper vehicle progression on the corridors, including outdated offsets or short-term variations in traffic volume. Under congested conditions, lengthy queues often disrupt progression. Under uncongested conditions, a phase skip or a gap-out on non-coordinated phases triggers an earlier return to green on the coordinated phases which can result in a disruption of progression.

The purpose of this study is to quantify the benefits of coordinated actuated traffic signal control systems by conducting a field before-and-after study and a Synchro-based simulation. Site one (Gloucester, VA) was used to conduct field before and after study and Site two (Chesterfield, VA) was used for simulation comparison. In addition, the delta difference of the field performance was compared with that of Synchro to assess whether Synchro would be trusted to reflect the performance changes of the coordinated actuated traffic signal timing optimization.

2. LITERATURE REVIEW

Past studies on the benefits of the coordinated actuated traffic signal systems were summarized. These are categorized as simulation based and field studies.

2.1 Benefits from Simulation Studies

The City of Syracuse implemented a traffic signal interconnect design project in 1993 to improve air quality. In their project, Synchro (Husch et al., 2003) was used to assess the performance of the coordinated actuated traffic signal timing plans. The results showed that vehicle delay was reduced by 14 to 19 percent and total stops were reduced by 11 to 16 percent (DMJM, 2003).

Skabardonis (2001) summarized the benefits of optimizing traffic signal timing plans for coordinated signal control and implementing adaptive signal control. TRANSYT-7F results showed a 7.7 percent reduction in travel time, a 13.8 percent reduction in delays and a 12.5 percent reduction in stops.

Four consecutive intersections about 0.5 miles apart were coordinated to quantify benefits of a coordinated actuated traffic signal system. TRANSYT-7F results showed that the average delay decreased from 68.3 sec/veh to 37.2 sec/veh for morning peak hour and from 65.1 sec/veh to 35.6 sec/veh during evening peak hour (Nesheli et al., 2009).

The Denver region traffic signal system improvement program, which included 19 traffic timing and coordination projects between 2003 and 2008, improved more than 1,100 traffic signals and reduced delay by 36,000 vehicle hours per day and saved 15,000 gallons (FHWA 2009).

A traffic signal coordination study in Colorado Springs (2005) reported 10% to 30% improvement in travel time and potential benefits such as improved mobility, reduced vehicular crashes, reduced fuel consumption, and increased travel speed.

The adaptive split feature (or adaptive maximum feature) at an actuated traffic signal operation was evaluated using a microscopic traffic simulation. Yun et al. (2007) evaluated an actuated traffic signal system with the adaptive maximum feature via hardware-in-the-loop simulation (HILS). VISSIM was used as the simulation model and an EPAC300 traffic controller was used to implement the adaptive split feature. The results showed that the adaptive maximum feature outperformed the normal maximum green intervals. The average delay was reduced from 31.30 sec/veh to 28.07 sec/veh.

Zimmerman (2000) indicated that traffic signal coordination across two jurisdictions in Arizona resulted in a 21 percent delay reduction using the INTEGRATION simulation program.

2.2 Benefits Measured from Field Studies

A field study on the coordinated traffic signal timings across two jurisdictions in Arizona resulted in a 6.2 percent increase in vehicle speeds and 1.6 percent reduction in fuel consumption (Zimmerman, 2000).

Skabardonis (2001) conducted a field floating car study to assess the benefits of optimizing a traffic signal timing plan for coordinated traffic signal control and implementing adaptive traffic signal control. The field study results showed a 11.4 percent travel time reduction, a 24.9 percent delay reduction and a 27 percent reduction in stops.

The City of Richmond, VA installed an advanced signal system at 262 signalized intersections in the central business district area. The system coordinated four routes of isolated intersections. A test vehicle equipped with an automatic data collection system was used to collect field travel time data. The results showed that travel time decreased by by 9 to 14 percent, total delay decreased by 14 to 30 percent, and stops decreased by 28 to 39 percent (Hetrick et al., 1996).

3. SITE SELECTION

As noted, two study sites were selected. Site one included 5 actuated isolated signalized intersections in Gloucester County on Route 17 and site two included 6 coordinated actuated signalized intersections in Chesterfield County on US 60. Site one was used to quantify the benefits of coordination by comparing corridor travel times and stopped delays with and without coordination. Site two assessed benefits of the coordinated actuated signal system based on Synchro simulated results. Each site is described below:

3.1 Site One - Gloucester County, Virginia

Site one, located in Gloucester County, Virginia has five non-coordinated actuated signalized intersections. The total length of this site is about 2.4 miles, and the distance between the intersections varies from 0.15 miles to 1.5 miles. The peak hour traffic volume on the main arterial is about 600 vehicles per hour per lane. Thus, this site is considered to be uncongested.

3.2 Site Two - Chesterfield County, Virginia

Site two is located in Chesterfield County on US 60. Compared to site one, this site is congested. The total length of this site is about 3 miles, and the distance between adjacent intersections varies from 0.15 miles to 1.4 miles. There are two T-intersections within the site and several schools access the main corridor. Thus, traffic volume within this corridor varies by time of day based on school operations. The average traffic volume on the main arterials was around 750 vehicles per hour per lane. This site consists of six signalized intersections that have been operated as a coordinated actuated signal system.

4. DATA COLLECTION AND REDUCTION

Traffic volume, geometry and measures of effectiveness (i.e., stopped delay and travel time) data were collected from each of the two sites. Traffic volume and geometry data were used to develop Synchro network, and stopped delay and travel time were used as measures of effectiveness in the before-and-after study.

4.1 Stopped Delay

The following equation was used to calculate stopped delay.

- $$Stopped\ Delay = \frac{\sum V_{iq} \times l_s}{V_{tot}} \qquad \text{Eq. (1)}$$

Where:

V_{iq}:	The number of vehicle waiting at the intersection for each interval (veh)
l_s :	Vehicle-in-queue count interval (sec)
V_{tot}:	Total number of traffic volume during the period (veh)

4.2 Travel Time

Travel time was collected using two probe vehicles equipped with GPS navigation system that receives signals from the Department of Defense (DOD) system of earth-orbiting satellites. The GPS navigation recorded the location and corresponding time by every 0.1 seconds. Drivers tried to travel around average speeds of the traffic flow to ensure the travel times reflect average travel times.

4.3 Data Collection at Site One - Route 17 in Gloucester County, Virginia

Data were collected four times including off and pm peak periods over two weekdays; Two weekdays covered a before condition (i.e., the non-coordinated actuated timing plan) and an after condition (i.e., the coordinated actuated timing plan). Detailed data collection times and control modes are shown in Table 1.

Table 1. Data Collection at Gloucester, Virginia

	Control Mode	Off Peak	PM Peak
Before condition	Actuated Isolated	1:30pm to 3:00 pm	4:30pm to 6:00 pm
After condition	Actuated Coordination	1:30pm to 3:00 pm	4:30pm to 6:00 pm

4.4 Data Collection at Site Two - US 60 in Chesterfield County, Virginia

Data were collected again four times including off-peak and PM peak over two weekdays at the site two. The traffic signal controls were (i) coordinated actuated timing plan (before) and (ii) Synchro optimized coordinated actuated timing plan (after). Table 2 summarized the data collection times and traffic signal control modes. Again, both travel times and stopped delays on a few selected approaches were collected.

Table 2. Data Collection Time Plan at Chesterfield, Virginia

	Off Peak	PM Peak
Base coordinated actuated	1:30pm to 3:00 pm	4:30pm to 6:00 pm
Synchro optimized coordinated actuated		

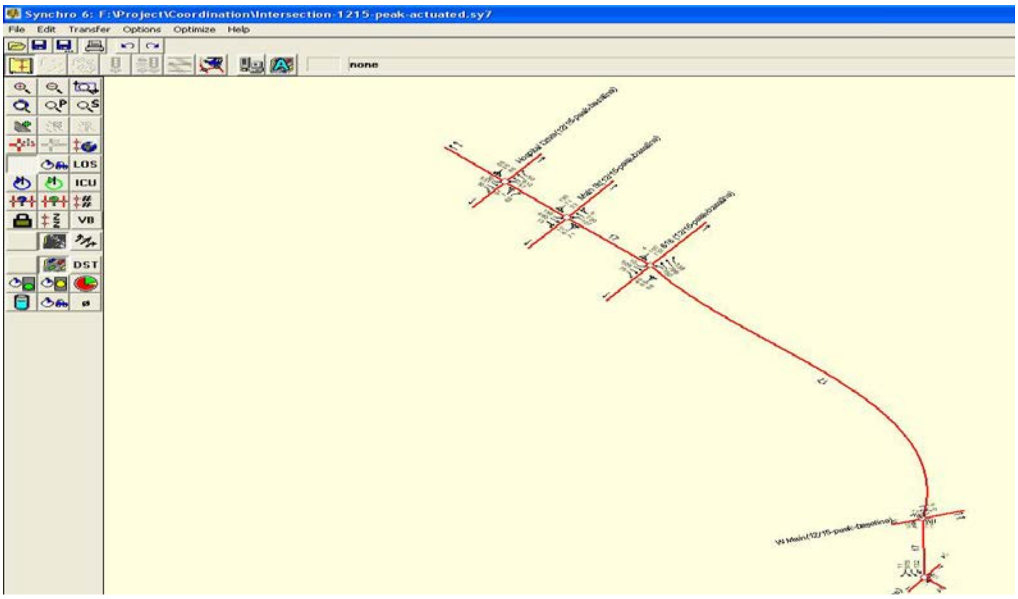
4.5 Traffic Volume Comparisons

The hypothesis of the before-and-after comparison was that the traffic volumes and other conditions, except for traffic signal timing plans, did not change much during the before-and-after study period. For both sites, the traffic volumes collected from field were compared. A statistical analysis of the traffic volumes during the before and after periods was conducted. The statistical results showed that there were no statistically significant differences.

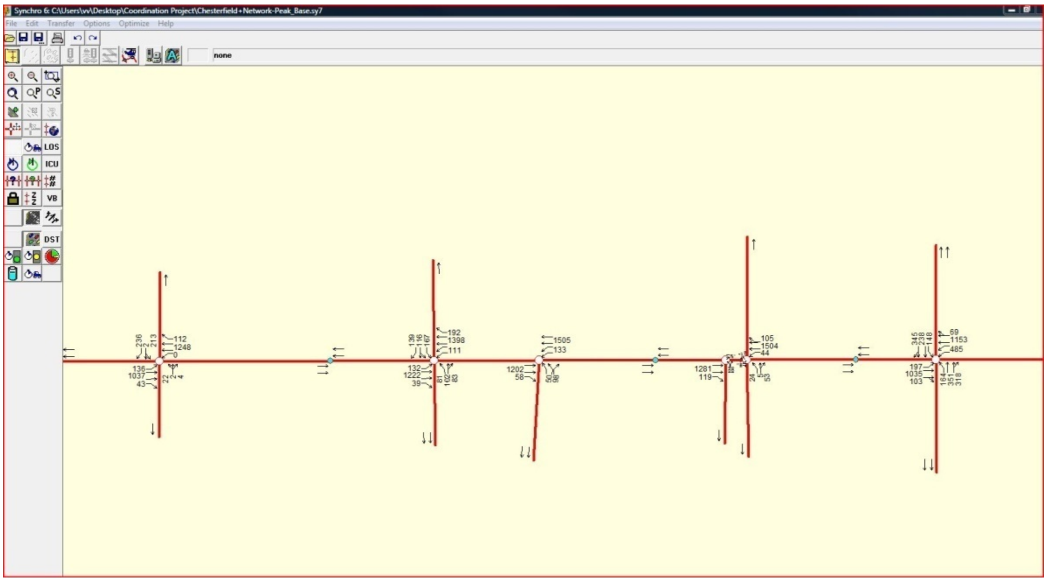
5. SYNCHRO MODELS

Synchro (Husch et al., 2003) is a macroscopic traffic signal optimization model, commonly used in the US. It optimizes cycle length, green times, phase sequences and offsets. Green times are allocated to serve 90th percentile arrival based on heuristics, phase sequences are optimized based on exhaustive search, offsets are optimized using semi-exhaustive search, and cycle length is optimized based on sequential evaluations.

Using the collected traffic volume and geometry, and traffic signal timings from the Virginia Department of Transportation, Synchro models of the two study sites were developed. Figure 1 shows the two study sites in Synchro.



(a) Gloucester County’s Synchro Network



(b) Chesterfield County's Synchro Network

Figure 1. Synchro Network

6. RESULTS

6.1 Benefits of Coordinated Actuated Traffic Signal Systems from Field (Site One)

Stopped Delay

Stopped delay was used to quantify the benefits of the coordinated actuated traffic signal control system. Tables 4 and 5 show the stopped delay comparison results at the site one. As noted, the stopped delays were collected from a few selected approaches where video cameras were easily mounted for field data collection.

Table 4. Stopped Delay Comparison for Selected Mainline Coordinated Approaches

Location	Uncoordinated Actuated (sec/veh)	Coordinated Actuated (sec/veh)	Improvements
Route 17 & Hospital Dr	9.4	8.3	12%
Route 17 & Main St (619)	21.2	4.7	78%

Table 5. Stopped Delay Comparison for Selected Uncoordinated Cross Street Approaches

Location	Uncoordinated Actuated (sec/veh)	Coordinated Actuated (sec/veh)	Improvements
Route 17 & Main St (619)	34	39	-15%
Route 17 & 616	44.6	59.7	-34%
Route 17 & W Main (Through)	26	26	0%
Route 17 & W Main (Left)	49	53	-8%

As shown in Tables 4 and 5, when compared to the uncoordinated actuated signal system, the coordinated actuated signal system showed large improvements in stopped delays on the coordinated approaches with increases in stopped delays on uncoordinated approaches. The intersection of Route 17 and Hospital Dr., which is the first intersection of the corridor's western end, showed relatively small improvement when compared to the intersection on Route 17 and Main St. (619), which is an intersection within the arterial. It is reasonable to expect large improvements on coordinated approaches within the arterial as opposed to those on the outer edges. It is noted that traffic volumes on uncoordinated approaches were much lower than those on coordinated approaches. Given that the objective of traffic signal timing optimization is to minimize total system delay, it makes sense to seek improvements on approaches carrying higher traffic volumes even when some lower volume approaches are made worse in the process.

Travel Time

Travel times were also used to assess the impacts of coordination along the corridor. Table 6 shows the travel times obtained from two probe vehicles equipped with GPS navigation systems during the before-and-after study at the site one.

Table 6. Field Travel Time Comparison (Site One: Mainline Through Traffic Only)

Gloucester County	Uncoordinated Actuated System (Before)		Coordinated Actuated System (After)		Improvements (sec, %)	
	Average (sec)	STDEV	Average (sec)	STDEV		
Off Peak	663	63	465	28	198	30%
PM Peak	713	115	473	40	240	34%

When compared to the uncoordinated actuated system, the travel times of the coordinated actuated system were decreased by 30 and 34 percent for off-peak and PM-peak hours, respectively. These results were consistent with those of the stopped delay comparisons on the selected coordinated approaches. A few possible reasons that the coordinated actuated signal system worked much better than the uncoordinated actuated signal system are (i) a good progression and (ii) the use of fixed force-offs (instead of float force-offs) in which provide less likelihood of early return to green.

6.2 Benefits of Coordinated Actuated Traffic Signal Systems from Synchro (Site Two)

Again, stopped delay was used to quantify the benefits of the coordinated actuated traffic signal system. Tables 9 and 10 show the stopped delay comparison results from Synchro at the site two for both off-peak and peak periods. The comparison was made at the intersection level. Synchro optimized coordinated actuated signal system produced 11-13% improvements over Synchro optimized isolated actuated signal system.

Table 9. Stopped Delay Comparison from Synchro for Off-Peak Hour at Site Two

	Synchro Optimized Isolated Actuated (sec/veh)	Synchro Optimized Coordinated Actuated (sec/veh)	Synchro Improvement
US 60 & Otterdale	14	12	14%
US 60 & Winterfield	22	23	-5%
US 60 & Chater Colony Pkwy	8	6	25%
US 60 & Coalfield Rd	13	9	31%
US 60 & Crowder Rd	15	10	33%
US 60 & Old Buckingham Rd	32	32	0%
Network	18	16	11%

Table 10. Stopped Delay Comparison from Synchro for PM-Peak Hour at Site Two

	Synchro Optimized Isolated Actuated (sec/veh)	Synchro Optimized Coordinated Actuated (sec/veh)	Synchro Improvement
US 60 & Otterdale	24	18	25%
US 60 & Winterfield	36	31	14%
US 60 & Chater Colony Pkwy	8	7	13%
US 60 & Coalfield Rd	15	11	27%
US 60 & Crowder Rd	16	7	56%
US 60 & Old Buckingham Rd	70	67	4%
Network	31	27	13%

6.3 Evaluation of the Synchro Program

Synchro is a widely adopted engineering tool to evaluate and optimize traffic signal timing plans. However, its validity in replicating field measurements has not been well investigated. This study evaluated whether Synchro can effectively reflect the traffic signal optimization impacts or not. That is, delta changes between the before-and-after field measurements were compared to those of the before-and-after Synchro estimates. Comparing the differences in before-and-after measurements from both field data and Synchro could overcome legitimate differences in absolute values. If the delta changes from the field and Synchro are similar, it would indicate that Synchro is a valid tool for evaluating the impacts of traffic signal timing optimizations and evaluations.

Synchro evaluations were conducted at both sites. At the site one (US 17, Gloucester, VA), the comparisons were made between uncoordinated and coordinated conditions. At the site two (US 60, Chesterfield, VA), the comparisons were made between coordinated actuated signal systems developed by Virginia Department of Transportation (VDOT) and Synchro.

Evaluation Results from Site one

At the study site one, both the uncoordinated actuated and the coordinated actuated timing plans were implemented in the field. These timing plans were evaluated in Synchro. Tables 11 and 12 summarized the comparison results using stopped delay measures. It is clear that the delta changes of the before-and-after measurements indicate that Synchro generally well reflects field changes.

Table 11. Delta Changes in Stopped Delay between Field and Synchro (Coordinated Approaches)

Coordinated Approaches	Field measurements (sec/veh)			Synchro estimates (sec/veh)		
	Before	After	[B – A]	Before	After	[B – A]
Route 17 & Hospital Dr	9.4	8.3	+1.1	17.2	13.4	+3.8
Route 17 & Main St. (619)	21.2	4.7	+16.5	21.1	5.7	+15.4

Table 12. Delta Changes in Stopped Delay between Field and Synchro (Uncoordinated Approaches)

Non-coordinated Approaches	Field measurements (sec/veh)			Synchro estimates (sec/veh)		
	Before	After	[B – A]	Before	After	[B – A]
Route 17 & Main St (619)	34	39	–5	19.1	19.9	–0.8
Route 17 & 616	44.6	59.7	–15	40.7	40.5	+0.2
Route 17 & W Main (Through)	26	26	0	29.6	29.4	+0.2
Route 17 & W Main (Left)	49	53	–4	36.2	47.7	–11.5

Evaluation Results from Site Two

As noted, two coordinated actuated traffic signal timing plans were implemented in the field – one was current VDOT timing plan and the other was Synchro optimized timing plan. Thus, the delta comparisons were made between the VDOT's timing plan and the Synchro optimized timing plan. Tables 13 and 14 show the delta changes in stopped delays. In general, delta changes of before-and-after stopped delays from Synchro well reflect those from the field measurements.

Table 13. Delta Changes in Stopped Delay between Field and Synchro (Peak period)

Peak	Field measurements (sec/veh)			Synchro estimates (sec/veh)		
	Before	After	[B – A]	Before	After	[B – A]
Otterdale Coord. East	7	11	–4	6	7	–1
Coalfield Coord. West	6	4	+2	8	9	–1
Crowder Minor North	36	32	+4	43	32	+11
Winterfield Minor North	51	40	+11	51	51	+0

Table 14. Delta Changes in Stopped Delay between Field and Synchro (Off-Peak period)

Off-Peak	Field measurements (sec/veh)			Synchro estimates (sec/veh)		
	Before	After	[B – A]	Before	After	[B – A]
Coalfield Coord. West	4	4	0	9	7	+2
Crowder Minor North	43	28	+15	53	35	+18

7. CONCLUSIONS AND RECOMMENDATIONS

Based on the study conducted in this paper, the following conclusions were made:

- Based on field measurements from the site one, the corridor travel times under the coordinated actuated signal system were improved by 30-34% over the isolated actuated signal system, while stopped delays on non-coordinated approaches were increased about 15%.
- Synchro comparison results at the site two showed that there were 11-13% stopped delay reductions with the implementation of the coordinated actuated timing plan over the isolated actuated timing plan.
- Although the absolute performance measures between Synchro and field measurement were quite different, their performance changes during the before-and-after conditions were very similar. Thus, Synchro can be trusted for assessing the impacts of traffic signal optimizations and evaluations.

Based on the study conducted in this paper, the following recommendations were made:

1. Traffic engineers should consider implementing the coordinated actuated traffic signal system over the uncoordinated actuated traffic signal system. The coordinated actuated signal system might increase delays at uncoordinated approaches. However, improvements in coordinated approaches outweigh small increase in uncoordinated approaches.
2. Traffic engineers may trust Synchro in assessing the performances of before-and-after studies (e.g., expected performance between non-coordinated and coordinated traffic signal systems).

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