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16. Abstract

Closed-loop systems are widely implemented in Texas arterials to provide efficient operation of arterial intersections while still providing signal progression. Nevertheless, poor progression can be observed along most arterials due to outdated offsets, short-term variations in traffic patterns (early-return-to-green), or changes in arterial's speed and changes in traffic volumes.

The limited abilities of closed-loop systems to adapt to traffic variations have stimulated interest into incorporating the technologies of adaptive control systems (ACSs) into closed-loop systems in order to address such issues. These integrated-type systems require lower cost and minimal staff training, in comparison to fully adaptive systems, since traffic engineers and technicians managing the traffic signal operating systems are already familiar with the closed-loop logic.

The objective of this research is to develop, implement, and test an algorithm that will address the limitations of previous efforts in this area of real-time offset-tuning. This first-year report lays the foundation for the development of this algorithm. The report also documents the proposed structure for field implementation.

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FOUNDATION FOR SELF-TUNING CLOSED-LOOP PROGRESSION SYSTEM

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CHAPTER 1: INTRODUCTION

OVERVIEW

Researchers in the traffic control field have invested extensive efforts in the development of Adaptive Control Systems (ACSs) over the last few decades. The most common and recognized ACSs that were developed in the United States are the Optimized Policies for Adaptive Control (OPAC) and Real-Time, Hierarchical, Optimized, Distributed and Effective System (RHODES) *(1, 2)*. From overseas, Split, Cycle, Offset Optimization Technique (SCOOT) *(3)* and Sydney Coordinated Adaptive Traffic System (SCATS), were developed in the United Kingdom and Australia, respectively *(4)*. These adaptive control systems are based on applying specific proprietary software to a signal control system.

ACSs have several advantages over traditional control systems. ACSs can model and track individual vehicles on a second-by-second basis. An ACS is not bound by traditional control parameters such as cycles, splits, and offsets. Rather, ACS optimizes the green duration and phase sequencing in real time, providing the most optimal control of traffic signals. ACSs, however, typically require an extensive input of system parameters for favoring individual movements plus a large number of vehicle detectors to collect movement-specific traffic data. A major drawback of these systems is the extensive effort required for training personnel on the new proprietary architecture.

On a parallel track, the private sector has developed closed-loop systems that are operated by coordinated-actuated controllers. A closed-loop system consists of a master traffic signal controller connected to a series of traffic signal controllers using hard wire connections, fiber-optic cables, or spread spectrum radio. The on-street master supervises the individual intersection controllers and issues commands to implement timing plans stored at the local controllers. The master controller can also report detailed information back to a traffic management center using dial-up telephone or other similar communications channel for monitoring purposes.

Closed-loop systems provide actuated control capabilities through their ability to respond to cycle-by-cycle variation in traffic demand while still being able to provide progression for the arterial movement. These systems are widely implemented in Texas arterials to provide efficient operation of arterial intersections while still providing signal progression. Nevertheless, poor progression can be observed along most arterials due to outdated offsets, short-term variations in traffic patterns (early-return-to-green), or changes in arterial's speed and changes in traffic volumes and waiting queues.

RESEARCH OBJECTIVES

The objectives of this research are to develop, implement, and test an algorithm that will automatically fine-tune offsets in real time in response to changes in traffic patterns measured at an upstream detector. This algorithm will address the limitations of previous efforts in this area to improve progression in both directions of the arterial when feasible. Such an algorithm will be able to reduce traffic congestion and fuel emission by minimizing vehicle stops and delays at arterial intersections.

Expanding the control logic for modern coordinated-actuated systems to account for problems such as outdated offsets, early-return-to-green, and waiting queues in an adaptive fashion would address many of the day-to-day problems associated with closed-loop systems. Additional training would be minimized, in comparison to fully adaptive systems, since traffic engineers and technicians managing traffic signal operating systems are already familiar with coordinated-actuated logic. Fundamental concepts and communication systems for coordinated-actuated systems would also remain the same, and extra cost would be kept to a minimum.

RESEARCH APPROACH

ACSs have the greatest potential to provide the most optimal control of traffic signals. However, ACSs come with a high price both in terms of initial system cost and in operation and maintenance cost. Closed-loop systems operated with a Traffic Responsive Plan Selection mode (TRPS) come next to ACSs, and far exceed the performance of closed-loop systems operated with outdated timing plans with time-of-day mode (TOD) *(5)*. Both adaptive control systems and closed-loop systems have inherent limitations: assumptions about travel time and platoon dispersion characteristics. Previous research has introduced an innovative "at-the-source" (ATS) method to adaptively fine-tune offsets in real time *(6)*. The ATS method does not suffer from the limitation associated with assumptions about travel time and platoon dispersion characteristics. Augmenting the control strategy with an ATS algorithm can greatly increase the "net benefit" of the control strategy. This approach is illustrated in Figure 1. The developed algorithm will address the most critical limitation of previous efforts in this area.

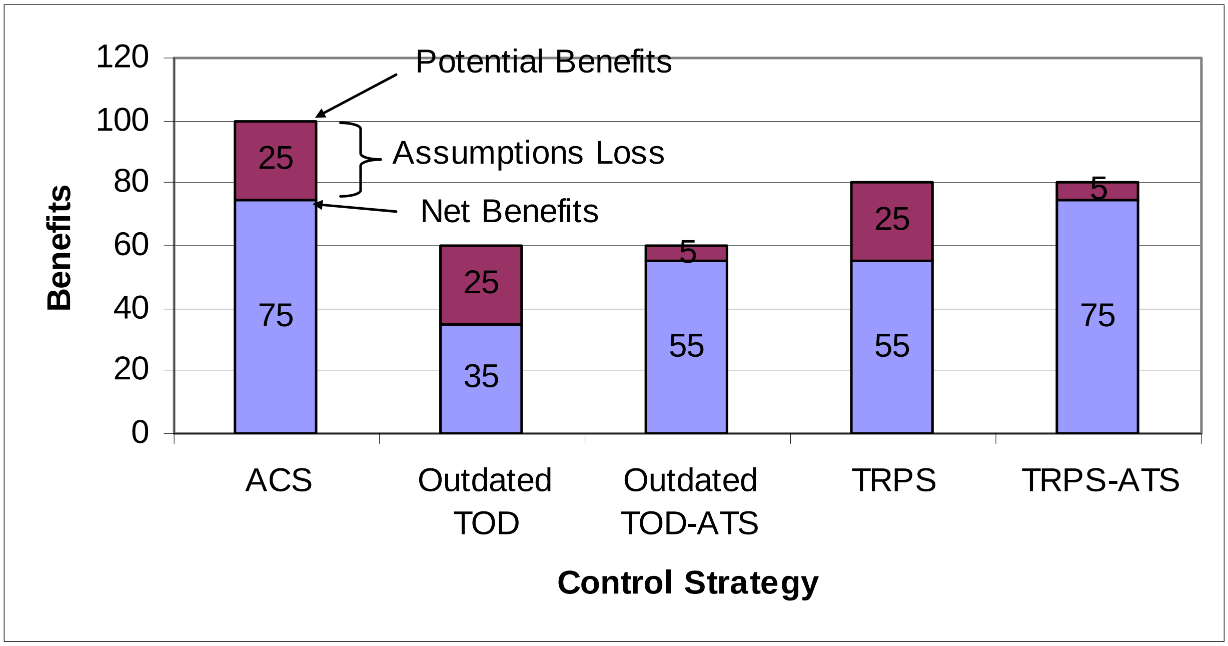

Figure 1. Research Approach.

CHAPTER 2: ADAPTIVE AND CLOSED-LOOP CONTROL SYSTEMS

ADAPTIVE CONTROL SYSTEMS AND ALGORITHMS

There are two primary motivations for the development of adaptive control algorithms. The first motivation is the need for the controllers to react to unexpected deviations from historical traffic patterns, either as a result of incidents or day-to-day random variations of the magnitude and temporal distribution of the demand peaks. The second motivation is that even for predicted traffic conditions there are a finite number of time-of-day plans that can be handled by current controllers. Also, pre-selected plans do not typically perform well during periods of temporal transitions in traffic patterns. Adaptive strategies usually respond to changes in traffic patterns in real time, either reactively or proactively. Reactive adaptive strategies “follow” the change in traffic patterns and therefore are always lagging; whereas, proactive strategies try to “predict” the change in traffic pattern, aiming at a better performance.

History of Adaptive Control Systems

The Federal Highway Administration (FHWA) started the development of a structured approach to centralized traffic signal control, called urban traffic control software (UTCS), in the 1970s. The UTCS defined and tested various levels of traffic control, ranging from time-of-day plan selection to real-time adaptive signal timing. Although the UTCS efforts did not achieve many of its objectives, it resulted in the development of many concepts and system displays that are currently used in traffic operation centers.

The first generation control (1-GC) of UTCS used a library of pre-stored signal timing plans calculated off-line, based on historical traffic data, in the same way as the pre-timed control strategies. The original 1-GC selected a particular timing plan by either time-of-day or pattern matching every 15 minutes. The second generation control (2-GC) used surveillance data and predicted values to compute and implement timing plans in real time. Timing plans were updated no more than once per 10-minute period to avoid transition disturbances from one implemented plan to the next *(7).* The third generation control (3-GC) differed from the 2-GC in its shorter periods after which the timing plans are revised. The cycle length in 3-GC was also allowed to vary among the signals, as well as the same signal, during the control period *(7)*.

Adaptive Control Algorithms

The experience with the 3-GC control in the UTCS experiments of the 1970s revealed that new strategies for adaptive control needed to be developed. Adaptive control attempts to achieve real-time optimization of signal operations by using current short-term vehicle information obtained from advanced detectors. However, the performance of the adaptive control system response is entirely dependent on the quality of the prediction model *(7)*. The implementation of adaptive control logic is not always superior to pre-timed and actuated control, especially when traffic is highly peaked.

Significant advances in adaptive traffic control were achieved with the introduction of four control strategies, namely SCOOT, SCATS, OPAC, and RHODES. Researchers in the United Kingdom developed SCOOT. It is considered a UTCS-3-GC, although some authors put it into the 2-GC category. SCATS was developed in Australia and is considered to be a variant of the UTCS 2-GC. OPAC was introduced by Gartner in the U.S. and involved the determination of when to switch between successive phases based on actual arrival data at the intersection. RHODES consists of a distributed hierarchical framework that operates in real time to respond to the natural stochastic variation in traffic flow.

SCATS

SCATS calculates degree of saturation (DS) and uses it to make cycle-by-cycle split adjustments based on equal DS. Outside of Australia, SCATS has seen limited deployment. Each SCATS controller has a micro-controller that uses stop line detector information. The philosophy of SCATS is that it has no comprehensive plans, rather, it selects from a library of offsets and phase splits to optimize timing plans in real time. SCATS divides the network into sub-regions with homogeneous flow characteristics. In each region, the intersection with the highest saturation determines the cycle length of the region.

Information from micro-controllers is passed to a central computer, which calculates target timing plans (cycle, split, and offset) in real time to minimize stops in the whole subsystem. Each subsystem can have one or more signals, but only one of them must be critical. As traffic patterns change, the computer at a higher level “marries” and “divorces” intersections by reassigning them to regions with similar flow characteristics. Each subsystem makes independent decisions regarding timing parameters involving cycle, offset, and phase lengths.

The timing plans are incrementally adjusted to varying traffic conditions *(2)*. SCATS has limited deployment in the U.S., with the largest deployment in Oakland County, Michigan (575 intersections) *(7)*. However, system operators have not been particularly comfortable with the system because of the significant differences between SCATS conventions and National Electrical Manufacturers Association (NEMA) standards.

SCOOT

SCOOT is based on the Traffic Network Study Tool (TRANSYT) optimization model that runs in a background called the SCOOT Kernel *(8)*. SCOOT uses a central computer and immediate downstream detectors to measure flow profiles at detectors and predicts queues using phase data and estimated vehicle arrivals with dispersion. SCOOT uses cyclic flow profiles (CFP) the same way TRANSYT does. Since SCOOT has evolved from an on-line model of TRANSYT, it can be used to optimize performance indices such as the number of stops, delays, or a mix of both. SCOOT smoothes detected profiles using previous data, detects stationary vehicles at detectors, and takes appropriate action to prevent spillback. The algorithm minimizes average sum of delay due to queues with stop penalties and maintains a degree of saturation under a specified value (i.e., 90 percent). SCOOT also calibrates using specified travel time from detector to stopbar.

SCOOT timing parameters are communicated to the controller immediately. The controller makes incremental adjustments to the cycle lengths, phase lengths, and offsets for the current and next cycles. SCOOT has been installed in 56 intersections in Minneapolis, Minnesota *(7)*. The system showed 19 percent reduction in delay during special events. The main criticism of SCOOT is its inability to handle closely spaced signals due to its particular detection configuration requirements. Another common complaint is that SCOOT's interface is difficult to handle and its traffic terminologies are different from those used in the United States.

OPAC

OPAC uses detectors placed far upstream of the intersections to predict vehicle arrivals at the intersection and to proactively determine the phase timings. OPAC is a dynamic programming-based heuristic algorithm with rolling horizon, using actual arrival plus projected volumes. The first version of OPAC (OPAC-I) used dynamic programming to minimize delay at the intersection. The main limitation of OPAC-I was its need for elaborate, and most likely very costly, surveillance detectors since it needs the arrival data for the entire planning horizon. The algorithm has gone through several development efforts ranging from OPAC-I through OPAC-RT *(9)*. The last versions of OPAC had several enhancements and added features over OPAC-I, including the ability to optimize all eight phases, skip phases, and an algorithm to coordinate adjacent signals. OPAC is targeted toward oversaturated conditions and demand conditions change for the arterial *(10)*. Some simulation-based research showed that OPAC performs better in undersaturated traffic conditions, but limited field implementation revealed good performance for congested traffic conditions. OPAC was implemented on the Reston Parkway in Northern Virginia, and it showed an improvement of 5 to 6 percent over highly fine-tuned timing plans *(10)*. There is no fixed cycle length in OPAC. If smoothed occupancies are larger than a certain threshold, the algorithm allows phases to max-out.

RHODES

Head et al. introduced an adaptive control strategy entitled RHODES in 1992. RHODES is reported to be better than SCOOT and SCATS in the way it responds to the natural stochastic variation in traffic flow proactively *(2)*. RHODES is entirely based on dynamic programming, and it formulates a strategy that makes phase-switching decisions based on vehicle arrival data. REALBAND algorithm in RHODES minimizes delay to platoons using simulation and a decision tree method. The Controlled Optimization of Phases (COP) algorithm included in RHODES determines phase lengths based on delays and stops using predicted data. Data used include: phase and detector data from upstream links and detector data at subject link. RHODES uses predefined turn percentages and estimated travel time between two detector locations.

Like SCOOT, RHODES has the ability to use a variety of performance measures, including delays, queues, and stops. It also allows for phase sequencing to be optimized in addition to the various timing parameters. Table 1 shows a summary of the four major adaptive control algorithms' characteristics, along with those of other algorithms found in the literature.

Table 1. Adaptive Control Literature Review Summary.

Name	Installations/ Use		Control/ Frequency		Advance Detection		Stopbar Detector Data	Optimization Objective		Distributed System	Peer-to-Peer
	U.S.	Other	Center	Local	Location	Data		System	Local		
SCOOT	Some	Lots	Before phase change for splits and every cycle for offset		Near u/s signal	Flow Profile and O	No	PI = Delay + Stops	No	No	No
SCATS	Limit. use	Many	Strategic	Tactical CIC-type			15 ft Gaps	Coordinate for critical cycle and Minimize stops	Equalize DS on all critical phases	Constrained	No
OPAC-RT Version 2.0	Some Tests	No		Yes	400-600 ft from stopbar using 6X6 loops	V & O	No	No	Delay + Stops	Yes	No
UTOPIA/ SPOT	Omaha	Europe Italy, Sweden, Norway	5 minutes	3 seconds	From u/s signals	V & O	At or near stopbar V & O	Level of interaction between signals	Cost Function: Queue-Length, Stops, Wait time and stop to buses, maximum queue, & excess capacity	Yes	Yes. Data exchange every 3 seconds
RHODES/ COP	Some Tests			30-40 second prediction over a rolling horizon	100-130 ft from stopbar	From this and u/s signal	No	Platoon Delay	Delay + Stops	Yes	No

Table 1. Adaptive Control Literature Review Summary (continued).

Name	Installations/ Use		Control/ Frequency		Advance Detection		Stopbar Detector Data	Optimization Objective		Distributed System	Peer-to-Peer
	US	Other	Center	Local	Location	Data		System	Local		
GASCAP	Proto-type		When congest. occurs, use last 15-min data. Update every other fixed cycle.	Real-time split adjustment	600-700 ft	V & O. Keeps a 30-min record of data for use when congested	No	Minimize Q and progress via cycle-offset adjustment	Volume-based phase priority to minimize queue	Yes	No
PRODYN		Limited use		75 second planning horizon	150-160 ft for Q & min of {at exits from u/s signals or 600 ft}	Queue and Volume			Delay		Yes

DYNAMIC ARTERIAL RESPONSIVE TRAFFIC SYSTEM (DARTS)

DARTS is an open-loop system that was originally developed in the 1970s by Harvey Beierle of the San Antonio District of TxDOT *(11)*. The objective of DARTS was to provide platoon progression by dynamically linking adjacent signalized intersections. DARTS shares some aspects of the ACS in the sense that it does not use cycle, splits, and offset parameters. DARTS devices communicate messages about approaching platoons. Commands are executed external to the signal controller in the form of electrical signals applied to the cabinet back panel. DARTS has 14 timing mechanisms and parameters (platoon timer, detector disabled timer, etc.). Each of these timers needs to be set and calibrated to achieve good results. In addition to the cumbersome calibration needs, DARTS still suffers from ACS's drawbacks such as assumptions involved about platoon arrival time, platoon characteristics and identifications, etc. DARTS is not compatible with traditional coordination parameters such as cycle, splits, and offsets; therefore, it can not be easily incorporated with closed-loop systems.

CLOSED-LOOP SYSTEMS

Closed-loop systems were mainly developed by private sectors in order to "synchronize" individual intersections to provide arterial progression. A closed-loop system consists of a master traffic signal controller connected to a series of secondary traffic signal controllers using hard wire connections, fiber-optic cables, or spread spectrum radio. The master controller can also report detailed information back to a traffic management center using dial-up telephone or other similar communications channel for monitoring purposes.

There are four modes under which closed-loop systems can be operated:

- "Free" mode. In this mode, each intersection is running individually, usually under a fully actuated isolated signal control. This mode can only be efficient if no coordination is needed. It is therefore not recommended for intersections included in a closed-loop system unless under late night light traffic conditions.
- Manual mode. Under this mode, the closed-loop system is operated under a constant plan, unless changed by the system operator. This mode is typically not optimal.

- Time-of-day mode. In this mode, all intersections are coordinated under a common background cycle length. The timing plans are selected at specific times based on historical traffic conditions. The TOD is a common mode of operation and can provide a stable and good performance when traffic patterns are predictable. However, in networks where traffic patterns are not predictable, or where demands shift with time, TOD can cause the signal system to implement plans that are totally inappropriate for the actual traffic patterns.
- Traffic Responsive Plan Selection (TRPS). The TRPS mode provides a mechanism by which the traffic signal system is able to change timing plans in real time in response to changes in traffic demands. The objective is to enable the signal controller to implement timing plans that are optimal for the traffic conditions that currently exist, rather than for some set of average conditions.

The TRPS mode can provide the most optimal and snappiest operation over all the other closed-loop system operation modes. The TRPS mode switches the closed-loop system's current plan to a better plan when unexpected events, incidents, or temporal changes in traffic volume occur. Most importantly, the TRPS mode reduces the need for frequent redesign/update of the signal timing plans for new traffic patterns as required if running the TOD mode. This later statement stems from the fact that the TRPS mode automatically switches plans in response to changes in traffic patterns.

Nevertheless, closed-loop systems are still limited in comparison to adaptive control systems. One of the limiting factors is the small number of stored timing plans that the closed-loop system can choose from. Another major limiting factor is the inability of the closed-loop systems to react quickly to changes in traffic demand. Even with its most optimal mode of operation, the TRPS mode, there is always a trade-off between setting the closed-loop system to be very responsive and setting it to be reasonably stable (not bouncing off from one timing plan to another). Besides their own limitations, closed-loop systems share with the ACSs the limitation that they both are dependent on travel time estimations and assumptions. The only difference is that in case of ACSs, travel time estimation is used in real time (based on posted speed limits) to estimate arrival time of platoons at the downstream intersection, where in TOD and TRPS, travel time is used to calculate offsets in the design stage and store them in the controller's database.

BRIDGING THE GAP: PRO-TRACTS AND ACS LITE

Purdue Real-Time Offset Transitioning Algorithm for Coordinating Traffic Signals (PRO-TRACTS)

In 2001, researchers at Purdue University developed PRO-TRACTS to fine-tune offsets in real time *(12)*. PRO-TRACTS mitigates the effect of the early-return-to-green problem experienced with coordinated-actuated controllers and accounts for downstream vehicle queues that may impede vehicle progression. The algorithm can be viewed as an integrated optimization approach that is designed to work with traditional coordinated-actuated systems. The objective of the algorithm is to add to the actuated controllers the ability to adaptively change their offsets in response to changes in an arterial's traffic demand, providing an intermediate solution between traditional coordinated actuated control systems and adaptive control systems.

PRO-TRACTS used a novel approach by evaluating the quality of progression near the traffic signal itself *(6)*. This approach eliminated the need to estimate travel time between adjacent signals or any other assumptions about platoons' dispersion characteristics. PRO-TRACTS uses a real-time methodology for estimating the degree of shockwave effect on the coordinated traffic using one detector located 200 to 250 feet upstream of the signal. PRO-TRACTS uses a unique cycle-based tabulation of occupancy- and count-profiles at the upstream detector to test for the significance of the presence of shockwaves. The philosophy of PRO-TRACTS is that a bad offset will cause parts of the platoon to face the red interval causing several shockwaves to pass through the detector location. These different shockwaves will cause high variation in occupancy at the upstream detector. On the other hand, a well-designed offset will align the green window with the arrival of platoon, minimizing the proportion of traffic arriving at the signal during the red interval and therefore produce a minimal shockwave that does not reach the detector. PRO-TRACTS uses this philosophy to evaluate the existing offset's performance and adjusts it accordingly.

Although PRO-TRACTS uses an innovative "at-the-source" evaluation of progression, the algorithm improves progression in only one direction of the arterial. The impact on the other direction was typically an increase in the travel time. PRO-TRACTS was also found to exhibit an unstable performance when presented with high frequency of phase skips and oscillatory traffic patterns caused by spillbacks or lane blockages due to its reactive nature.

ACS Lite

While the original ACSs have shown promise in field tests, they still are lagging in their deployment efforts. The major reason for this lag is the significant investment needed to switch to completely adaptive systems. Operating agencies are faced with extensive efforts required for training personnel on the new proprietary architecture. In addition to the price of the hardware, implementing adaptive systems requires a large number of vehicle detectors to collect movement-specific traffic data.

Faced with these facts, the FHWA started a program that is intended to develop a lighter version of ACS. This version, named ACS Lite, is intended to support upgrading of existing closed-loop control systems to support adaptive control at a moderate initial cost *(13)*. ACS Lite is intended to adhere to traditional closed-loop systems signal control parameters (cycle, splits, and offsets). The software will create new signal timing plans in real time, like the ACSs. However, ACS Lite will re-compute timing plans less often, every 10 to 15 minutes. Siemens-Gardner Systems is currently developing the software. The algorithm is still under development but will likely work similar to TRPS control.

SUMMARY

ACSs can provide the most optimal control of traffic signals due to their ability to optimize the green duration and phase sequencing in real time. Although there are several adaptive control strategies that attempt to adapt to traffic patterns either reactively or proactively, each of these strategies performs differently under different types of conditions. The performance of the ACS response is entirely dependent on the quality of the prediction model. The major drawbacks of these systems are:

- Procurement, operation, and maintenance of ACSs can be very costly.
- ACSs require extensive detection infrastructure.
- ACSs require extensive efforts for training personnel on the new proprietary architecture.

On a parallel track, coordinated-actuated systems continued to be deployed in arterial systems to provide efficient operation with their ability to respond to cycle-by-cycle variations in traffic demand, while still being able to provide progression for the arterial movement. In most cases, coordinated-actuated control saves a significant amount of delay in arterial systems when compared to fixed-time systems. However, closed-loop systems are less optimal in comparison to adaptive systems due to their limited number of timing plans and their limited ability to quickly respond to changes in traffic demand.

The limited abilities of closed-loop systems to adapt to traffic variations have stimulated interest in incorporating the technologies of adaptive control systems into closed-loop systems. PRO-TRACTS and ACS Lite are two examples of such efforts. Both of these systems have their pros and cons. The objective of this research is to develop an algorithm that improves on previous efforts.

CHAPTER 3: EXPERIMENTAL DESIGN WITH TRAFFIC PARAMETERS

TRAFFIC PARAMETERS AFFECTING PROGRESSION

Vehicular progression through a closed-loop system can be affected by several traffic and signal parameters. Traffic parameters include the platoon ratio in the traffic stream. Platoon ratio is the percentile of arterial traffic that travels from the first intersection through the last intersection in the system. Traffic volume itself plays a major role in signal progression. As the traffic volume increases, traffic speed decreases and the platoon becomes denser. Signal parameters that might affect the offset are the cycle length, green/cycle ratio, and phase sequence. It is also important to note that signal performance will also depend on the amount of traffic on minor movements in two folds: (1) The traffic volume on cross street affects the percentage of traffic turning into the main street, and therefore affects the platoon ratio; and (2) low volume on minor movements results in an “early-return-to-green” situation, where extra green is given back to the coordinated movement.

EXPERIMENTAL DESIGN

Besides the need to study the effect of each of the above-mentioned factors on traffic coordination, there is also a need to find the optimal offset value for each situation. The latter requirement is especially important since most closed-loop systems will be operated using semi-actuated control, and none of the optimization software can accurately model this type of operation. In addition, it was also required to determine when two-way coordination could yield significant benefits to the system, both in terms of delay and stops. To achieve these objectives, researchers designed and conducted an experiment such that:

1) The effect of major arterial movement volume, cross-street volume, cycle length, green/cycle ratio at the first intersection (g1/c), green/cycle ratio at the second intersection (g2/c), phase sequence, and offset value on the system delay and stops can be determined. Figure 2 shows a sketch of the simulated system. Table 2 shows the levels of each of these factors used in the experiment.

2) The combination of each of the above parameters was simulated using CORSIM *(14)*. Figure 3 shows the CORSIM network.
3) Optimal offset for one-way and two-way progression was calculated from the simulation output. This step was performed by finding the least amount of stops and delay in one direction for a given combination of parameters and the associated offset value with that minimum delay and stops. The step was repeated again, but this time considering the overall delay and stops in both directions of the arterial.

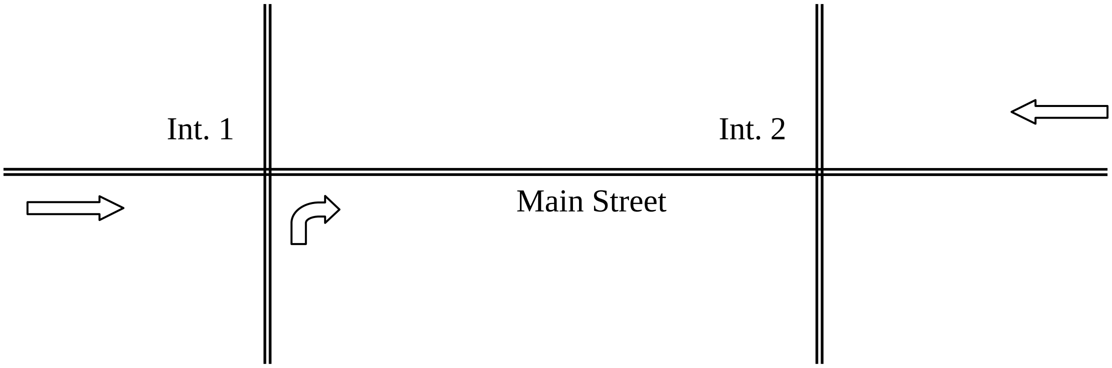

Figure 2. Experimental Simulation Network.

Table 2. Simulation Experiment Parameters.

Geometry	**Volume**			**Signal**				
Link length	**Main street**		**Cross street**	**Cycle**	**G1/C**	**g2/C**	**Phase sequence**	**Offset**
	EB	**WB**						
3000	400	400	200	60	0.2	g1/C-0.2 : : 0.9	LL-LL	5 sec intervals
	800	400						
		800			0.3			
		1200						
	1200	800		90	0.4		LL-LG	
		1200	400					
		1600			0.5			
	1600	800		120				
		1200			0.6		LG-LL	
		1600						
		2000	600	150	0.7			
	2000	1200						
		1600		180	0.8		LG-LG	
		2000			0.9			

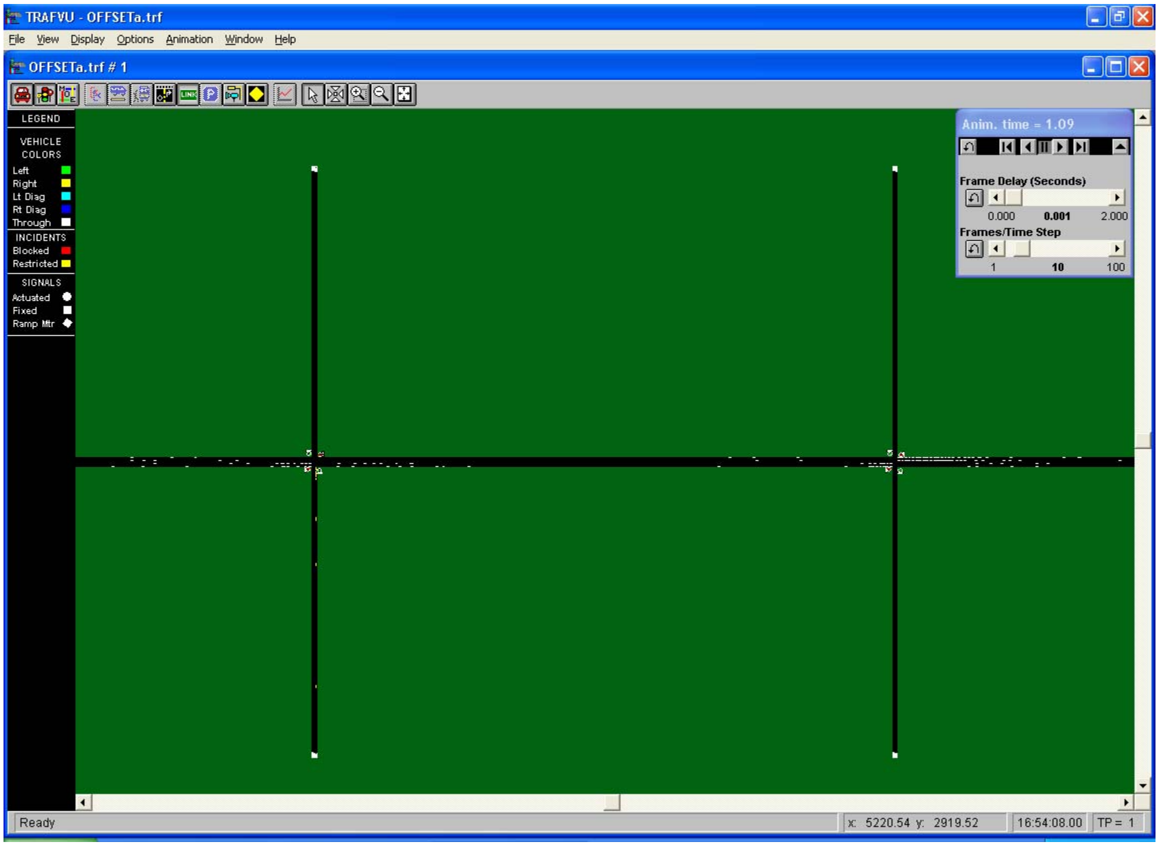

Figure 3. CORSIM - Simulation Network.

GENERAL FINDINGS

System Delay

A statistical analysis was performed on the simulation output with Statistical Analysis Software (SAS) *(15)*. Figure 4 and Figure 5 show the effect of the cycle length on both one-way and two-way mean total delay associated with the one-way best offset and two-way best offset. Note that, as expected, the larger the cycle the larger the delay could be. It should also be noted in the same figures that some combinations of g1/c and g2/c could result in a very minimal delay. This variation is also expected, since some very high g/c ratios on the major movement can cause very minimal delay for that movement. These graphs illustrate that larger cycle length can be associated with a very high variability in delay depending on the g/c ratio, where smaller cycle length will limit the amount of total delay exhibited on the system.

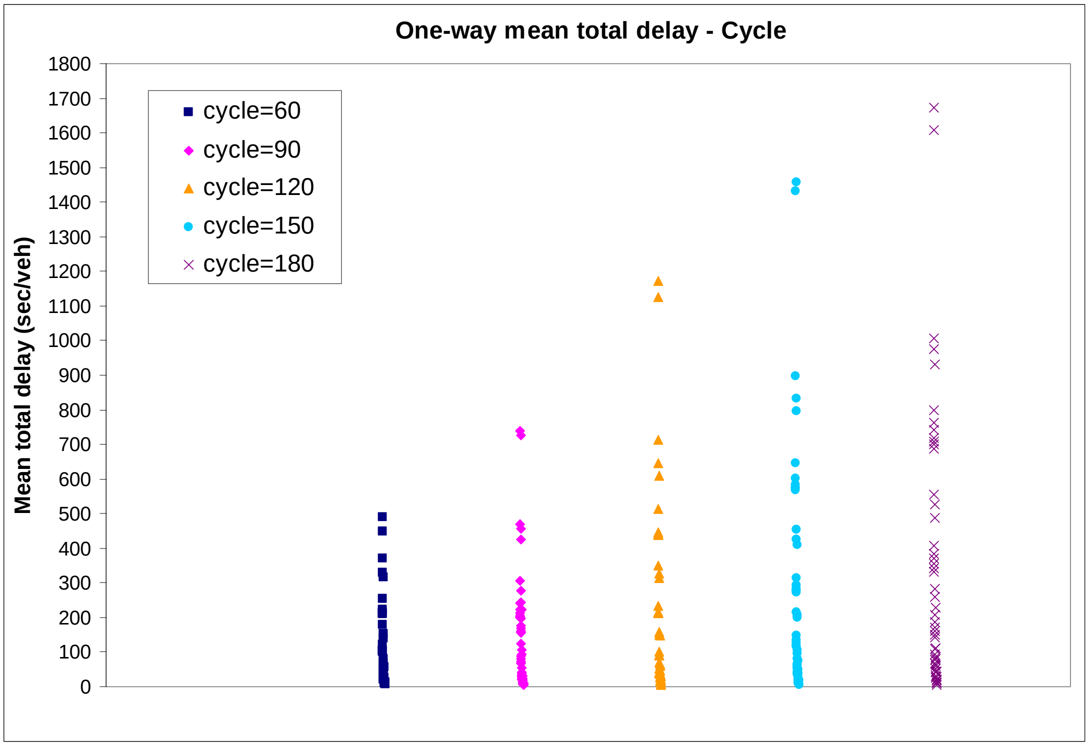

Figure 4. Cycle Effect on One-Way Intersection Delay.

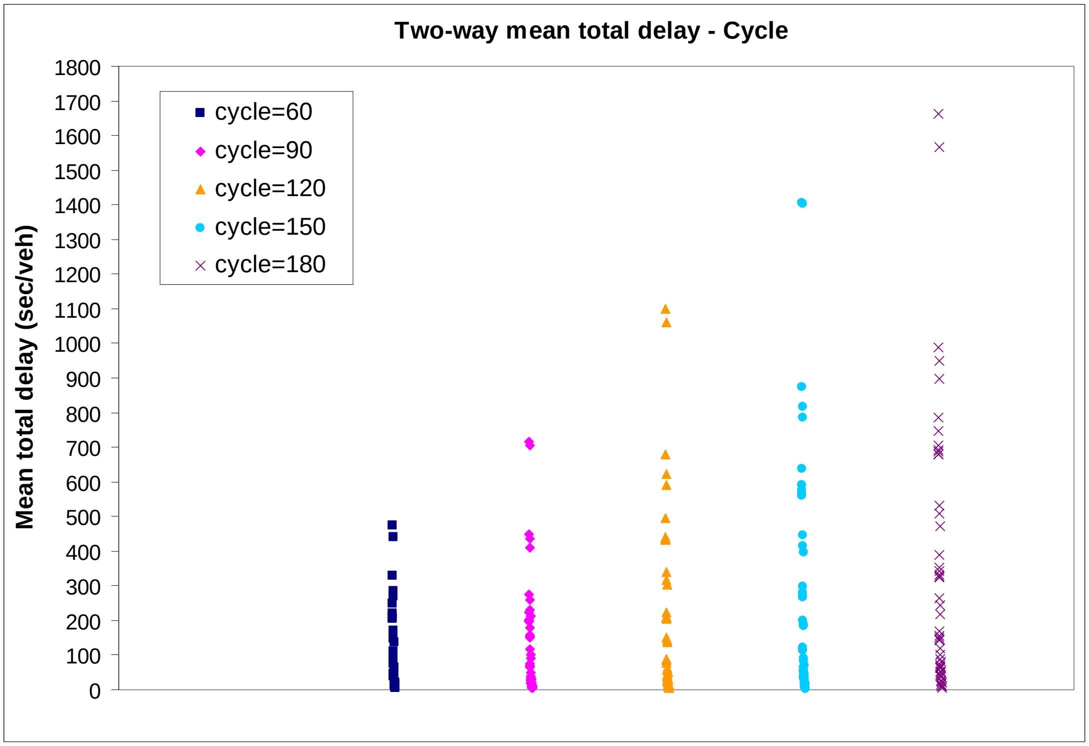

Figure 5. Cycle Effect on Two-Way Intersection Delay.

Figure 6 through Figure 9 show the effect of g1/c and g2/c on the one-way and two-way delay of the system. The g1/c ratio effect, as shown in Figure 6 and Figure 7, indicates that the less green assigned to the movement, the more the delay. This variation is expected. The interesting trend is the fact that as the g1/c ratio increases, the effect of other parameters (g2/c, cycle, volumes, etc.) diminishes very quickly. Figure 8 and Figure 9 show another interesting trend. As the g2/c ratio increases, there is still a possibility of high delay in the system. This trend could be attributed to delay already imposed at the first intersection. More importantly, note that the system delay is not strongly correlated with the g2/c ratio.

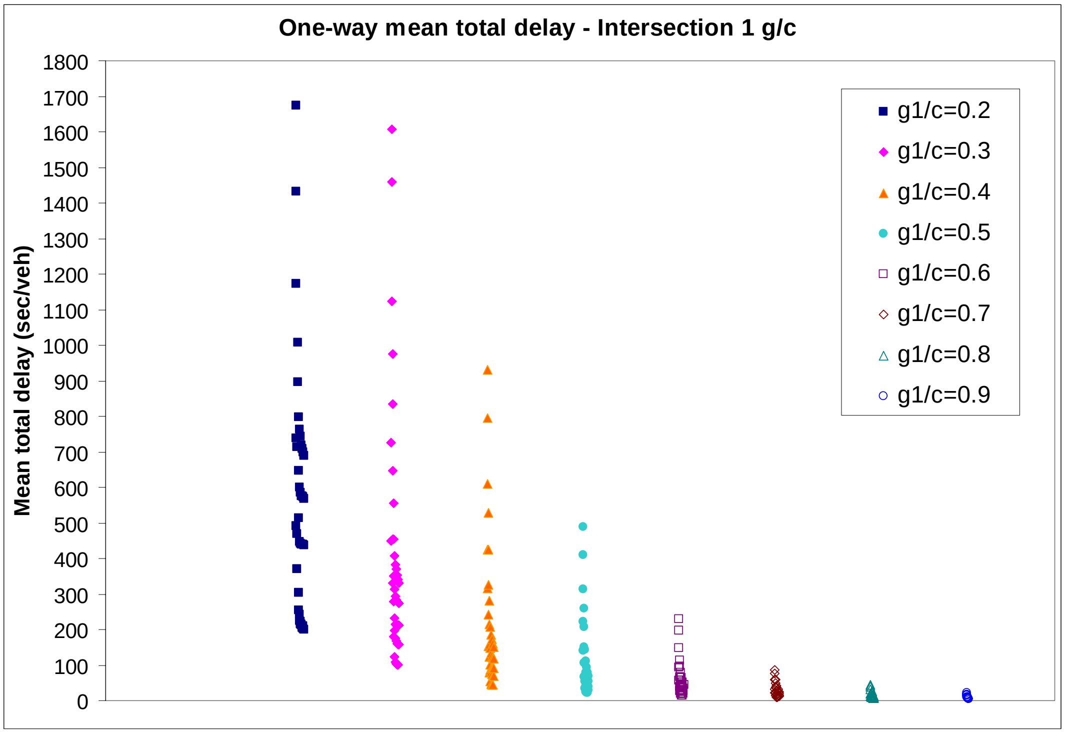

Figure 6. G1/C Effect on One-Way Intersection Delay.

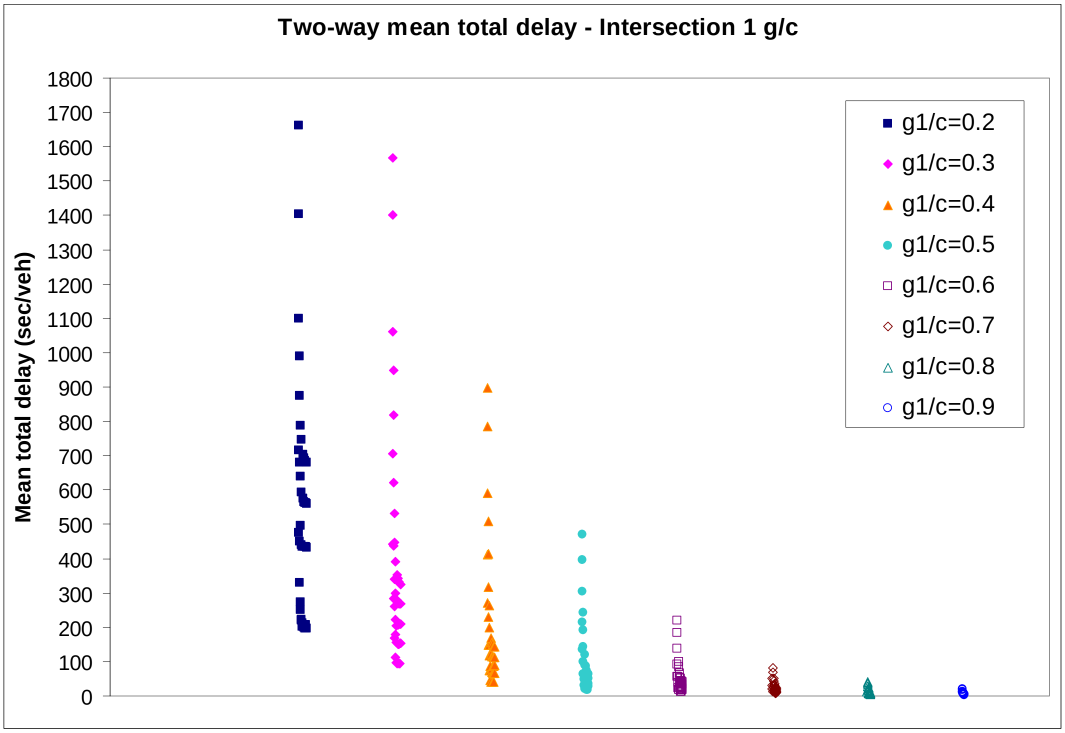

Figure 7. G1/C Effect on Two-Way Intersection Delay.

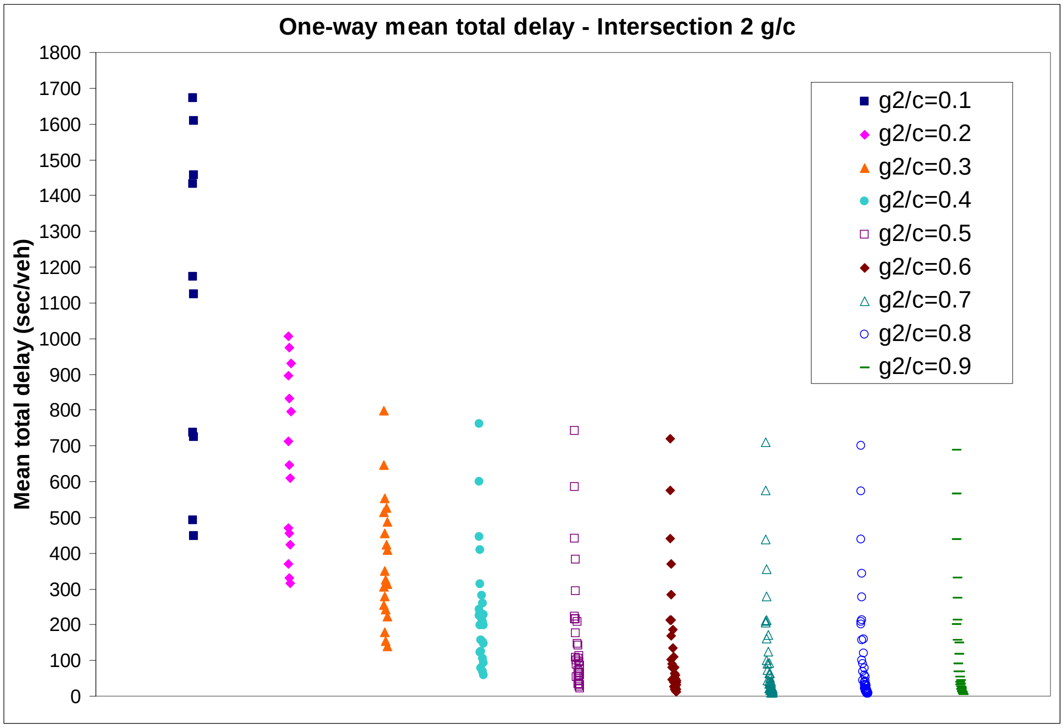

Figure 8. G2/C Effect on One-Way Intersection Delay.

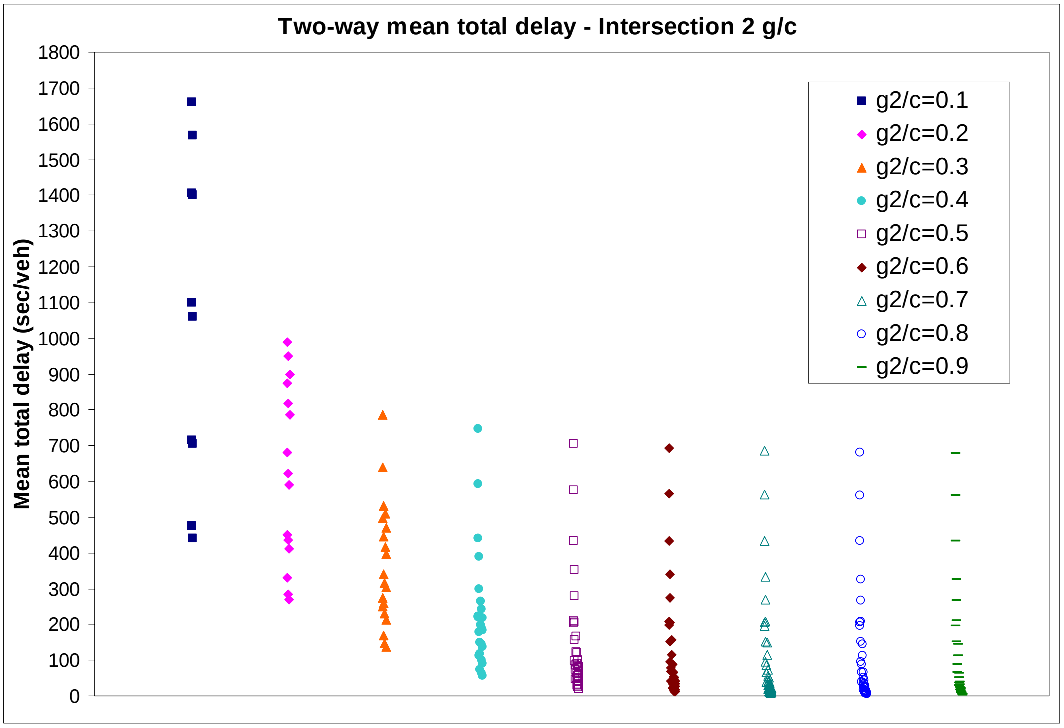

Figure 9. G2/C Effect on Two-Way Intersection Delay.

Arterial Stops

A statistical analysis was also conducted to examine the effect of experiment parameters on the arterial total number of vehicular stops. Figure 10 and Figure 11 show the effect of the cycle length on both one-way and two-way stops associated with the best offset. Note that the cycle length apparently has no effect on vehicular stops (as long as the optimal offset is in effect). Also note in the same figure that some combinations of g1/c and g2/c could result in a very high variability in stops depending on the g/c ratio.

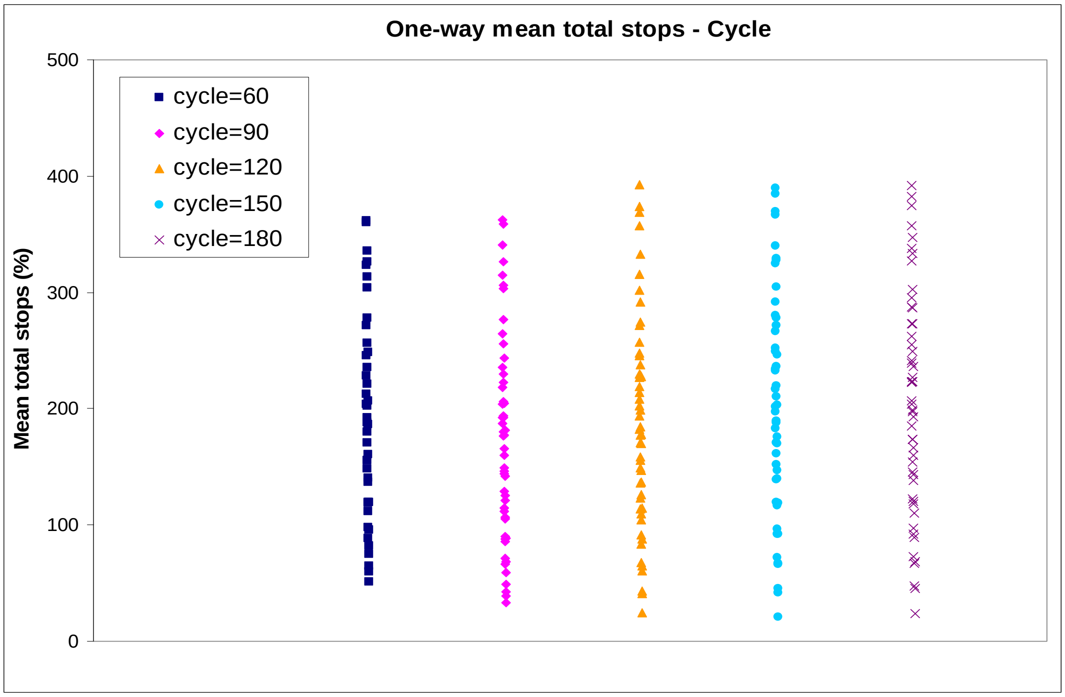

Figure 10. Cycle Effect on One-Way Intersection Stops.

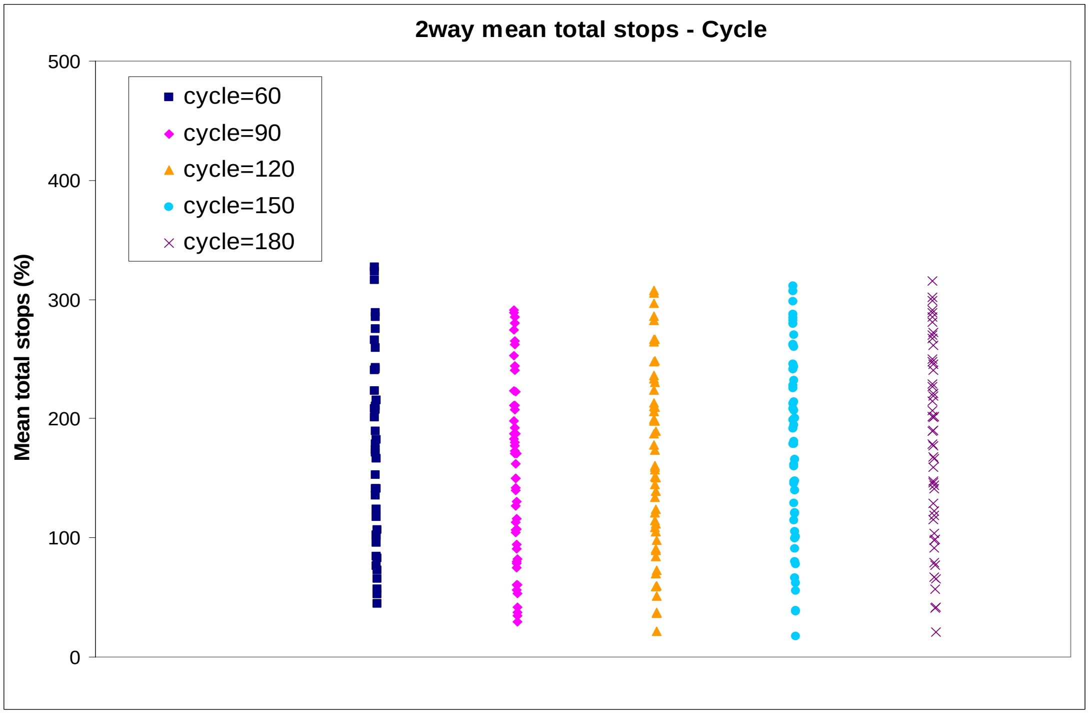

Figure 11. Cycle Effect on Two-Way Intersection Stops.

Figure 12 and Figure 13 show the effect of g1/c ratio on one-way and two-way stops is similar. In both cases, low g/c results in higher stops and higher variability in the number of stops.

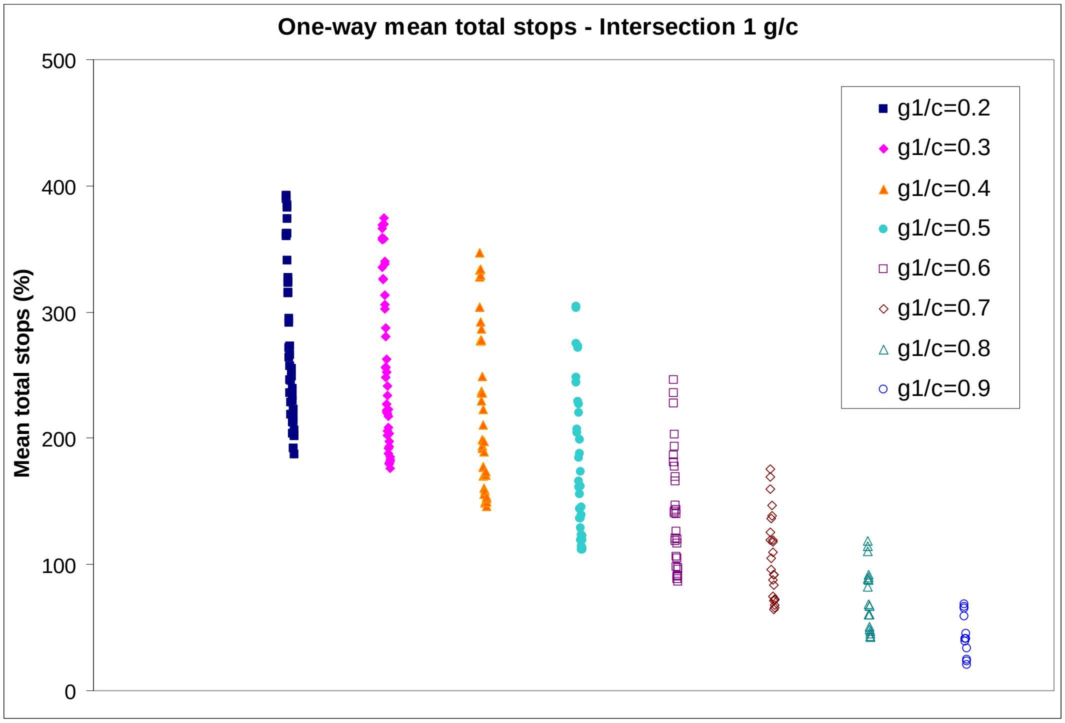

Figure 12. G1/C Effect on One-Way Intersection Stops.

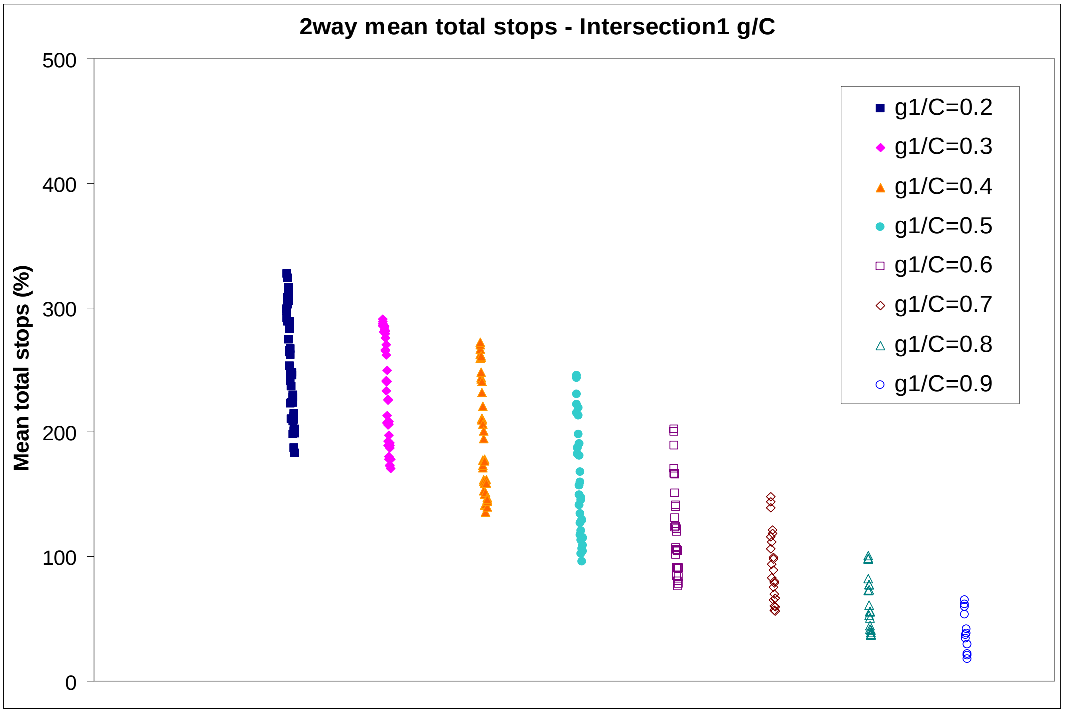

Figure 13. G1/C Effect on Two-Way Intersection Stops.

Figure 14 and Figure 15 show that the effect of g2/c ratio is again similar for one-way and two-way stop optimization. However, the interesting trend that can be observed in these figures is that the higher the g2/c ratio, the lower the stops and the higher the variability. Another fact that should be noted is that there is no high correlation between the g2/c ratio and the stops, since a great portion of stops is occurring at the first intersection.

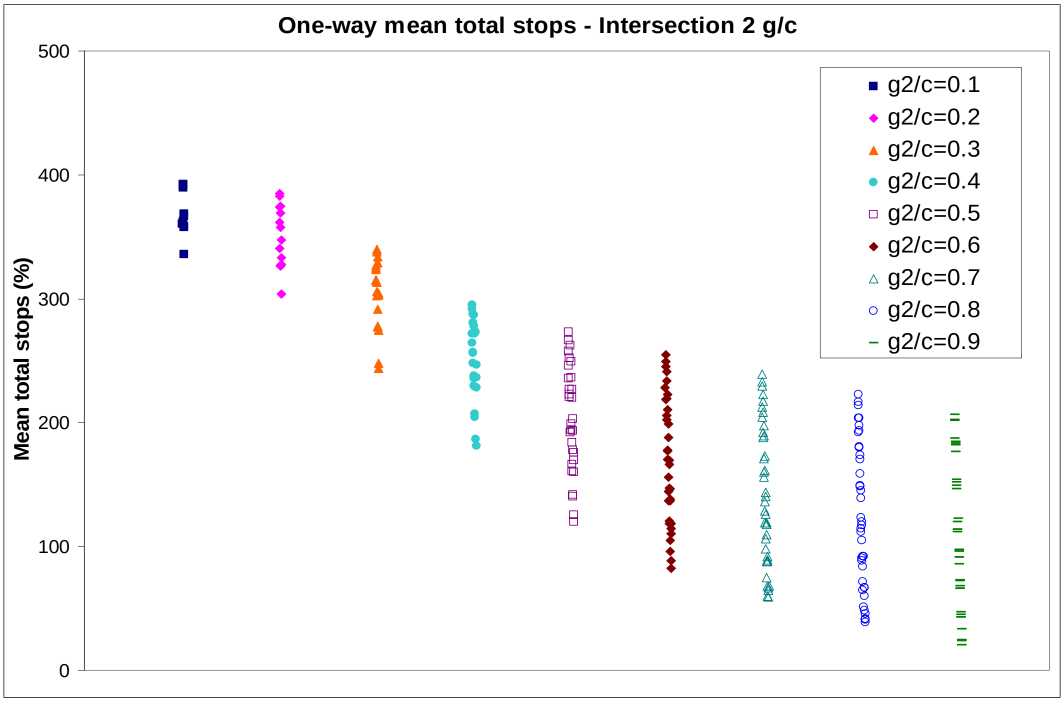

Figure 14. G2/C Effect on One-Way Intersection Stops.

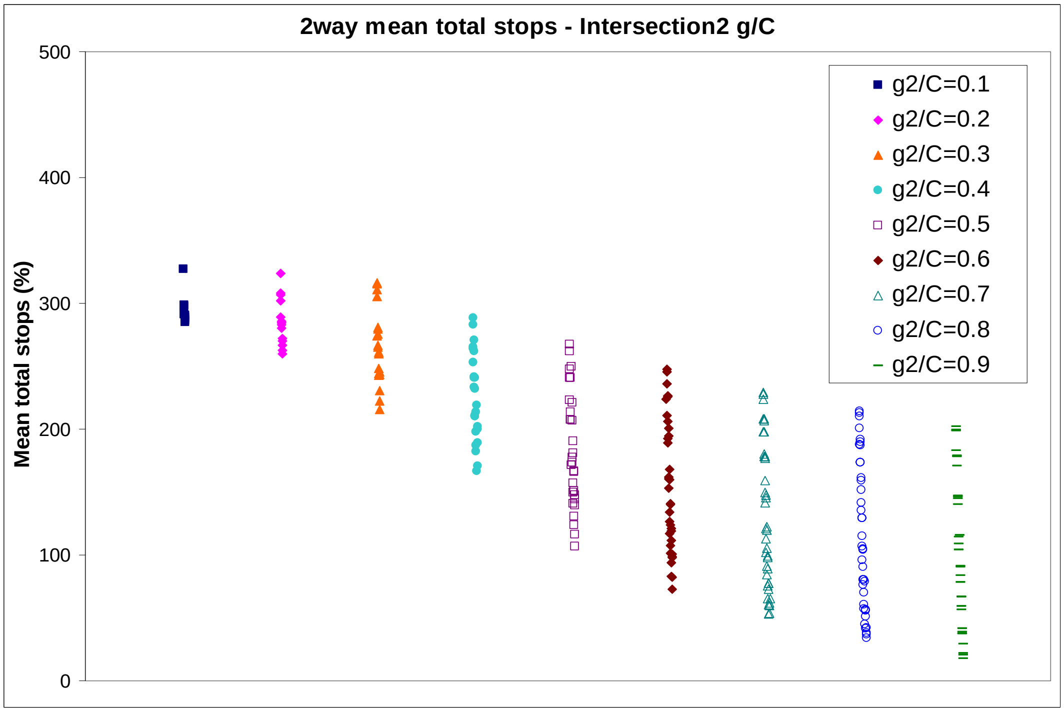

Figure 15. G2/C Effect on Two-Way Intersection Stops.

Comparison Between One-Way and Two-Way Offsets

Figure 16 shows the difference in delay obtained when optimizing the offset in one direction and two directions for a 60 second cycle length. Figure 17 shows the same information but for a 180 second cycle length. Both figures also show the optimized offset values. One can observe in these figures that there is not much change (or room for optimization) in offset to favor two-way progression versus one-way progression in smaller cycle lengths. In larger cycle length, more room is available. This could be attributed to the fact that larger cycle lengths have larger green windows to work with, which is especially important when optimizing phase sequences.

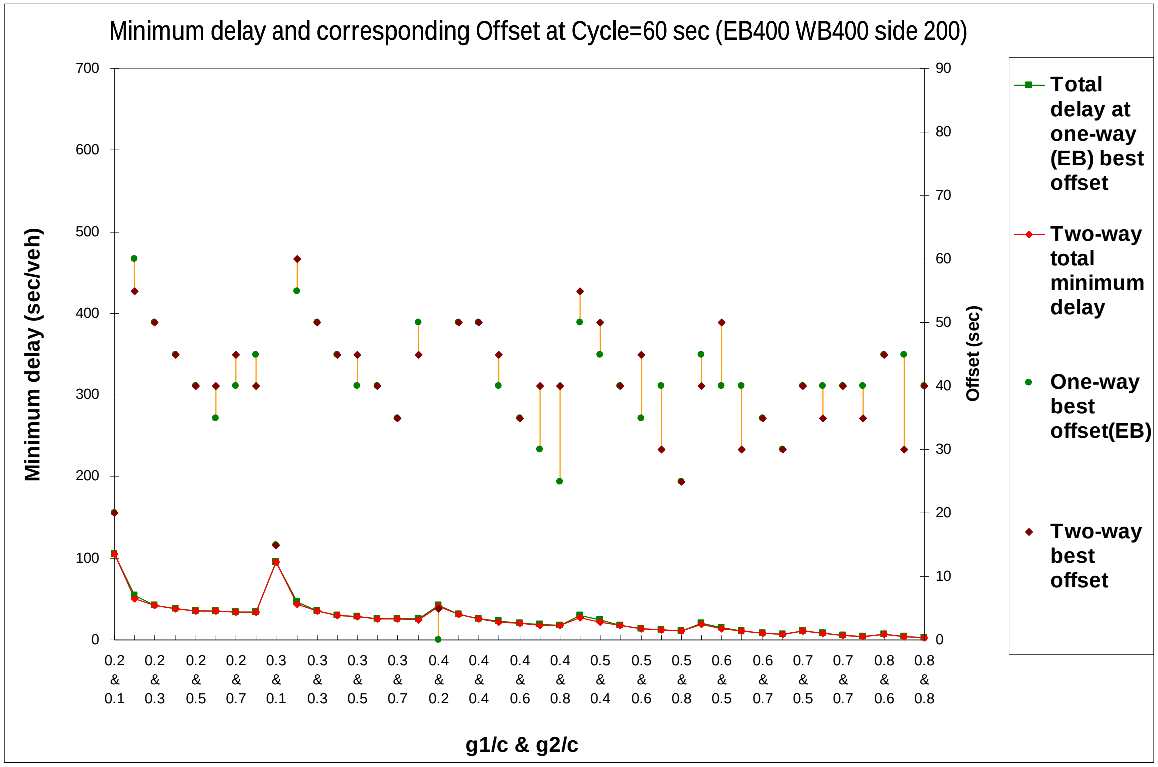

Figure 16. One-Way Versus Two-Way Optimization Effect—60 Second Cycle.

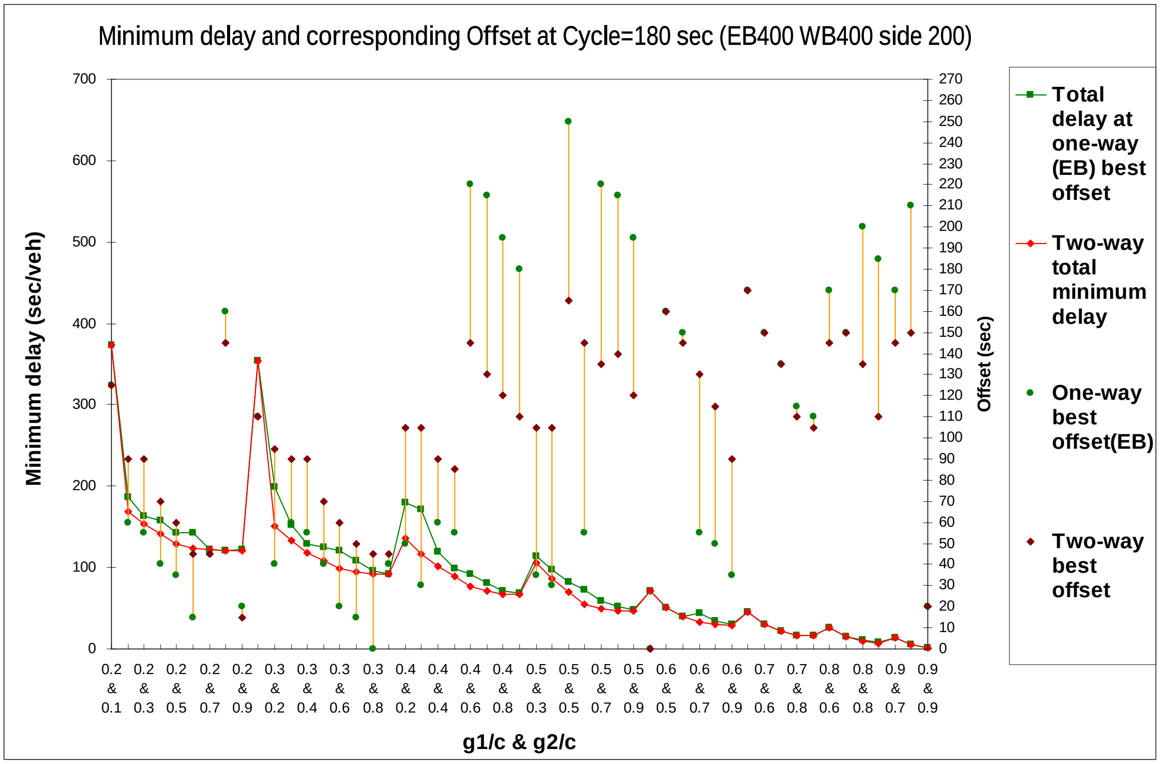

Figure 17. One-Way Versus Two-Way Optimization Effect—180 Second Cycle.

SUMMARY

This chapter explained the experiment performed to analyze the effects of traffic and signal timing factors on the performance measure of a closed-loop system. Findings reported in this chapter are incorporated into the algorithm design.

CHAPTER 4: ALGORITHM'S PROTOTYPE AND FIELD COMMUNICATION STRUCTURE

INTRODUCTION

The objective of the algorithm developed in this research is to evaluate the current offsets, decide whether a new offset is needed, and download any new offset in real time to the traffic controllers in the field. To achieve its objective, the developed system uses various hardware components and a custom software algorithm to monitor, in real time, data elements like phase indications, reason for phase terminations, current plan's cycle, splits, offset, status of stop bar detectors, and other detectors required by the algorithm at each intersection in the selected arterial test site. The system uses the monitored data to (1) calculate, in real time, the occupancy and count profile over the cycle length of each monitored detector; (2) calculate phase lengths during the cycle; and (3) determine the proper offsets or timing plan to download to the traffic controllers in the field.

ALGORITHM PROTOTYPE

The algorithm developed in this research is designed such that it can be easily evaluated with simulation. The module itself is written in the C programming language with a shared memory component as shown in Figure 18. The shared memory component facilitates the communication between the algorithm and the simulation program. This component is especially important during the evaluation phase of the algorithm as it allows the use of hardware-in-the-loop simulation before field deployment. The current algorithm prototype evaluates, determines, and downloads offsets to CORSIM—and can therefore be demonstrated in a hardware-in-the-loop simulation environment. The algorithm is being modified to address areas of improvement in published algorithms. These areas of improvements include: enhancements to algorithm stability to accommodate phase skips and cyclic platoon patterns, transitioning mechanism, and activation mechanisms. Development related to field implementation includes the interface with the field communication module. The field communication module is described in the next section.

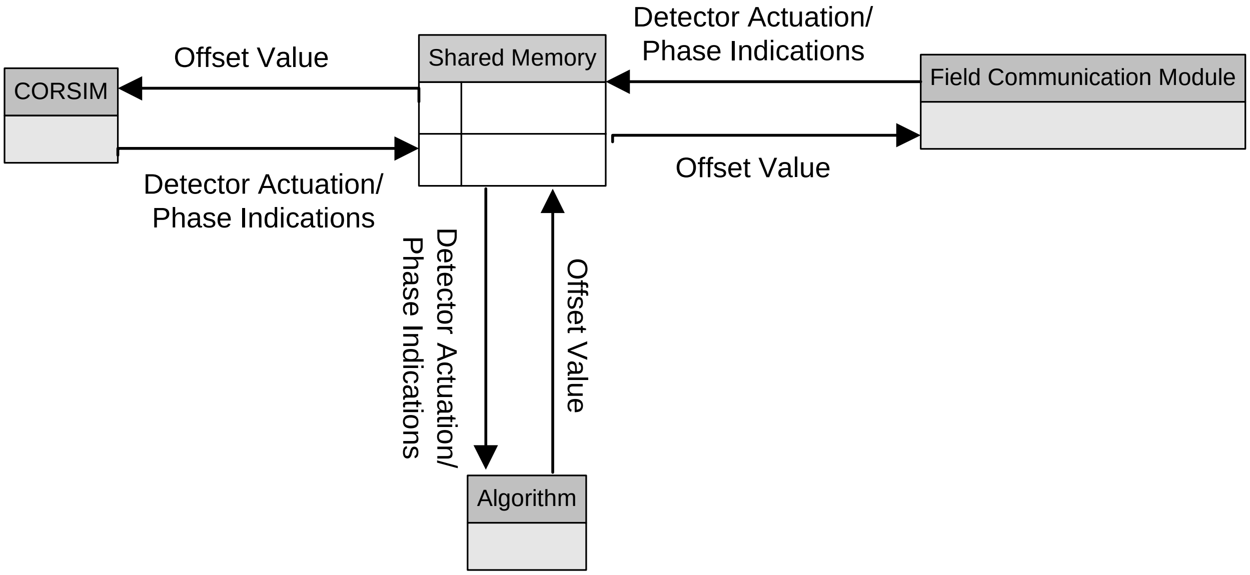

Figure 18. Algorithm's Shared Memory Structure.

FIELD COMMUNICATION MODULE

As illustrated in Figure 19, the field communication module consists of two components or subsystems: the master subsystem and a number of slave subsystems. The master subsystem consists of an industrial PC that runs the algorithm itself and issues commands to the slave subsystems. Each slave subsystem consists of a microcontroller where the slave subsystem's custom software algorithm resides and runs. The master subsystem is connected to the slave subsystem with wireless radios. The following sections describe in more detail the master and slave subsystem's software algorithms, specification of the hardware components used by each subsystem, and communications between the subsystems.

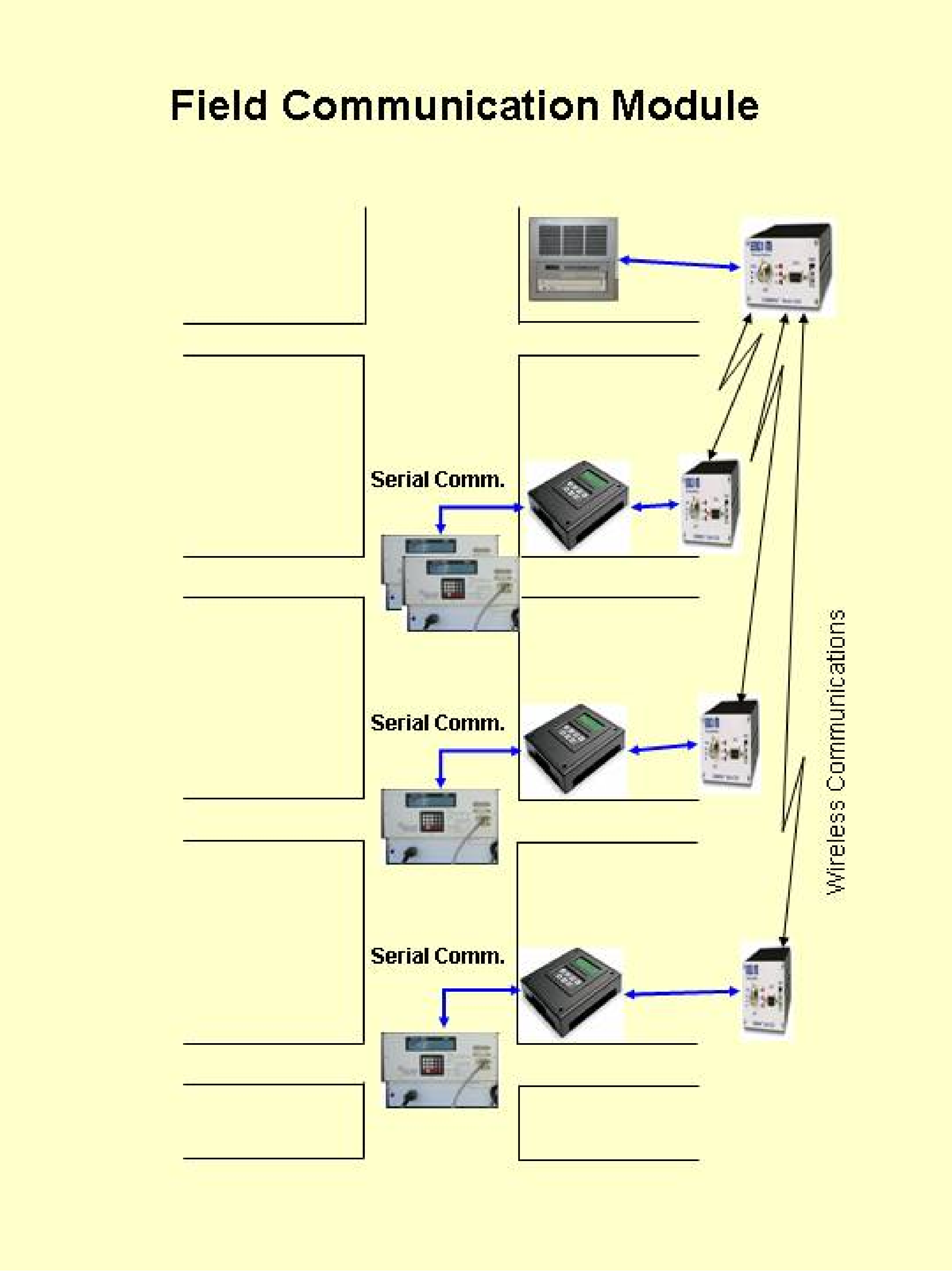

Figure 19. 47294 Master Subsystem.

Master Subsystem

The master subsystem (Figure 19) consists of an industrial PC that resides in the cabinet where the master controller resides at the selected arterial test site or in a central office depending on:

- the communication infrastructure available at the selected test site,
- the master controller used by the locality in charge of the arterial site, and
- the 47294 system final design.

The master subsystem software algorithm resides and runs on the industrial PC. The master subsystem communicates with slave subsystems either over an ENCOMM 5200 wireless transceiver or through the communication infrastructure available at the selected arterial test site. The master subsystem software algorithm receives data collected and calculated by slave subsystems including occupancy and count profile over the cycle length of stopbar and algorithm detectors, phase durations during each cycle, and reason for phase termination. The master software algorithm determines the optimal offset or timing plan in real time based on the data received from slave subsystems and transmits the new offset or timing plan to slave subsystems to download to the field controllers in real time.

Figure 20. Industrial PC.

Slave Subsystem

As shown in Figure 21, the slave subsystem consists of a ZWORLD BL2100 microcontroller running the Rabbit 2000 microprocessor at 22.1 MHz and an ENCOMM 5200 transceiver. The slave subsystem hardware components reside in the same cabinet as the traffic controller at each intersection in the selected arterial test site. The slave subsystem software algorithm resides and runs on the BL2100 microcontroller. The slave subsystem software algorithm communicates regularly in real time with the traffic controller in the cabinet and monitors the phase indications, reason for phase termination, stopbar and algorithm detectors' occupancy and count profile, and current plan's cycle, splits, and offset, and calculates phase durations. For cabinets equipped with a National Transportation Communication for ITS Protocol (NTCIP) compliant traffic controller, the microcontroller collects the required data by exchanging NTCIP standard messages with the controller over an RS-232 serial port.

Figure 21. Microcontroller.

Communication Subsystem

The information collected by the BL2100 microcontroller is transmitted on a regular basis to the master subsystem via the ENCOMM 5200 wireless transceiver (shown in Figure 22). The slave subsystem also receives through the ENCOMM 5200 wireless transceiver the offset or timing plan to be downloaded to the local controller from the master subsystem.

Figure 22. Wireless Radio.

CHAPTER 5: CONCLUSION

OVERVIEW

ACSs have several advantages over traditional control systems. An ACS is not bound by traditional control parameters such as cycles, splits, and offsets. Rather, ACS optimizes the green duration and phase sequencing in real time, providing the most optimal control of traffic signals. ACSs, however, typically require an extensive input of system parameters for favoring individual movements plus a large number of vehicle detectors to collect movement-specific traffic data. A major drawback of these systems is the extensive effort required for training personnel on the new proprietary architecture.

On the other hand, closed-loop systems provide actuated control capabilities through their ability to respond to cycle-by-cycle variation in traffic demand while still being able to provide progression for the arterial movement. These systems are widely implemented in Texas arterials to provide efficient operation of arterial intersections while still providing signal progression. Nevertheless, poor progression can be observed along most arterials due to outdated offsets, short-term variations in traffic patterns (early-return-to-green), or changes in arterial’s speed and changes in traffic volumes and waiting queues.

This research aims at augmenting commonly installed closed-loop systems with the abilities of an adaptive control system. This work addresses some of the major limitations of previous research in this area.

RESEARCH APPROACH

ACSs have the greatest potential to provide the most optimal control of traffic signals. However, ACSs come with a high price both in terms of initial system cost and in operation and maintenance cost. Closed-loop systems operated with a TRPS come next to ACSs, and far exceed the performance of closed-loop systems operated with outdated timing plans with a TOD mode. Both adaptive control systems and closed-loop systems have inherent limitations: assumptions about travel time and platoon dispersion characteristics. Previous research has introduced an innovative “at-the-source” method to adaptively fine-tune offsets in real time.

This research adds and improves on the ATS algorithm to the TRPS control.

FUTURE WORK

Further improvements to the algorithm are underway. These areas of improvements include: improvement to algorithm stability to phase skips and cyclic platoon patterns, transitioning mechanism, and activation mechanisms. Development related to field implementation includes the interface with the field communication module. The improved algorithm will be tested in two arterials in Texas using off-the-shelf components.

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