MBTC Project 2093:

Improved Traffic Signal Efficiency in Rural Areas Through the Use of Variable Maximum Green Time

Final Report

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1. Introduction

On April 20, 2005, the first National Traffic Signal Report Card[1] was issued by a coalition of leading transportation organizations. This evaluation of traffic signal operations was based on input from 378 state, county, and local agencies. The overall national grade of D- clearly indicates need to address several key aspects of traffic signal operations. One key issue identified in the report: a lack of regular updates to traffic signal timing.

Such poor results came as little surprise to transportation professionals. The Federal Highway Administration reports[2] that an estimated 75% of the 330,000 traffic signals in the United States could be improved "by updating equipment or by simply adjusting and updating the timing plans." The same report indicates that poor timing is likely responsible for "5-10% of all traffic delay or 295.8 million vehicle-hours of delay each year."

The importance of efficient traffic signal operations has increased significantly in the past two decades, as the growth of travel has greatly outpaced that of roadway capacity. From 1980 to 1998, growth in roadway capacity increased about 1% per year while travel grew by 72%[3]. If agencies were able to provide proper traffic signal timing at all signalized intersections, estimates suggest that motorists could expect a 10 to 40% reduction in delay[4], up to a 10% reduction in fuel consumption, and up to a 22% reduction in harmful emissions[5].

While both the problem and potential improvements have been clearly identified, there are two major obstacles to signal timing improvements: a lack of trained personnel and a lack of sufficient funding to update signal timing. Fortunately, the continuing reduction in cost for computing capabilities has brought with it more advanced traffic signal control capabilities, including many new features which have not yet been tested. One such feature is commonly referred to as a Variable Maximum Green Time (VMGT). This feature, provided on at least five control platforms by at least three different manufacturers, allows a local signal controller to determine if a phase failed to serve all waiting vehicles, and to adjust its length accordingly in subsequent cycles. The goal: improved traffic signal efficiency through real-time adaptation of signal timing to current conditions.

The current state-of-the-practice in traffic signal operations is a fixed maximum green time which terminates a phase after a given period of time. While detection systems can allow a phase to terminate early in the absence of demand, there is no mechanism to determine or adjust for unmet demand. VGMT allows for variation in the maximum green based on the presence or absence of unmet demand, essentially providing more green time in the following cycle to phases with unmet demand in the current cycle, and vise-versa. While VGMT is available on several current controllers, it is rarely used due to a lack of data on its effectiveness, an absence of guidelines for its application, and a lack of understanding of its purpose.

Similar “adaptive” control strategies have been studied over complex systems of intersections with encouraging results. Reports indicate the potential for reduced delay (as much as 30%[6]), increased throughput, and more equitable distribution of delay[7]. To date, most such studies have focused on large, highly complex, very costly systems for multiple intersections without considering the benefits of low cost isolated intersection techniques like VMGT.

The objective of this research was to investigate the potential to improve traffic signal operating efficiency through the use of VMGT as low cost local adaptive control. The primary measures of intersection efficiency investigated were average delay and intersection throughput. The primary investigative method involved software-in-the-loop simulation, which allows for computerized traffic simulations to be connected in real time with field traffic signal controller software, thus allowing multiple strategies to be tested with identical traffic conditions and without the difficulties of in-field traffic disruption.

2. Key Definitions and Past Research

As noted above, there has been little research on expected operations using VMGT. In addition, because traffic signals have been developed by competing manufacturers who wish their products to stand out, there are frequent different terms for the same controller function. To that end, this chapter begins with some key definitions, then discusses the two most significant investigations into VMGT operations to date, and concludes with a short discussion of the role of this research.

2.1. Project Definitions

The title of the project identifies the focus of this work to include traffic signals in rural areas. While the term **rural** is frequently defined in terms of population, that definition may not be best suited for this work. The primary deficiencies identified by the National Traffic Signal Report Card[1], were related to areas which did not have a dedicated traffic engineering staff to provide for regular traffic signal timing maintenance. So, for the purpose of this report, the term **rural** signifies areas which do not have a dedicated traffic engineering staff. Because of this, the results of this research will be applicable not only to rural population areas, but also to many smaller suburban population areas.

The research also focuses on isolated traffic signals. Typically, the term **isolated** refers to traffic signals which are separated from other signals by a sufficient distance so that vehicles arrive randomly, rather than in platoons generated by upstream signal timing. In this research, however, the need for truly isolated traffic signals was minimized because the research methods involved simulation. Because the simulations did not include upstream signals, research sites were not specifically required to be fully isolated.

2.2. Traffic Signal Definitions

While different manufacturers like to use personalized terminology, there are common reference documents provided by the industry which define operational terms. Exhibit 2-1 provides the industry standard term, other common terms, and the industry standard definition as published in the NEMA Standards Publication TS 3.5-1996[8].

Exhibit 2-1. Select Traffic Signal Term Definitions (from 8)

Standard Term	Also Called	Standard Definition
Minimum Green	Min Green, Initial Green	The first timed portion of the Green interval which may be set in consideration of the storage of vehicles between the zone of detection for the approach vehicle detector(s) and the stop line.
Passage	Passage Time, Gap Time, Gap, Vehicle Extension	The extensible portion of the Green shall be a function of vehicle actuations that occur during the Green interval. The phase shall remain in the extensible portion of the Green interval as long as the passage timer is not timed out.
Maximum Green 1	Maximum Green, Max Green, Max1, Normal Max	This time setting shall determine the maximum length of time this phase may be held Green in the presence of a serviceable conflicting call
Dynamic Max Limit	Dynamic Max, Variable Maximum Green Time, Variable Max, Max3	Setting Dynamic Max Limit greater than zero enables dynamic max operation with the normal maximum used as the initial maximum setting.
Dynamic Max Step	Dynamic Step, Variable Maximum Step, Variable Step, Step Size, Step	This object shall determine the automatic adjustment to the running max in tenth seconds

Those standards go on to define the typical operation of VMGT as follows:

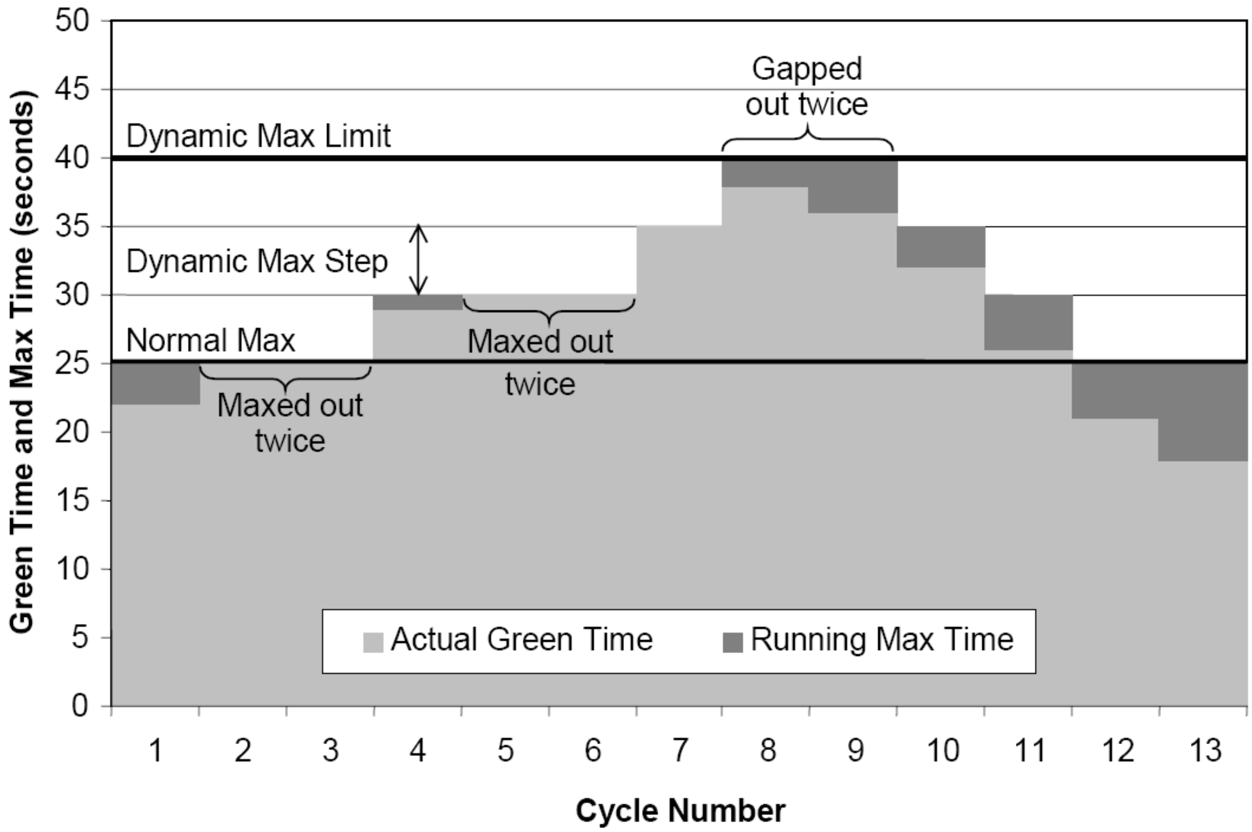
> When a phase maxes out [serves the entire maximum green because of constant demand] twice in a row, and on each successive max out thereafter, one dynamic max step value shall be added to the running max until such addition would mean the running max was greater than the larger of normal max or dynamic max limit.
>
> When a phase gaps [ends the green before reaching the maximum because of a

gap in demand] out twice in a row, and on each successive gap out thereafter, one dynamic max step value shall be subtracted from the running max until such subtraction would mean the running max was less than the smaller of the normal max or the dynamic max limit.

If a phase gaps out in one cycle and maxes out in the next cycle, or vice versa, the running max will not change. (from 8)

To help understand this operation, Exhibit 2-2 provides a graphical representation of VMGT operations.

Exhibit 2-2. Graphical Representation of VMGT Operation (from 9)



2.3. Key Literature on VMGT

Engelbrecht, et. al.[9] were the first to perform a significant investigation into the potential benefits of VMGT. This research evaluated VMGT's potential to improve operations at diamond interchanges by allowing the exit ramp phase to dynamically adjust to meet surges in traffic demand caused by freeway incidents. The results of this investigation concluded that "the dynamic maximum green time feature [aka VMGT] can reduce delays and queues significantly when used on a phase controlling traffic subject to demand variations."

While this investigation proved positive benefits, it made use of VMGT only for the exit ramp phases – normal maximum green operation was used for all other phases. The signal was otherwise well timed for the traffic present.

Yun, et. al.[10] performed a more thorough evaluation of VMGT, applying this method of operations to all phases, and comparing it with both a normally optimized maximum green and an arbitrarily large maximum green. As with the prior investigation, the results of this research were positive, and the authors concluded that "benefits can be achieved by utilizing the Adaptive Maximum [aka VMGT] feature over the large or optimized maximum green settings."

Again, this investigation proved positive benefits; however, the variable maximum green was determined as a function of the optimized maximum green. In both of these studies, therefore, the baseline for VMGT operations was a well timed signal.

2.4. The Role of This Research

This research differed from prior studies in several ways. For one, this investigation focused on the evaluation of a generic set of VMGT parameters, as opposed to basing VMGT parameters on site-specific optimized timing. These same parameters were applied to all phases in use at each intersection, and were not based on optimized timing.

In addition, where the previous studies made use of peak hour volumes, this investigation made use of 16-hour volumes (aggregated in 15-minute increments) to evaluate the continually changing performance of VMGT over an day's traffic. Finally, the "optimal" timing plans used as a benchmark included the use of three different time-of-day maximum greens, one for off peak conditions, one for the AM peak, and another for the PM peak.

This design is focused to determine if a generic set of VMGT parameters can provide operations similar to those of an optimized set of green times, but without significant cost or traffic expertise which would be unavailable to most rural agencies. If successful, the output should be that generic set of VMGT parameters which can be installed in rural traffic signal controllers, resulting in improved operations.

3. Research Plan

This chapter presents the research plan, both as originally envisioned and as modified during the course of the project. None of the modifications were major ones, and the outcome of the project matches the original goals. The text presents each task as it was originally scoped, and then presents any alterations which occurred during the project timeline.

3.1. Task 1: Initial Community Contact

Original Description: *During Task 1, the research team will have face-to-face meetings with the personnel responsible for traffic signal maintenance in the rural communities surrounding Tennessee Tech University. In addition to building a mutually beneficial working relationship, these meetings will provide insight into current equipment, personnel, and maintenance practices.*

With one exception, Task 1 went essentially as planned. As the project got underway, the research team contacted the City of Cookeville's Public Works Department, which included the technicians responsible for traffic signal maintenance. Apparently, the City of Cookeville contracts with virtually all the surrounding communities to provide traffic signal support, so the only nearby agency is the City of Cookeville.

3.2. Task 2: Site Selection

Original Description: *During Task 2, which runs concurrently with Task 1, the research team will develop selection criteria and identify 5-10 sites from the lists compiled during community contact for preliminary investigation. From this list, 2-5 sites will be selected for use during the remainder of the study. The selection criteria will be developed with input from the community contact meetings. Once the sites have been selected, the required data collection will take place to provide required model inputs.*

Two factors had significant influence on Task 2. First, due to contract issues, the project got a late start. In an effort to get the project back on schedule, the research team decided to use a total of 3 sites, one remote and two local. Second, because the City of Cookeville was the only local agency available to contact, the two local sites were chose with their assistance, eliminating the need for preliminary site investigations. The primary considerations in site selection were: a variety of traffic volumes, known recurrence of queuing, and isolated (non-coordinated) operation.

3.3. Task 3: Base Model Development

Original Description: *During Task 3, the research team will first develop a baseline model of each selected site. This model will be checked for reasonable similarity with known field conditions. Following the development of a reasonable model of field conditions, new simulations will be developed to evaluate optimal timing under the current operational strategy as well as to test the initial control strategies developed during Task 4.*

This task proceeded generally as expected.

3.4. Task 4: Control Strategy Development

Original Description: *During Task 4, the research team will develop and refine VMGT-based control strategies. An initial set of strategies will be developed for the first round of testing, and then additional strategies will be developed and refined in an iterative process including Tasks 4-6. In this manner, the research team can focus a second round of testing on the strategies which seem most promising. Results from the second round of testing should help provide a base set of VMGT settings for improved traffic signal efficiency.*

This task proceeded generally as expected.

3.5. Task 5: HITL / CSITL Simulation

Original Description: *As each strategy is developed, the research team will proceed with a combination of Hardware-in-the-Loop (HITL) and Controller-Software-in-the-Loop (CSITL) simulations to determine the expected operational characteristics. Both HITL and CSITL simulation methods require multiple simulations of each case. Because HITL methods require significantly longer run times, CSITL methods will be used more heavily, with HITL used as a supplement to verify the CSITL results.*

Between the original proposal and the time of this task, both the capabilities of and the confidence in CSITL (now more commonly referred to as Software-in-the-Loop Simulation, or SILS) grew tremendously, eliminating the need for HITL methods. The project used only SILS methods for evaluation.

3.6. Task 6: Preliminary Evaluation

Original Description: *The preliminary evaluations provide the feedback necessary in the iterative process of Tasks 4-6. A limited portion of the results for each control strategy, primarily from the CSITL simulation methods, will be used as inputs to developing new control strategies, allowing the research team to focus their efforts on the most promising aspects of each strategy.*

Information about Tasks 6 and 7 can be found following the description of Task 7.

3.7. Task 7: Data Reduction and Evaluation

Original Description: *In addition to the preliminary evaluations of Task 6, the research team will undertake more advanced data reduction and evaluation to quantify the* *operational characteristics of each strategy tested. The anticipated results include generic VMGT settings for improved traffic signal operating efficiency.*

Tasks 6 and 7 were essentially combined during the project. Preliminary investigations proved to be insufficient for refinement of VMGT control strategies, so full evaluations were completed for use in determining refinements.

3.8. Task 8: Documentation of Results

Original Description: *The documentation phase includes multiple efforts. First, the research team will prepare a final report for the MBTC. Second, the research team will prepare a journal and/or conference paper to distribute the findings of the research. Thirdly, the results of the study will be shared with the personnel responsible for traffic signal maintenance in the areas surrounding Tennessee Tech University. Finally, based on positive evaluations of VMGT, the research team will prepare follow-up research requests in an effort to move forward with field verification of the simulation results.*

This task proceeded generally as planned. To date, one journal submission has been made, on masters thesis is underway, and at least one additional journal submission is planned.

4. Field Data Collection and Reduction

This chapter presents a brief overview of the study sites and examples of how field data were collected and summarized for use in the project. First, information about the geometry and signal phasing is discussed for each of the three selected sites. This is followed by the process used to determine traffic volumes. Note that the final intersection turning movement counts can be found in Appendix A.

4.1. Site 1 – NC 211 at NC 5

As noted above, the project team chose to use one remote site, namely Site 1. This site was located near Pinehurst, NC, at the intersection of NC 211 and NC 5. This was a low volume site, with an average daily traffic (ADT) of about 20,000 vehicles per day. A schematic of the intersection, taken from the traffic signal plan prepared by the North Carolina Department of Transportation (NCDOT) is shown in Exhibit 4-1. A summary of the traffic signal control is shown in Exhibit 4-2.

Exhibit 4-1. Site 1 Geometry

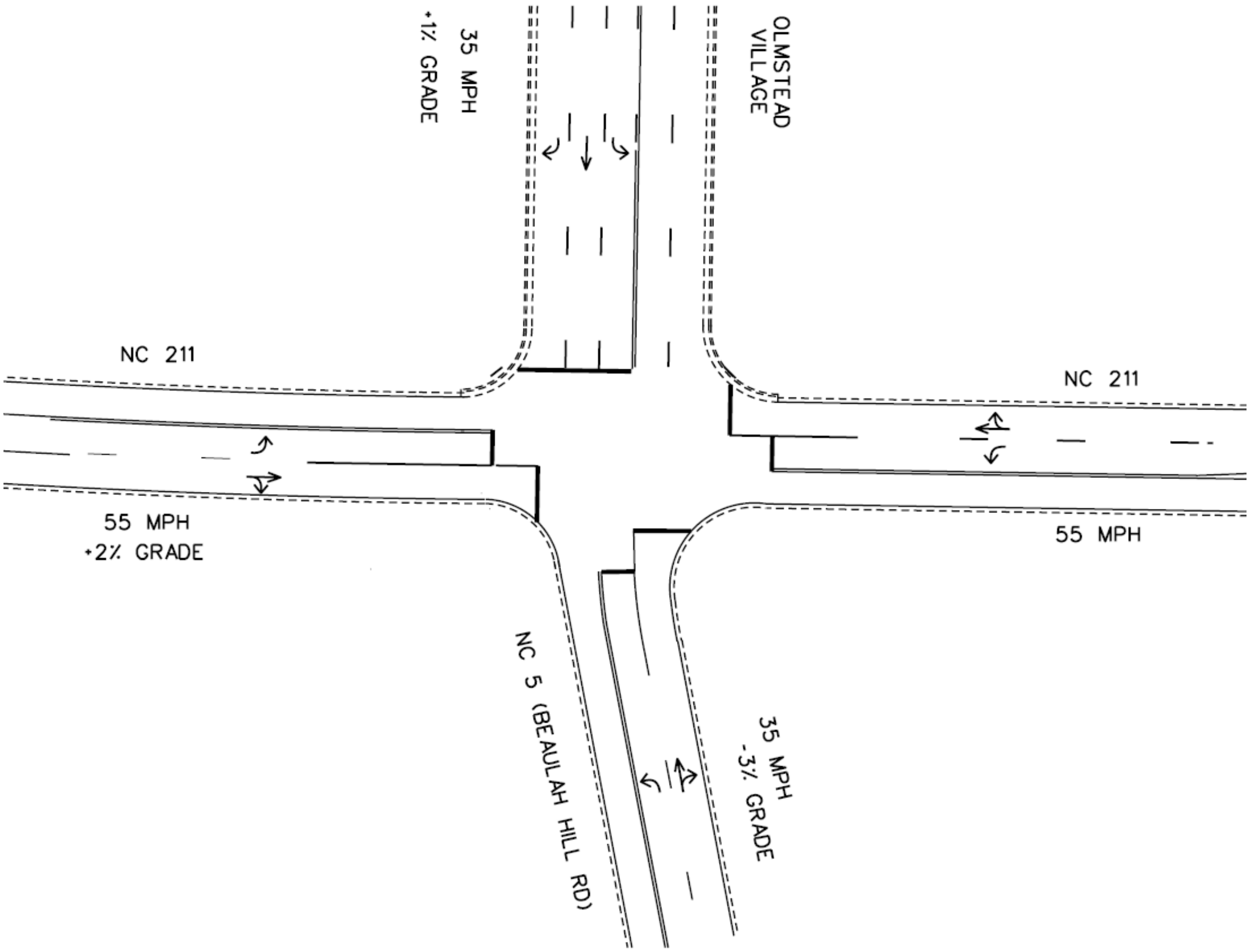


Exhibit 4-2. Site 1 Phasing Summary

	Eastbound	Westbound	Northbound	Southbound
Left Turn Treatment	Permitted	Permitted	Protected-Permitted	Permitted
Left Turn Phase	-	-	3	-
Through Phase	2	6	8	4

4.2. Site 2 – 9th Street at Dixie Avenue

Site 2 was the first of two local sites, and was located in Cookeville, TN at the intersection of 9th Street and Dixie Avenue. This was another low volume site, again with an ADT of about 20,000 vehicles per day. An aerial image of the intersection is shown in Exhibit 4-3. A summary of the traffic signal control is shown in Exhibit 4-4.

Exhibit 4-3. Site 2 Aerial Image

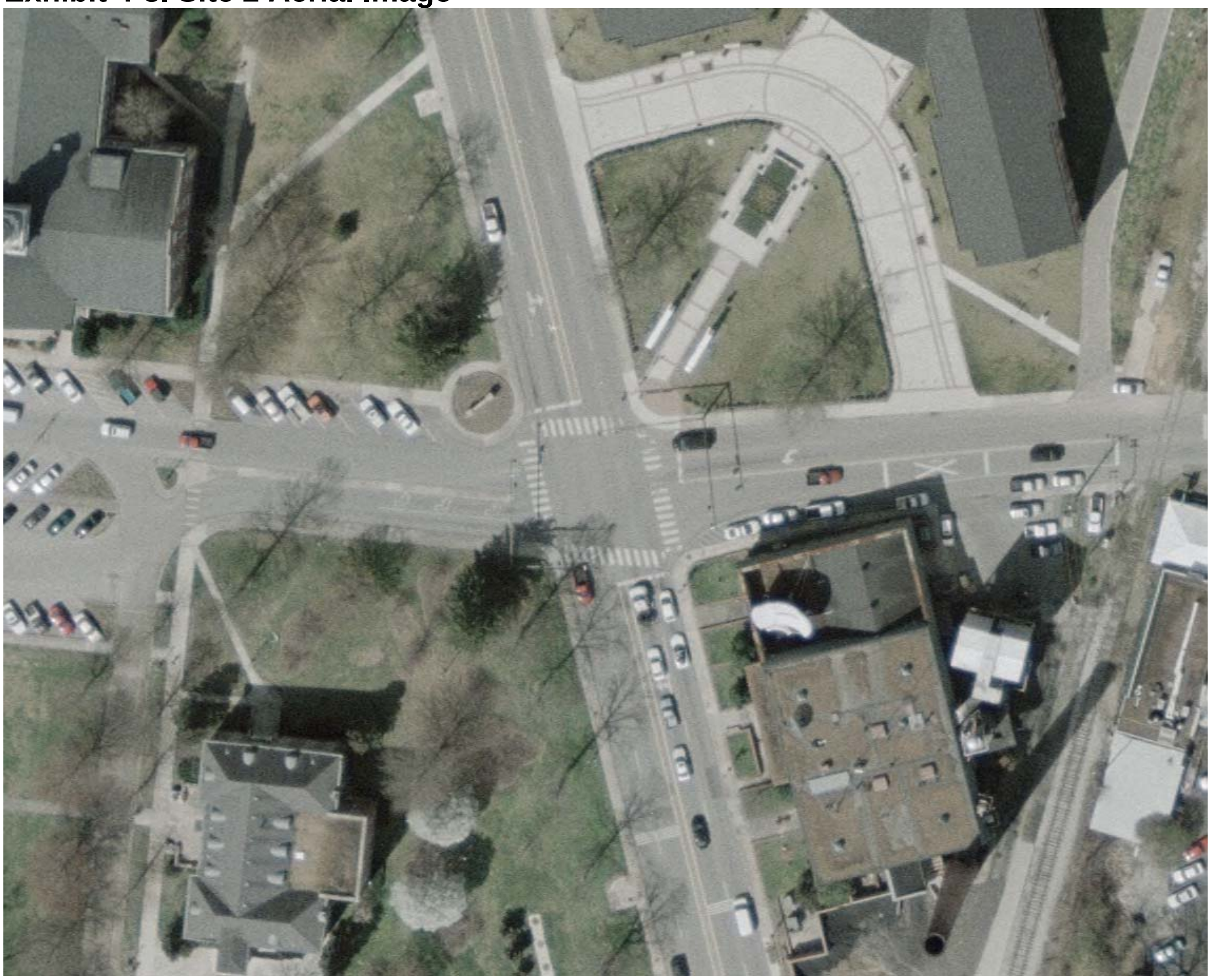


Exhibit 4-4. Site 2 Phasing Summary

	Eastbound	Westbound	Northbound	Southbound
Left Turn Treatment	Protected-Permitted	Protected-Permitted	Split	Split
Left Turn Phase	7	3	2	1
Through Phase	4	8	2	1

4.3. Site 3 – Jackson Street at Willow Avenue

Site 3 was the second of two local sites, and was located in Cookeville, TN at the intersection of Jackson Street and Willow Avenue. This was a high volume site, with an ADT of about 40,000 vehicles per day. An aerial image of the intersection is shown in Exhibit 4-5. A summary of the traffic signal control is shown in Exhibit 4-6.

Exhibit 4-5. Site 3 Aerial Image

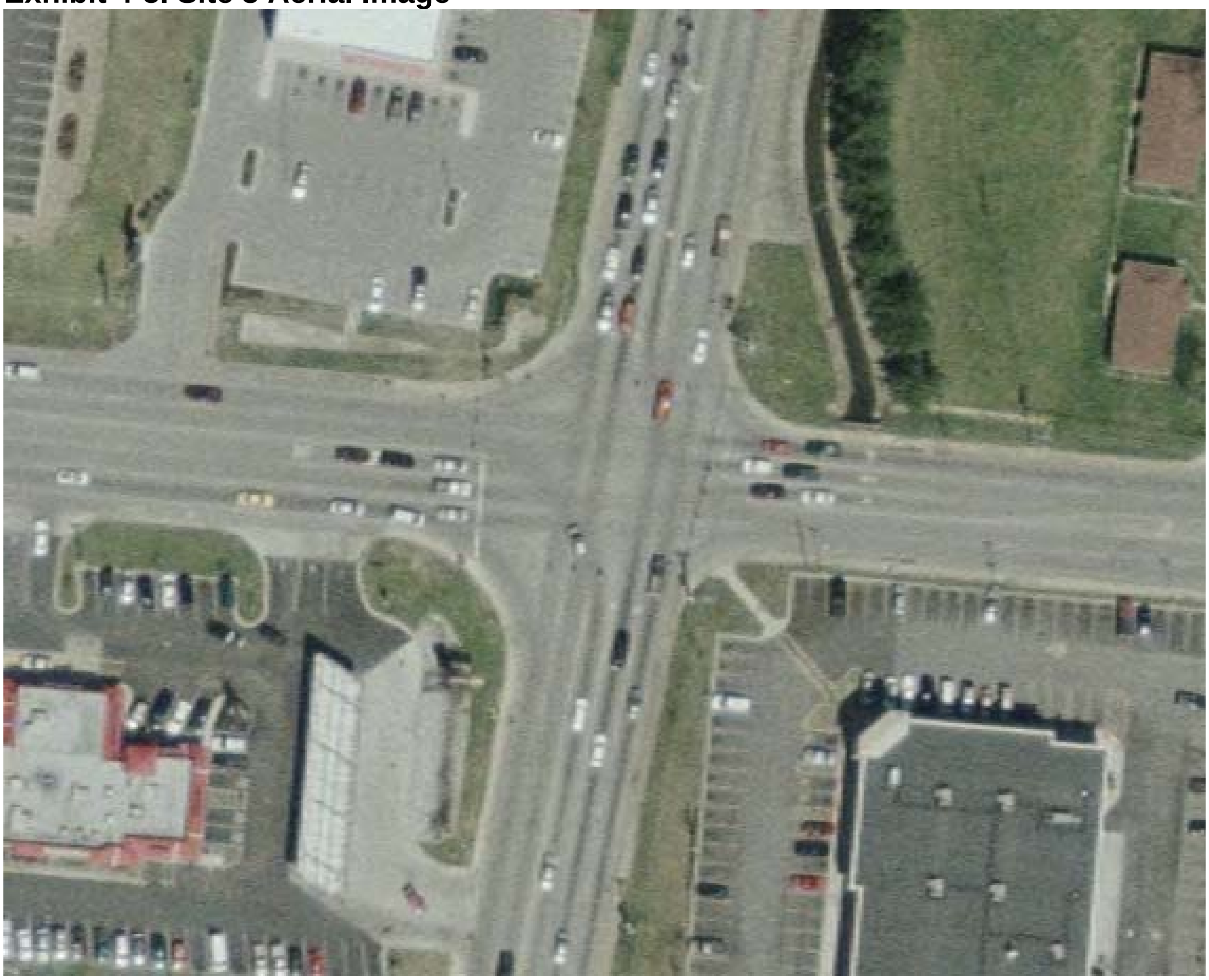


Exhibit 4-6. Site 3 Phasing Summary

	Eastbound	Westbound	Northbound	Southbound
Left Turn Treatment	Protected-Permitted	Protected-Permitted	Protected-Permitted	Protected-Permitted
Left Turn Phase	7	3	5	1
Through Phase	4	8	2	6

4.4. Determining Intersection Volumes

For Site 1, the remote site, volumes from a prior investigation by NCDOT were available to the project team. For Sites 2 and 3, however, it was necessary to collect volume data from the field. The project team chose a complex layout of tube counters and collected data over multiple days to determine current volumes.

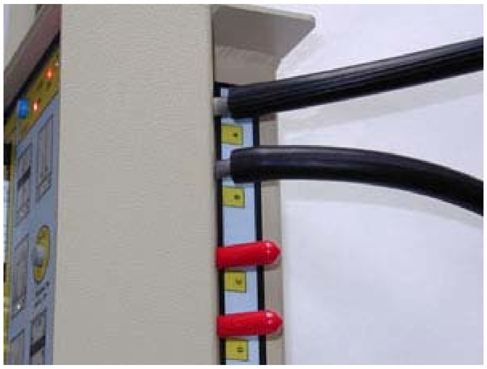
4.4.1. Tube Counter Layout

While tube counters are frequently used for directional volumes on roadways, their application to gather turning movement count data is more complex. Fortunately, the project team was assisted with tube placement by the Traffic Signal Division staff of Public Works Department in Cookeville, Tennessee. Several varieties of TimeMark[11] tube counters were used for this project. Some images of tube counters and tubes on the roadway are provided in Exhibit 4-7. A more detailed schematic of the layout required for intersection counts is provided in Exhibit 4-8.

Exhibit 4-7. Typical Tube Counter

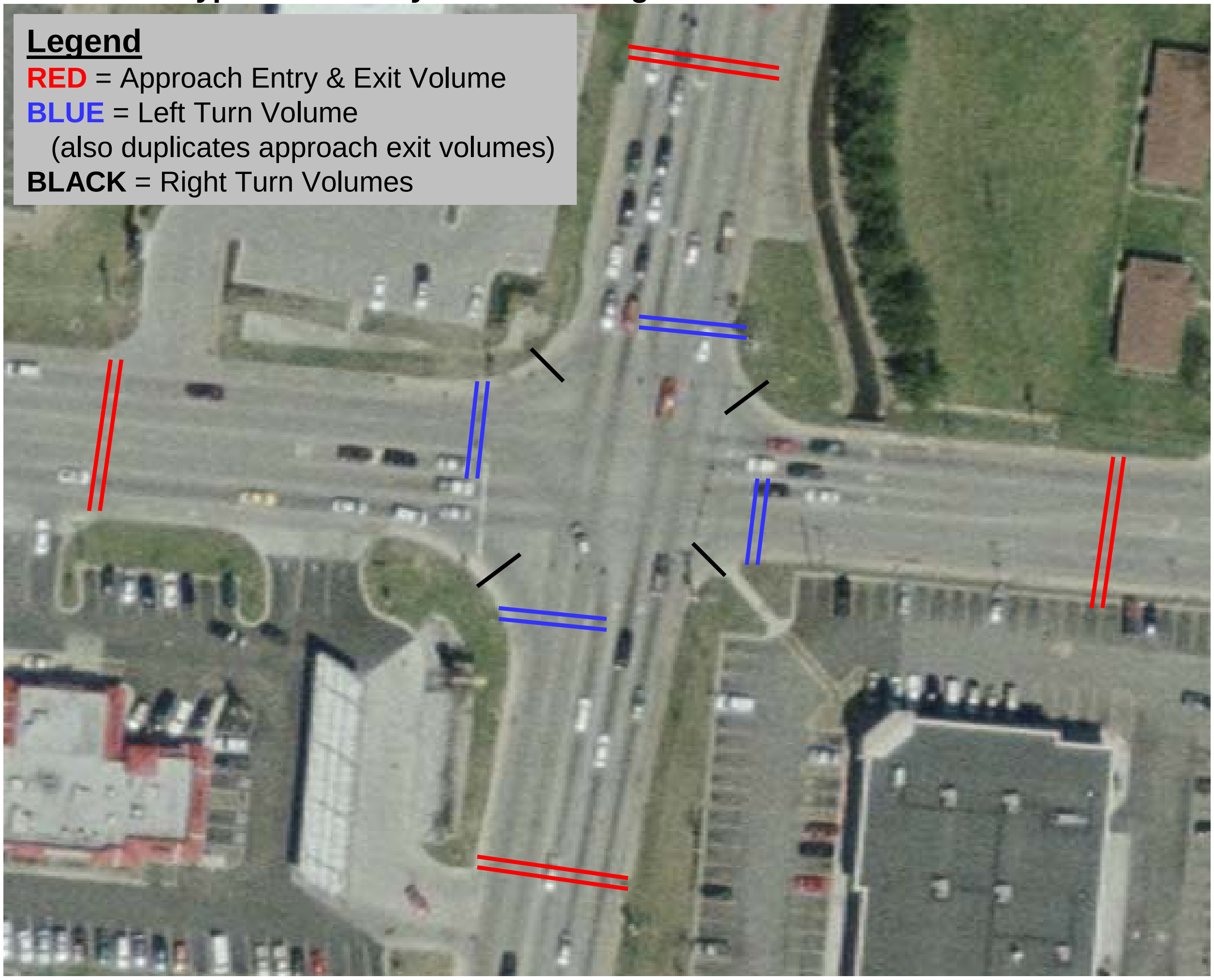
Front Panel

Hose Connections



Tubes on Roadway

Exhibit 4-8. Typical Tube Layout for Turning Movement Counts



4.4.2. How Tube Counters Work

Tube counters determine traffic volumes by counting the number of times each tube has been run over (actuated) and what time the actuation occurred. Assuming the tubes are installed correctly, each passenger car would result in two actuations as the vehicle crosses each tube. Vehicles with more than 2 axels would produce one actuation for each axel. Double tubes, usually placed 6-12 feet apart, can also determine the direction a vehicle is traveling based on the sequence of tube actuations.

As noted in Exhibit 4-8, the project team used double tubes across the entire roadway upstream of the intersection to gather total approach entry and exit volumes. Double tubes which crossed the exit lanes and entry left turn lanes were installed near the stop line to gather left turn volumes. These tubes also gave a duplicate count of approach exit volume, though this volume is less accurate than from tubes placed further away, as vehicles may not yet have completed their turning arcs when they cross these tubes. Finally, single tubes crossed the paths of right turning vehicles to gather right turn volumes.

Determination of volume is based on assumptions about the percentage of vehicles with a certain number of axels, resulting in an average number of actuations per vehicle. Then, the total actuations in a given time period can be divided by the average number of actuations per vehicle to determine the number of vehicles.

For this project, the average number of actuations per vehicle was assumed to be 2.0, or 100% passenger cars. Because of this, heavy vehicles like semi trucks will be counted as slightly more than one vehicle, resulting in an elevated volume. More advanced count techniques could be used to classify each vehicle and directly determine the average number of axels per vehicle, but this was considered unnecessary for this investigation.

4.4.3. Determining Intersection Volumes from Tube Counter Data

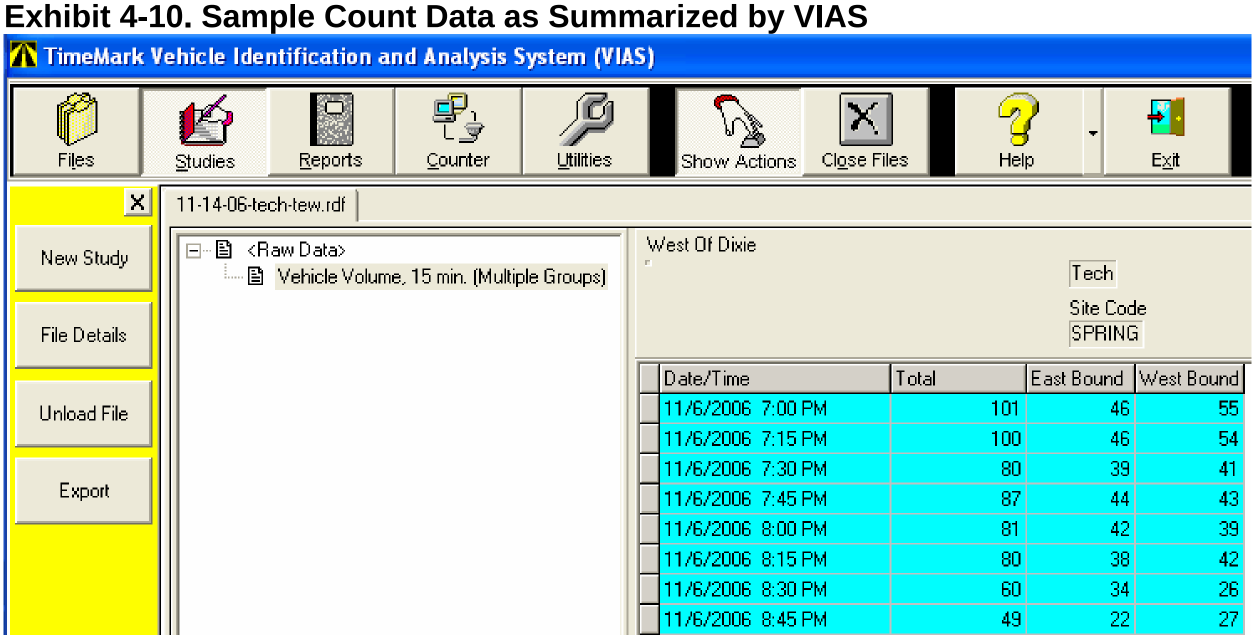
Raw tube counter data is simply a timestamp for each tube actuation. A sample of this data is shown in Exhibit 4-9.

Exhibit 4-9. Sample Raw Tube Counter Data

Date	Time	Tube 1	Tube 2	Date	Time	Tube 1	Tube 2
22-Nov-06	07:00:25.75		X	22-Nov-06	07:00:25.75		X
22-Nov-06	07:00:25.97	X		22-Nov-06	07:00:25.97	X	
22-Nov-06	07:00:26.01	X		22-Nov-06	07:00:26.01	X	
22-Nov-06	07:00:26.14		X	22-Nov-06	07:00:26.14		X
22-Nov-06	07:00:26.36	X		22-Nov-06	07:00:26.36	X	
22-Nov-06	07:00:26.40	X		22-Nov-06	07:00:26.40	X	
22-Nov-06	07:00:29.41	X		22-Nov-06	07:00:29.41	X	
22-Nov-06	07:00:29.70		X	22-Nov-06	07:00:29.70		X
22-Nov-06	07:00:29.76		X	22-Nov-06	07:00:29.76		X
22-Nov-06	07:00:30.19	X		22-Nov-06	07:00:30.19	X	
22-Nov-06	07:00:30.41	X		22-Nov-06	07:00:30.41	X	
22-Nov-06	07:00:30.47		X	22-Nov-06	07:00:30.47		X
22-Nov-06	07:00:30.61	X		22-Nov-06	07:00:30.61	X	
22-Nov-06	07:00:30.70		X	22-Nov-06	07:00:30.70		X
22-Nov-06	07:00:30.80		X	22-Nov-06	07:00:30.80		X
22-Nov-06	07:00:30.90		X	22-Nov-06	07:00:30.90		X
22-Nov-06	07:00:31.01		X	22-Nov-06	07:00:31.01		X
22-Nov-06	07:00:32.47	X		22-Nov-06	07:00:32.47	X	
22-Nov-06	07:00:32.71		X	22-Nov-06	07:00:32.71		X
22-Nov-06	07:00:32.96	X		22-Nov-06	07:00:32.96	X	
22-Nov-06	07:00:33.21		X	22-Nov-06	07:00:33.21		X

This raw data is then processed by vendor-provided software, in this case the TimeMark VIAS[12] software. This software package provides data summaries customized to the needs of the specific user. In this case, the goal was 15-minute counts for each direction at each set of tubes. A sample of such a summary as provided by the VIAS software is shown in Exhibit 4-10.

Exhibit 4-10. Sample Count Data as Summarized by VIAS



After gathering these summaries, two steps remained. The first was to average the data over multiple data collection days. This was done by porting the data to Microsoft Excel and determining the average traffic for non-holiday weekdays at each location for each interval.

The final step was to determine intersection turning movement volumes from the summarized tube count data. Generally, this was a straightforward process, as summarized in Exhibit 4-11.

Exhibit 4-11. Determining Intersection Turning Movement Volumes

Left Turn Volume	Taken Directly from Averaged Counts
Through Volume	Should Equal the Difference of These: Total Approach Entry Volume – Approach Left Turn Volume – Approach Right Turn Volume
Right Turn Volume	Taken Directly from Average Counts
Approach Exit Volume Check	Should Equal Sum of These: Left Turn Volume from first approach + Through Volume from second approach + Right Turn Volume from third approach

As noted above, the turning movement volumes used for each site can be found in Appendix A.

5. Experimental Design

This chapter focuses on the experimental design, including the base methodology, model selection, and treatment development. As noted above, the project made use of software-in-the-loop simulation (SILS) as the primary evaluation tool. The chapter begins with a more detailed look at with SILS is, then proceeds to discuss strategy development and implementation.

5.1. Software-in-the-Loop Simulation

One of the greatest challenges in testing new traffic signal control strategies is finding safe and repeatable conditions in which to implement such strategies. Field trials of unproven control strategies raise concerns about the safety of the motoring public (in the event a strategy fails to serve traffic well), and while daily traffic is generally predictable, normal daily fluctuations can unexpectedly bias experimental results.

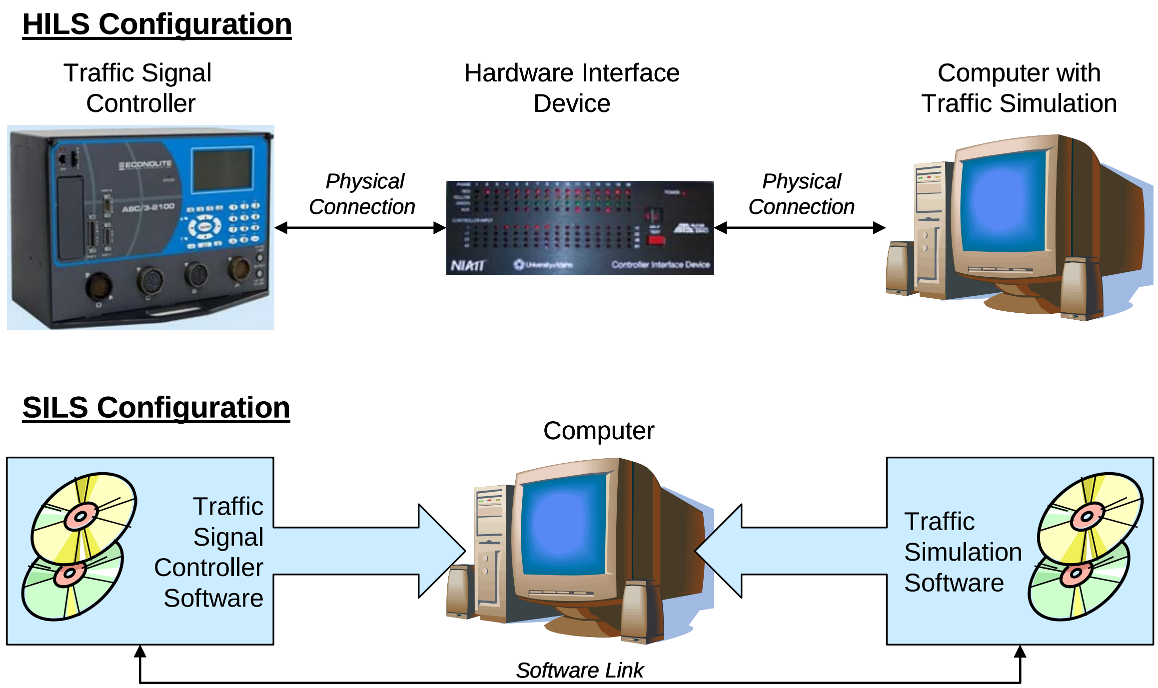
As a result, most initial strategy testing is done via simulation models. These models provide repeatable conditions and do not create safety issues when a strategy fails. They also provide the option of specifically testing a “worst case” scenario.

Unfortunately, most simulation models fail to accurately replicate traffic signal control as it would be provided by a field controller. As a result, some features simply could not be tested via simulation, or the results from such tests are questionable. To address these issues, hardware-in-the-loop simulation (HILS) allowed for direct connection of actual traffic signal controllers to computer based traffic simulation models.

While a great step forward in developing accuracy in testing of traffic signal operations, HILS had several drawbacks. Most notably, HILS requires all simulation to be done in “real time” – that is, one second of simulation had to take one second of real time. This greatly lengthened the simulation process. As a result, most studies either tested fewer treatments or used fewer replications of each treatment.

Recently, advances in software technology and development have allowed for a “next generation” to evolve, namely sogtware-in-the-loop simulation (SILS). SILS replaces the hardware connections in HILS with a software connection, a replacement made possible by porting the traffic signal controller software onto the same computer as the traffic simulation model. A schematic of HILS and SILS is shown in Exhibit 5-1.

Exhibit 5-1. Schematic of HILS and SILS



5.2. Software Used

At the time of this research, there was only one modern traffic signal controller software package readily available for the SILS environment, namely the Econolite ASC/3[13] (the ASC/3 SIL). While multiple traffic simulation packages were available, the project team chose the VISSIM[14] model from PTV for use in the project. VISSIM provided the best combination of capabilities and professional respect of the available simulation models. More specific information about the use of these software packages is provided later.

5.3. Simulation Experiments

For each site, the project team wanted to determine how well a single generic VMGT strategy would operate. To achieve this goal, the team prepared three traffic signal treatments for each site – default, optimized, and VMGT. These treatments differed in only one parameter: the maximum green time.

The default treatment represented a worst case scenario. After an investigation into the default parameters provided by various traffic signal controller manufacturers, a maximum green time of 20 seconds was chosen as the worst case. This should provide operations similar to a controller which has never been adjusted based on existing traffic conditions – it still has its original defaults.

The optimized treatment represented a best case scenario. The goal of this treatment was to replicate operations resulting from an agency determining and using optimized maximum green times. These times could be provided by an on-staff traffic engineer or by hiring a consulting firm. To truly provide a best case scenario, the project team chose to provide three sets of maximum greens which would be used based on time of day. While most rural agencies would provide only one set of maximum green times to use all day, providing three sets should improve overall operations, and make the results of the investigation more applicable to larger areas as well.

To determine the three sets of maximum green times, the project team first determined the AM, Noon, and PM peak volumes. Optimized maximum green times were determined from these volumes using the PASSER V-03[15] model. Times based on the AM and PM peak volumes were used during their respective peak hours, plus half an hour before and after the peak. The maximum green times used the remainder of the day were based on the Noon peak volumes. This is a typical schedule.

The final treatment was a test of generic VMGT parameters. As noted above, prior research typically based VMGT parameters on optimized green times. In contrast, this study determined one set of VMGT parameters for use at all sites, regardless of optimal timing.

The first parameter required was the normal maximum green time. This is the lower bound for maximum green, and is the starting point from which the maximum can increase based on traffic. To be consistent with the default treatment, the project team chose 20 seconds as the normal maximum green time.

The next parameter required was the dynamic maximum green time. This is the upper bound for maximum green – the controller will not exceed this value even when continually maxing out. To avoid selecting a value based on the optimized timings, the project team discussed an appropriate maximum with local traffic signal maintenance personnel from the City of Cookeville. Based on this and other input, 60 seconds was chosen.

The final parameter was the dynamic step. This is the amount the maximum green time will increase or decrease each time a change is warranted. This is an important balancing parameter in VMGT operations. A large step size can quickly respond to excess traffic, providing additional green time quickly; however, that same large step size causes the maximum green to drop quickly after successive gap outs, and may reduce capacity too quickly. A small step size preserves capacity as the maximum slowly reduces, but may not increase fast enough to keep up with rising demand. After due consideration, the project team chose 10 seconds as the step size.

5.4. The "Existing" Treatment

While specific results are presented later in this report, there were issues with the optimized treatment for Site 3. At this site, the Passer V-03 model apparently did not produce reasonable optimized values, as the performance of the optimized treatment was almost identical to the performance of the default treatment. To address this issue, the project team chose to use the maximum green times currently in use in the field. This is called the existing treatment, and is only used for Site 3.

6. Simulation Inputs and Outputs

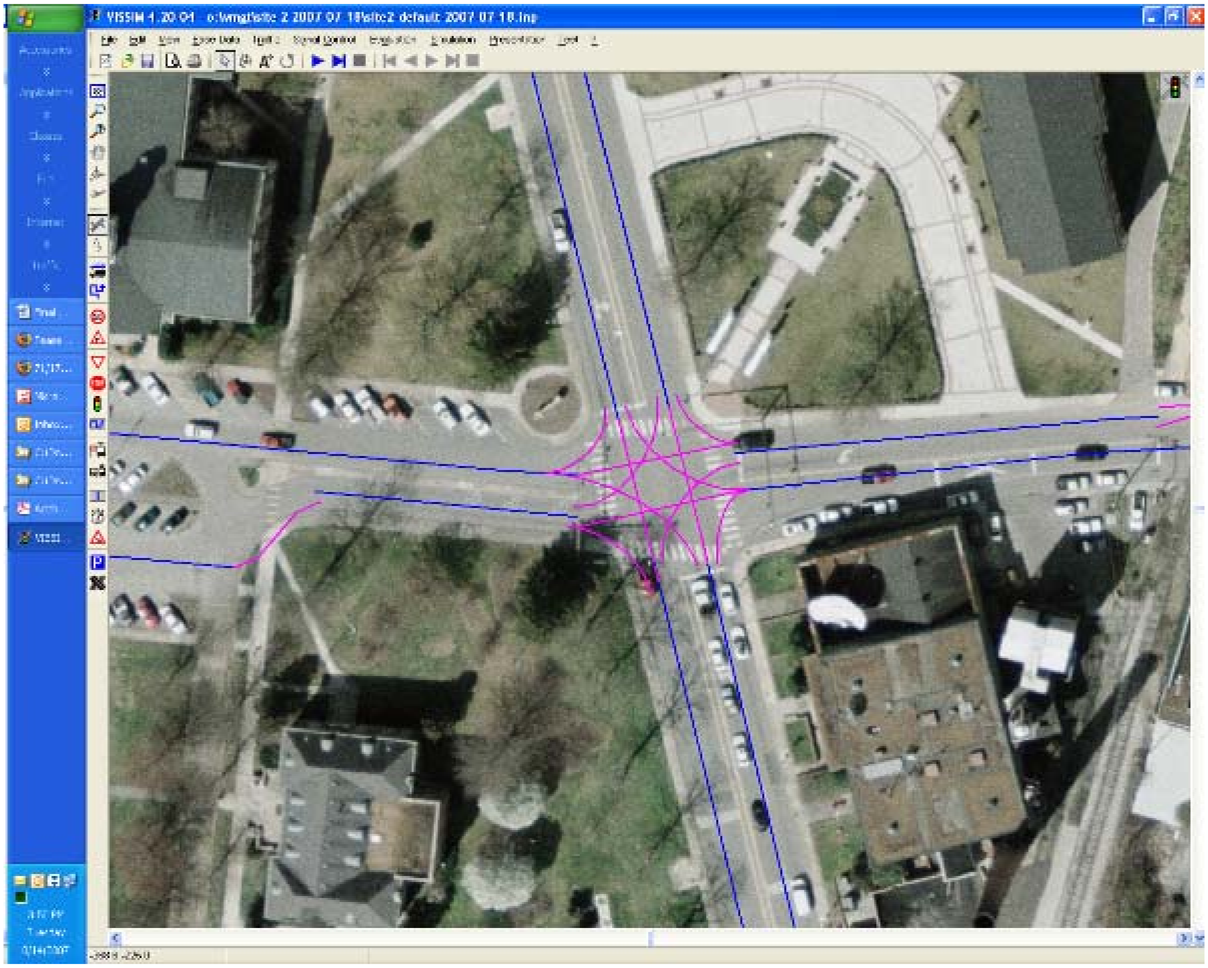
As noted above, this research made use of the VISSIM traffic simulation model with the Econolite ASC/3 SIL. This chapter begins with an overview of the input process: developing the network and programming the ASC/3 SIL, and then concludes with a description of the raw output data and the processes used to summarize it. Note that depending on the complexity of a network, the simulation development process can take from several hours to several weeks, so the discussion of the input process is necessarily a brief, very general overview.

6.1. The Input Process

6.1.1. Links and Connectors

The first step was to create the network of links and connectors over which traffic would flow. This process can be simplified by use of an aerial image as a background on which to draw the network. An example is provided in Exhibit 6-1. For this research, entry and exit links were typically 1000 feet, in order to capture all the delay associated with the signal.

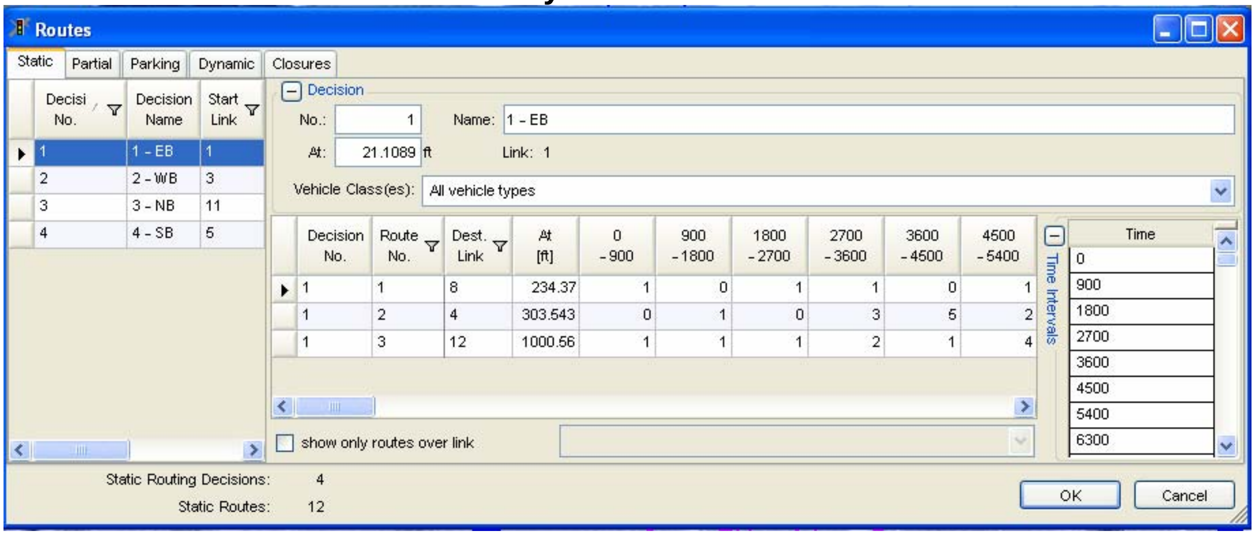
Exhibit 6-1. VISSIM Links and Connectors



6.1.2. Vehicle Inputs and Routes

As shown in Appendix A: Intersection Turning Movement Counts, volumes for each site were entered for each of the twelve standard turning movements in fifteen minute intervals over a sixteen hour simulation period, starting at 6:00 AM and ending at 10:00 PM. A sample of the route data entry dialogue is given in Exhibit 6-2. Note that in VISSIM, time is referenced in seconds, so the 0-900 second interval represents 6:00 to 6:15 AM.

Exhibit 6-2. VISSIM Route Data Entry



6.1.3. Distributions: Speed and Traffic Composition

The VISSIM model allows the user to input several distributions, which help to control how traffic behaves on the network. Two important distributions are the desired speed distribution and the traffic composition distribution.

The desired speed distribution helps to account for the fact that all vehicles do not travel at exactly the same speed. For this study, specific speed studies were not performed, so a general set of speed distribution rules were determined based on the posted speed limit for each link. Essentially, the 15% and 85% desired speeds were assumed to be -/+ 3 mph from the speed limits, and the minimum and maximum desired speeds were assumed to be -/+ 6 mph from the speed limit. Speed distributions during turns were centered on 9 mph for right turns and 15 mph for left turns. These are reasonably standard turn speed values.

The traffic composition distribution helps to account for the fact that not all vehicle types have the same acceleration and deceleration capabilities. As with speed, no specific vehicle classification study was performed, so a general traffic composition was used.

In this case, the project team chose to use a predefined composition which included 96% cars and 4% trucks.

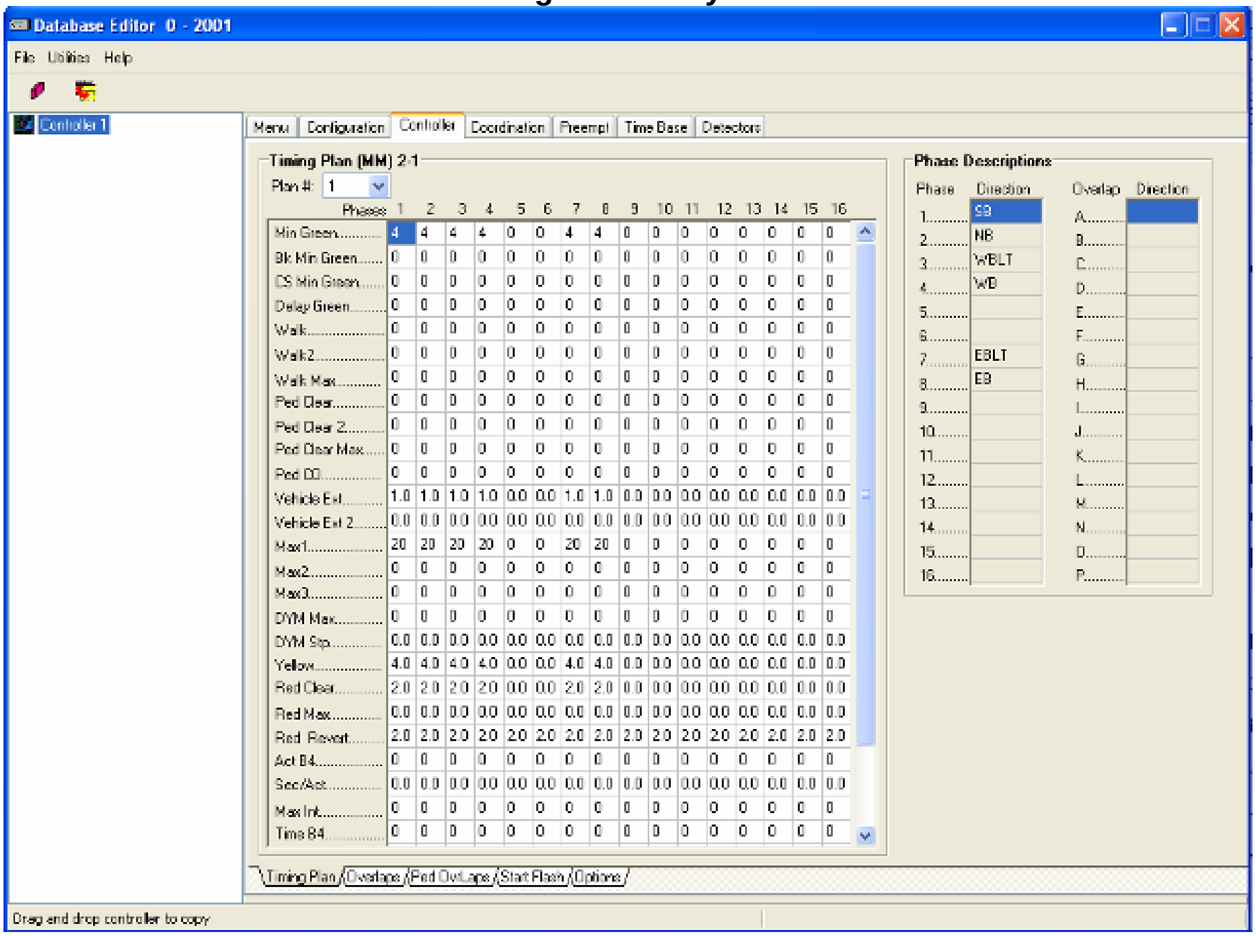
6.1.4. Traffic Signal Programming

The traffic signal programming involved two separate elements, one in VISSIM and one in the ASC/3 SIL.

In VISSIM, the first step is to locate the stop line for each phase. Then, priority rules for permitted and protected-permitted left turns are required, including any left turn sneaker preferences (how many vehicles will make a permitted left turn when the yellow interval begins). Based on observation of local behavior, and with the general understanding that rural traffic tends to be less aggressive than urban traffic, the project team decided to only allow a single left turn sneaker vehicle per phase.

Most of the traffic signal operating parameters were entered via the ASC/3 SIL. Phases in use, phase sequence, phase timing parameters, loop and gap settings, and time of day schedule information were all entered here. For each site, location specific minimums, clearance intervals, and gap settings were applied. At a given site, the only differences between ASC/3 SIL data were to vary the maximum green treatments as described above. A sample screen from the phase timing parameter data entry dialogue is shown in Exhibit 6-3.

Exhibit 6-3. ASC/3 SIL Phase Timing Data Entry



Phases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Min Green	4	4	4	4	0	0	4	4	0	0	0	0	0	0	0	0
Bk Min Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CS Min Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Delay Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walk2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walk Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped Clear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped Clear 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped Clear Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped CO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vehicle Ext	1.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vehicle Ext 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max1	20	20	20	20	0	0	20	20	0	0	0	0	0	0	0	0
Max2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DYM Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DYM Stp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Yellow	4.0	4.0	4.0	4.0	0.0	0.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Clear	2.0	2.0	2.0	2.0	0.0	0.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Revert	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Act B4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sec/Act	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Int	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time B4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Phase	Direction	Overlap	Direction
1	SB	A	
2	NB	B	
3	WBLT	C	
4	WB	D	
5		E	
6		F	
7	EBLT	G	
8	EB	H	
9		I	
10		J	
11		K	
12		L	
13		M	
14		N	
15		O	
16		P	

6.1.5. Treatment Replications

When using a stochastic traffic simulation model, multiple replications of each simulation are required to determine appropriate confidence intervals. While there has been much discussion of the required number of replications, Click[16] tested the convergence of results and concluded that 10 replications should be sufficient, so this research used 10 replications of each treatment.

6.2. Raw Output Data and Output Data Summaries

6.2.1. Throughput and Delay Data

Both the throughput and delay analyses were based on the same raw output, called the delay table. This output, which is transferred by the VISSIM model directly into a Microsoft Access[17] database table, provides information for each vehicle at it completes its trip through the network. This information includes the vehicle type, an identification number, the path the vehicle followed through the network, the time at which the vehicle exited the network, and the amount of delay experienced by the vehicle during its trip. A sample subset of this output data is found in Exhibit 6-4.

Exhibit 6-4. Sample VISSIM Delay Table

Vehicle ID	Vehicle Type	Path Number	Arrival Time	Delay
2	100	22	29.9	0.0
4	100	31	65.9	1.1
3	100	12	71.6	35.0
1	100	13	75.4	31.9
6	100	12	79.7	0.0
5	100	31	94.8	4.7
8	100	12	117.3	18.2
9	100	12	119.0	11.9
7	100	13	120.4	15.2
10	100	12	121.3	5.1

To determine the throughput for a given interval, entries were sorted based on arrival time, then a count taken for each 15 minute interval. Counts could be made at the movement, approach, and intersection level. Counts from each iteration were combined to determine an average and a standard deviation.

To determine the delay for a given interval, entries were again sorted based on arrival time; then the delay values were averaged over each 15 minute interval. Again, delay could be determined at the movement, approach, and intersection level. Delays from each iteration were combined to determine an average and a standard deviation.

After throughputs and delays were summarized in Access, the resulting tables were transferred to Microsoft Excel[18] for further processing, primarily to allow the creation of charts and graphs.

6.2.2. Traffic Signal Data

The second raw output of interest was called the signal table, another output which VISSIM provides as an Access database table. This table lists every state change for every traffic signal in the network, including the signal identification number, the phase number, the time of state change, the new state, and the duration of the previous state. A sample of this data is found in Exhibit 6-5.

Exhibit 6-5. Sample VISSIM Signal Table

Signal ID	Phase	SimTime	State	Prev. Duration
2001	8	4011.6	green	51.3
2001	8	4019	amber	7.3
2001	8	4023	red	4
2001	2	4025	green	15.4
2001	2	4029	amber	4
2001	2	4033	red	4
2001	1	4035	green	44.8
2001	1	4039	amber	4
2001	1	4043	red	4
2001	2	4045	green	12

As with the delay table, the signal table can be sorted by simulation time and then summarized in 15 minute intervals. The key statistics that can be determined from this table are the average green for each phase and the number of cycles (and thus apparent average cycle length) for each interval. Again, averages over multiple replications are determined and then transferred to Excel.

7. Results of the Initial Simulation Experiments

This chapter presents the results of the initial simulation experiments. The results of these initial experiments are broken down into three sections – throughput analysis, delay analysis, and signal analysis.

7.1. Throughput Analysis

The first consideration in evaluating the effectiveness of VMGT is: Can a signal using VMGT serve the same amount traffic as a signal using optimized timings? Using the summarized data as discussed above, the project team plotted the total volume served in each 15 minute interval for comparison between treatments. Then, to help ensure that smaller differences were not hidden at the intersection level, the project team compared the approach level volumes for the AM, midday, and PM peak periods.

7.1.1. Site 1 Throughput Analysis

The intersection volumes for Site 1 are shown in Exhibit 7-1, and the approach peak hour volumes are shown in Exhibit 7-2. These exhibits include vertical range bars, which indicate the standard deviation for each treatment in each interval. When these ranges overlap for two treatments, the difference is unlikely to be significant, though the general trend may still hold true.

Exhibit 7-1. Site 1 Intersection Throughput

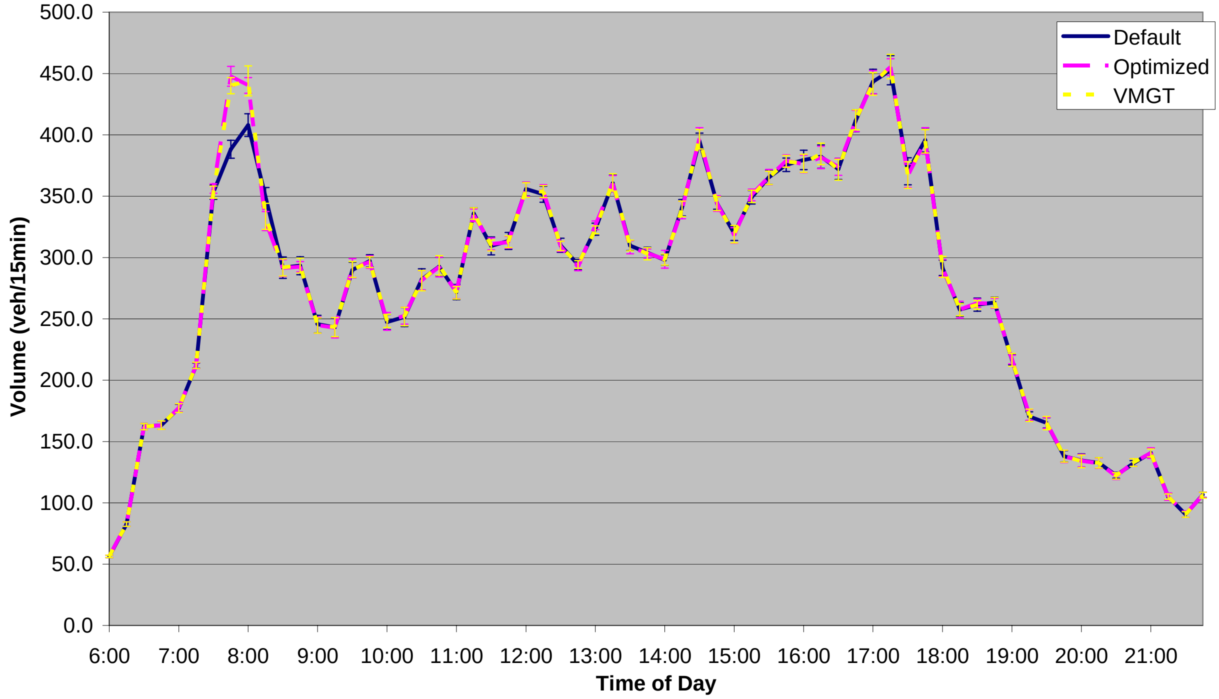
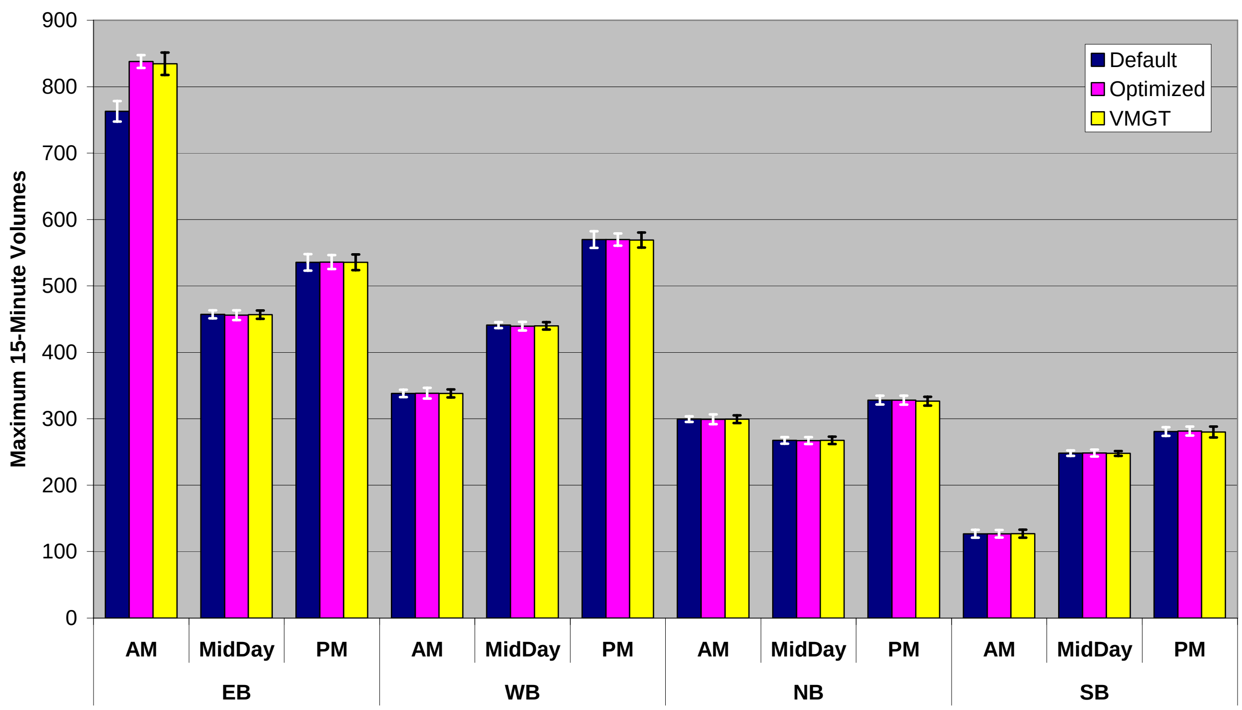


Exhibit 7-2 Site 1 Approach Throughput



At Site 1, the VMGT treatment was able to serve essentially identical volumes to the optimized. While the AM peak did show a difference between these treatments and the default, the rest of the day showed equal throughput for all treatments.

During the AM peak, only the EB approach showed differences in throughput. Clearly, the demand on this approach exceeds the capacity of the default treatment, but is served equally by both the optimized and the VMGT treatments.

7.1.2. Site 2 Throughput Analysis

The intersection volumes for Site 2 are shown in Exhibit 7-3, and the approach peak hour volumes are shown in Exhibit 7-4. As before vertical range bars indicate the standard deviation for each treatment.

Exhibit 7-3. Site 2 Intersection Througput

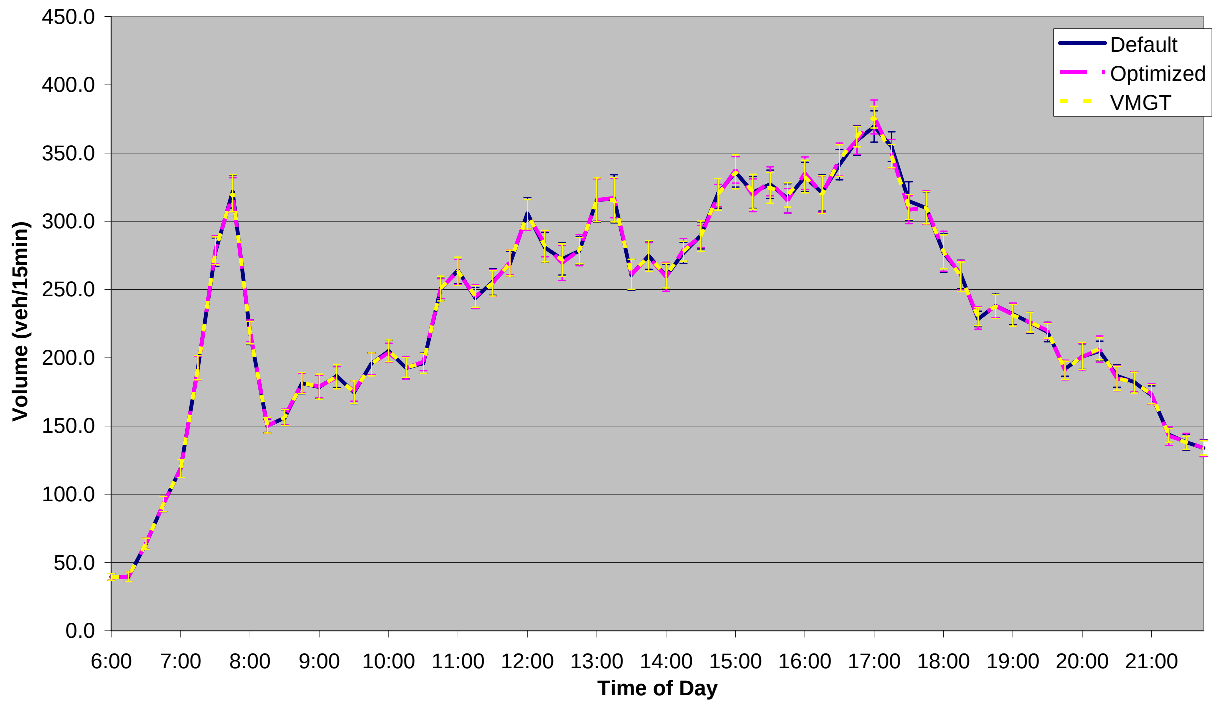
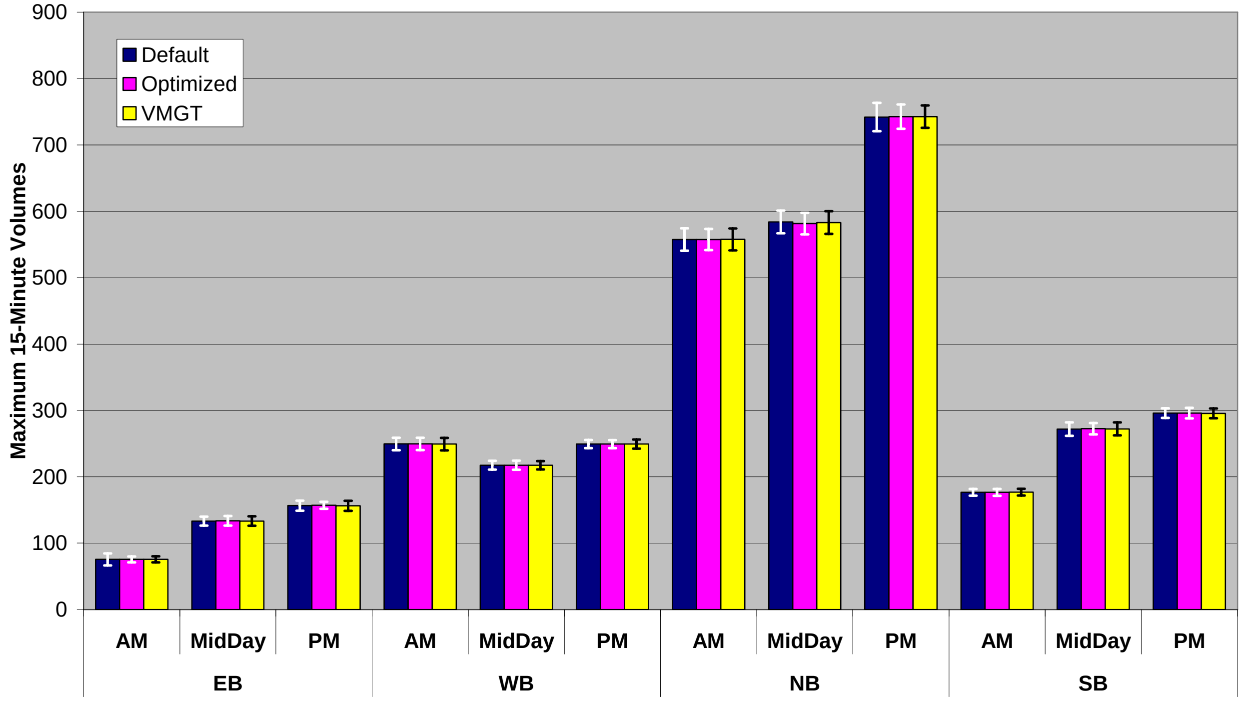


Exhibit 7-4. Site 2 Approach Throughput



At Site 2, the demand was low enough that all three treatments had sufficient capacity throughout the day. There were no discernable differences at the intersection or approach level.

7.1.3. Site 3 Throughput Analysis

The intersection volumes for Site 3 are shown in Exhibit 7-5, and the approach peak hour volumes are shown in Exhibit 7-6.

Exhibit 7-5. Site 3 Intersection Throughput

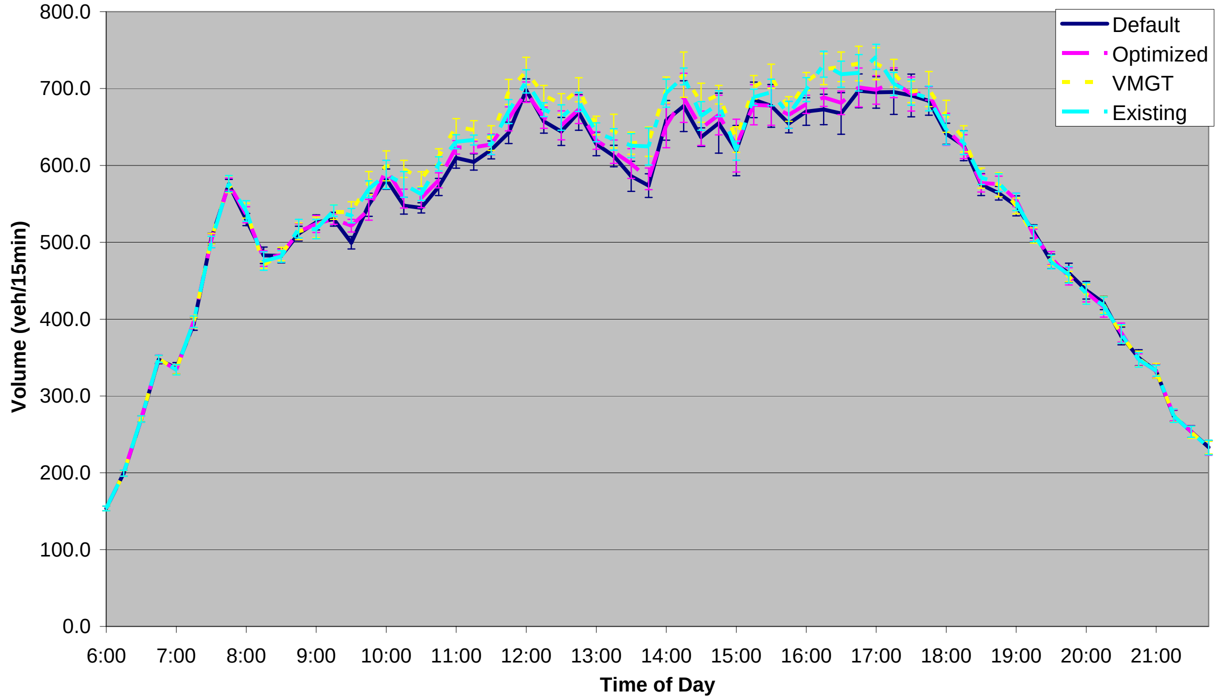
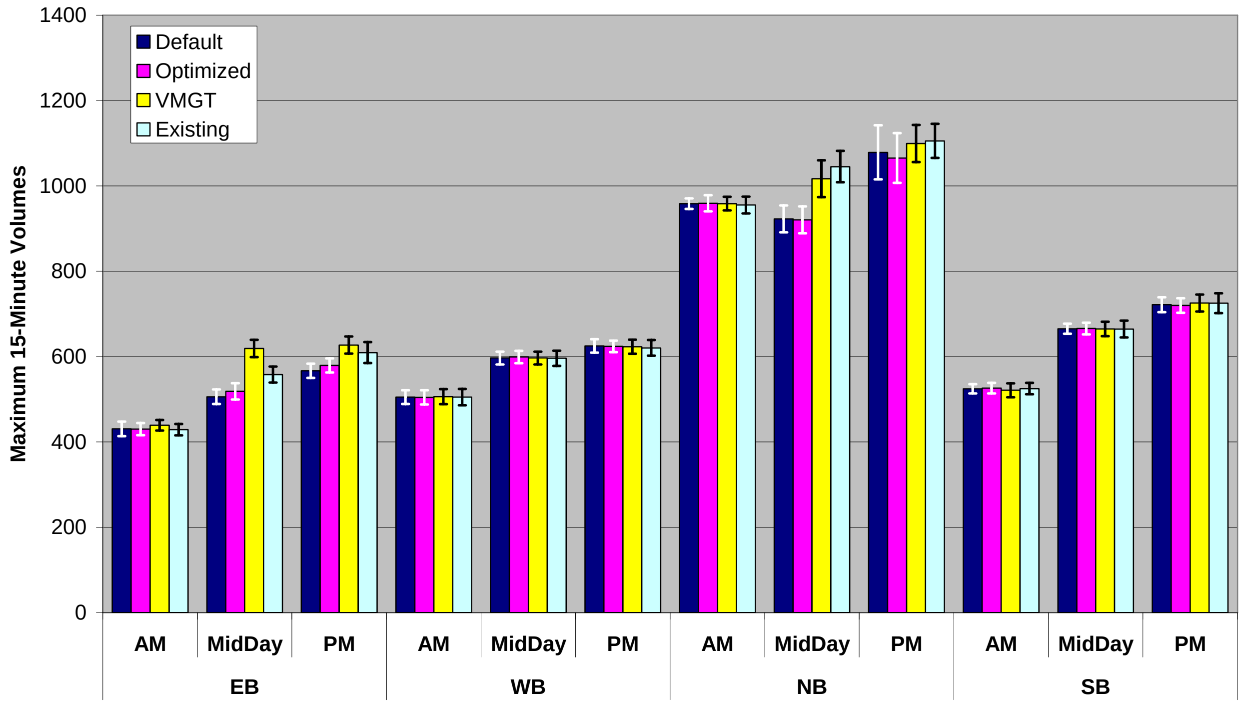


Exhibit 7-6. Site 3 Approach Throughput



As noted in Chapter 5, the optimized green times provided by PASSER V-03 did not perform well at Site 3. More discussion of these issues follows later in this chapter. For that reason, the existing treatment, which used the maximum green times currently programmed in the field, is shown and considered the “optimal” solution.

Unlike the prior sites, there are minor differences in intersection throughput from around 9:00 to 18:00. While most of these differences are still within the range of one standard deviation, the general trend indicates that VMGT provided more total throughput than the other treatments.

Inspection of the approach information reveals addition details. All the treatments served both the WB and SB approaches equally. On the EB approach, the VMGT treatment served the highest volume, especially during the MidDay peak, when its volume is significantly higher than any of the others. On the NB approach, the existing treatment served slightly more volume than all the others, though the difference between the existing and VMGT is still within the standard deviation range.

7.1.4. Conclusions: Throughput

Based on these three sites, a traffic signal using these generic VMGT parameters can be expected to provide equal and perhaps better intersection throughput than a signal using optimized green times. While the total throughput is at least equal, different approaches may experience higher or lower throughputs based on the current distribution of green time.

7.2. Delay Analysis

The second consideration in evaluating the effectiveness of VMGT is: Can a signal using VMGT serve traffic with the same or better delay than a signal using optimized timings? To investigate this issue, the project team investigated two component parts: the total intersection delay and the worst approach delay.

Comparison of total intersection delay provides an overall picture of how well the intersection is operating. Comparison of the worst approach delay provides insight into how equally the delay is spread to all vehicles. Note that the worst approach delay is selected for each interval, not globally for the entire day.

The project team also made comparisons of the worst movement delay. These results showed the same trends as the investigation into the worst approach, so they are not presented herein.

7.2.1. Site 1 Delay Analysis

The average intersection delay for Site 1 is shown in Exhibit 7-7. As before, the vertical range bars indicate the standard deviation. The worst average approach delay is shown in Exhibit 7-8.

Exhibit 7-7. Site 1 Average Intersection Delay

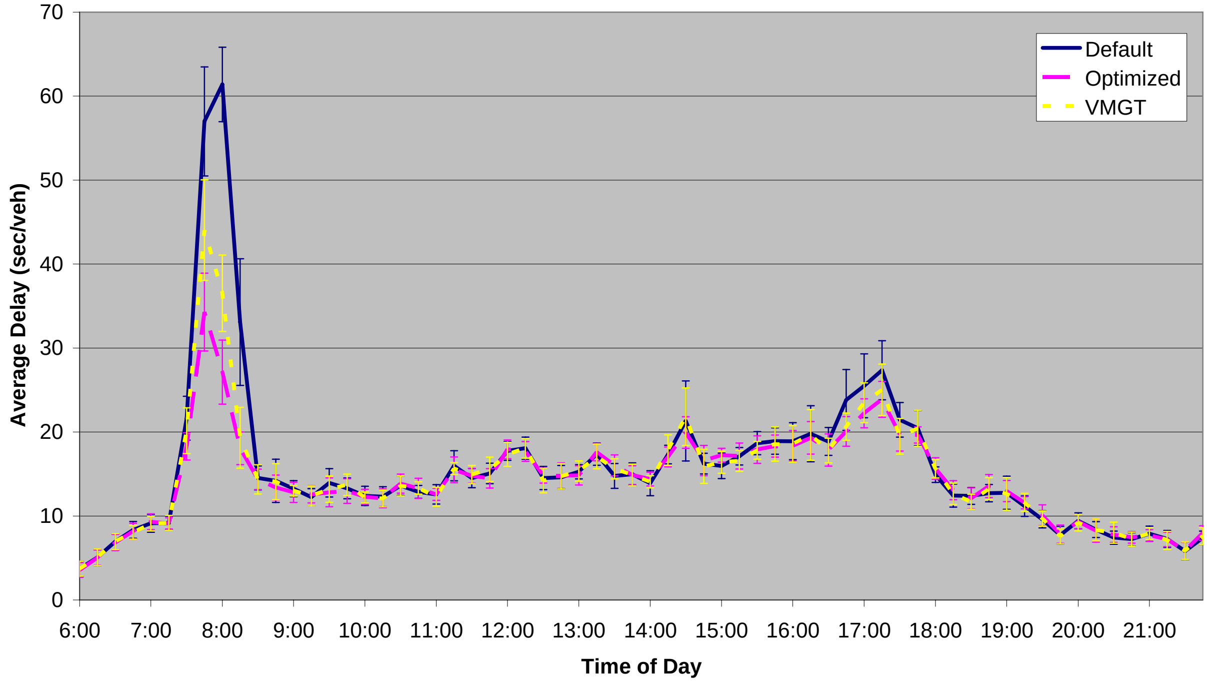
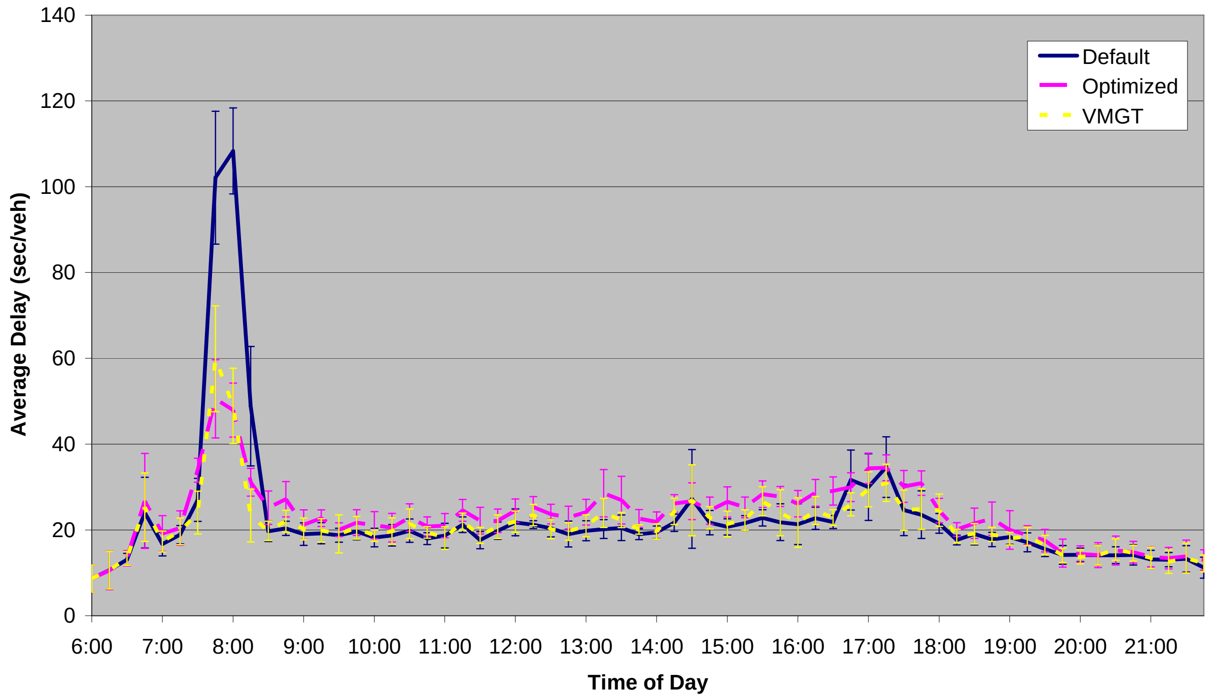


Exhibit 7-8. Site 1 Worst Average Approach Delay



As with throughput, the time of greatest differentiation is the AM peak. During this interval, the optimized treatment has the lowest average intersection delay, and the difference between it and VMGT is greater than the standard deviation. The VMGT is also significantly lower than the default.

The differences are much less pronounced when considering the worst approach. Here, both the optimized and the VMGT are significantly lower than the default during the AM peak, but the difference between optimized and VMGT is less than the standard deviations, though the trend is that the optimized is still provides lower delay than VMGT.

During the remainder of the day, all three treatments provide similar average intersection delays, and only marginally different worst average approach delays. The trend in worst average approach delay was surprising: the optimized treatment was most frequently the highest delay. This indicates that the optimized signal is penalizing one or more light volume approaches in favor of heavier volume approaches.

7.2.2. Site 2 Delay Analysis

The average intersection delay for Site 2 is shown in Exhibit 7-9, and the worst average approach delay is shown in Exhibit 7-10.

Exhibit 7-9. Site 2 Average Intersection Delay

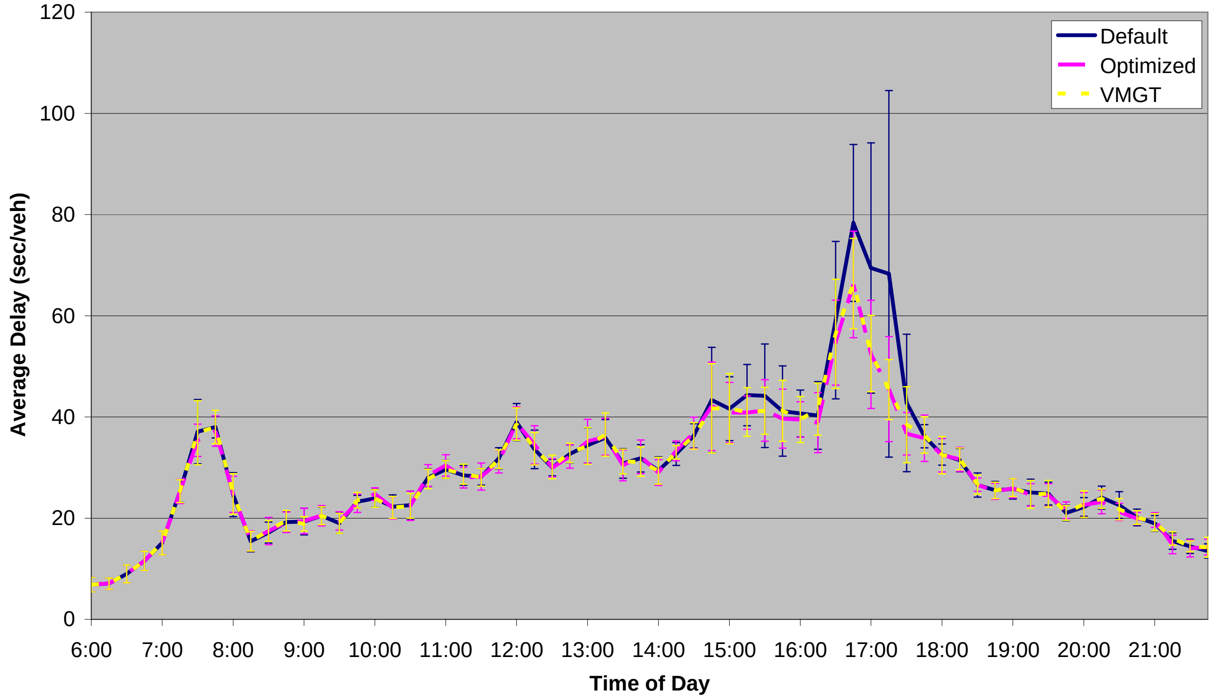
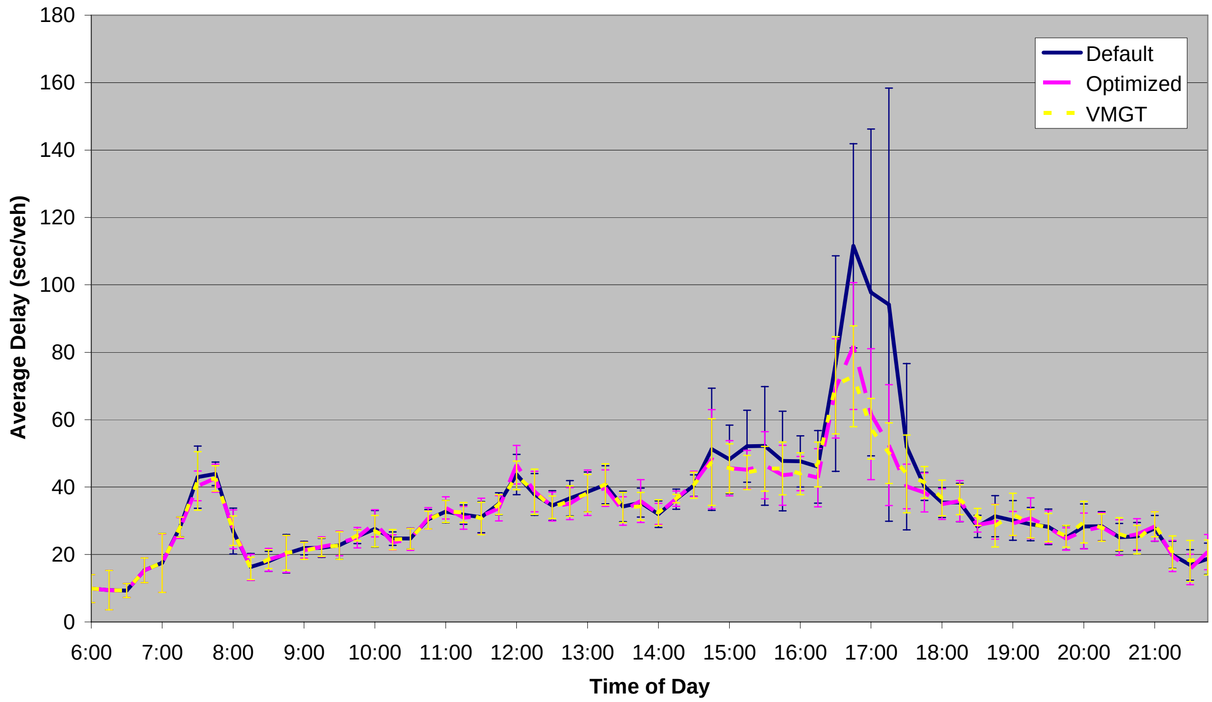


Exhibit 7-10. Site 2 Worst Average Approach Delay



At Site 2, the optimized and VMGT treatments performed almost identically through the entire day both in average intersection delay and in worst average approach delay. None of the intervals showed a difference greater than the standard deviations, and the only time period in which there was a noticeable difference was between 16:00 and 18:00, when the VMGT provided a slightly better worst average approach delay initially, and the optimized later.

7.2.3. Site 3 Delay Analysis

The average intersection delay for Site 3 is shown in Exhibit 7-11.

Exhibit 7-11. Site 3 Average Intersection Delay

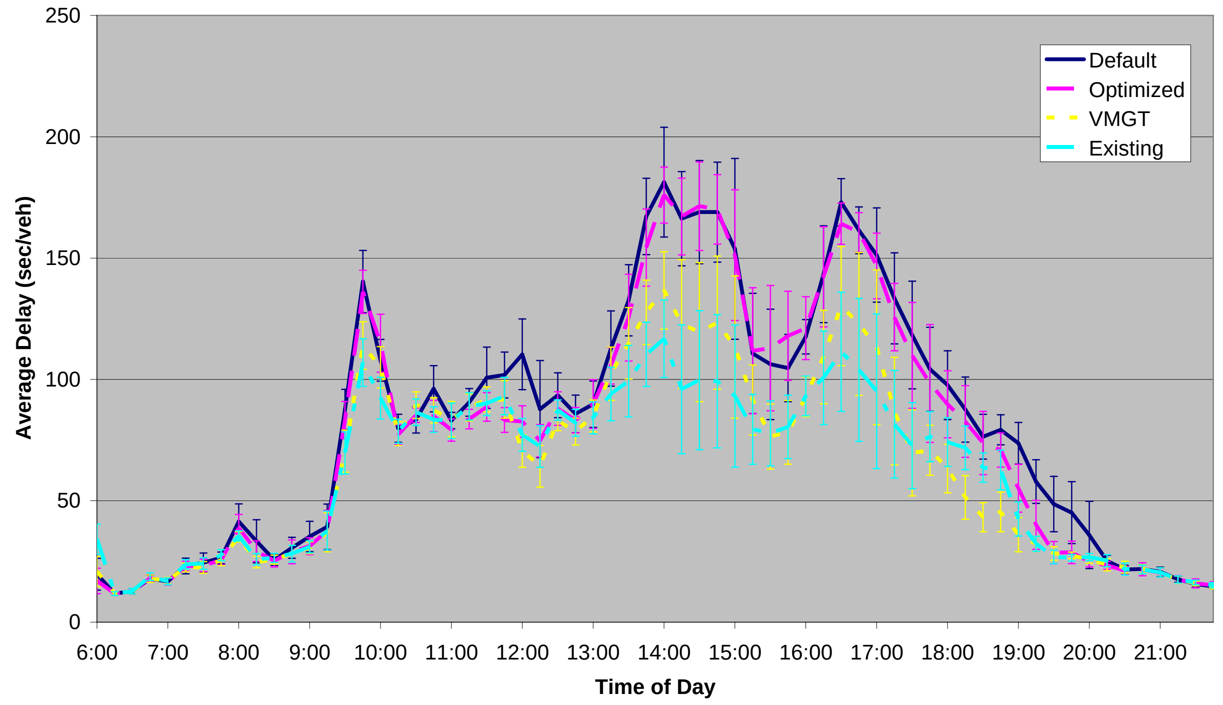


Exhibit 7-11 illustrates the problem with the optimized treatment at Site 3, first discussed in Chapter 5. The optimized treatment provided only marginally better delays than the default treatment, causing the project team to question the PASSER V-03 results for this site. Because of this issue, the project team decided to include an additional treatment, the existing treatment, which would evaluate the existing field settings. Based on the results shown, this clearly provided for better intersection delays than the optimized treatment, so it is used as the basis of comparison.

As would be expected with its higher volumes, Site 3 experiences significantly more delay than Site 1 and 2, and also experiences greater differentiation in delay between treatments. All three treatments perform reasonably similar until about 9:00, after which both the existing and the VMGT provide for improved operations when compared to the default.

During the majority of the afternoon, the existing timing provides for better performance than the VMGT; however, these differences typically remain less than the standard deviations and may not be significant. There are also periods, most notably in the early evening, when the VMGT provides for better operations than the existing treatment, with some differences greater than the standard deviations.

Because of the increased complexity of delay comparisons at this site, a more detailed numerical analysis of the delay results is provided in Exhibit 7-12. This table provides summarized delay data for four hour time blocks, the peak hour within each of those blocks, and the peak 15 minutes within those blocks. Note that in the table, negative values indicate a reduction in delay.

Exhibit 7-12. Site 3 Analysis of Average Intersection Delay Differences

		Morning			MidDay			Afternoon			Evening		
		Full Interval	Peak Hour	Peak 15-min	Full Interval	Peak Hour	Peak 15-min	Full Interval	Peak Hour	Peak 15-min	Full Interval	Peak Hour	Peak 15-min
Start Time		6:00	7:30	7:45	10:00	11:30	13:15	14:00	16:30	17:15	18:00	18:00	18:00
End Time		10:00	8:30	8:00	14:00	12:30	13:30	18:00	17:30	17:30	22:00	19:00	18:15
Avg Delay (sec/veh)	Default	41.1	76.1	140.3	101.3	104.4	132.6	141.2	149.0	143.4	53.8	85.6	97.7
	Existimized	36.5	62.2	107.0	87.6	89.7	99.3	92.5	102.4	100.7	40.6	68.3	74.1
	VMGT	36.3	64.2	113.9	89.6	94.7	114.9	103.7	114.0	109.2	34.3	51.3	63.3
Delay Difference (sec/veh)	Exist - Def	-4.6	-13.9	-33.4	-13.7	-14.7	-33.3	-48.7	-46.6	-42.7	-13.2	-17.3	-23.5
	VMGT - Def	-4.8	-11.9	-26.4	-11.6	-9.7	-17.7	-37.5	-35.0	-34.2	-19.5	-34.4	-34.4
	VMGT - Exist	-0.2	1.9	7.0	2.1	5.0	15.6	11.3	11.6	8.6	-6.3	-17.0	-10.9
Percent Difference	Exist - Def	-11%	-18%	-24%	-14%	-14%	-25%	-35%	-31%	-30%	-25%	-20%	-24%
	VMGT - Def	-12%	-16%	-19%	-11%	-9%	-13%	-27%	-23%	-24%	-36%	-40%	-35%
	VMGT - Exist	0%	3%	5%	2%	5%	12%	8%	8%	6%	-12%	-20%	-11%

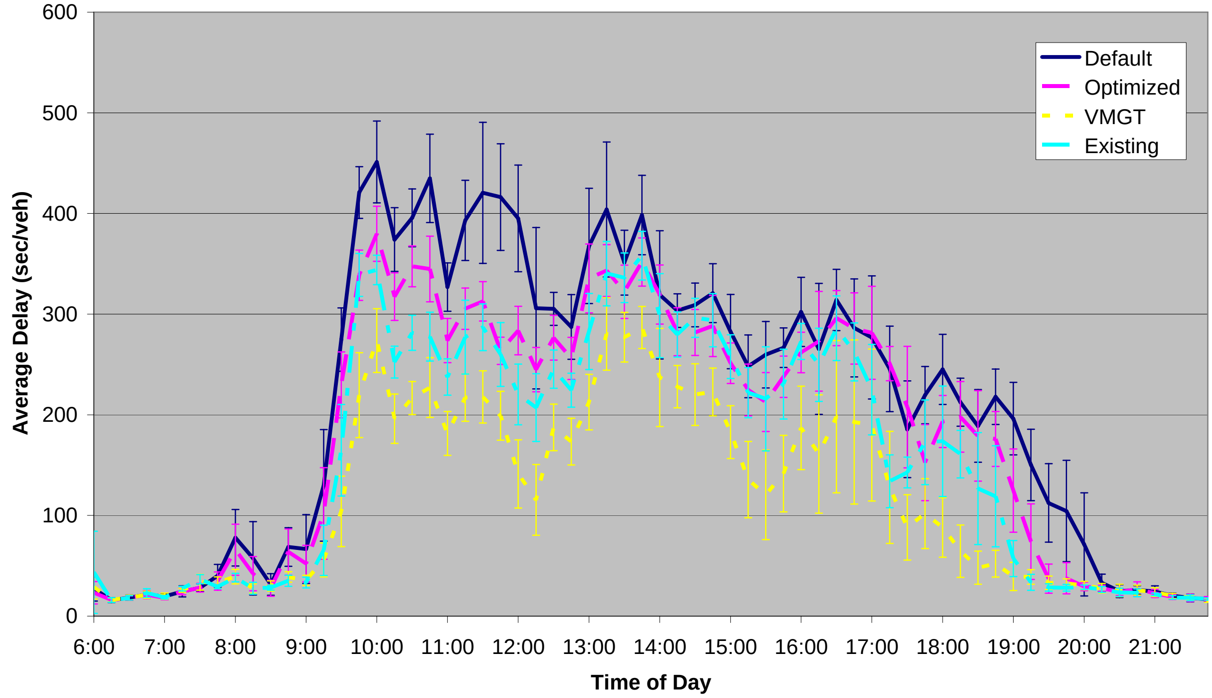
As noted above, both the existing and VMGT result in less delay than the default treatment. These differences range from about 10-40%, depending on time of day and length of interval considered. With the exception of the evening period, the existing and VMGT treatments appear to provide reasonably similar reductions in delay, typically within about 10% of each other.

In the morning, midday, and afternoon blocks, the existing treatment tends to slightly outperform the VMGT, though there are individual intervals where the reverse is true. In the evening, the reverse is true: the VMGT provides for the best delay.

This suggests a potential benefit from VMGT operations. Traffic signal optimization tends to focus on the AM and PM peak period, with occasional consideration of the Noon peak. Few agencies, rural or otherwise, have the resources to provide optimized timing for periods other than these. VMGT, on the other hand, continually adjusts itself to match traffic conditions, providing reasonable timing even during intervals that traditional optimization would not consider – late evening, weekends, and holidays.

The worst average approach delay comparison also produced some interesting results, as seen in Exhibit 7-13.

Exhibit 7-13. Site 3 Worst Average Approach Delay



For the majority of the day, the VMGT treatment provides for the lowest worst average approach delay. Given its reasonable equivalence to the existing in average intersection delay, this indicates that the VMGT treatment is providing a more equal distribution of delay among the approaches at this site. As seen with Site 1, the existing treatment apparently favors some approaches over others, resulting in slightly lower intersection delays but an unequal distribution of delay across all traffic.

7.2.4. Conclusions: Delay

With a few exceptions, the generic VMGT timing parameters proved able to provide equivalent delays to optimal traffic signal settings. One such exception was at Site 1 during the AM peak, where the VMGT provided better delay than the default, but not as good as the optimized. This issue will be the focus of a potential VMGT strategy revision, discussed in the next chapter.

For the remainder of the day at Site 1, and for the entire day at Site 2, the VMGT and optimized delays were essentially the same. At Site 3, the relationship was more complex. During the morning, midday, and afternoon, the optimized treatment provided a slightly better delay, but the difference was not significant. In the evening, VMGT provided for better delay, and the difference was significant during several intervals.

When looking at worst average approach delay, VMGT proved to be as good or better than optimal timing. At Sites 1 and 2, the VMGT and optimized treatments gave equivalent results, while at Site 3 the VMGT provided a significantly lower worst average approach delay than the existing.

This raises a question related to traffic management strategies – some agencies would prefer a slightly higher intersection delay that resulted in an equal distribution of delay, where others would give preference to higher volume movements to reduce average intersection delay at the expense of some approaches. Either way, VMGT appears to provide for reasonable delay.

7.3. Analysis of Traffic Signal Operations

The final consideration in evaluating the effectiveness of VMGT is: Does VMGT provide for reasonable traffic signal operations? In other words, are the resulting green times and cycle length reasonable, or do they spiral upward to unacceptable levels?

While the available data did not include a direct measure of cycle length, it was possible to determine how many times each phase terminated during each 15 minute interval, and the phase with the largest number of terminations provides a reasonable estimate for the number of cycles in the interval. The total length of the interval, 900 seconds, could then be divided by the apparent number of cycles, thus providing an apparent cycle length for each interval. Note that this method of calculation does not lend itself to determination of standard deviation of apparent cycle length.

7.3.1. Sites 1 and 2 Signal Analysis

The apparent cycle length for Sites 1 and 2 are shown in Exhibit 7-14 and Exhibit 7-15.

Exhibit 7-14. Site 1 Apparent Cycle Length

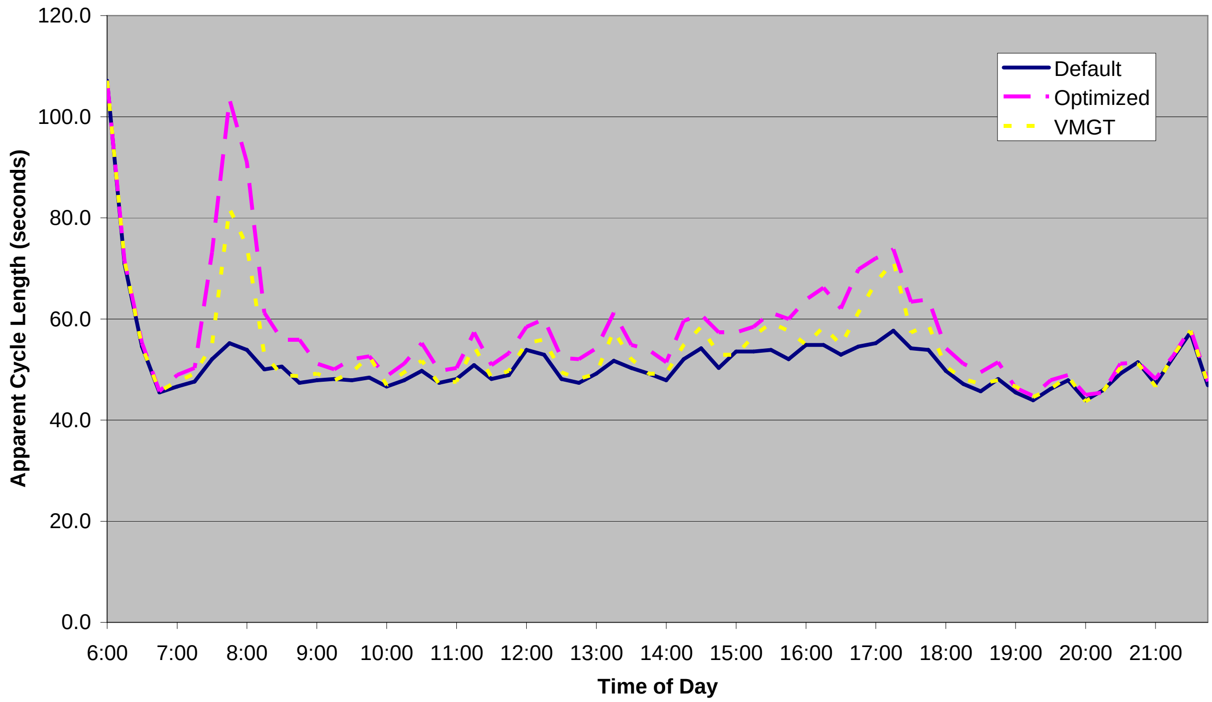
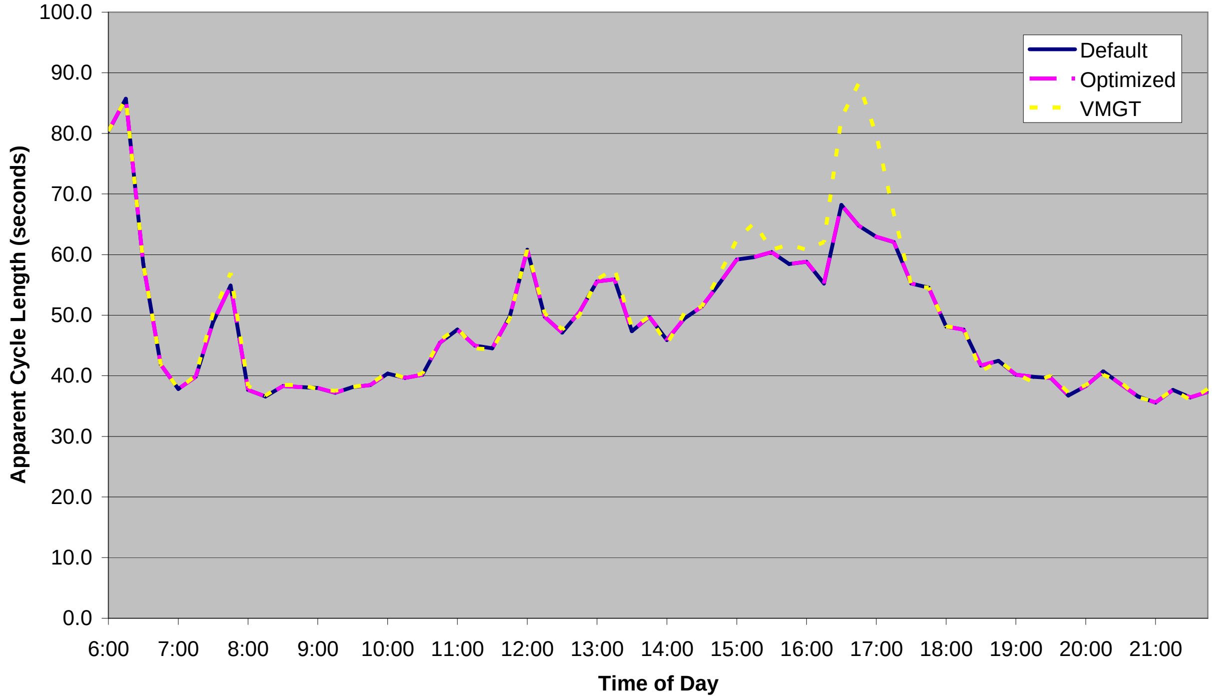


Exhibit 7-15. Site 2 Apparent Cycle Length



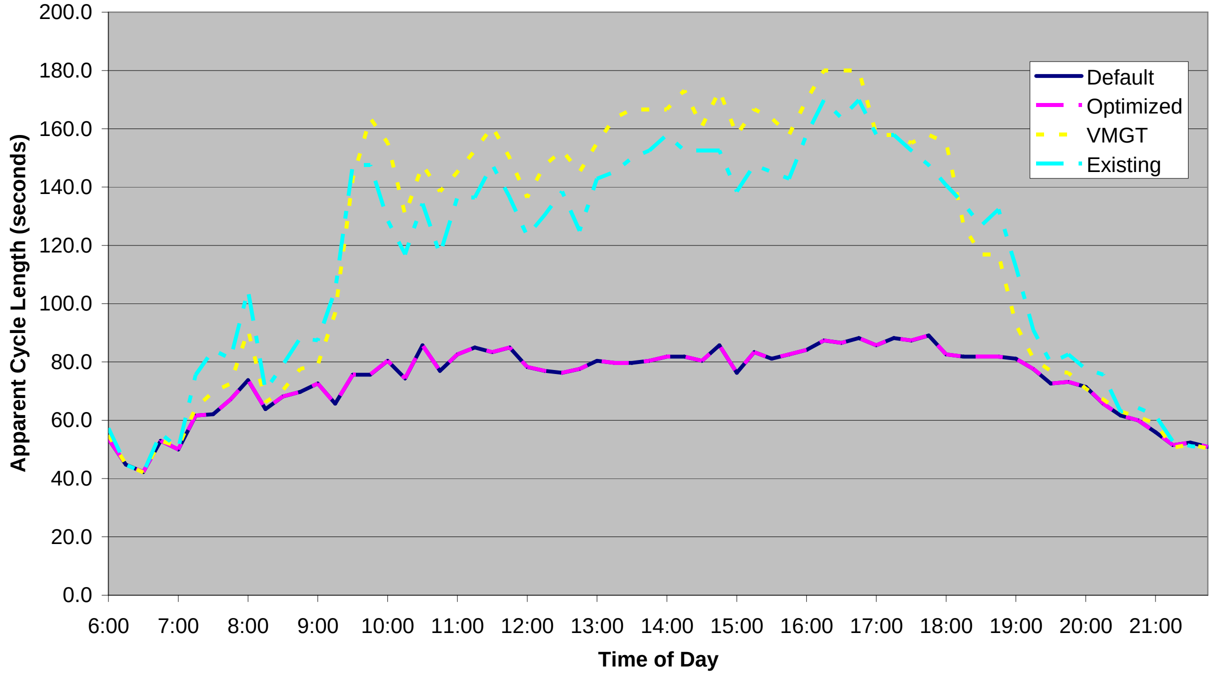
As both Sites 1 and 2 were low volume sites, it was not likely that phase or cycle lengths would increase to unacceptable limits. At both sites, the VMGT treatment resulted in average cycle lengths less than 100 seconds, certainly acceptable to most, if not all, agencies. At Site 1, the VMGT cycle length was slightly lower than the optimized, and at Site 2 it was typically the same, except for the PM peak, when it did become about 15-20 seconds longer than the optimized.

There were no significant trends in the average phase length comparisons. These comparisons can be found in the appendices.

7.3.2. Site 3 Signal Analysis

The apparent cycle length for Site 3 is shown in Exhibit 7-16.

Exhibit 7-16. Site 3 Apparent Cycle Length



Despite traffic heavy enough to result in Level of Service F conditions, the cycle length did not spiral up to its theoretical maximum, though it did result in slightly longer cycles than the existing treatment from about 10:00 to 18:00. As expected, while the traffic volume did cause individual phases to increase, natural fluctuations within the traffic flow prevented all the phases from simultaneously increasing to their variable maximum green.

With the notable exception of Phase 4, the individual phases followed reasonable trends of increase and decrease. Again, these comparisons can be found in the appendices. The Phase 4 results will be discussed in the next chapter, which presents potential refinements to the generic VMGT parameters.

7.3.3. Conclusions: Signal Operations

Based on the results from all sites, the generic VMGT parameters provide for reasonable traffic signal operations. There is no reason to expect phase or cycle lengths to spiral up to unacceptable lengths.

8. Potential Refinements to the VMGT Parameters

During the analysis of the initial simulations, two potential refinements to the generic VMGT parameters were identified. This chapter presents those refinements and the analysis of their impact on operations.

8.1. Larger Step Size

When analyzing the average intersection delay for Site 1, the VMGT treatment did not perform as well as the optimized during the AM peak (Exhibit 7-7). At the same time, the VMGT cycle length was less than the optimized (Exhibit 7-14). It is possible that the variable maximum did not increase quickly enough to keep up with rising demand, resulting in excess queuing, which then caused additional delay.

As a potential refinement to the generic VMGT strategy, the project team evaluated the impact of increasing the dynamic step size from 10 to 20 seconds. The key results are shown in Exhibit 8-1 and Exhibit 8-2.

Exhibit 8-1. Site 1 Average Intersection Delay with Larger Step Size

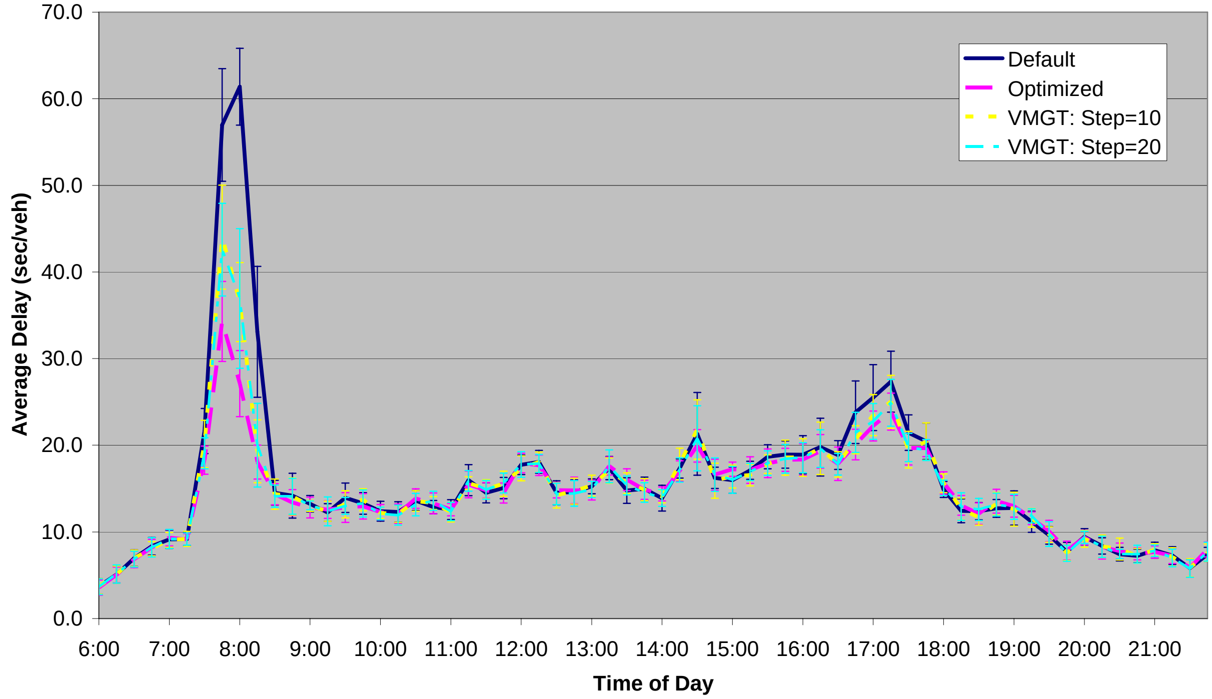
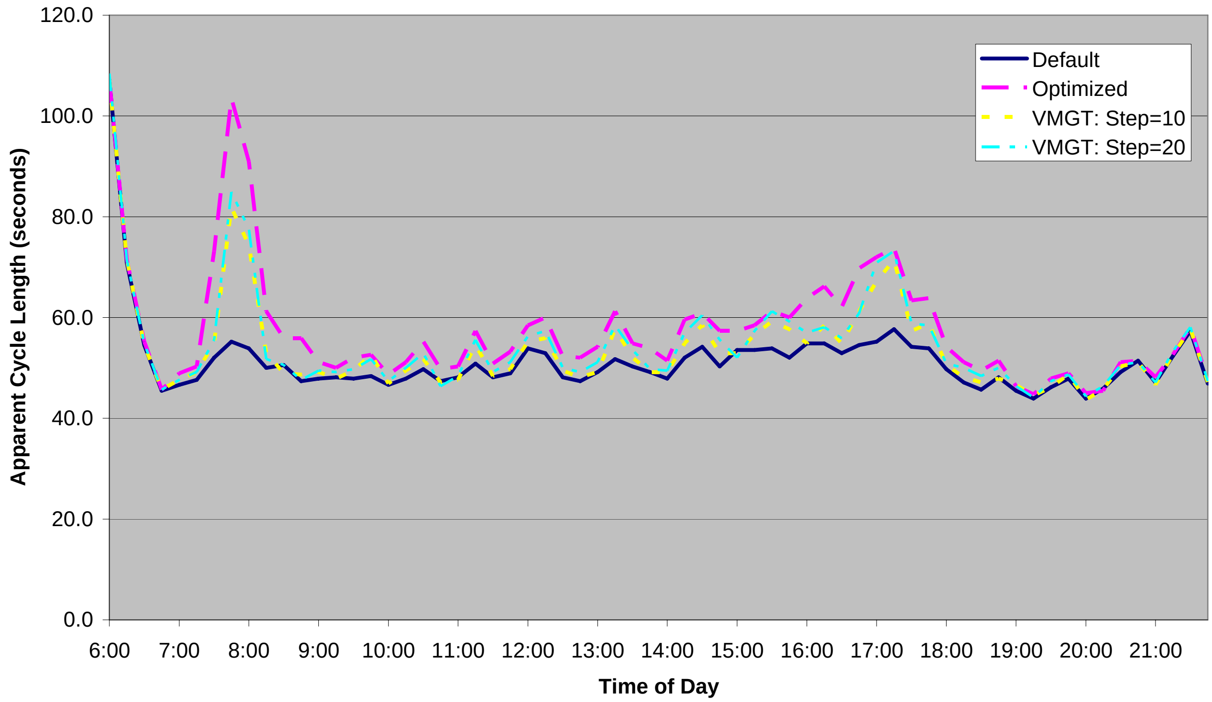


Exhibit 8-2. Site 1 Apparent Cycle Length with Larger Step Size

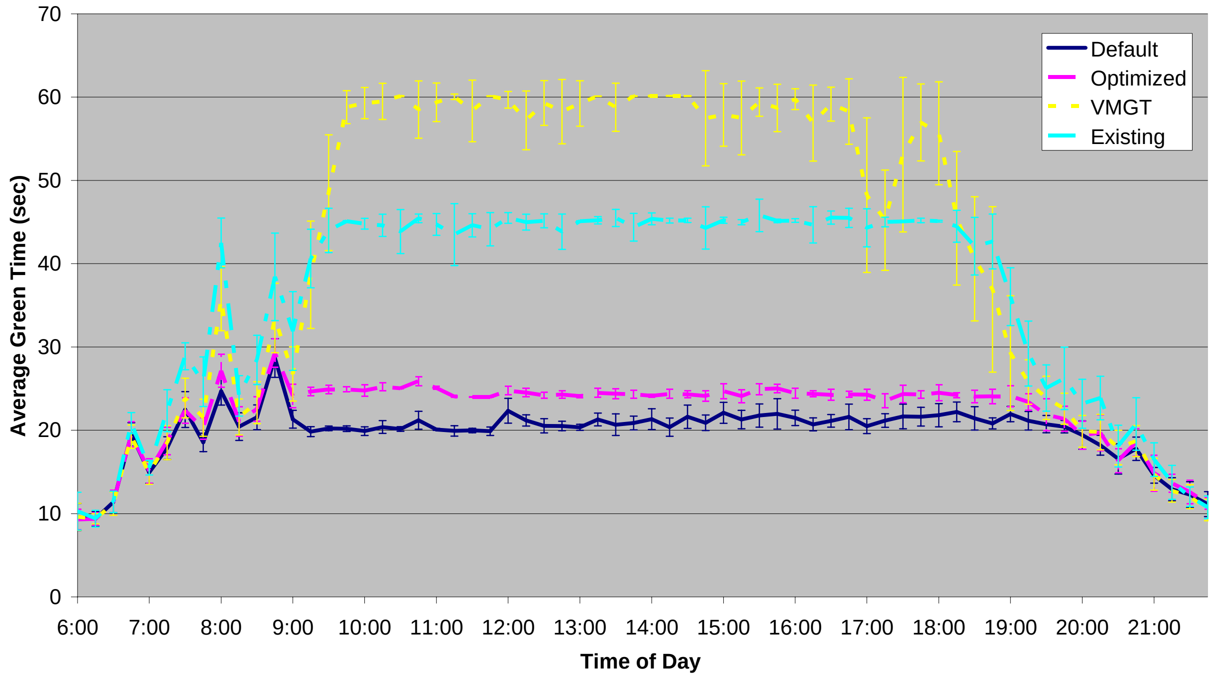


Increasing the step size resulted in only marginal differences in apparent cycle length, and these differences caused no noticeable change in either average intersection delay.

8.2. Larger Variable Maximum Green

As noted above, the investigation into the average phase length of Phase 4 at Site 3 produced a different pattern than was seen for other phases. This information is presented in Exhibit 8-3.

Exhibit 8-3. Site 3 Phase 4 Average Phase Duration



Regardless of treatment, Phase 4 spent significant time at or near its absolute maximum value. In the VMGT treatment, this condition endured from about 9:30 to 16:30. VMGT provided for a similar average intersection delay (Exhibit 7-11) with a lower worst average approach delay (Exhibit 7-13), even though the average duration of Phase 4 indicates that more time may have been needed.

As a potential refinement to the generic VMGT strategy, the project team evaluated the impact of increasing the dynamic maximum green from 60 to 100 seconds. This change was applied to all phases, not just Phase 4. The impacts of this change on phase and cycle lengths are shown in Exhibit 8-4 and Exhibit 8-5.

Exhibit 8-4. Site 3 Phase 4 Duration with Larger Variable Maximum Green

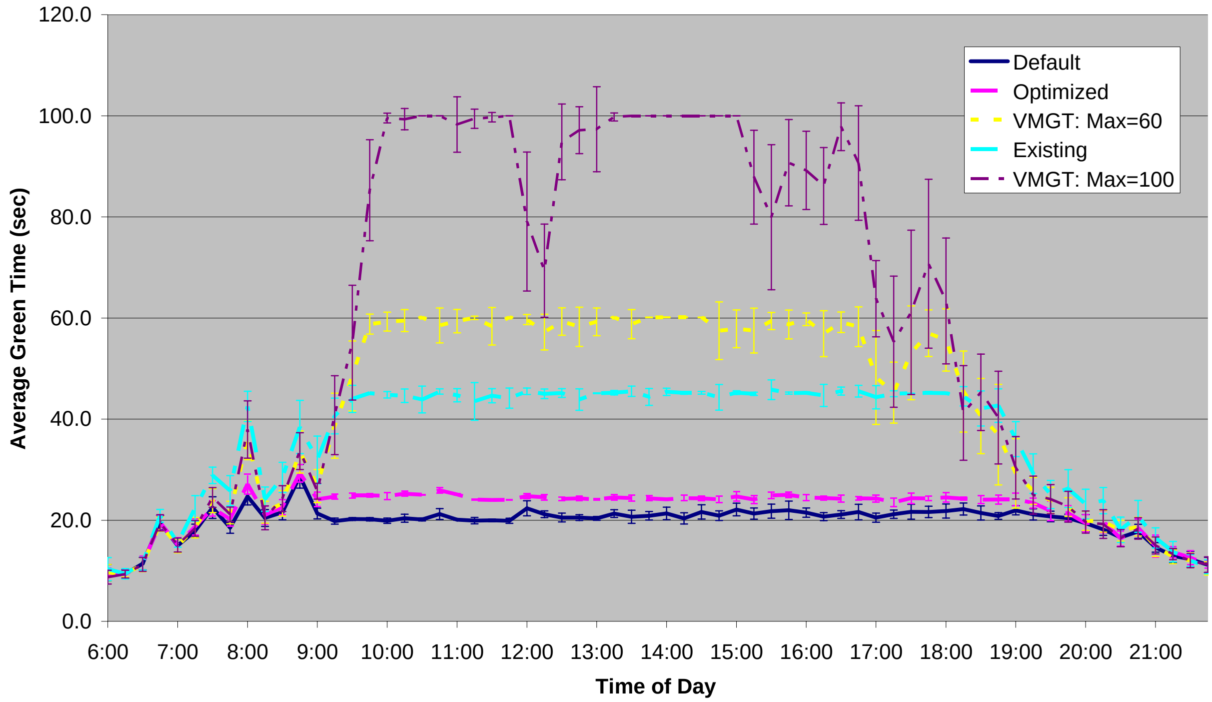
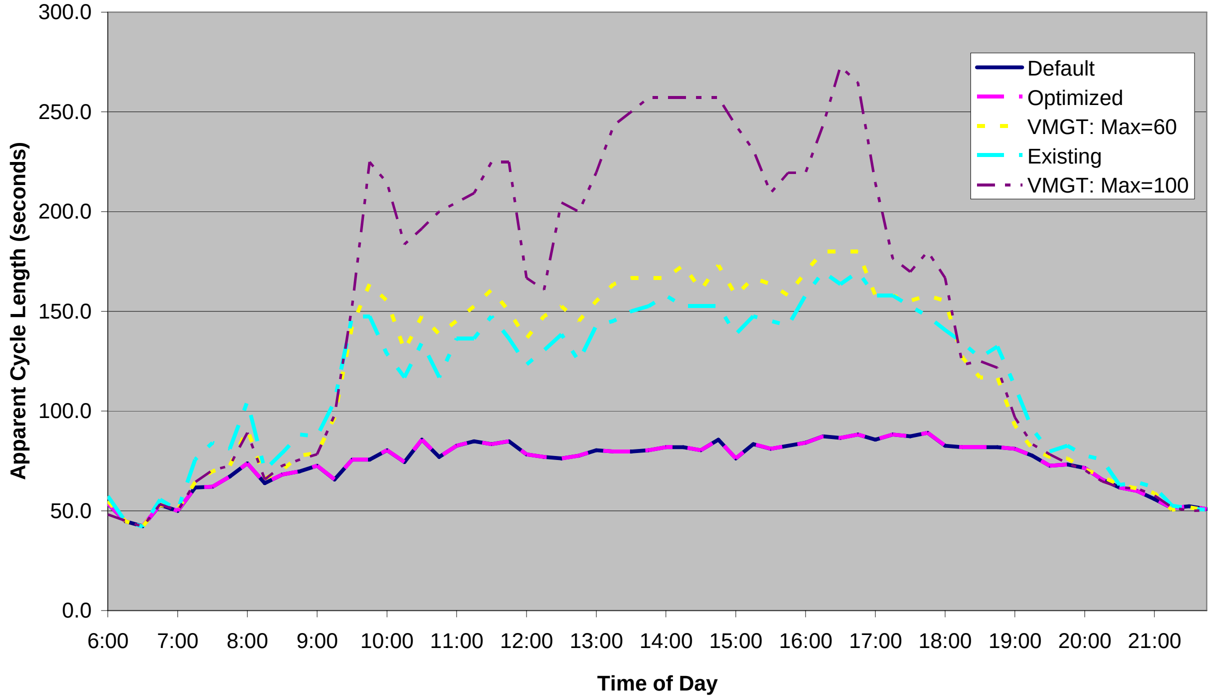


Exhibit 8-5. Site 3 Apparent Cycle Length with Larger Variable Maximum Green



Even with the larger maximum, Phase 4 still experienced long periods at or near its maximum. The approach served by this phase includes a heavy right turn volume, more than can apparently be served conveniently. The apparent cycle length has also seen a significant increase, especially from about 13:00 to 18:00. As noted above, agencies have differing views on appropriate cycle lengths for given conditions, and some would consider the 250 second cycles which resulted from this refinement to be too long.

Next, consider the impact of the larger variable maximum green on intersection delay, shown in Exhibit 8-6 and Exhibit 8-7.

Exhibit 8-6. Site 3 Average Intersection Delay with Larger Variable Maximum

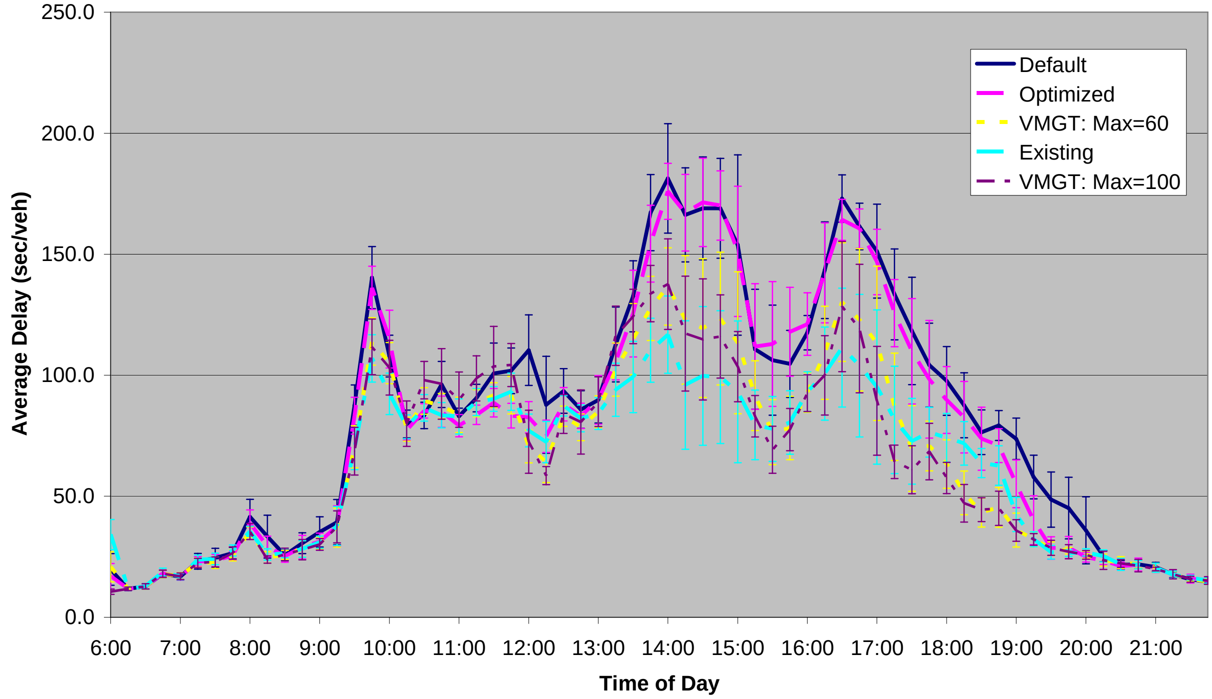
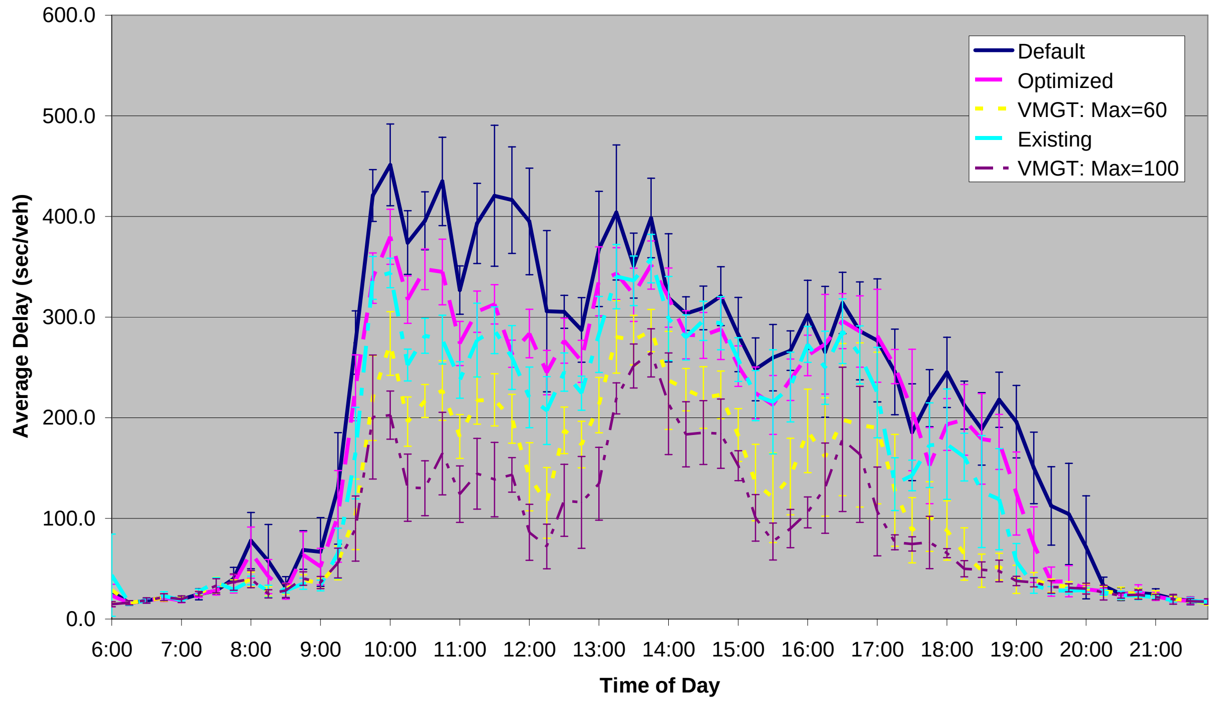


Exhibit 8-7. Site 3 Worst Average Approach Delay with Larger Variable Maximum



Increasing the variable maximum green from 60 to 100 seconds did not significantly impact the average intersection delay, but it did significantly decrease the worst average approach delay. Thus, the larger maximum allows for a more even distribution of delay among approaches without changing the overall performance.

Finally, consider the impact of the increased maximum on intersection throughput, as shown in Exhibit 8-8 and Exhibit 8-9.

Exhibit 8-8. Site 3 Intersection Throughput with Larger Variable Maximum Green

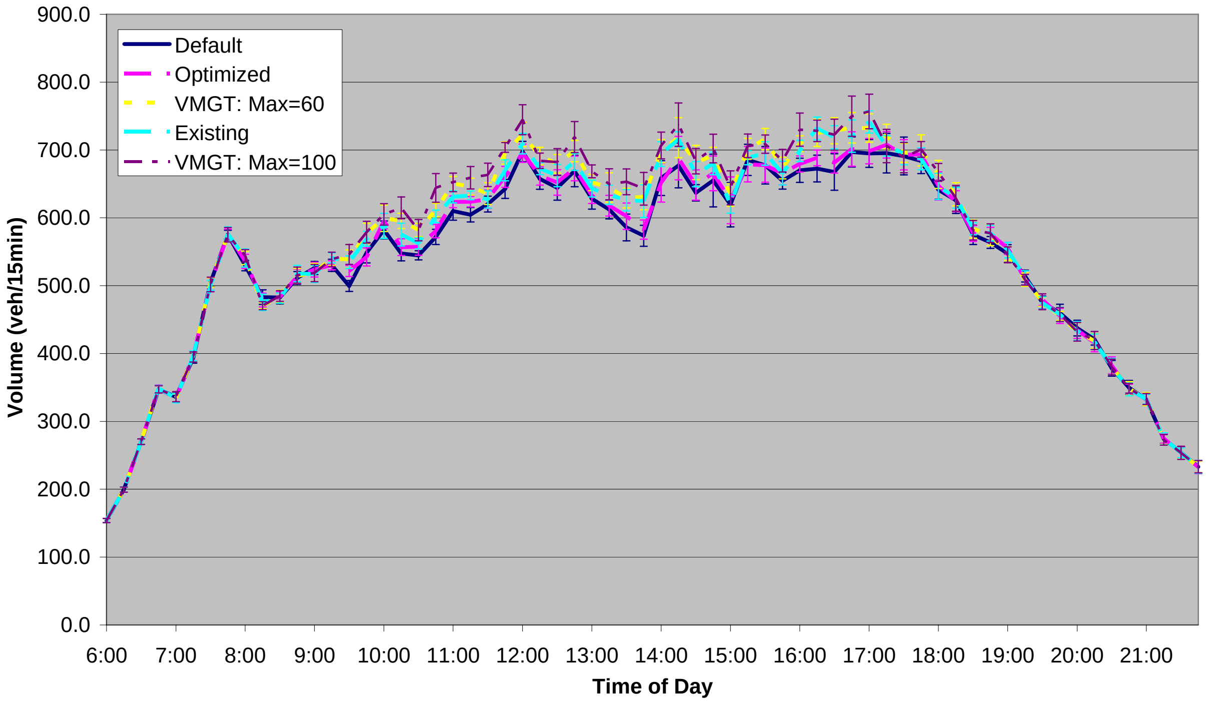
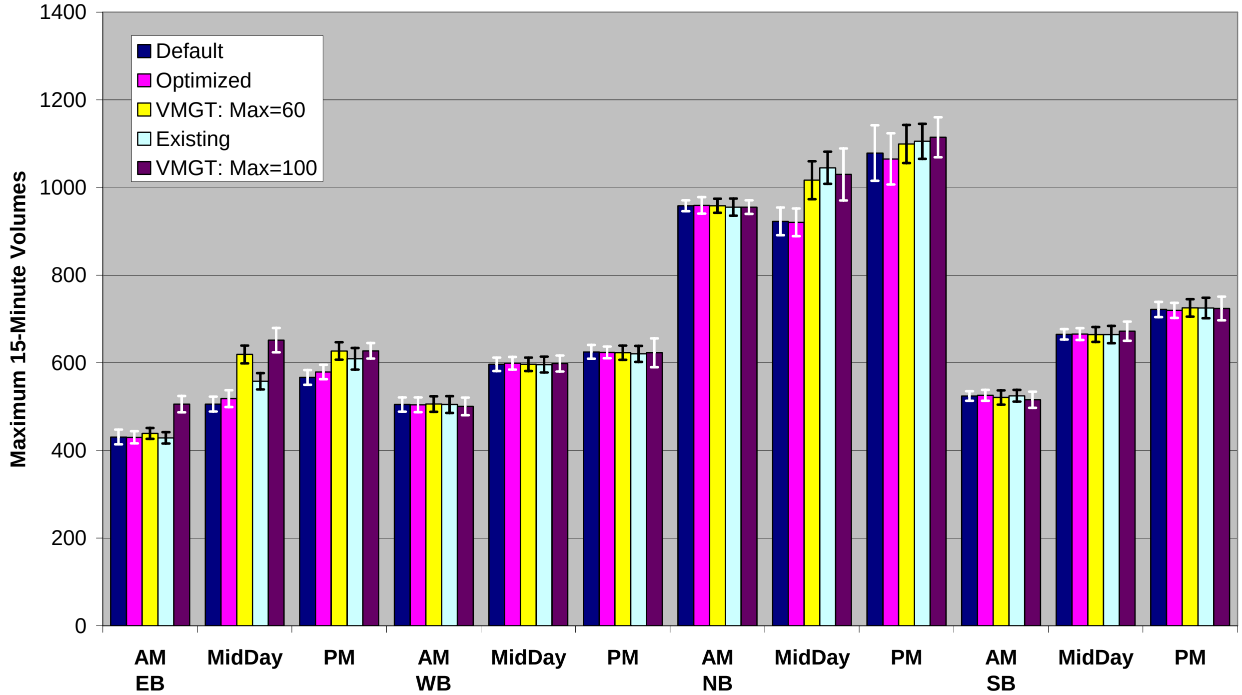


Exhibit 8-9. Site 3 Approach Throughput with Larger Variable Maximum Green



At the intersection level, the increased maximum allowed the intersection to serve slightly more traffic than the other treatments, though the difference may not be significant. At the approach level, the results are mixed. On the WB and SB approaches, there were no apparent differences between any of the treatments. On the EB approach, the VMGT with 100 second variable maximum served at least as much as the other treatments, and served the most during the AM and midday peaks. On the NB approach, the treatments were virtually equal in the AM, and the midday and PM peaks show opposite results – the VMGT with increase max is lower than the existing in the midday, but highest in the PM. Again, with the exception of the AM peak on the EB approach, the trends are noticeable, but may not be significant.

The inconsistent results are likely caused by two factors. Theoretically, longer cycle lengths should allow for greater capacity, which should result in higher throughputs. However, as phases become longer, the efficiency with which they serve traffic tends to drop. As noted above, the approach served by Phase 4 has a heavy right turn volume throughout the day, but that traffic all uses one of the two lanes served by Phase 4. When Phase 4 becomes very long, only one of the two lanes served by that phase may still have demand, so even though there is additional capacity, it may not result in additional throughput.

8.3. Conclusions: Refinements

The project team specifically investigated two potential refinements to the generic VMGT settings originally proposed: an increased step size and an increased maximum green time. Increasing the dynamic step size from 10 to 20 seconds did not have a significant impact; therefore the project team continues to recommend 10 seconds as the dynamic step size.

Increasing the dynamic maximum green time from 60 to 100 seconds provided a slight increase in intersection throughput and a significant reduction in worst average approach delay without an increase in the average intersection delay. This change also resulted in significantly longer apparent cycle lengths. The project team suggests that individual agencies choose a dynamic maximum green time between 60 and 100 seconds based on their own preferences – shorter values will result in shorter cycles with a less equitable distribution of delay and longer values will result in longer cycles with a more equitable distribution of delay.

9. Conclusions and Recommendations

The objective of this research was to investigate the potential to improve traffic signal operating efficiency through the use of VMGT as low cost local adaptive control. The primary measures of intersection efficiency investigated were average delay and intersection throughput. The primary investigative method involved software-in-the-loop simulation, which allows for computerized traffic simulations to be connected in real time with field traffic signal controller software, thus allowing multiple strategies to be tested with identical traffic conditions and without the difficulties of in-field traffic disruption.

The project team developed a generic set of VMGT parameters for study, namely:

- Normal Maximum Green Time = 20 seconds
- Dynamic Maximum Step Size = 10 seconds
- Dynamic Maximum Green Time = 60 seconds

9.1. Conclusions

Based on the results of this investigation, the project team reached the following conclusions:

- The generic VMGT treatment proved able to serve equivalent traffic volumes as an optimized signal. At all sites, the intersection throughput of the VMGT and the optimized or existing treatments were equivalent.

- The generic VMGT treatment provide able to provide similar average intersection delays to an optimized signal. At Sites 1 and 2, the delays were essentially identical, except for the sharp AM peak at Site 1, when the optimized signal performed better. At Site 3, the delays were similar throughout the day, with periods when the existing treatment performed better and periods when the VMGT treatment performed better.

- The generic VMGT treatment can provide for a more equitable distribution of delay. At Sites 1 and 2, the worst approach delays were essentially the same for the optimized and VMGT treatments. At Site 3, however, the VMGT treatment provided for a significantly lower worst approach delay than the existing treatment.

- The generic VMGT treatment can provide reasonable traffic signal operations. At Sites 1 and 2 the VMGT cycle length stayed below 100 seconds, and was very similar to the optimized cycle length most of the day. At Site 3, the VMGT treatment resulted in cycle lengths that were comparable to those of the existing treatment, with both periods of lower and higher cycle length than the existing treatment. The cycle length did not increase to the theoretical maximum at either site.

- Because of its continual operation, the generic VMGT treatment may provide for improved operations during times which are normally ignored during the optimization process. Few agencies have the resources to provide customized timings for conditions like late evening, weekends, or holidays, but VMGT can continue to adjust itself to match changing traffic conditions.

- An increased dynamic maximum step size did not significantly change the performance. This option was tested on Site 1, with no differences noted. Thus, the 10 second step size is reasonable.

- An increased dynamic maximum green resulted in a longer cycle length, and in a more equal distribution of delay among approaches and movements while maintaining the same average intersection delay. Essentially, this allows individual agencies to select a dynamic maximum green time based on their cycle length preferences. Agencies which prefer shorter cycles can use the original 60 second dynamic maximum limit, and those which prefer longer cycles can increase it to as much as 100 seconds.

9.2. Agency Recommendations

Based on the results of this study, the project team recommends that rural agencies who desire to improve traffic signal operations without the typical cost associated with traffic signal optimization studies install the generic VMGT parameters shown below:

- Normal Maximum Green Time = 20 seconds
- Dynamic Maximum Step Size = 10 seconds
- Dynamic Maximum Green Time = 60 to 100 seconds, based on agency preferences related to maximum desired cycle length and equitable distribution of delay

Note that most controllers by default require two max outs to increase and two gap outs to decrease the variable maximum green time. For those controllers which allow the user to set this value, the study team recommends using two.

Note also that effective use of VMGT requires functional detection at the intersection. For locations without detection, or in locations where detection is faulty and will not be regularly maintained, the project team does not recommend VMGT.

9.3. Recommendations for Future Research

Given the results of this study, there are several areas which are in need of further investigation. Some of the more pressing needs include:

- Field investigations. This research used a simulation approach to ensure a safe and repeatable test of VMGT parameters. Given the positive simulation results, field tests to confirm the simulation results should be acceptably safe and should be performed.

- Different Phase Configurations. This research involved three sites, none of which included fully protected left turn phasing. Investigation into sites with protected left turn phasing, as well as sites with other phasing schemes which differ from those in this project is recommended.

- Different Traffic Conditions. This research involved rural sites. Investigation into the applicability of VMGT at suburban and rural sites, with their different driver characteristics, is recommended.

9.4. Acknowledgements

The project team would like to thank the three sponsoring agencies for making this research possible:

- The Mack-Blackwell Rural Transportation Center at the University of Arkansas, Fayetteville.
- The Center for Energy Systems Research at Tennessee Tech University.
- The Department of Civil and Environmental Engineering at Tennessee Tech University.

The project team would also like to thank the Traffic Signal Division of the Cookeville Public Works Department for their information and assistance during the project.

10. Appendix A: Intersection Turning Movement Counts

Site 1 Intersection Turning Movement Counts

Pk 15	Pk Hr	Time	NC 5			NC 5			NC 211			NC 211			Totals	
			NB			SB			EB			WB				
			L	T	R	L	T	R	L	T	R	L	T	R		
		6:00	7	0	1	1	0	0	0	23	14	0	11	1	58	471
		6:15	10	1	3	1	0	3	1	30	14	1	17	3	84	
		6:30	22	3	1	0	0	1	0	67	31	2	32	6	165	
		6:45	31	2	7	2	1	1	1	45	33	2	38	1	164	
		7:00	24	8	3	6	3	5	6	56	25	3	34	4	177	1219
		7:15	23	7	7	3	4	4	6	65	22	5	56	12	214	
	AM	7:30	46	5	13	7	4	8	15	128	61	8	60	12	367	
AM	AM	7:45	74	11	14	7	10	10	7	164	80	6	65	13	461	
	AM	8:00	58	7	13	9	7	11	16	135	72	4	90	11	433	1334
	AM	8:15	36	10	14	13	5	8	8	108	47	3	56	11	319	
		8:30	25	8	17	13	10	9	16	97	34	4	46	10	289	
		8:45	21	11	15	11	6	4	7	102	35	6	56	19	293	
		9:00	35	7	3	10	8	10	7	75	28	7	39	16	245	1080
		9:15	30	9	7	8	8	7	7	66	41	5	38	17	243	
		9:30	21	8	15	10	9	10	12	83	49	3	61	11	292	
		9:45	29	16	4	12	10	8	8	91	31	8	72	11	300	
		10:00	25	16	5	13	9	8	2	63	26	8	48	21	244	1074
		10:15	20	9	12	12	8	12	12	63	26	9	49	21	253	
		10:30	29	9	7	13	14	9	13	68	40	7	49	25	283	
		10:45	21	26	11	8	15	15	5	74	33	2	57	27	294	
		11:00	22	18	10	11	10	12	5	44	36	8	72	22	270	1232
		11:15	35	20	7	13	21	14	17	91	32	10	51	29	340	
	MD	11:30	18	20	8	24	18	21	8	67	31	8	60	26	309	
	MD	11:45	23	18	10	25	20	17	11	62	30	11	52	34	313	
	MD	12:00	54	30	9	22	18	21	14	48	34	10	68	30	358	1308
	MD	12:15	43	26	6	17	22	23	18	52	33	12	74	25	351	
		12:30	26	16	6	9	24	15	6	51	29	11	89	24	306	
		12:45	31	10	10	24	7	18	6	69	27	4	64	23	293	
		13:00	29	16	5	25	18	15	7	75	35	8	69	25	327	1299
MD		13:15	31	23	15	23	15	19	22	76	38	13	61	27	363	
		13:30	36	19	12	20	15	14	10	47	23	12	71	27	306	
		13:45	32	15	5	19	10	19	6	52	41	5	75	24	303	
		14:00	28	17	6	13	18	19	11	58	25	7	73	23	298	1381
		14:15	52	12	7	21	16	17	11	55	29	10	87	26	343	
		14:30	63	19	12	20	19	18	10	87	45	8	82	15	398	
		14:45	25	17	10	13	15	16	9	72	54	12	77	22	342	
		15:00	44	14	4	19	21	25	7	56	23	15	67	24	319	1415
		15:15	40	16	6	17	17	15	8	53	38	16	91	34	351	
		15:30	50	19	9	15	17	10	16	65	45	15	75	32	368	
		15:45	38	27	7	13	18	28	10	65	52	11	79	29	377	
		16:00	51	26	11	18	21	30	10	68	33	5	80	24	377	1553
		16:15	54	24	12	17	27	27	9	55	48	14	70	28	385	
	PM	16:30	40	20	12	15	22	20	8	51	43	12	96	33	372	
	PM	16:45	49	17	12	16	23	14	12	86	68	9	79	34	419	
	PM	17:00	52	18	9	26	21	22	14	88	39	10	110	34	443	1656
PM	PM	17:15	59	21	11	27	18	34	16	71	43	14	112	30	456	
		17:30	36	11	12	26	16	24	11	49	39	8	95	33	360	
		17:45	53	23	13	26	14	28	12	72	33	6	94	23	397	
		18:00	39	11	6	15	10	11	8	59	21	7	80	16	283	1043
		18:15	PM	7	2	16	13	16	9	67	17	8	59	17	231	
		18:30	20	14	10	16	10	10	6	67	20	8	60	24	265	
		18:45	25	3	7	12	15	18	8	51	28	10	58	29	264	
		19:00	26	4	6	15	13	12	8	41	22	8	35	23	213	682
		19:15	25	5	4	18	10	7	8	31	15	5	26	15	169	
		19:30	11	6	4	10	8	13	6	23	13	12	44	14	164	
		19:45	10	6	2	10	6	5	11	31	10	5	28	12	136	
		20:00	11	4	3	7	8	20	1	20	8	5	35	13	135	521
		20:15	7	7	6	6	9	12	7	21	7	9	29	12	132	
		20:30	11	1	2	8	6	7	4	24	6	4	43	5	121	
		20:45	10	4	2	4	3	9	5	35	16	2	34	9	133	
		21:00	7	6	3	9	8	10	1	16	10	4	60	7	141	441
		21:15	10	1	1	8	2	8	5	13	5	5	41	4	103	
		21:30	11	2	1	4	2	3	5	11	15	2	27	6	89	
		21:45	13	8	0	8	3	10	2	21	7	4	28	4	108	
		Totals	1937	794	487	859	758	869	547	3919	2008	475	3834	1222	17709	
			3218			2486			6474			5531				

	NB L	NB T	NB R	SB L	SB T	SB R	EB L	EB T	EB R	WB L	WB T	WB R	Total
AM Peak	214	33	54	36	26	37	46	535	260	21	271	47	1580
MidDay Peak	138	94	33	88	78	82	51	229	128	41	254	115	1331
PM Peak	200	76	44	84	84	90	50	296	193	45	397	131	1690

Site 2 Intersection Turning Movement Counts

Pk 15	Pk Hr	Time	NC 5 NB			NC 5 SB			NC 211 EB			NC 211 WB			Totals	
			L	T	R	L	T	R	L	T	R	L	T	R		
		6:00	1	10	10	4	4	1	1	0	1	9	2	2	45	248
		6:15	1	7	9	3	4	1	0	1	1	9	0	3	39	
		6:30	2	14	19	7	3	2	1	0	1	12	4	3	68	
		6:45	2	18	28	9	2	2	1	3	2	12	12	5	96	
		7:00	4	26	38	10	11	2	0	5	1	11	10	6	124	954
	AM	7:15	5	45	75	18	6	4	1	2	4	24	15	10	209	
	AM	7:30	12	60	101	26	12	5	1	0	8	31	29	10	295	
AM	AM	7:45	22	58	90	29	12	13	1	0	14	41	31	15	326	
	AM	8:00	13	44	36	15	17	9	1	0	7	26	13	7	188	680
		8:15	8	34	30	12	15	4	1	3	5	20	8	6	146	
		8:30	11	33	38	13	18	6	1	0	7	17	9	7	160	
		8:45	15	39	38	17	15	11	1	4	7	26	6	7	186	
		9:00	13	36	35	16	18	10	1	1	12	21	9	6	178	740
		9:15	9	38	39	14	18	12	1	5	12	21	12	8	189	
		9:30	8	40	38	14	12	8	2	6	9	20	11	5	173	
		9:45	10	42	48	19	13	8	2	7	10	21	15	5	200	
		10:00	12	42	49	15	22	11	2	7	12	22	4	9	207	858
		10:15	10	39	45	18	20	7	1	6	11	20	4	7	188	
		10:30	10	45	49	16	23	7	2	3	12	20	8	6	201	
		10:45	10	56	62	22	23	12	3	9	14	23	19	9	262	
		11:00	11	55	59	22	20	13	2	11	18	27	16	8	262	1033
		11:15	11	48	59	19	21	10	2	11	14	25	15	8	243	
		11:30	13	54	63	21	22	13	2	11	12	20	20	7	258	
		11:45	11	62	65	27	10	16	3	7	18	26	16	9	270	
		12:00	16	59	70	28	14	17	3	30	17	25	24	11	314	1138
		12:15	11	60	63	23	19	12	2	17	12	26	19	7	271	
	MD	12:30	13	58	66	20	29	11	2	11	9	28	15	9	271	
	MD	12:45	18	57	72	25	19	13	3	13	13	25	15	9	282	
MD	MD	13:00	22	62	71	21	43	13	2	10	18	29	17	14	322	1164
	MD	13:15	21	61	63	33	21	20	4	16	19	26	20	12	316	
		13:30	15	51	54	24	24	11	3	10	13	26	8	9	248	
		13:45	15	61	71	24	28	11	2	11	11	22	15	7	278	
		14:00	18	54	51	22	36	10	2	9	13	22	10	8	255	1159
		14:15	13	64	69	24	28	11	3	14	12	19	19	10	286	
		14:30	17	58	71	27	24	13	3	17	12	18	20	9	289	
		14:45	19	74	80	31	27	12	3	16	14	12	33	8	329	
		15:00	17	69	79	30	34	14	2	20	13	23	22	15	338	1302
		15:15	22	66	79	27	34	11	2	13	12	37	5	13	321	
		15:30	16	72	81	32	29	12	3	12	14	31	13	13	328	
		15:45	15	70	75	30	32	12	2	16	10	29	15	9	315	
		16:00	18	73	84	27	35	11	2	18	13	25	19	11	336	1374
		16:15	16	78	81	25	29	13	2	18	9	23	15	10	319	
	PM	16:30	12	75	89	39	11	12	2	40	14	28	37	9	368	
	PM	16:45	15	82	90	31	29	8	2	25	10	26	25	8	351	
PM	PM	17:00	19	84	103	24	43	9	2	23	9	23	31	9	379	1333
	PM	17:15	18	74	85	27	43	9	1	20	9	26	20	9	341	
		17:30	16	71	72	23	36	11	2	13	9	25	16	10	304	
		17:45	12	71	78	23	28	15	2	11	12	29	17	11	309	
		18:00	12	65	66	22	35	8	2	8	8	26	8	10	270	992
		18:15	12	59	63	21	35	6	1	12	6	32	4	7	258	
		18:30	11	53	51	19	31	6	2	7	7	27	1	9	224	
		18:45	14	57	53	17	42	6	2	6	6	23	3	11	240	
		19:00	5	59	57	19	30	6	1	9	5	21	8	9	229	854
		19:15	8	55	49	19	37	6	1	9	5	19	9	7	224	
		19:30	8	53	52	14	34	7	2	8	6	17	7	9	217	
		19:45	7	48	37	14	26	8	1	9	4	16	6	8	184	
		20:00	8	54	44	15	29	7	1	10	6	14	9	9	206	776
		20:15	7	58	44	15	29	5	1	10	6	18	6	7	206	
		20:30	6	50	36	17	20	6	2	8	7	11	12	8	183	
		20:45	8	46	30	16	27	8	1	12	7	12	7	7	181	
		21:00	9	45	31	15	27	5	1	11	3	11	8	5	171	577
		21:15	6	39	19	13	23	5	2	6	3	10	4	6	136	
		21:30	6	37	24	13	22	5	1	8	4	8	7	4	139	
		21:45	7	33	16	12	31	5	1	5	3	10	4	4	131	
		Totals	752	3360	3592	1287	1514	577	111	643	595	1382	841	528	15182	
			7704			3378			1349			2751				

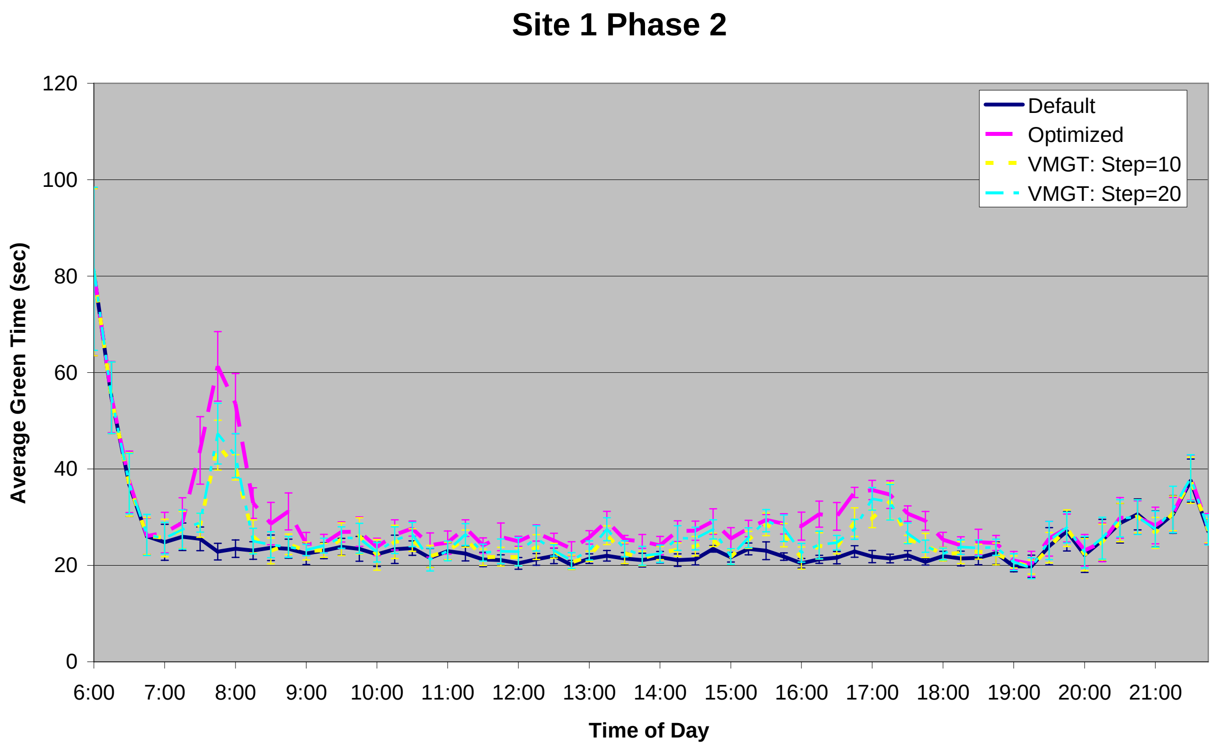
	NC 5 NB L	NC 5 NB T	NC 5 NB R	NC 5 SB L	NC 5 SB T	NC 5 SB R	NC 211 EB L	NC 211 EB T	NC 211 EB R	NC 211 WB L	NC 211 WB T	NC 211 WB R	Totals
AM Peak	52	207	302	88	47	31	4	2	33	122	88	42	1018
MidDay Peak	74	238	272	99	112	57	11	50	59	108	67	44	1191
PM Peak	64	315	367	121	126	38	7	108	42	103	113	35	1439

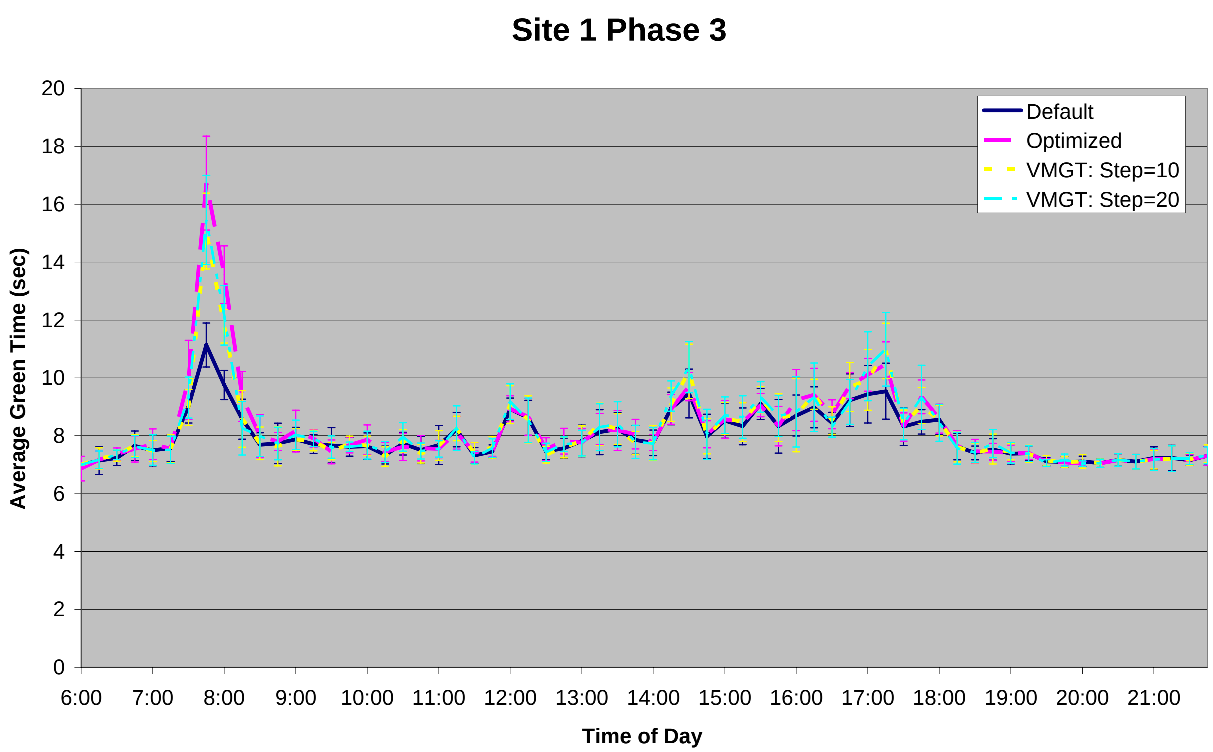
Site 3 Intersection Turning Movement Counts

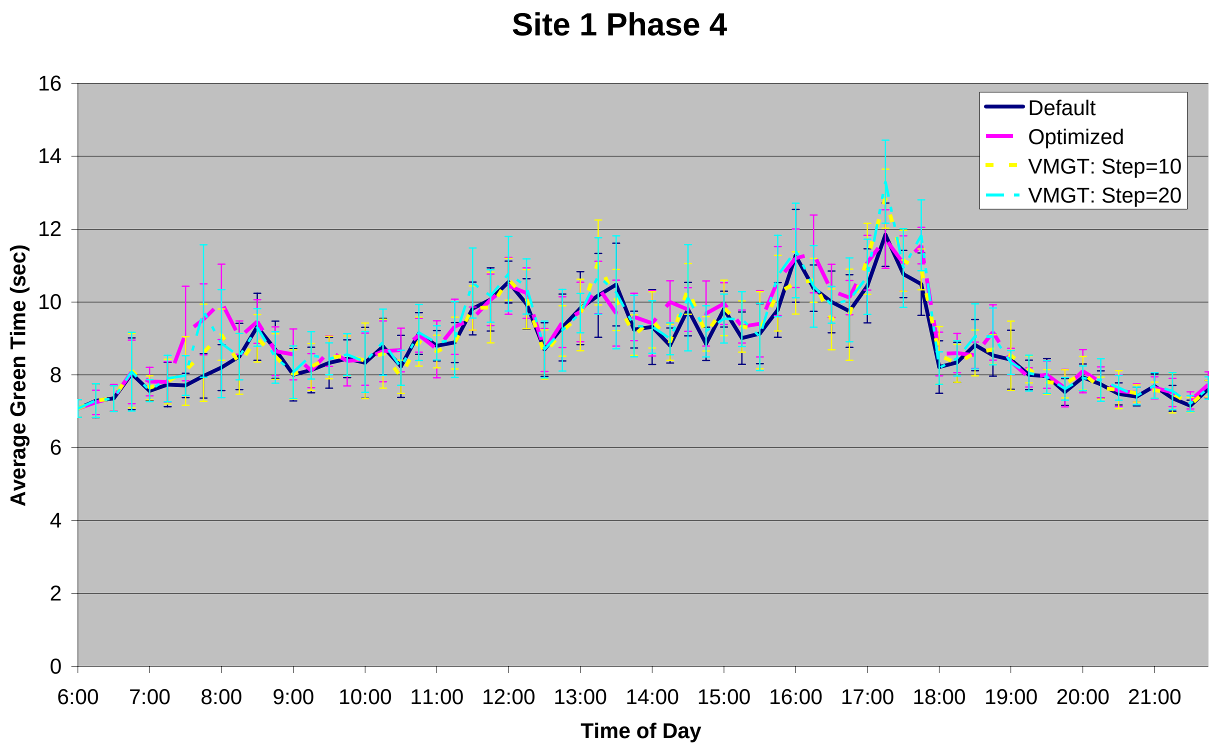
Pk 15	Pk Hr	Time	NC 5 NB L	NC 5 NB T	NC 5 NB R	NC 5 SB L	NC 5 SB T	NC 5 SB R	NC 211 EB L	NC 211 EB T	NC 211 EB R	NC 211 WB L	NC 211 WB T	NC 211 WB R	Totals	
		6:00	10	34	12	7	41	9	3	11	26	2	5	9	169	1003
		6:15	9	41	23	8	45	12	4	7	36	4	4	9	202	
		6:30	14	55	31	10	61	15	4	15	52	5	0	14	276	
		6:45	18	82	32	12	48	18	7	29	73	8	13	16	356	
		7:00	24	82	54	18	38	15	5	4	54	9	14	15	332	1836
		7:15	22	100	78	16	43	15	8	1	67	11	23	23	407	
		7:30	27	127	126	20	49	23	11	0	76	12	18	20	509	
		7:45	34	117	138	26	69	19	14	0	82	21	36	32	588	
		8:00	30	97	68	27	71	24	14	28	88	23	39	33	542	2011
		8:15	27	90	56	22	66	25	10	21	69	20	25	23	454	
		8:30	31	91	75	24	57	26	14	13	79	18	36	26	490	
		8:45	44	113	77	24	65	27	14	11	67	21	36	26	525	
	AM	9:00	41	95	82	22	65	35	17	10	66	17	36	34	520	2280
	AM	9:15	46	93	73	24	79	34	17	23	69	22	42	29	551	
	AM	9:30	53	103	72	27	66	39	20	21	82	18	57	34	592	
AM	AM	9:45	62	105	83	31	62	33	22	12	88	22	63	34	617	
		10:00	43	95	78	36	67	31	20	24	78	28	65	38	603	2485
		10:15	46	81	77	39	47	37	24	29	109	28	68	34	619	
		10:30	55	91	81	33	49	37	28	19	106	27	68	32	626	
		10:45	51	85	76	41	48	36	29	27	94	30	82	38	637	
		11:00	51	94	74	37	68	38	27	42	93	29	80	39	672	2733
		11:15	55	82	76	40	75	42	30	39	91	36	78	37	681	
		11:30	53	96	75	43	71	42	32	37	92	35	68	35	679	
		11:45	58	95	67	45	75	37	36	46	101	35	72	34	701	
		12:00	56	94	75	48	81	48	35	28	85	37	84	38	709	2834
		12:15	62	90	76	43	85	45	41	38	87	40	70	35	712	
		12:30	54	100	88	43	63	46	44	27	96	39	69	30	699	
	MD	12:45	60	83	76	47	67	33	44	44	103	41	75	41	714	
	MD	13:00	62	99	80	43	70	42	47	30	88	38	68	39	706	2838
	MD	13:15	62	109	79	40	61	45	34	37	95	34	70	36	702	
MD	MD	13:30	59	105	70	43	66	40	41	46	104	33	78	33	718	
		13:45	62	105	87	47	59	34	34	30	102	35	81	36	712	
		14:00	78	91	91	47	71	33	34	29	101	34	71	47	727	2882
		14:15	73	99	106	40	91	37	35	23	100	27	77	36	744	
		14:30	75	111	91	39	58	32	35	28	91	34	78	36	708	
		14:45	65	96	109	42	84	34	35	3	99	31	72	33	703	
		15:00	74	97	104	43	81	35	41	14	89	40	62	42	722	2843
		15:15	64	105	88	42	91	41	29	15	90	46	63	34	708	
		15:30	78	105	94	42	67	29	28	17	98	41	67	40	706	
		15:45	79	93	83	45	77	31	36	40	97	34	54	38	707	
	PM	16:00	75	112	102	43	86	41	26	7	87	41	75	36	731	2961
PM	PM	16:15	77	107	89	45	106	37	32	20	87	38	89	38	765	
	PM	16:30	81	106	95	38	96	38	27	22	79	41	73	39	735	
	PM	16:45	82	88	88	50	107	37	25	13	87	36	75	42	730	
		17:00	76	122	103	41	93	35	31	6	70	40	81	32	730	2825
		17:15	83	95	82	40	99	28	30	22	82	29	74	38	702	
		17:30	77	94	61	35	89	30	33	42	85	30	79	43	698	
		17:45	73	98	60	38	91	37	28	45	88	28	74	35	695	
		18:00	67	95	51	32	84	26	21	51	86	22	79	37	651	2423
		18:15	63	86	55	29	74	30	22	49	76	16	79	38	617	
		18:30	55	77	50	28	65	34	24	49	84	17	70	34	587	
		18:45	58	81	50	28	67	28	22	52	68	13	69	32	568	
		19:00	54	65	43	30	73	27	21	43	70	14	66	34	540	1968
		19:15	49	67	41	22	59	30	18	37	68	13	63	33	500	
		19:30	45	54	32	25	60	26	19	47	64	10	58	32	472	
		19:45	39	59	35	23	49	24	16	37	62	14	68	30	456	
		20:00	43	52	32	23	51	19	13	36	54	13	56	36	428	1585
		20:15	39	59	28	18	58	22	14	34	55	13	50	29	419	
		20:30	37	44	23	22	49	19	12	29	49	13	52	30	379	
		20:45	26	49	22	19	46	14	14	31	49	11	48	30	359	
		21:00	29	50	24	20	46	16	11	22	40	10	41	24	333	1101
		21:15	19	41	16	14	39	14	10	23	36	6	41	26	285	
		21:30	19	44	11	14	35	17	6	18	34	9	22	23	252	
		21:45	17	37	16	15	35	10	8	13	28	7	26	19	231	
		Totals	3250	5508	4290	2018	4254	1913	1486	1666	4951	1549	3675	2048	36608	
			13048			8185			8103			7272				

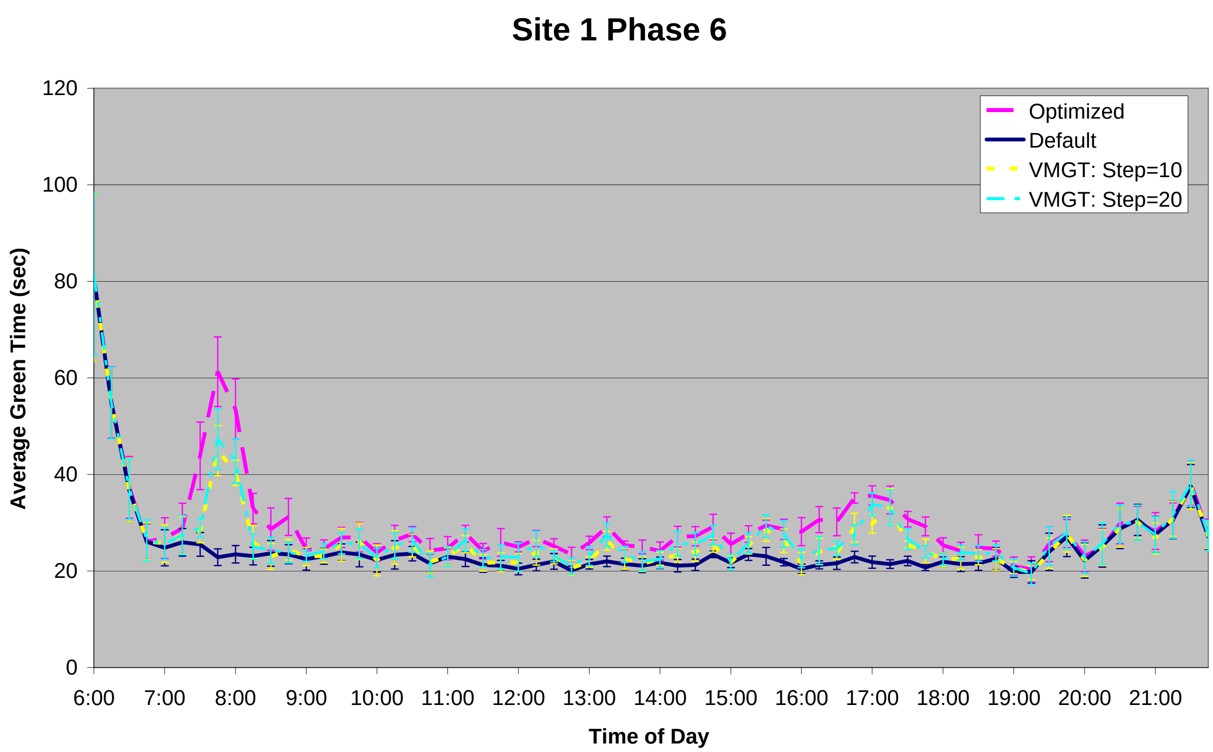
	NB L	NB T	NB R	SB L	SB T	SB R	EB L	EB T	EB R	WB L	WB T	WB R	Total
AM Peak	202	396	310	104	272	141	76	66	305	79	198	131	2280
MidDay Peak	243	396	305	173	264	160	166	157	390	146	291	149	2840
PM Peak	315	413	374	176	395	153	110	62	340	156	312	155	2961

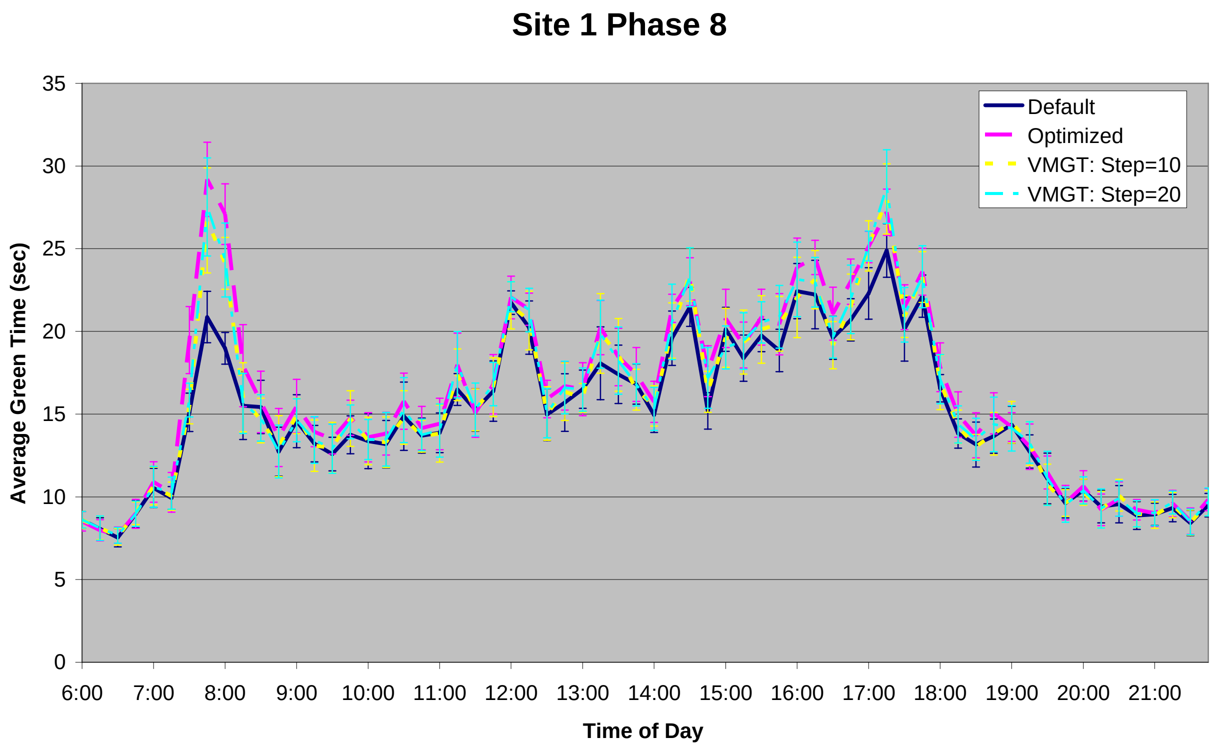
11. Appendix B: Site 1 Phase Length Comparisons


Site 1 Phase 2
120
100
80
60
40
20
0
Average Green Time (sec)
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day
Default
Optimized
VMGT: Step=10
VMGT: Step=20

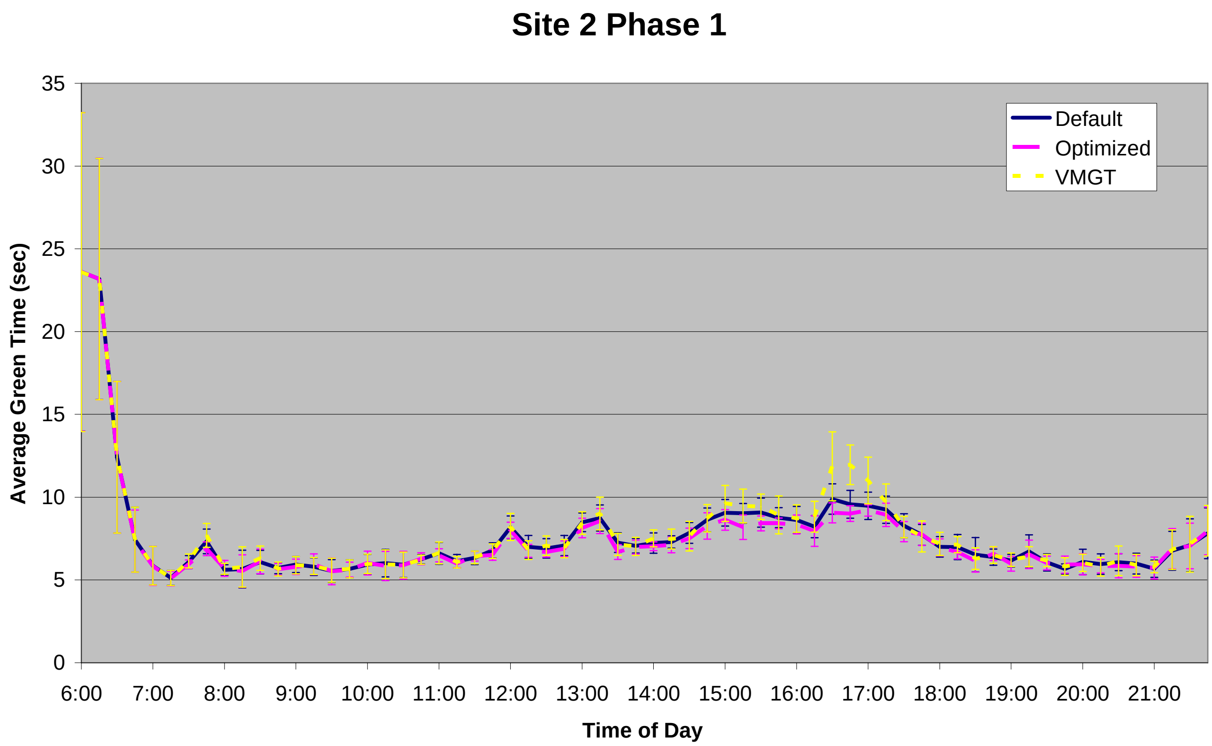

Site 1 Phase 3
20
18
16
14
12
10
8
6
4
2
0
Average Green Time (sec)
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day
Default
Optimized
VMGT: Step=10
VMGT: Step=20

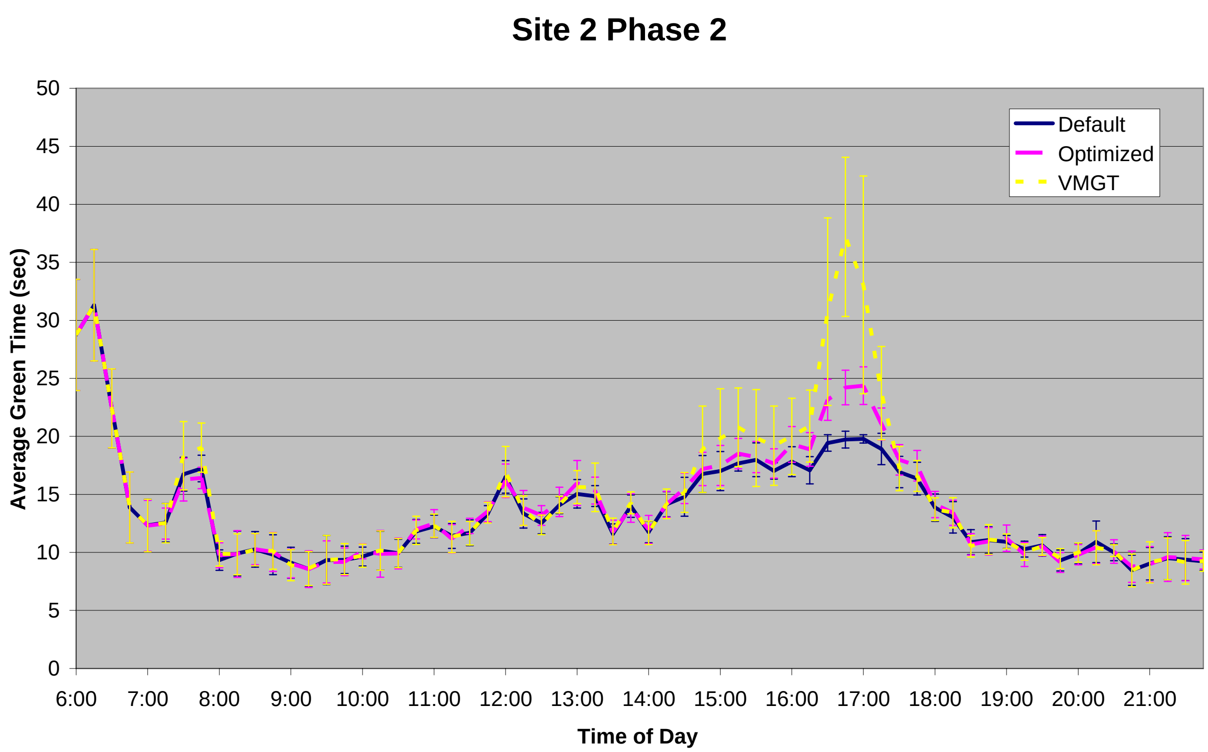

Site 1 Phase 4
Average Green Time (sec)
Time of Day
Default
Optimized
VMGT: Step=10
VMGT: Step=20
0
2
4
6
8
10
12
14
16
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00

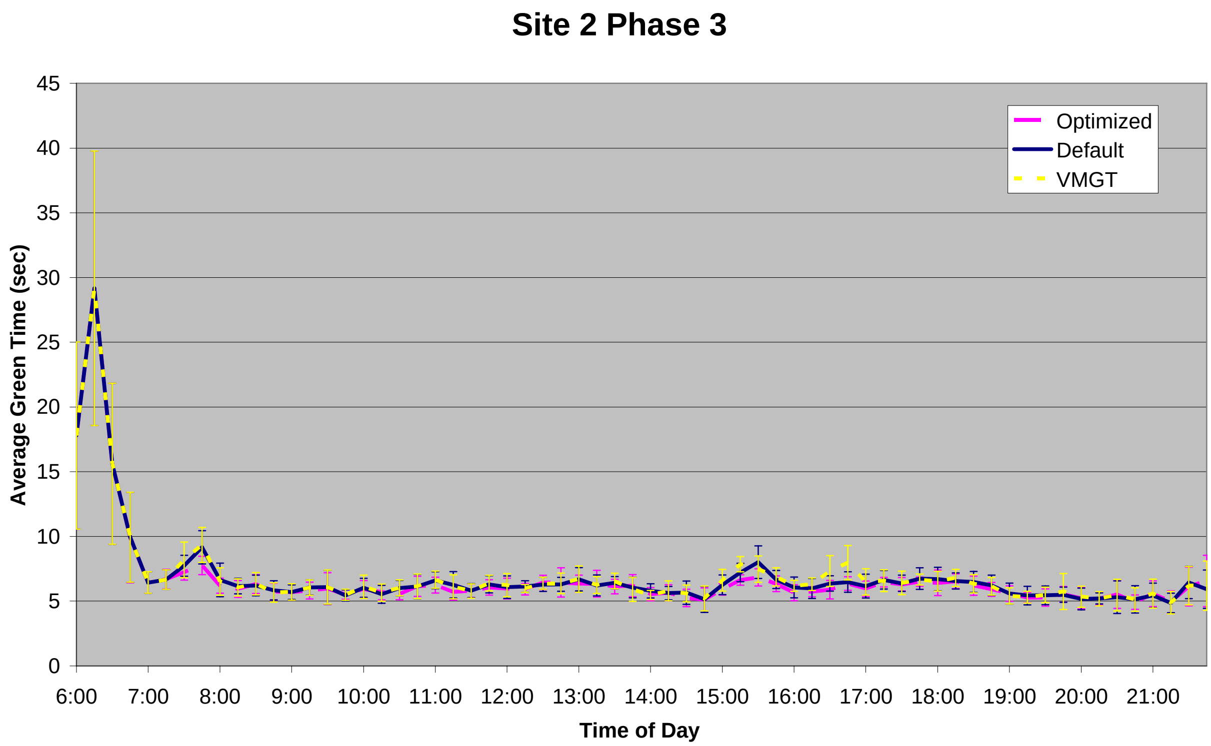

Site 1 Phase 6
Average Green Time (sec)
Time of Day
Optimized
Default
VMGT: Step=10
VMGT: Step=20
0
20
40
60
80
100
120
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00

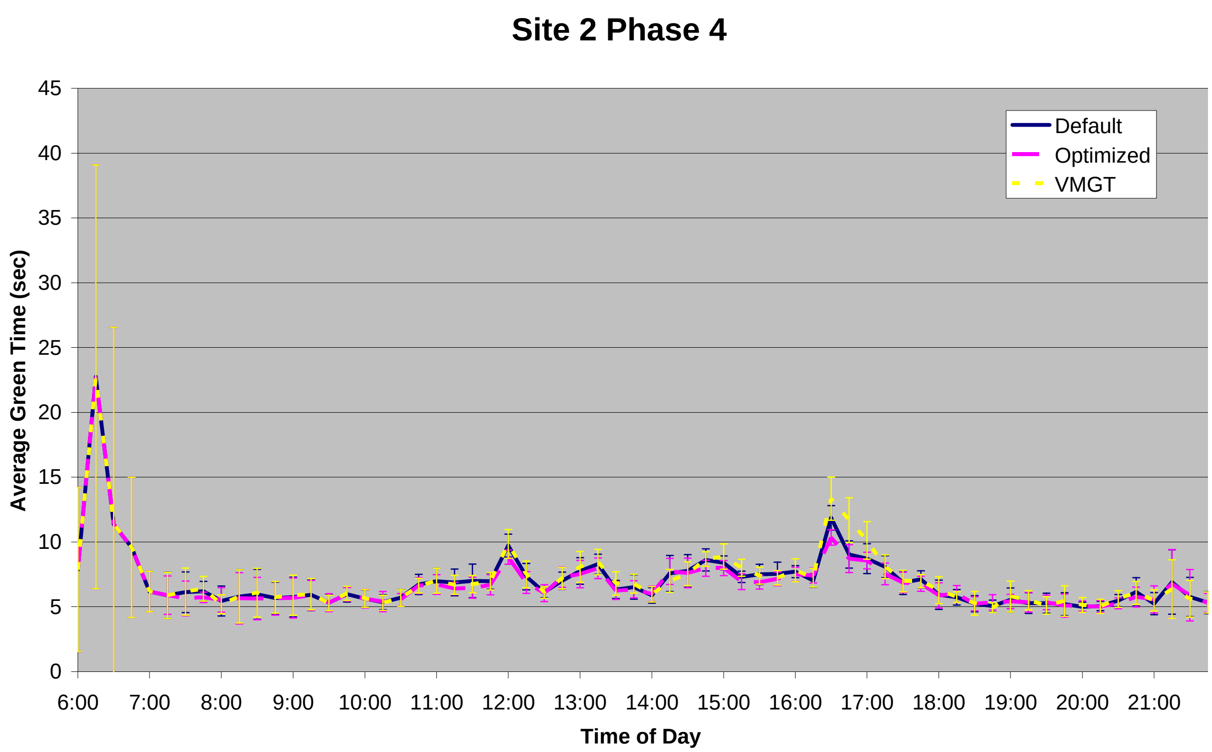

Site 1 Phase 8
Average Green Time (sec)
Time of Day
Default
Optimized
VMGT: Step=10
VMGT: Step=20
0
5
10
15
20
25
30
35
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00

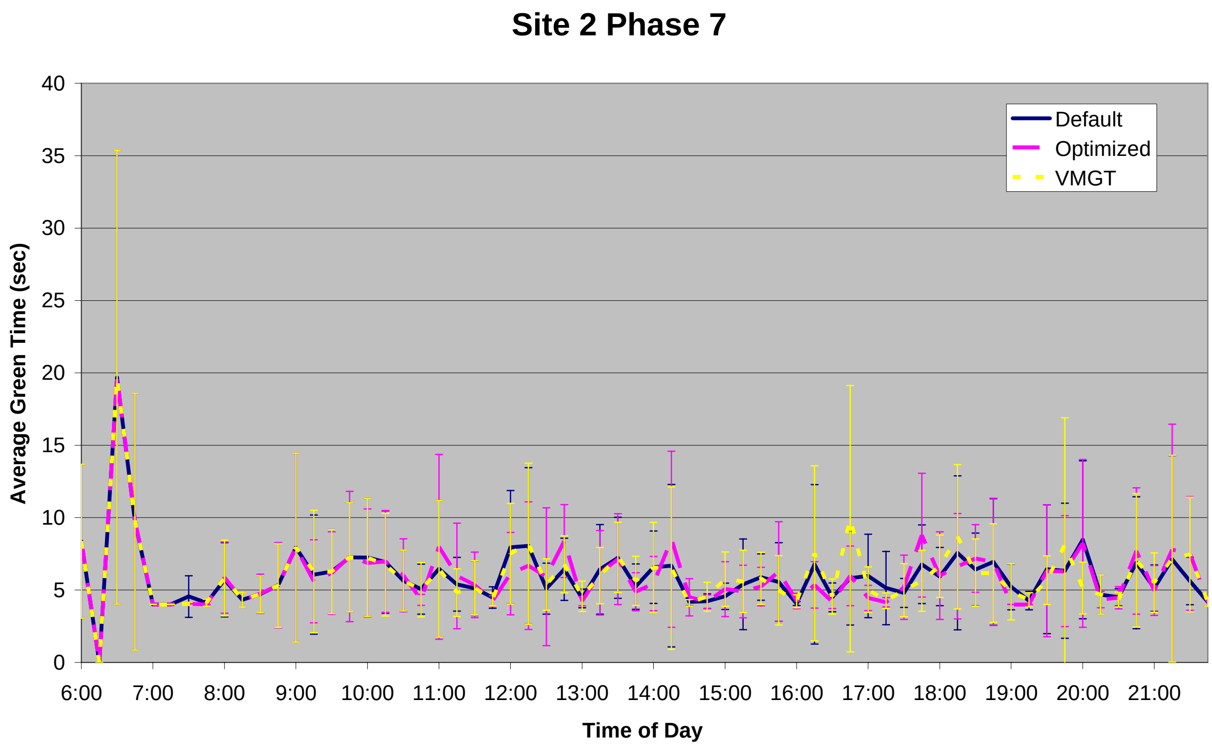
12. Appendix C: Site 2 Phase Length Comparisons

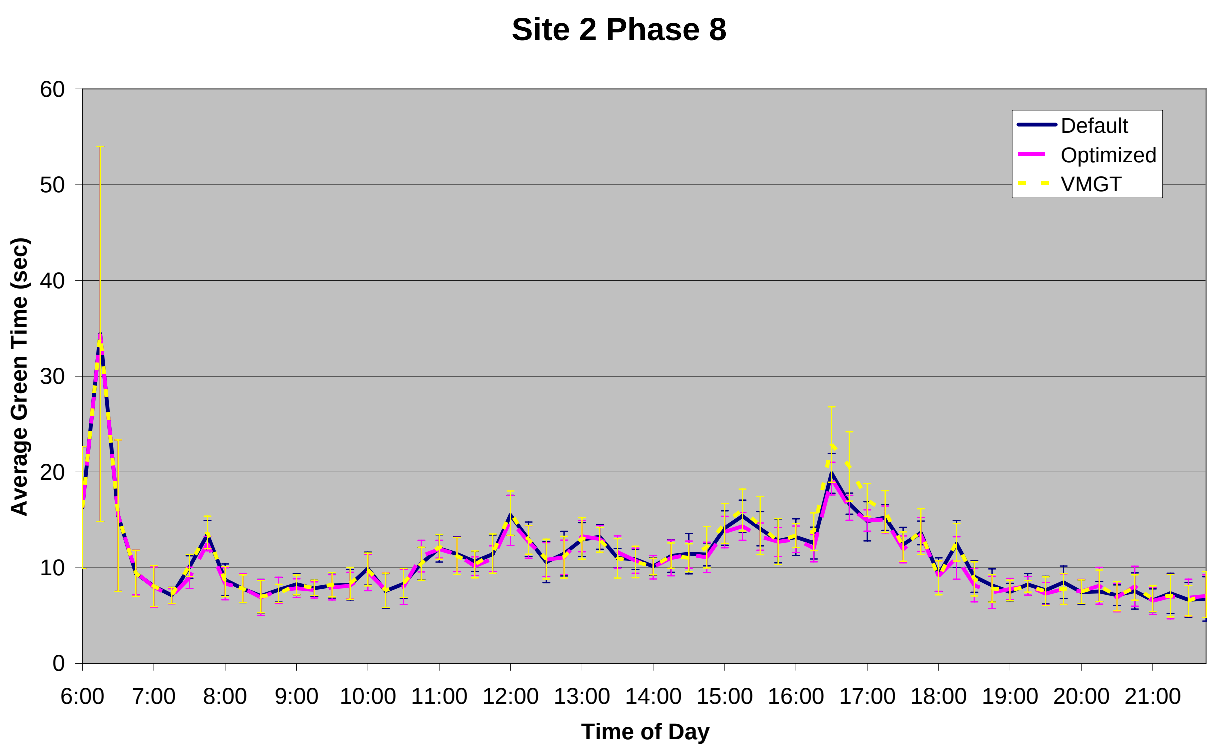

Site 2 Phase 1
Average Green Time (sec)
35
30
25
20
15
10
5
0
Default
Optimized
VMGT
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day


Site 2 Phase 2
Average Green Time (sec)
50
45
40
35
30
25
20
15
10
5
0
Default
Optimized
VMGT
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day

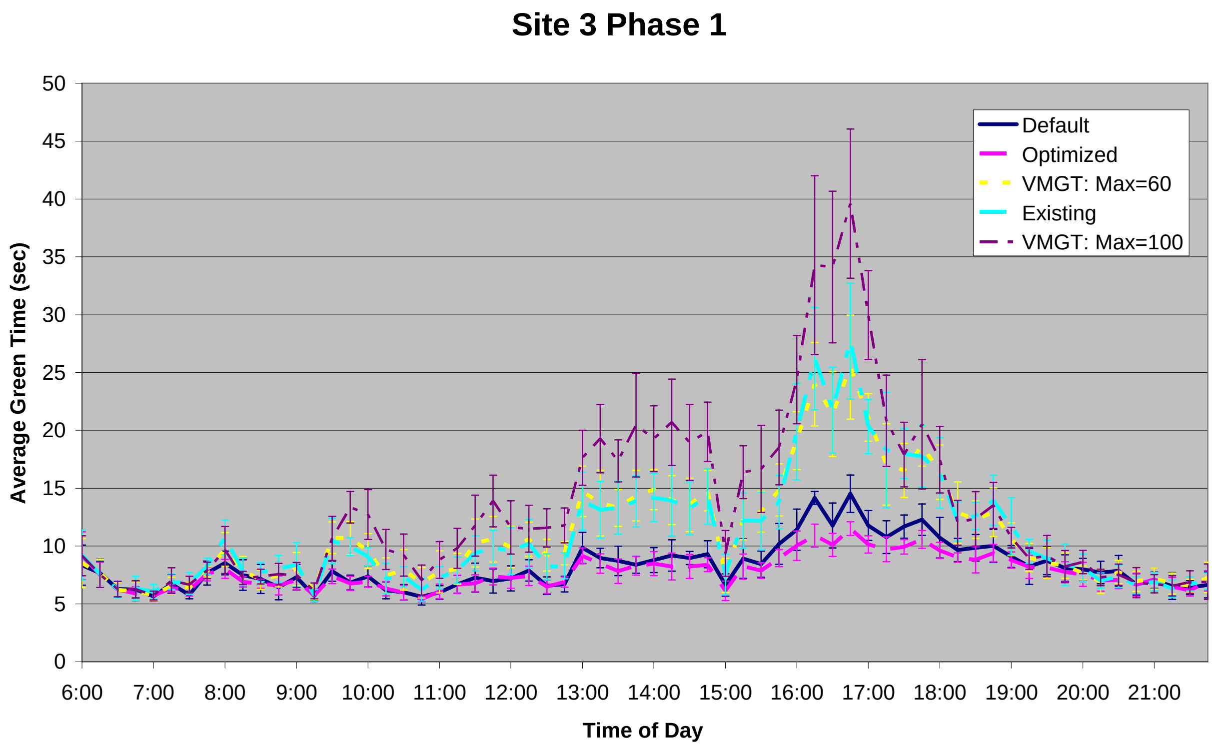

Site 2 Phase 3
Average Green Time (sec)
0
5
10
15
20
25
30
35
40
45
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day
Optimized
Default
VMGT

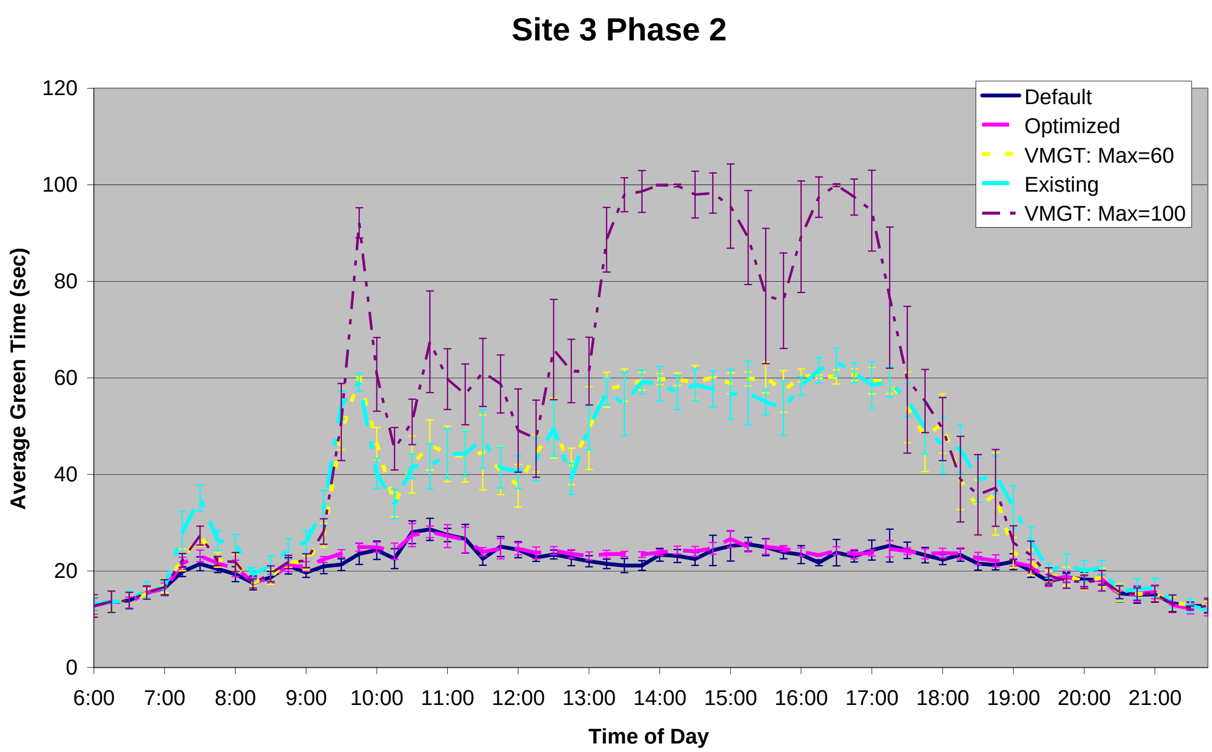

Site 2 Phase 4
Average Green Time (sec)
0
5
10
15
20
25
30
35
40
45
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day
Default
Optimized
VMGT

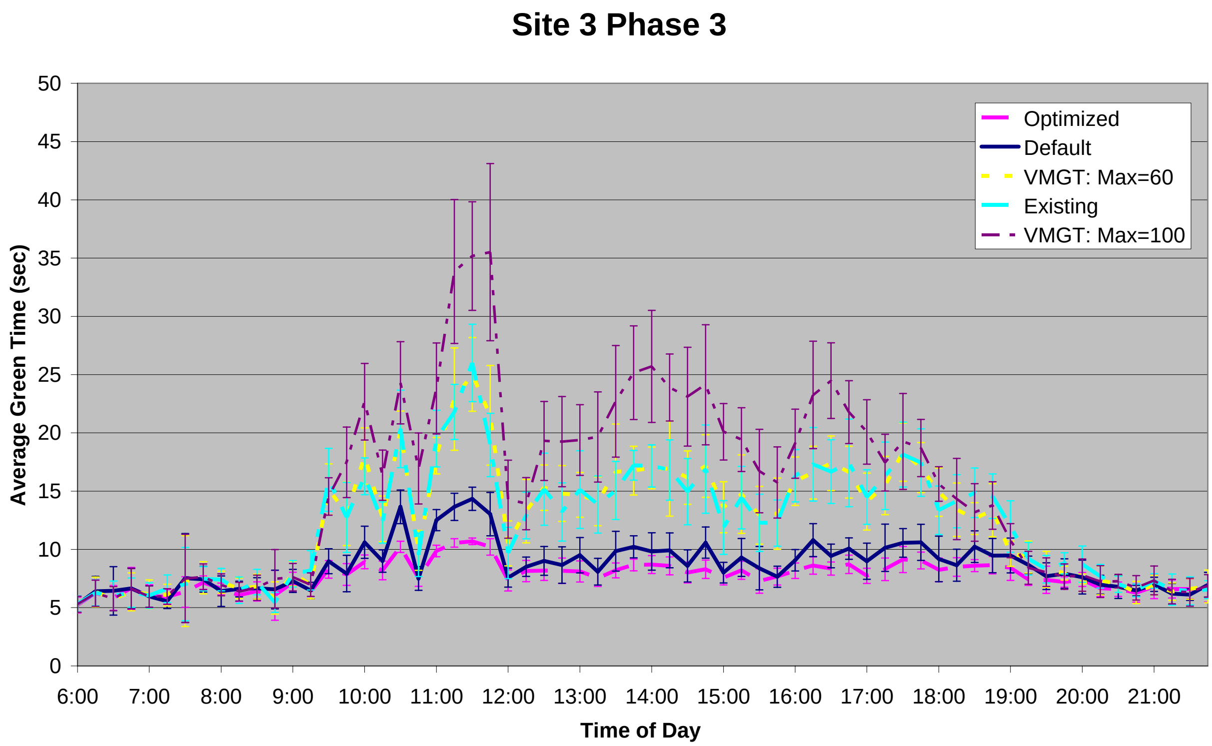

Site 2 Phase 7
Average Green Time (sec)
0
5
10
15
20
25
30
35
40
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day
Default
Optimized
VMGT

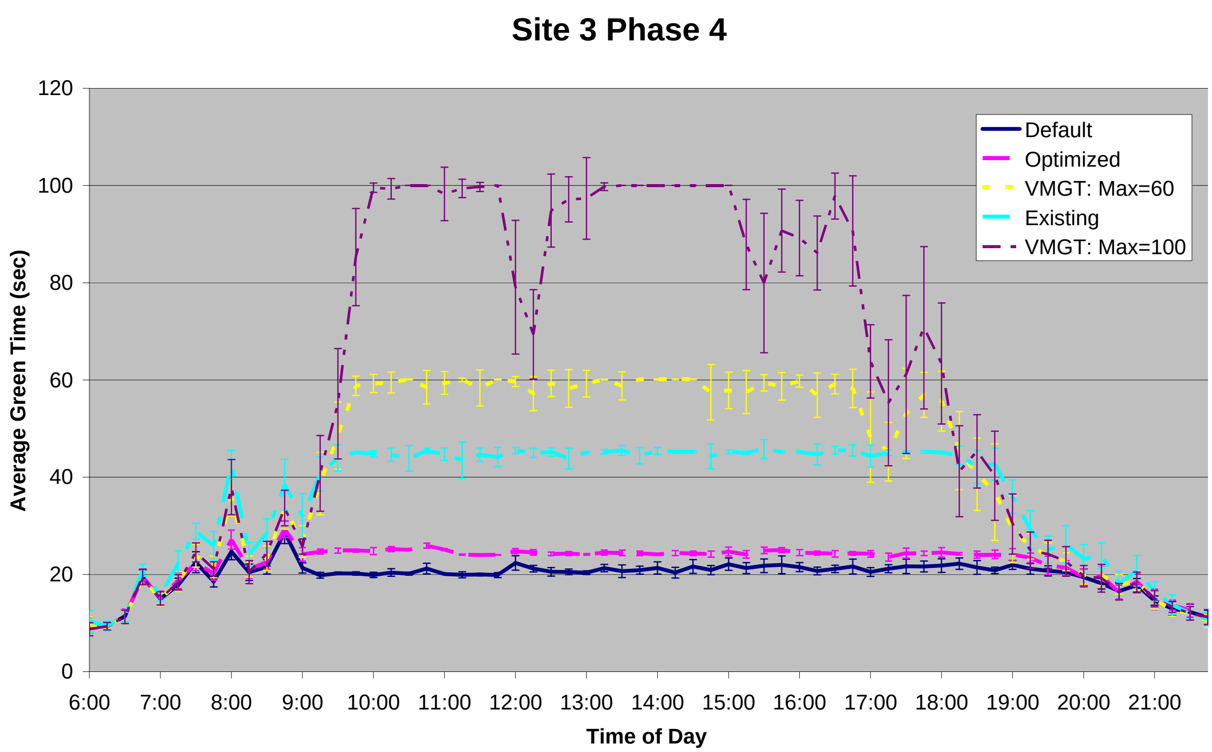

Site 2 Phase 8
Average Green Time (sec)
0
10
20
30
40
50
60
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time of Day
Default
Optimized
VMGT

13. Appendix D: Site 3 Phase Length Comparisons

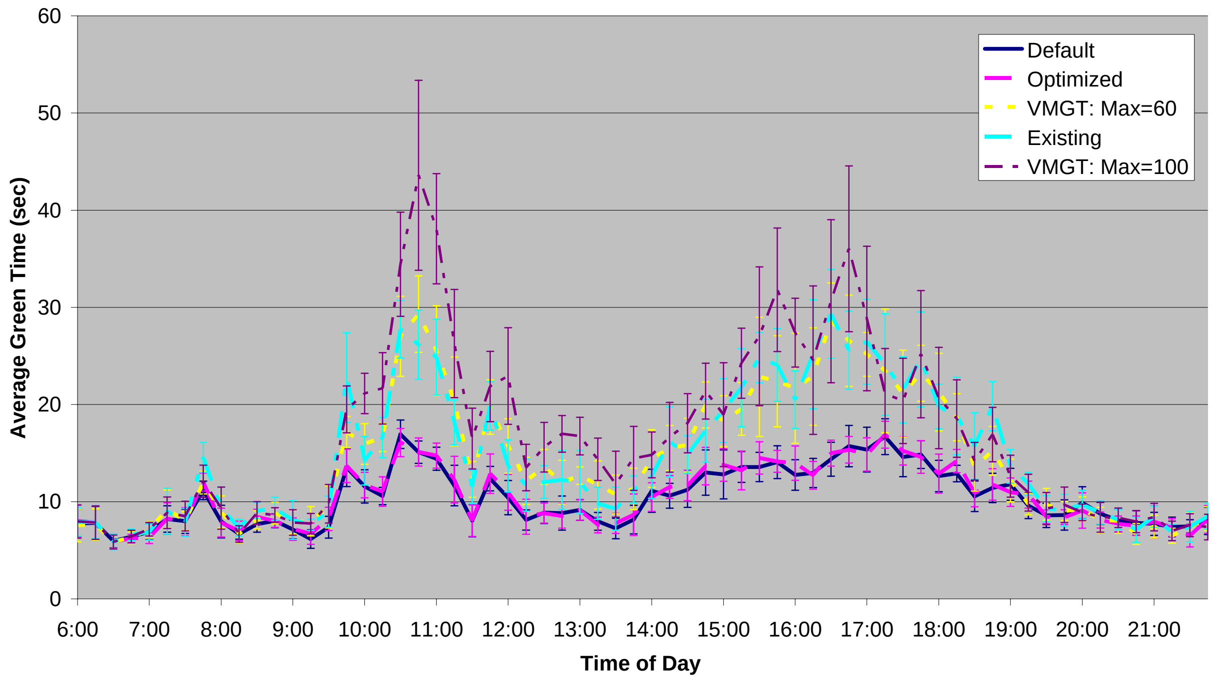

Site 3 Phase 1
Average Green Time (sec)
Time of Day
Default
Optimized
VMGT: Max=60
Existing
VMGT: Max=100
0
5
10
15
20
25
30
35
40
45
50
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00


Site 3 Phase 2
Average Green Time (sec)
Time of Day
Default
Optimized
VMGT: Max=60
Existing
VMGT: Max=100
0
20
40
60
80
100
120
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00

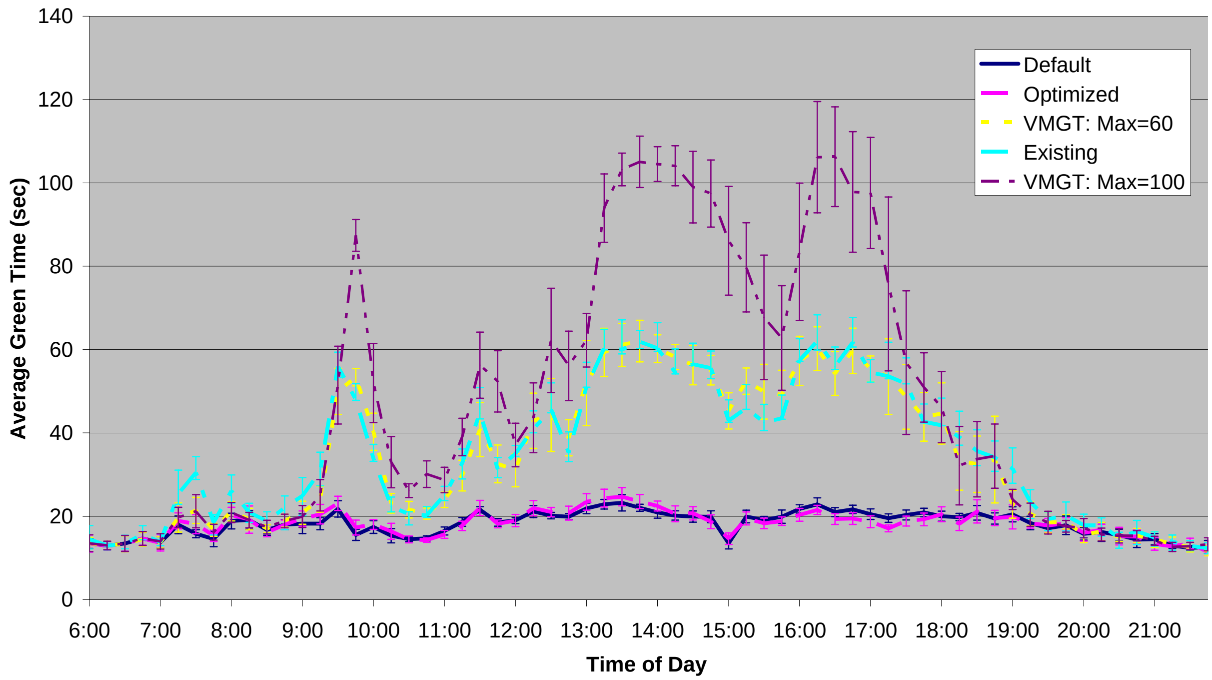

Site 3 Phase 3
Average Green Time (sec)
Time of Day
Optimized
Default
VMGT: Max=60
Existing
VMGT: Max=100

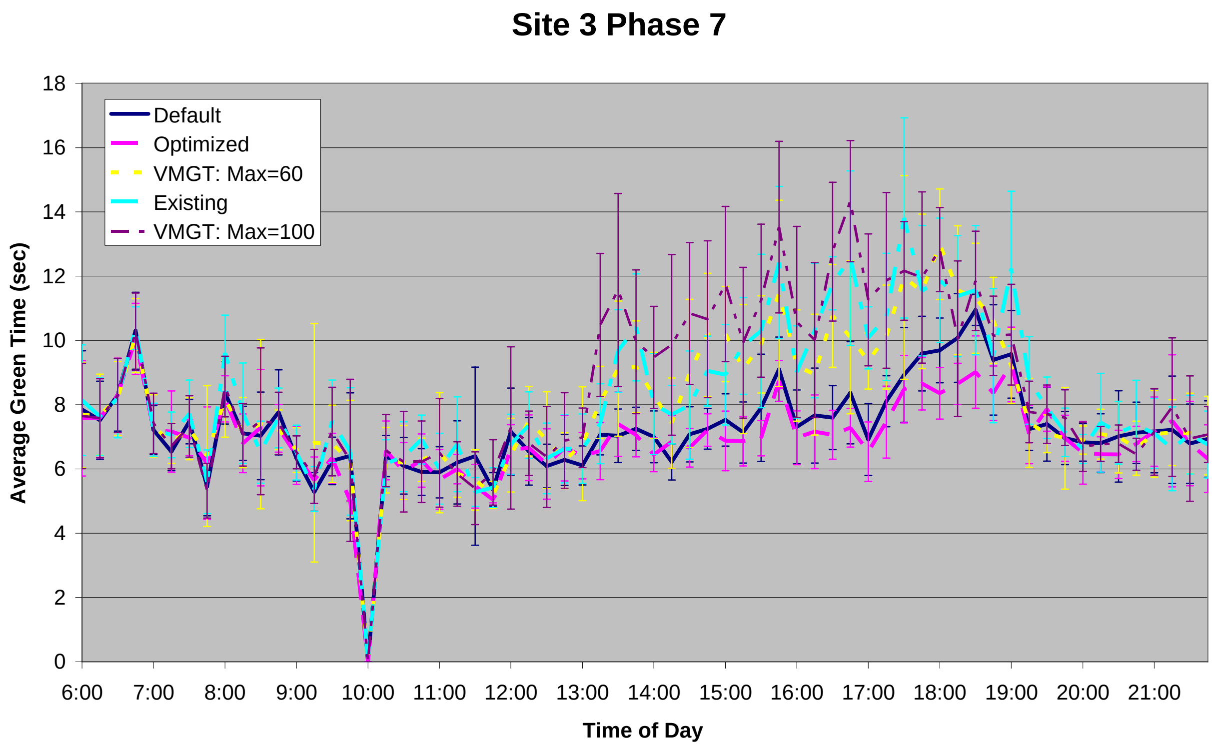

Site 3 Phase 4
Average Green Time (sec)
Time of Day
Default
Optimized
VMGT: Max=60
Existing
VMGT: Max=100

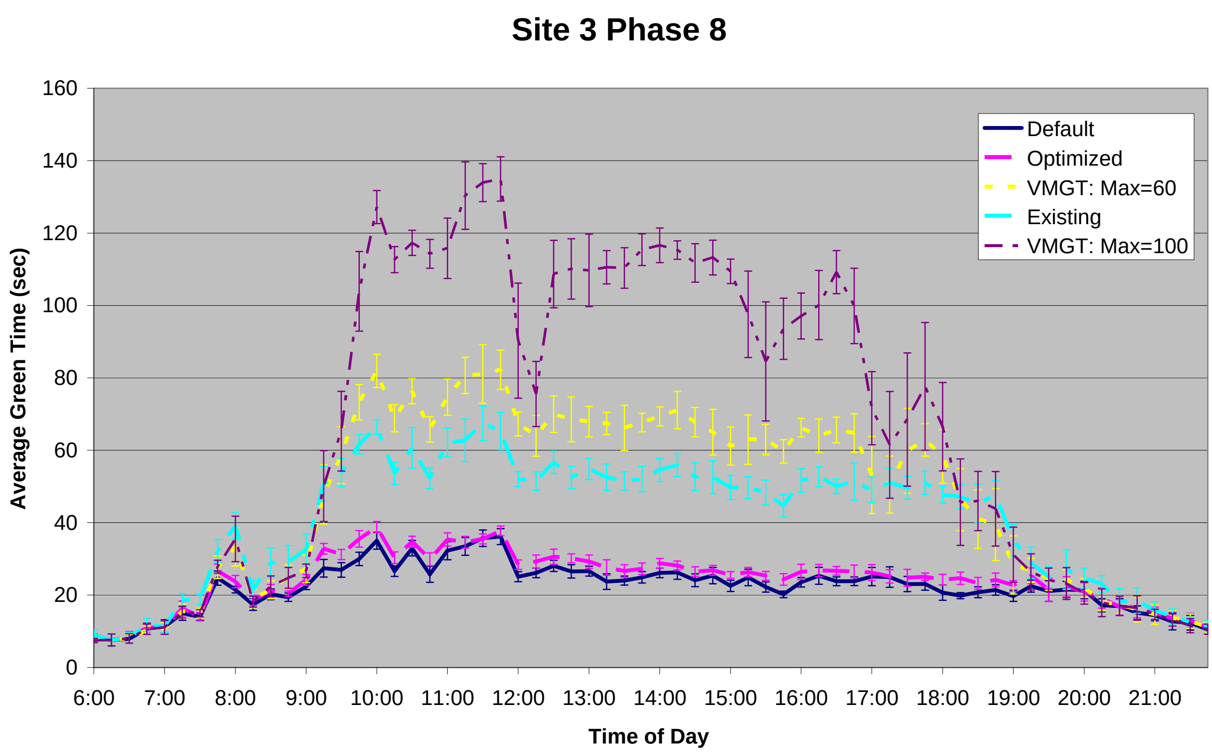
Site 3 Phase 5



Site 3 Phase 6




Site 3 Phase 7
Average Green Time (sec)
Time of Day
Default
Optimized
VMGT: Max=60
Existing
VMGT: Max=100
0
2
4
6
8
10
12
14
16
18
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00


Site 3 Phase 8
Average Green Time (sec)
Time of Day
Default
Optimized
VMGT: Max=60
Existing
VMGT: Max=100
0
20
40
60
80
100
120
140
160
6:00
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