FINAL
CONTRACT REPORT
VTRC 08-CR9

EVALUATION OF PRE-EMPTION AND TRANSITION STRATEGIES FOR NORTHERN VIRGINIA SMART TRAFFIC SIGNAL SYSTEMS (NVSTSS)

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Research Council

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Standard Title Page - Report on State Project

Report No.	Report Date	No. Pages	Type Report:	Project No.:
VTRC 08-CR9	February 2008	40	Final Contract Period Covered:	80636 Contract No.

Title: Evaluation of Pre-Emption and Transition Strategies for Northern Virginia Smart Traffic Signal Systems (NVSTSS)	systems, signal controller Pre-emption, transition, signal
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Supplementary Notes

Abstract

Modern traffic signal control systems provide emergency vehicle preemption (EVP) capabilities by utilizing advanced sensors and communication technologies. EVP strategies are widely implemented by urban transportation management agencies. One of the challenges of implementing EVP under coordinated-actuated signal systems is selecting the best coordination recovery strategy at the end of preemption such that disruptions to the normal traffic signal operations are minimized. Similarly, time-of-day (TOD) traffic operations also produce such disruptions while transitioning between TOD modes and require returning to coordination.

This report presents the evaluation results of various EVP recovery and TOD transition strategies in an urban corridor including four coordinated-actuated signals along Lee Jackson Memorial Highway in Chantilly, Virginia. Since field testing of various preemption and TOD transition strategies is impractical, the study was performed using hardware-in-the-loop simulation, which consisted of a well-calibrated VISSIM microscopic simulation model, four traffic controllers, and four controller interface devices.

The study results showed that advanced controllers (e.g., 2070 and ASC/3) have advantages over the 170 controller for the EVP recovery strategies, while the 170 controller's TOD transition strategies outperformed those of the newer controllers.

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Contract Research Sponsored by
Virginia Transportation Research Council

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

February 2008
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NOTICE

ABSTRACT

Modern traffic signal control systems provide emergency vehicle preemption (EVP) capabilities by utilizing advanced sensors and communication technologies. EVP strategies are widely implemented by urban transportation management agencies. One of the challenges of implementing EVP under coordinated-actuated signal systems is selecting the best coordination recovery strategy at the end of preemption such that disruptions to the normal traffic signal operations are minimized. Similarly, time-of-day (TOD) traffic operations also produce such disruptions while transitioning between TOD modes and require returning to coordination.

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INTRODUCTION

Traffic signal coordination provides increased mobility and delay savings on a traffic network by providing vehicle platoon progression capabilities to major thoroughfares. The use of coordinated traffic signal controllers helps to accomplish this. A coordinated signal environment, however, is tightly controlled and disruptions can mitigate the benefits of signal coordination.

One potential disruption to signal coordination is emergency vehicle preemption (EVP). EVP provides emergency vehicles (e.g., fire trucks, ambulances, police cars, etc.) with the right-of-way at signalized intersections. With the implementation of EVP, emergency vehicles can receive green indications along their routes to reach their destinations more quickly. EVP does, however, often disable signal coordination among controllers, disrupting smooth flow along a coordinated arterial or network. In the case of an EVP call originating from a cross street, extensive queuing often results on the mainline.

Another potential disruption to signal coordination is a change of time-of-day (TOD) plans. Because consecutive TOD plans typically have different cycle lengths and offsets, controllers in a coordinated signal network must break coordination to achieve these new settings. This has a significant effect on coordinated network conditions since it happens several times daily.

After an EVP call or a TOD plan change, the subject intersections are likely no longer in sync in the coordinated network. As a result, the now uncoordinated controllers must recover coordination. They accomplish this through the use of transition methods, of which there are several in each type of controller. Generally, these methods work by lengthening or shortening the local cycle length—the total cycle length specific to each intersection—by a predetermined amount and allocating the extra green times to specified phases. The controllers complete a specified process, based on a selected transition strategy, over each cycle length until the affected signals are back in coordination.

One of the main ways to mitigate the negative effects of EVP and TOD plan changes is to select a transition method that minimizes delays while returning the controller to coordination. Controller software manufacturers (e.g., Econolite, Siemens, etc.), however, do not currently provide information as to the best performing method nor do they provide guidelines advising which method to use in a given scenario (e.g., size of network, roadway volume, etc.).

PURPOSE AND SCOPE

The purpose of this project was (1) to quantify the mobility effects of EVP on a coordinated signal network, (2) to identify the controller transition strategies that minimize any negative effects on the total network delay during EVP operations, and (3) to determine the best transition strategy for changes in TOD plans during daily operations.

This project was confined to a given study network—a four-signalized-intersection corridor in Chantilly, Virginia. The field signal timings developed by Northern Virginia Smart Traffic Signal Systems (NVSTSS) were used in the study. Additionally, two sets of traffic volumes collected at the test network were used. The study only considered the mobility on the network, and thus, the specific mobility of the emergency vehicle was not considered. Additionally, the safety aspect of EVP and was not factored into the analysis.

METHODS

Task 1: Literature Review

The first project task was to identify and obtain the current literature with regards to controller transitioning after EVP and TOD changes. First, literature about controller functionality (e.g., available transition methods) was collected. Then, previously completed studies of controller transition methods after EVP or TOD changes were obtained and reviewed.

Task 2: Test Site Selection and Data Collection

The second project task was to identify a test network site for the EVP and TOD transition study. Data were collected to calibrate the test network and to provide inputs for the experiments. Any further information needed (e.g., signal timing data) was obtained from the Virginia Department of Transportation (VDOT).

Task 3: Hardware-in-the-Loop Simulation Setup

Given that performing a field evaluation for the proposed study was impractical, a laboratory evaluation environment based on the hardware-in-the-loop simulation (HILS) was established.

Task 4: Experimental Design

For the experimental design, the various parameters for the evaluation of the EVP and TOD transition strategies were developed. Factors considered under the EVP transition evaluation included the length of the EVP calls, the traffic volume conditions, and the traffic controllers used in the study, while the TOD transition evaluation considered the time-of-day traffic patterns and the controllers and their strategies.

Task 5: Evaluation of Test Results

Task 5 consisted of an evaluation of the results of the EVP and TOD transition study. The results of this task helped to quantify the impacts that EVP and TOD plan changes have on a coordinated signal network and to determine the transition strategies that reduce traffic delays caused by the disruptions in signal coordination.

RESULTS AND DISCUSSION

Task 1: Literature Review

Transition Methods

Shelby et al. (2006) outlined the transition methods available in the Eagle EPAC300, Econolite ASC2S, Siemens NextPhase, and the Naztec Model 980 controllers. These methods are explained below:

- **Dwell:** Remains in coordinated phase green until controller regains coordination.
- **Max Dwell:** Remains in coordinated phase green until controller regains coordination or a specified maximum dwell time per cycle is reached. This maximum time is set as either a number of seconds per cycle or a percentage of the cycle length per cycle. If the controller reaches this set maximum time before returning to coordination, it then cycles through the non-coordinated phases before dwelling in coordinated phase green again. This process repeats until coordination is regained. In Eagle controllers, this method is referred to as Dwell with Interrupt.
- **Add:** Lengthens all phases in proportion to their split times. Similar to the Max Dwell method, an upper limit is placed on the length of the local cycle time extension, usually between seventeen and twenty percent of cycle length. Add is also known as Add Only, Longway, Long, and Shortway Plus across various controller types and software.
- **Subtract:** Shortens all phases in proportion to their split times in a manner similar to the way Add lengthens all phase lengths. Subtract was previously referred to as Shortway and is now commonly known only as Subtract or Short.

- **Minimax:** Is another term for Shortway, which selects either Add or Subtract for the transition method, depending on which is expected to achieve better results. It is referred to as Short/Long (Naztec Model 980) and Shortway 2 (Eagle).
- **Bestway:** Selects Add or Subtract based on the optimum ratio of the needed offset adjustment to the maximum adjustment per cycle. In Siemens NextPhase, it is referred to as Shortway, although it uses the total time needed to return to coordination as the selection criteria rather than the above ratio.
- **Shortway:** Adds green time only to the coordinated phases and subtracts green time only from the non-coordinated phases. There are no adjustments by more than fifty percent of the cycle length, and Add must be used if Subtract is expected to take more than five cycles to return to coordination. In CORSIM, Shortway selects Add or Subtract based on the least amount of time needed to return to coordination. One constraint, however, is that CORSIM cannot lengthen or shorten the cycle length by more than twenty percent.

Previous Studies

Several studies have showed the effects of EVP on traffic signal systems, specifically the transition and recovery strategies of these systems. Using software-in-the-loop simulation (SILS) with CORSIM and the Siemens NextPhase Suitcase Tester software, Obenberger and Collura (2007) evaluated five transition strategies available in Siemens NextPhase—Hold/Dwell, Maximum Dwell, Long Way/Add, Short Way, and Best Way/Smooth. In this study, they used three volume conditions—a base case, a twenty percent increase case, and a forty percent increase case. The direction of the EVP call, however, remained constant, traveling in one direction through all four intersections in their test CORSIM network. Based on the current state-of-the-practice, they found that no condition exists that specifies or limits the use of any one transition strategy for EVP. In addition, they recommended the utilization of SILS or HILS for research studies associated with EVP.

In one comprehensive study, Shelby, Bullock, and Gettman (2006) compared several transition methods—Dwell, Max Dwell, Add, Subtract, Shortway, Immediate, Two-Cycle, Three-Cycle—using CORSIM (TSIS 5.2) which was enhanced to support research on ACS-Lite. Two different sites were studied—an isolated intersection and a four-intersection arterial. The results indicate that the level of saturation is a significant factor in determining the optimum transition method. For instance, in the arterial network study, at eighty percent or less saturation, the Best Way method was most effective. At ninety percent or higher saturation, the Add method outperformed best way in some instances. Overall, it was found that the Minimax class of transition methods (Smooth, Best Way, Long/Short, Shortway) outperformed Dwell, which can actually degrade performance at low saturation levels. Further, it was found that a three-cycle transition period was better than a two-cycle period, which in turn outperformed a one-cycle period. In all, transition was found to cause around eighteen percent additional delay time.

The use of HILS to evaluate EVP has become a more viable option for researchers recently. Nelson and Bullock (2000) performed a study of EVP’s effect on closely spaced intersections along an arterial in West Lafayette, Indiana. Using a HILS consisting of CORSIM and actual controllers, the study tested between one and four emergency vehicle preemption calls to evaluate the performance of the transition methods. A single EVP call had little effect on network performance, resulting in only small increases in travel time and delay. Multiple EVP calls, however, spaced at short intervals greatly affected network performance. In the evaluation of the Smooth, Dwell, and Add Only transition methods, Smooth performed best.

In a previous 2001 study, Obenberger and Collura (2001) used CORSIM with the Siemens NextPhase Suitcase Tester to study the effectiveness of controller transitioning algorithms. Using a one-mile, four-intersection corridor as a test bed, the authors simulated one emergency vehicle traveling through the entire network. This process was repeated employing different controller transitioning methods—Hold, Long, Short, and Best Way—which are similar to those used in the Econolite software. Hold, similar to Dwell, maintains coordinated phase green indications until the controller returns to coordination. Long and Short, respectively, increase and decrease phase lengths proportionally by a predetermined time, and Best Way, similar to Smooth, selects either the Long or Short method to return the controller to coordination. Three levels of traffic demand were specified in the experimental design—base, twenty percent increase, and forty percent increase. Under the base traffic demand condition, Short was the least efficient while there were no significant differences between the other transition methods. With a twenty percent increase in demand, Best Way outperformed, and Short and Long were the least efficient. In the forty percent increased demand case—similar to the base case—Short was the least efficient while no significant difference existed between Hold, Long, and Best Way.

The CORSIM simulation program also has the capability to emulate controller transition methods. Cohen, Head, and Shelby (2007), using CORSIM Version 6.0, studied the performance of the Dwell, Max Dwell, Subtract, and Shortway methods on two different traffic networks. One such network—Speedway Boulevard in Tucson, Arizona—contained ten intersections along a 4.4-mile-long corridor. To break signal coordination, all ten intersections transitioned to different offsets, and five intersections changed phase splits slightly. The study results showed that delay and travel times under Dwell and Max Dwell spiked early in the transition process. In a hypothetical six-intersection network that was close to over-saturated conditions, results also showed a spike in delay under Dwell and Max Dwell while Subtract and Shortway allowed for a smoother return to coordination. Cohen et al. concluded that, due to this "shockwave" in delay during the transition period cause by Dwell and Max Dwell, those methods are not appropriate for major-crossing thoroughfares.

Task 2: Test Site Selection and Data Collection

This section describes the test site selection, data collection efforts, and the calibration of the VISSIM simulation network.

Test Site Selection

The test site for this study is an urban corridor in Chantilly, Virginia. As shown in Figure 1, the corridor is a one-mile section of Lee Jackson Memorial Highway/U.S. Route 50 and includes four coordinated-actuated signals between Sullyfield Circle and Chantilly Road. The dotted circles in Figure 1 outline the four intersections under examination. In this document, the intersections are referred to as Intersections 13 through 10, from west to east, as follows:

- Centerview Drive/Sullyfield Circle and Route 50 (Intersection 13)
- Centerville Road/Walney Road and Route 50 (Intersection 12)
- Metrotech Drive/Elmwood Street and Route 50 (Intersection 11)
- Chantilly Road and Route 50 (Intersection 10)

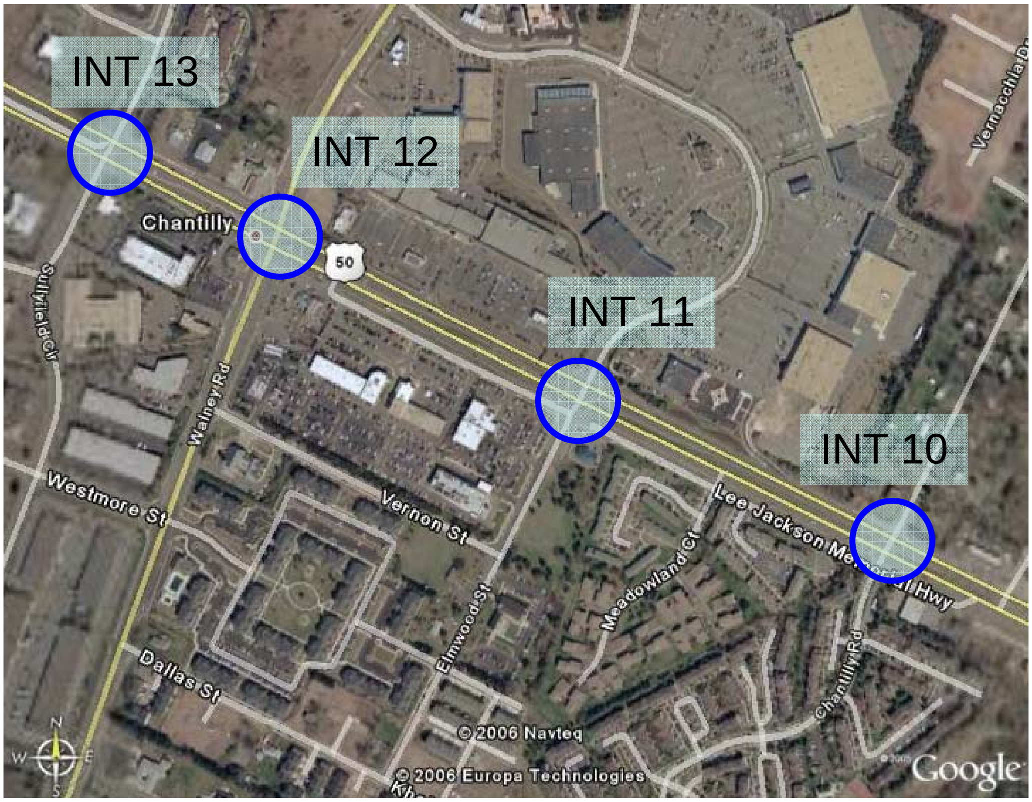

Figure 1. Test site: Lee Jackson Memorial Highway, Chantilly, Virginia (http://earth.google.com/)

Data Collection and VISSIM Simulation Network Calibration

The project team conducted data collection on one weekday in 2006 between 3:00 p.m. and 4:00 p.m. The data were collected directly from the site and included traffic and pedestrian counts and travel times along the major arterial. In addition, VDOT provided the existing EVP settings and three SYNCHRO networks, including the TOD timing plans and traffic counts for the a.m. peak, midday, and p.m. peak periods.

Since the use of a well-calibrated microscopic simulation model is an important step to achieve reliable results for any simulation-based evaluation, the case study network was calibrated before it was used in the HILS evaluations. A proposed microscopic simulation model calibration and validation procedure by Park et al. (2006) was applied for the VISSIM network. This procedure includes the following steps:

- Simulation model setup
- Initial evaluation of a microscopic simulation model with default calibration parameters
- Feasibility test using 200 samples generated by Latin Hypercube Design

- Parameter calibration using a genetic algorithm with ten populations and twenty generations
- Evaluation of the parameter set
- Validation and visualization

There are numerous VISSIM parameters that can be calibrated to replicate field traffic conditions (Planung Transport Verkehr AG). For the Route 50 network calibration, eleven parameters, which consisted of car following behavior, lane changing behavior, and speed distributions, were tuned such that the eastbound and westbound travel times on Route 50 in VISSIM approximated those recorded in the field. This was accomplished using an initialization period of 1000 seconds and a simulation time of 3,600 seconds.

The statistical summaries in Table 1 were produced using the travel times from 100 randomly seeded VISSIM simulation runs based on the default and the calibrated parameters resulted from applying Park and Qi's procedure (Park and Qi, 2005). Even though the VISSIM network with the default calibration parameters yielded similar travel times to the observed ones from the test site, the calibrated network produced closer to field measured travel times. Thus, the calibrated VISSIM network was used in the HILS experiments.

Table 1. Calibration Results

Type of Run	Average Travel Time in Seconds (Standard Deviation)	
	Eastbound	Westbound
Observed travel time	102	116
100 VISSIM runs with default parameters	107 (3)	119 (3)
100 VISSIM runs with calibrated parameters	102 (2)	114 (3)

Task 3: Hardware-in-the-Loop Simulation Setup

This section presents the HILS setup as well as preliminary test results on the EVP runs.

Hardware-in-the-Loop Simulation

HILS is one of the most advanced forms of microscopic simulation available for traffic signal control systems. It provides a physical link between the microscopic simulation model and the traffic controller via a controller interface device (Bullock and Catarella, 1998). HILS allows for the evaluation of controller functionality in a realistic and safe environment. For the analysis of controller transition strategies, VISSIM-based HILS consisted of the VISSIM microscopic simulation software Version 4.1, four controller interface device and four traffic signal controllers was established. Figure 2 shows the physical and logical connections for the VISSIM-based HILS.

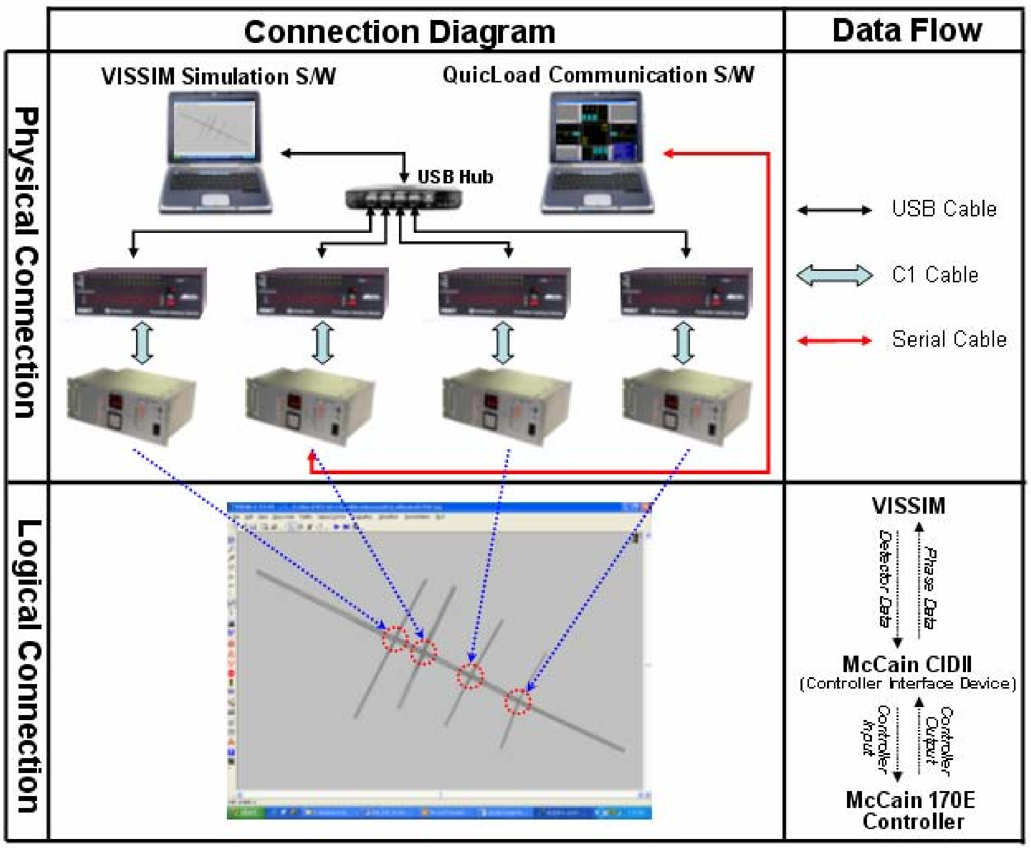

Figure 2. Physical and Logical Connections of HILS Applied to the Test Site

Emergency Vehicle Preemption Implementation

This section describes the EVP algorithm implemented for this study and the results of preliminary experiments of the EVP implementation. It also details the testing of the impact of the EVP call location within the local cycle timer and the development of an automation program for EVP evaluations.

EVP Algorithm

Although signal control during EVP can be simulated accurately, the actual movements of the emergency vehicle and the other vehicles on the network are more difficult to mimic. Thus, an algorithm was devised that accounts for the vehicles yielding to the emergency vehicle moving through the intersection.

The travel time of the emergency vehicle from the location of the start of the preemption call through the intersection was first calculated. Based on the hardware specifications, the maximum distance at which the preemption receiver can receive an EVP call is 1,300 feet from the preemption transmitter. Assuming a free-flow speed of fifty miles per hour—ten miles-per-hour above the posted speed limit at the study site—the estimated emergency vehicle travel time is eighteen seconds from the location of the start of the EVP call to the intersection. Thus, eighteen seconds was the assumed total EVP call time. In other words, the traffic controller has at most eighteen seconds to provide green to the emergency vehicle. Depending on the location of the EVP call within the local cycle and traffic conditions, the controller may not be able to provide green to the EVP movement. For these cases, it is likely that queued vehicles would yield to an emergency vehicle while the signal is red. Thus, it is necessary to estimate the time when the emergency vehicle would actually enter the proximity of the intersection, at which point the vehicles would begin to yield. Here, proximity to the intersection is considered to be between 200 and 300 feet. It is at this point that any vehicles present along the emergency vehicle's path would start to yield, which is simulated in the VISSIM network by giving a red signal to that approach for a few seconds. After this time period, it is assumed that the emergency vehicle would have passed through the intersection, and signals in the VISSIM network would begin to operate again according to the signal controller settings.

Using the variable α—the time between when the EVP call is first made and when the preemption movements can be served—the times at which to display red in the VISSIM network and to terminate the EVP call can be determined. In this analysis, α is compared to the free-flow travel time (FFTT) for the entire emergency vehicle travel, which was calculated to be eighteen seconds, as described earlier. In addition, the travel time for the emergency vehicle in the 200-300-foot proximity of the intersection—five seconds—is used as the time of the red signal in the VISSIM network. One of three possible scenarios can occur after an EVP call during a simulation run:

1. **α > FFTT:** Due to this long period required to time the preemption phases, likely because of pedestrians crossing at the intersection, the emergency vehicle is going to be held up by a red light. As a result, it is assumed that the EVP call is removed at time (FFTT + 5) seconds, when the emergency vehicle is estimated to have cleared the intersection.
2. **(FFTT – α) < 5 seconds:** In this case, the emergency vehicle is in the proximity of the intersection, and the other vehicles will yield. A five-second red indication is then given for the preemption phases in VISSIM to simulate the vehicle yield, which is followed by ending the preemption call.
3. **(FFTT - α) > 5 seconds:** Here, the emergency vehicle is not yet in the proximity of the intersection, so the five-second red indication on the preemption phases in VISSIM is not given until (FFTT - α) is less than 5 seconds. The EVP call is then terminated after this five-second period.

Location of EVP Call in Local Cycle Timer

As noted, the EVP recovery (or transition) operations vary according to the location in the local cycle timer when an EVP call occurs. Note that the location is a point of time within the local cycle timer. Figure 3 illustrates the relationship between the location of EVP calls and the resultant network-wide average vehicle delay using three HILS runs with 170 controllers (Shortway, three cycles to return to coordination). To account for this impact, this study selected twenty different locations in the local cycle timer for EVP calls. For the first simulation run, the preemption call was placed at ten seconds after the termination of the green indications for phases 2 and 6 following the six-minute simulation warm-up time. The preemption call for the subsequent simulation runs occurred at ten-second increments, allowing for the twenty total runs to span the entire 200-second cycle length across individual VISSIM-based HILS runs. The length of an EVP call was determined by the assumed free-flow travel time of the emergency vehicle through the intersection (eighteen seconds for the northbound scenario) and the time needed to serve the preemption phases after the EVP call was first made. If the latter was greater than the free-flow travel time due to the need to serve current minimum green and pedestrian walk times, the emergency vehicle was likely waiting at the intersection for a green indication, so the EVP call was held until five seconds after the preemption phases begin timing to simulate the vehicle traveling through and leaving the intersection. Otherwise, the EVP call lasted for eighteen seconds. In addition, to consider the variability in the VISSIM microscopic traffic simulation model linked to HILS, three randomly seeded replications were made for each location, which are referred to as Runs 1, 2, and 3 in Figure 3, such that a total of sixty HILS runs were made for each case.

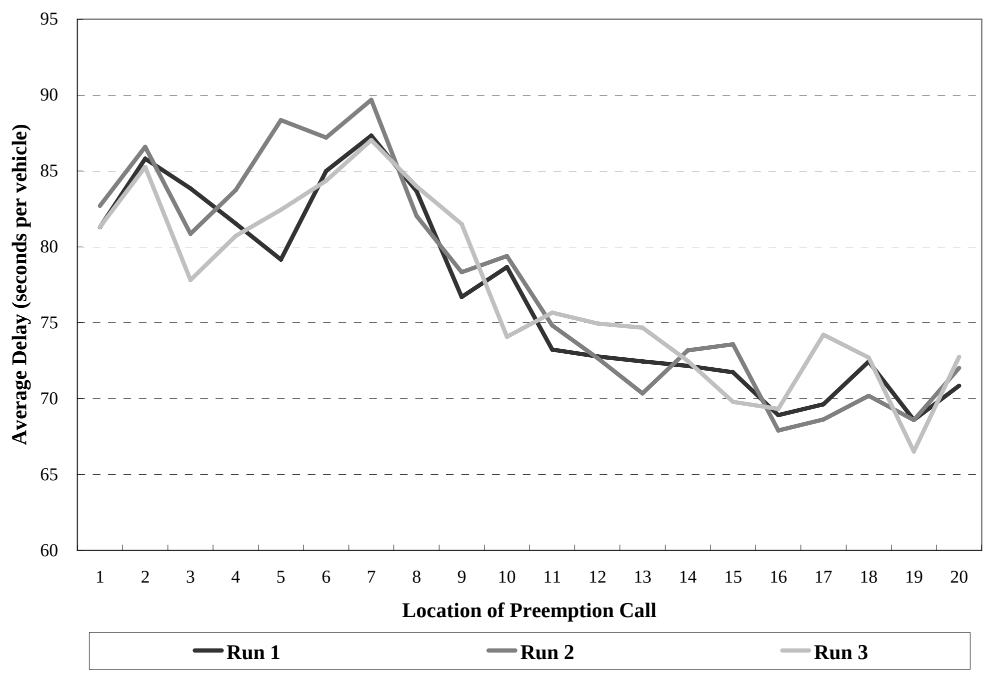

Figure 3. Network Performance Variability Due to Location in Local Cycle Timer of EVP Call

Figure 4 provides an example of the EVP and transition processes in the 170 controller. In this example, it took 363 seconds for the controller to return to coordination after receiving a preemption call. When the controller received the preemption call, phase 8 was terminated as soon as its minimum green time was satisfied to serve EVP (phases 4 and 7). Twenty seconds after the termination of the preemption call, the controller provided ten seconds of green time - the clearance time - to the EVP phases. The transition process was then initiated with the controller setting the master timer and the local timer to zero. When the master timer reached the background cycle length (200 seconds), the controller reset the master timer to its internal value as if there was no preemption call. Meanwhile, the local timer ran up to its adjusted cycle length according to the selected transition method and number of cycles. In the first cycle during transition, the controller increased the cycle length up to 236 seconds with the force-off points for all phases adjusted in proportion to the increase of cycle length (phase 3 was skipped in the first cycle). In the second cycle, the controller decreased the cycle length to ninety-one seconds with the force-off points for all phases adjusted proportionally and finally returned to coordination.

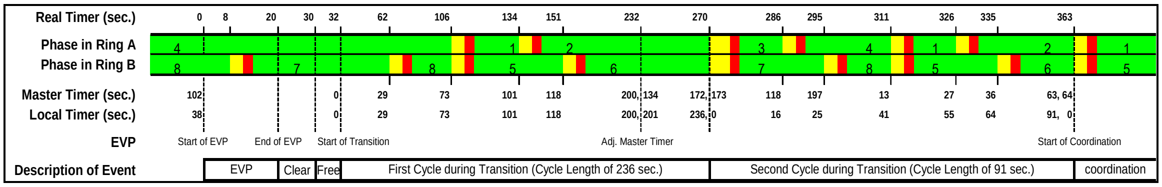

Figure 4. EVP and Transition Process in 170 Controller

EVP Automation Program

To initiate and terminate the emergency vehicle preemption calls, this study used a software program built in C# language that has the following abilities:

- To initiate a VISSIM simulation run
- To transmit an EVP call to the subject controller after the simulation warm-up time
- To terminate the EVP call
- To terminate the VISSIM simulation run
- To save VISSIM output files

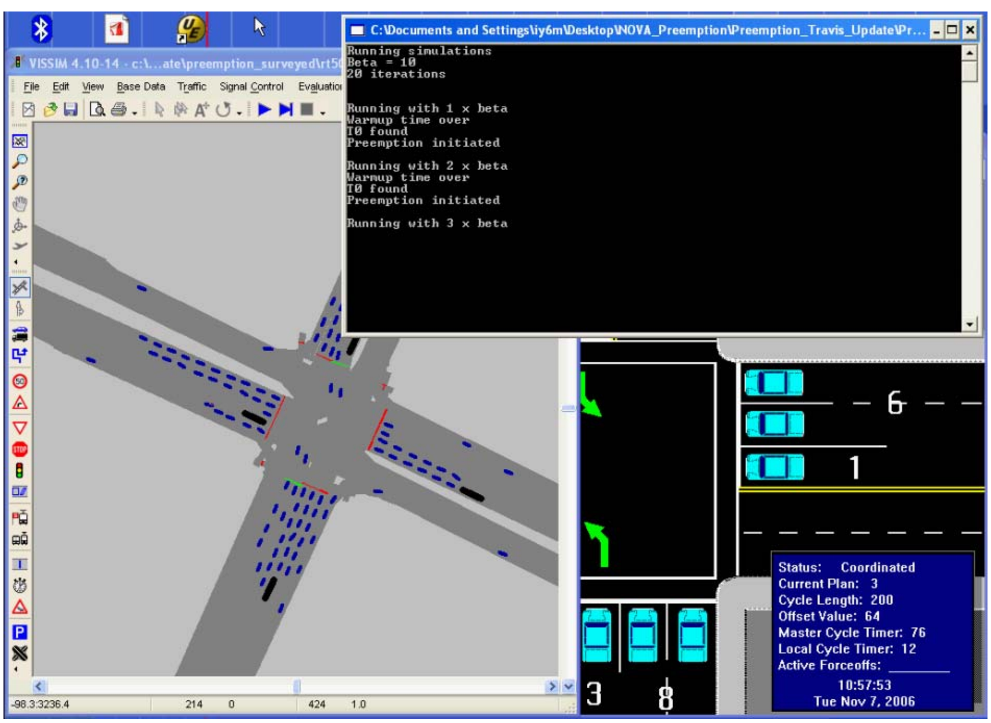

Figure 5. HILS screen shot with VISSIM, QuicLoad display, and EVP program display

This program functioned for both the northbound and eastbound preemption cases. Figure 5 shows a screen shot of the program display along with the VISSIM program animation and the QuicLoad software display, which shows the 170 controller's current status.

Task 4: Experimental Design

This section discusses the experiments conducted for the EVP transition and TOD transition evaluations.

EVP Transition Evaluations

Controllers

To study the effects of transition methods after EVP, this study used three different traffic signal controllers—170, 2070, and ASC/3—with McCain (170) and Econolite (2070, ASC/3) software. The internal functionality of each controller was compared, the 2070's increased functionality was compared to that of the 170, and the ASC/3 was compared to the 2070. It is noted that the NVSTSS currently uses the 170 controller.

Transition Methods

In the 170 controller, the available transition methods—Shortway and Dwell—were evaluated while varying the number of cycles needed to return to coordination (3, 2, or 1). In the 2070 controller, Smooth, Add Only, and Dwell were evaluated. For Dwell, three different Max Dwell values were used—100 seconds, 200 seconds, and 255 seconds. In the ASC/3 controller, only Smooth was considered in an attempt to reduce the number of scenarios. In stead of evaluating exit phase strategies under logic processor with all possible transition methods, this study selected the Smooth method which is generally superior to other transition methods.

EVP Direction

Two directions for the EVP vehicle were developed for this study—northbound and eastbound. The northbound scenario simulated an EVP call at one location only—the northbound approach at Intersection 12, which corresponds to current field conditions. The eastbound scenario simulated an emergency vehicle traveling east through all four intersections in the test network. Only one EVP vehicle was simulated in each case.

Exit Phases

Additionally, the effects of the exit phases after preemption were studied for this project. Exit phases can be specified in the 2070 and ASC/3 controllers (i.e., not available in the 170 controller) and can be served immediately after the preemption phases and followed by the normal phase sequencing. In the 170 controller, the cross street phase sequence was changed from lead-lead to lead-lag, creating de facto exit phases. In the 2070 and ASC/3 controllers, phases 1 and 5, 2 and 6, 3 and 8, and 4 and 8 were all determined to be practical exit phases for the northbound EVP study. For the eastbound study, phases 1 and 6, 2 and 6, and none were identified as the most practical exit phase choices. Figure 6 shows the Intersection 12 phase numbers, which apply to both the northbound and eastbound EVP cases.

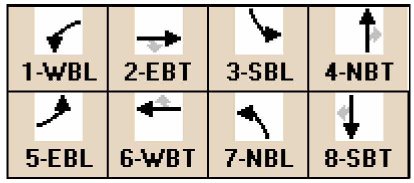

Figure 6. Intersection 12 Phase Numbers

Volume

Two different volume cases were used in this study—off-peak and peak. Off-peak volumes were collected along the study network between 3:00 p.m. and 4:00 p.m. on a May weekday. P.M. peak volumes were provided by NVSTSS and used for the peak volume condition.

Location of EVP Call in Local Cycle Timer

For each run, twenty VISSIM iterations were made with the EVP call spaced at ten-second intervals within the local cycle timer. For example, after the six-minutes of warm-up time, the first run’s EVP call was placed at ten seconds after the yield point. The second run’s EVP call was then made at twenty seconds after the yield point following warm-up time. This pattern continued for the next eighteen runs and thus covered the entire 200-second cycle length for peak and off-peak conditions.

TOD Transition Evaluations

Transition Methods under Examination

For the 170 controller, the Shortway transition method was selected out of two available methods (i.e., Shortway and Dwell) with three different transition cycles (i.e., one, two, and three transition cycles). This was due to the fact that the Dwell transition method in the 170 controller did not always return the controller to coordination in a previous study (Yun et al., 2007). For the 2070 controller, three transition methods (i.e., Smooth, Add Only, and Dwell) with three different maximum dwell times (i.e., 100 seconds, 200 seconds, 255 seconds) were evaluated. Although the ASC/3 controller possesses similar transition methods to those in the 2070 controller, it provides Smooth and Add Only with different transition times, so 100 seconds, 200 seconds, 255 seconds and the default transition time were implemented in this study. Table 2 summarizes all the test cases with the VISSIM-based HILS.

Table 2. Transition Methods Studied for Three Controllers

Controller	Case Name	Transition Method	Transition Cycles or Transition Time (no. or sec)
	170-1	Shortway	1
170	170-2	Shortway	2
	170-3 [a]	Shortway	3
	2070-1	Smooth	N/A
	2070-2	Add Only	N/A
2070	2070-3	Dwell	100
	2070-4	Dwell	200
	2070-5	Dwell	255
	ASC3-1	Smooth	N/A
	ASC3-2	Smooth	100
	ASC3-3	Smooth	200
	ASC3-4	Smooth	255
	ASC3-5	Add Only	N/A
ASC/3	ASC3-6	Add Only	100
	ASC3-7	Add Only	200
	ASC3-8	Add Only	255
	ASC3-9	Dwell	100
	ASC3-10	Dwell	200
	ASC3-11	Dwell	255

[a] current field setting

Implementation of the Changes of TOD Timing Plans in HILS

In this experiments, all controllers were set to change TOD timing plans (i.e., from the a.m. plan to the midday plan or from the midday plan to the p.m. plan) according to a predetermined schedule.

The starting times of the VISSIM-based HILS runs were synchronized with the change of TOD timing plans in the controllers. To start the change between TOD timing plans at an exact time, this study used a software program built in C# language that initiated and terminated a VISSIM-based HILS run at a predetermined time. The VISSIM networks used for HILS employed six minutes of warm-up time and thirty minutes of simulation time. The thirty minutes of simulation time consisted of two different traffic demands according to the current TOD timing plan. For example, in the case of a change from the a.m. timing plan to the midday timing plan, the first fifteen minutes of simulation time used the a.m. traffic demand, and the last fifteen minutes of simulation time used the midday traffic demands. In this case, the break point of these two TOD timing plans was located at the halfway point of the thirty-minute-long simulation time. The relevant measures of effectiveness (MOEs), however, were extracted only during the last fifteen minutes of simulation time to focus on the impact of the transition methods immediately after the TOD timing plan change. This could be more clearly examined in a short analysis period and after the TOD plan break point. In addition, the actual simulation run time of fifteen minutes for each TOD plan was sufficient to consider the entire transition period.

Task 5: Evaluation of Test Results

EVP Transition Evaluation Results

170 Controller

Northbound EVP. For the 170 controller northbound off-peak EVP evaluation, nine transition strategies were first established. First, the two transition methods available in the 170 controller—Shortway and Dwell—with three different cycle settings (one, two, and three cycles needed to return to coordination) were tested using the current phase sequence, in which phases 3 (southbound left turn) and 7 (northbound left turn) are used as lead phases on the cross street. Figure 7 shows the phase diagram and timings for this configuration at Intersection 12. Second, with an attempt to improve the transition operation, this study examined an alternative phase sequence—lead-lag left turns—on cross streets. In this phase sequence, phase 3 was served after phase 4 (lagging left turn) to provide alternative phasing after EVP. Since the 170 controller does not allow for exit phase specification, this step creates new de facto exit phases. In this new sequence, shown in Figure 8, the green intervals used in the lead-lag left turns case are identical to those of the lead-lead case.

Figure 7. Intersection 12 Phase Diagram and Timings of Lead-Lead Phase Configuration

Figure 8. Intersection 12 Phase Diagram and Timings of Lead-Lag Phase Configuration

Table 3 summarizes the nine EVP strategies evaluated in this case study. The Dwell transition method for the lead-lag left turn case was not considered because the intersection signal often did not return to coordination (Yun et al., 2007).

Table 3. Emergency Vehicle Preemption Strategies Under Examination

Case Name	Left Turn Phase Sequence	Transition Method	Transition Cycles
LeadS3	Lead-lead	Shortway	3
LeadS2	Lead-lead	Shortway	2
LeadS1	Lead-lead	Shortway	1
LeadD3	Lead-lead	Dwell	3
LeadD2	Lead-lead	Dwell	2
LeadD1	Lead-lead	Dwell	1
LagS3	Lead-lag	Shortway	3
LagS2	Lead-lag	Shortway	2
LagS1	Lead-lag	Shortway	1

Table 4 shows the results of the northbound EVP study for the 170 controller. The strategies using the Dwell method and one cycle to return to coordination were not studied for the peak volume condition because they did not return to coordination consistently during the off-peak volume condition. The comparison between the base case, where no EVP calls were observed, and LeadS3, which is the current transition setting in the field at Intersection 12, indicates the degree of coordination disturbance caused by a single EVP call during a twenty-minute time interval. The network-wide average vehicle delay increased by seventeen percent during off-peak conditions and five percent during peak conditions. These results indicate that a single EVP call disturbed coordination significantly during off-peak condition.

Table 4. Network Performance for 170 Controller Northbound EVP Cases

Case	Off-Peak			Peak		
	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)
Base	65	103	120	100	168	174
LeadS3	76	132	149	105	185	179
LeadS2	77	135	151	109	193	185
LeadS1	77	135	151	N/A	N/A	N/A
LeadD3	82	151	163	N/A	N/A	N/A
LeadD2	81	146	160	N/A	N/A	N/A
LeadD1	81	147	159	N/A	N/A	N/A
LagS3	74	125	142	105	185	177
LagS2	75	128	144	106	187	183
LagS1	75	129	144	N/A	N/A	N/A

In the comparison of the Shortway and Dwell transition methods, Shortway outperformed Dwell for all numbers of cycles to return to coordination. Additionally, based on an analysis of the QuicLoad controller display – an interface software program between the controller and the computer that displays what is happening in the controller – during the simulation runs, controllers using Dwell did not return to coordination in 38.8 percent of the twenty-six-minute simulation runs. For this analysis, only 160 HILS runs were analyzed out of a total of 180 runs of LeadD3, LeadD2, and LeadD1. When using Shortway, however, the controllers returned to coordination routinely except in the one-cycle case (LeadS1), in which coordination was not recovered in approximately 8.3 percent of the HILS runs.

In the comparison of the different phase sequences on the cross streets, the transition operations using lead-lag left turns performed better than those using lead-lead left turns. Average network delay decreased by approximately two seconds per vehicle in each comparative case. This indicated that exit phases after EVP were significant and helped to justify the study of the effects of different EVP exit phases with the 2070 and ASC/3 controllers.

In the comparison of the number of cycles for transition, no number of cycles outperformed any other by a significant margin. Within the Shortway cases, there were no significant statistical differences between the two best performing scenarios in average network delay. The results from the two-cycle and one-cycle cases were expected to be negligible, however, as their transitioning algorithms executed in similar fashions (upper limits of 250 and 255 seconds, respectively). When employing Dwell, there were no significant differences among the three numbers of cycles for any of the three main MOEs.

Eastbound EVP. For the eastbound EVP portion of the 170 study, Shortway was studied with one, two, and three cycles required to return to coordination. Dwell was not included in the eastbound portion due to its poor performance in the northbound EVP study. Additionally, phase sequences were not changed for this evaluation because EVP occurred along the coordinated street.

Table 5. Network Performance for 170 Eastbound EVP Cases

Case	Off-Peak			Peak		
	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)
Base	65	103	120	100	168	174
LeadS3	73	115	137	108	163	184
LeadS2	74	115	138	112	155	177
LeadS1	73	112	136	112	153	175

Table 5 shows the results of the 170 controller eastbound EVP cases. Eastbound EVP had a significant impact on network conditions under the off-peak volume scenario. Under the LeadS3 case, average network delay increased by thirteen percent under off-peak conditions and by eight percent under peak volumes.

Among the different transition strategies, there were no significant differences during the off-peak volume condition. In the peak volume scenario, however, Lead S3 improved average network delay by four percent over LeadS2 and LeadS1.

2070 Controller

Northbound EVP. The main reason for testing the 2070 and how its performance compared to the 170 controller was to determine the significance of the ability to specify the exit phases that executed right after the EVP termination. Thus, 2070 HILS runs were made in a similar fashion to the previous 170 runs. First, however, 2070 HILS northbound EVP runs were made using different exit phases (4 and 8, 3 and 8, 1 and 5, 2 and 6). In addition, comparisons were made specifying the EVP phases as either track clearance or hold phases with the exit phases.

Table 6 shows the results of this part of the study. Since the Shortway method outperformed the Dwell method by such a significant amount in the 170 study, its 2070 counterpart—Smooth—was exclusively used in this analysis.

Table 6. 2070 Northbound EVP Exit Phase Test Results

Exit Phases	Average Network Delay (sec/veh)	Eastbound Travel Time (sec)	Westbound Travel Time (sec)
4 & 8	68	117	125
3 & 8	68	117	125
1 & 5	67	115	123
2 & 6	66	111	117

Using Tukey's method to differentiate between the four test cases, no one method was found to be outstanding when using the average network delay MOE. Exit 2 & 6, however, showed significant differences in eastbound and westbound travel times with approximately five seconds and six seconds, respectively, of improvement over Exit 1 & 5. As a result, phases 2 and 6 were chosen as the exit phases for the 2070 northbound EVP study.

Once phases 2 and 6 were established as the exit phases for northbound EVP, the different transition methods available in the 2070 were studied. Five total cases were established for five different transition methods—Smooth, Add Only, Dwell with 100-second dwell period (Dwell 100), Dwell with 200-second dwell period (Dwell 200), and Dwell with 255-second dwell period (Dwell 255). Table 7 shows the results.

Table 7. Network Performance for 2070 Northbound EVP Cases

Case	Off-Peak			Peak		
	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)
Base	63	103	113	93	150	155
Smooth	66	110	117	99	164	158
Add Only	73	135	139	112	194	193
Dwell 100	64	103	111	101	166	165
Dwell 200	70	110	118	103	163	158
Dwell 255	70	110	119	100	160	159

In this analysis, the off-peak base case only differed by a slight margin from the best transition scenario, Dwell 100, because this scenario behaved in a manner very similar to normal signal operations (i.e., the exit phases (eastbound and westbound through/right) timed for approximately the same length of time as they normally did in coordination). As a result, when EVP occurred after the cross street phases and toward the beginning of the coordinated phases, delay was very low due to the small effect that EVP had on the coordinated phases. This lowered the overall network delay MOE by a significant amount. Figure 9 shows the variability of average network delay over the local cycle length for the Dwell 100 transition method. In the peak case, EVP caused an increase of seven percent in average network delay when using the best performing case, Smooth.

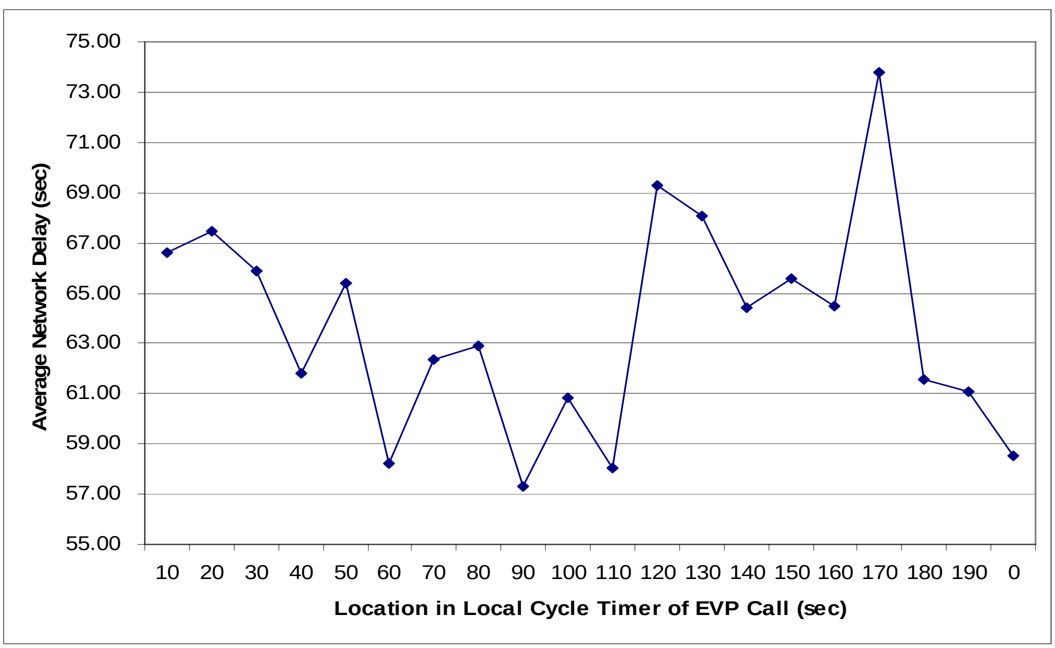

Figure 9. Average Network Delay Under Dwell 100 Transition Method

The off-peak results show that Dwell 100 performed the best in average network delay by two seconds over the second best case, Smooth. Dwell 100's improvements were realized most clearly at the non-coordinated movements—northbound, southbound, eastbound left, and westbound left approach delays were much lower for Dwell 100 while eastbound and westbound approach delays were very similar among all cases except Add Only. From these results, it was evident that 100 seconds was at or exceeded the amount of green time needed to dissipate queues on Route 50. Any dwell period greater than 100 seconds yielded little marginal returns and ended up taking away green time needed on the cross street and main street left turn approaches.

Eastbound EVP. The eastbound 2070 HILS runs considered many different exit phase configurations due to each of the four intersections potentially having different optimal exit phases. To select optimal exit phases, this study used the off-peak traffic volumes and the Smooth transition method with three sets of exit phases – 2 and 6, 1 and 6, and none specified. Table 8 shows the results for these three sets of exit phases used. Although one best case could not be identified based on eastbound travel time and average network delay, using phases 1 and 6 as exit phases resulted in six seconds of westbound travel time savings over the second best case. As a result of these findings, phases 1 and 6 were used as the default phases for the 2070 eastbound EVP study with changing exit phases.

Table 8. 2070 Eastbound HILS Preliminary Results

MOE		Unit	Exit Phases		
			2 & 6	1 & 6	None
Route 50	Eastbound Travel Time	seconds	114	114	116
	Westbound Travel Time	seconds	127	121	129
Network Performance	Total Travel Time	hours	149	149	150
	Total Delay Time	hours	60	60	61
	Average Delay Time	sec/veh	68	67	69
	Total Stop Delay	stops	43	43	44
	Average Stop Delay	sec/veh	49	48	50
	Number of Stops	stops	5670	5650	5781
	Average Number of Stops	stops/veh	1.8	1.8	1.8

After determining the best exit phase configuration for eastbound EVP, the transition methods available in the 2070 controller were evaluated. Table 9 shows the results of the analysis. Comparing the base case and the best EVP case, Smooth, EVP had a detrimental effect on network conditions. Average network delay increased by six percent due to EVP in the off-peak case but did not increase by a statistically significant amount during the peak case. Since more green time was given to the eastbound and westbound left movements under eastbound EVP, delay decreased for these movements. As a result, overall average network delay remained unchanged under the increased traffic volume conditions.

Based on Tukey's statistical tests, Smooth outperformed the other transition methods by a significant amount in average network delay in the off-peak case. In the peak case, when using the Smooth method, average network delay decreased significantly by three seconds over the second best method, Dwell 100.

Table 9. Network Performance for 2070 Eastbound EVP Cases

Case	Off-Peak			Peak		
	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)	Average Delay (sec/veh)	EB Travel Time (sec)	WB Travel Time (sec)
Base	63	103	113	93	150	155
Smooth	67	114	121	96	164	157
Add Only	72	127	131	105	187	170
Dwell 100	69	110	124	99	162	161
Dwell 200	70	108	125	100	153	162
Dwell 255	70	108	125	100	153	162

170 Controller vs. 2070 Controller

Northbound EVP. As shown in Tables 4 and 7, for the off-peak case, the best transition strategies for each controller were compared. In this analysis, the best case for the 2070—Dwell 100 with exit phases 2 and 6—showed substantial improvement over the best case for the 170—LagS3. Here, average delay time was reduced by fourteen percent.

The peak case was also considered in the comparison between the 170 and 2070 controllers. The 2070 Smooth method with exit phases 2 and 6 performed much better than the LagS3 resulting an average network delay improvement by five percent.

Eastbound EVP. As shown in Tables 5 and 9, the transition strategies were then compared for the eastbound EVP case. For the off-peak case, the best 170 method, LeadS1, and the best 2070 method, Smooth with exit phases 1 and 6, were chosen for evaluation. In this comparison, average network delay decreased by nine percent under the 2070’s Smooth method.

For the peak case, the 170’s LeadS3 and the 2070’s Smooth with exit phases 1 and 6 were compared. Average network delay decreased by eleven percent under Smooth.

ASC/3 Controller

The ASC/3 controller contains advanced functionality not available in the 2070 and 170 controllers. One such function is the Logic Processor, which allows users to program up to 100 if-then-else statements into the ASC/3. The Logic Processor is useful for studying preemption transition because of its ability to call different preemptor sequences based on the location in the local cycle timer that the preemption call occurs.

Northbound EVP. For this study, the logic statements were based on the 2070 runs with varying exit phases. The preemptors with specific exit phases that showed the lowest average network delay for a given EVP call location were then programmed to run for the same location in the ASC/3 simulation runs. Figure 10 shows the average total network delay time for the northbound simulation runs with the different exit phases used and the resulting delay measurements based on the location of the EVP call within the local cycle timer. From the graph, it is evident that there are benefits to employing different exit phases based on the location of the EVP call in the local cycle timer. The Logic Processor in the ASC/3 controller was thus programmed to call preemptors with different specified exit phases based on the location within the local cycle timer at which the EVP call was made. Figure 10 also shows the programmed exit phases and how they correlate with the intersection signal timing.

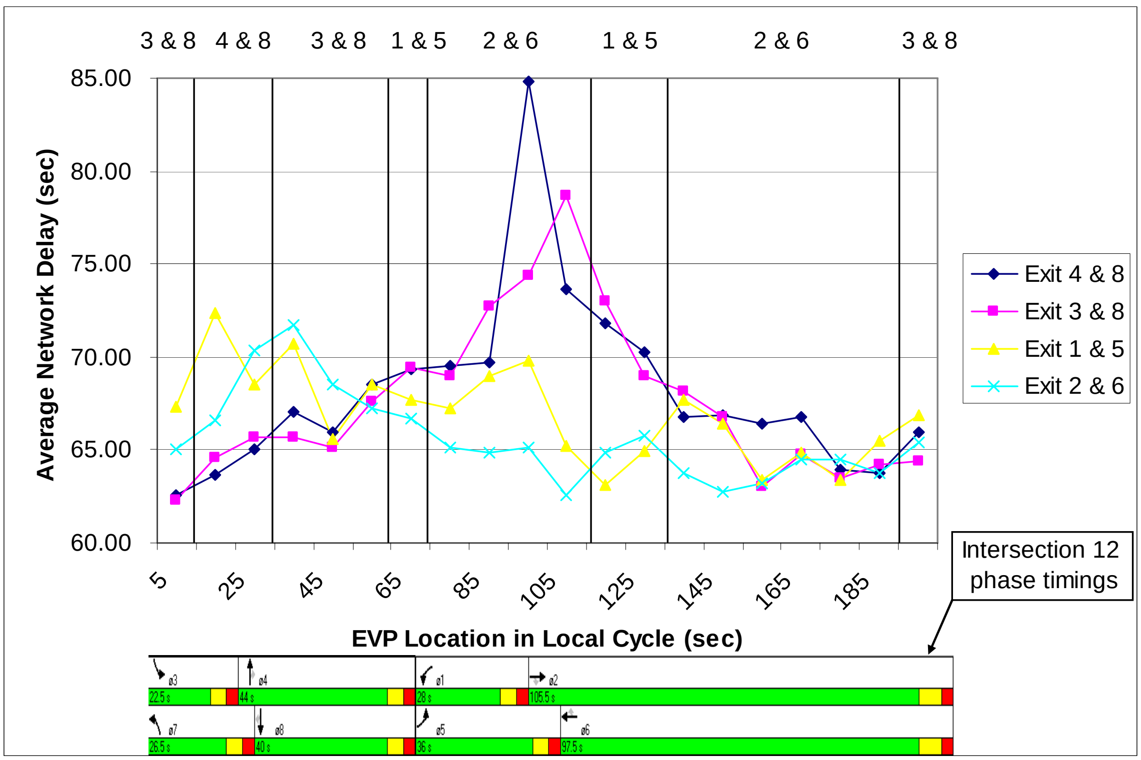

Figure 10. Average Total Network Delay as a Function of Exit Phases and Location of EVP Call in Local Cycle Timer

HILS runs were then made with the programmed ASC/3 controllers using the off-peak traffic data and the Smooth transition method. Results were obtained based on five sets of twenty simulation replications with different EVP call locations in the local cycle timer. Figure 11 shows the graph from Figure 10 with the ASC/3 simulation results added. Based on the graph, using the ASC/3's Logic Processor does not significantly improve network delay over the best 2070 case. Overall, average network delay for the ASC/3 runs was unchanged compared to five

2070 runs with exit phases 2 and 6. The Logic Processor's functionality, however, does warrant further study using different traffic volumes and conditions.

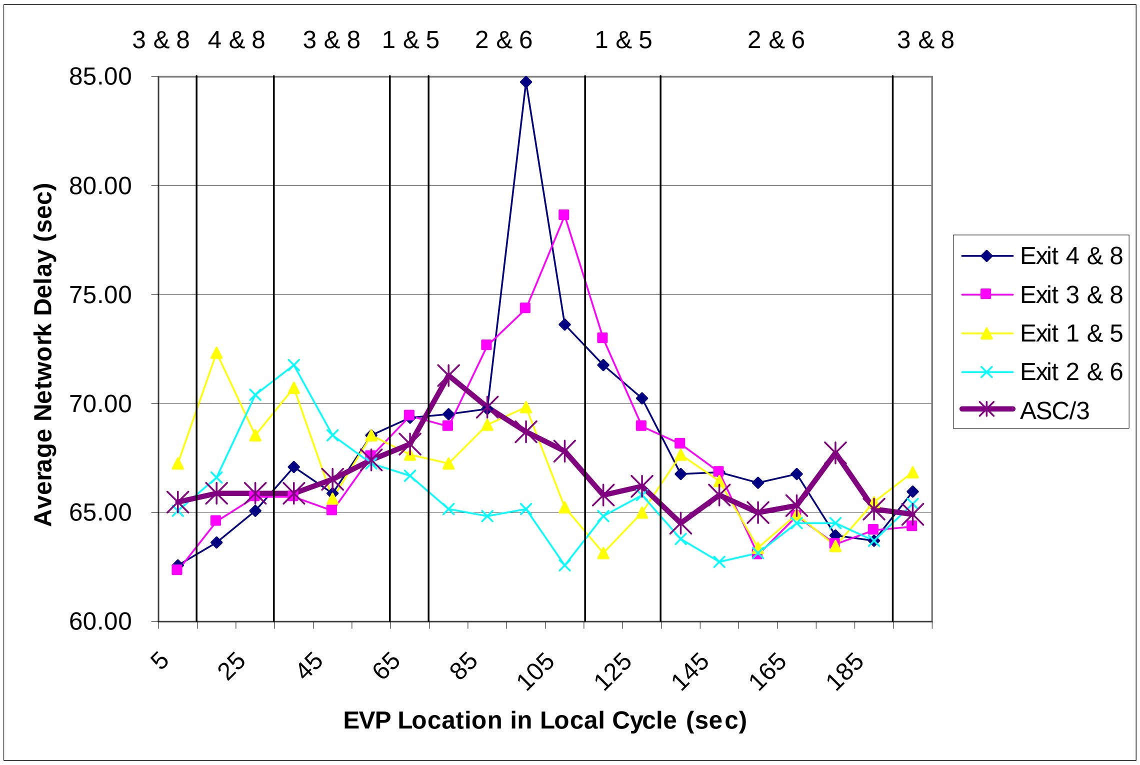

Figure 11. Average Network Delay as a Function of Exit Phases and Location of EVP Call in Local Cycle Timer with ASC/3 Results

Eastbound EVP. A similar procedure to the northbound EVP scenario was then applied to the eastbound EVP scenario. Here, different sets of exit phases—1 and 6, 2 and 6, 1 and 5, and next (no preemption phases specified, allowing the next phases in sequence to serve after EVP)—were chosen due to the expected effect of eastbound EVP. The overall exiting process, however, was similar, as "next" in eastbound EVP corresponded with the phases serving after northbound EVP (phases 4 and 8). Additionally, phases 1 and 6 were the phases opposite to eastbound EVP as phases 3 and 8 served opposite to northbound EVP. The remaining two exit phase sequences were used in both EVP directions. Instead of using average network delay, however, average intersection delay was employed to choose the exit phase intervals for each of the four network intersections. That is, the performances of the exit phases were evaluated at each intersection by fixing exit phases to 1 and 6 for remaining intersections. This was to reduce the number of combinations from 3^4 (i.e., three cases per intersection for four intersections) to 12 (i.e., three independent cases per intersection for four intersections).

Programming exit phase intervals for the eastbound EVP HILS runs resulted in improved network performance. Average network delay decreased by approximately two percent over the best performing 2070 case, in which each intersection used the westbound phases (1 and 6) to exit EVP. Figure 12 shows a graphical comparison of the ASC/3 and 2070 cases in terms of average network delay.

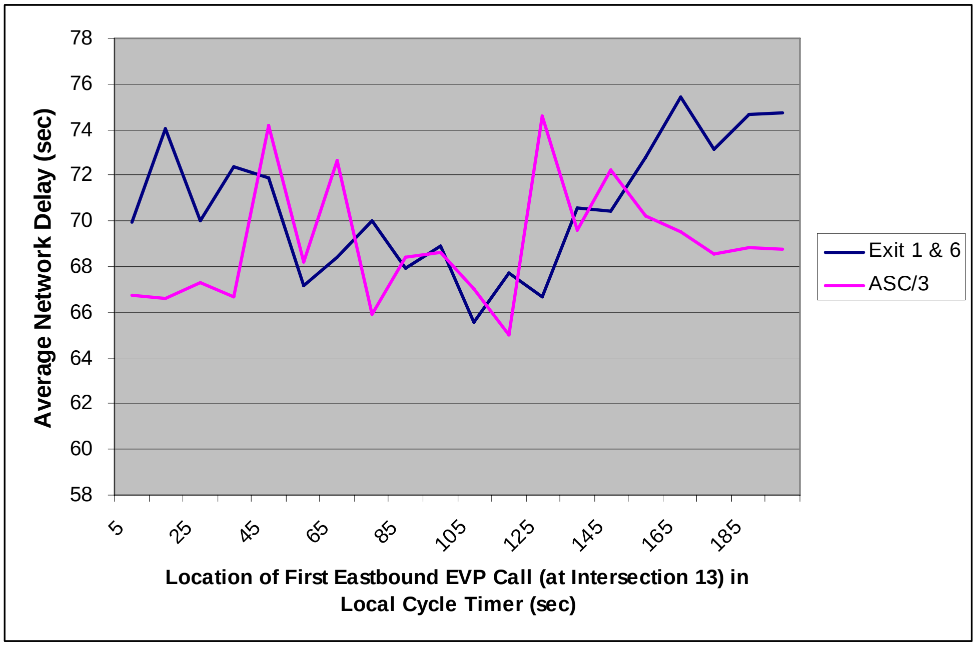

Figure 12. Comparison Between ASC/3 Controller and Best 2070 Case - Eastbound EVP

Time-of-Day (TOD) Transition Evaluation Results

TOD plan transition evaluations were conducted for the a.m. peak to midday transition and the midday to p.m. peak transition. This section summarizes the results of the TOD transition evaluations for the three controllers.

170E Traffic Controller

For the 170E controller, the three cases shown in Table 2 were evaluated using the VISSIM-based HILS. Table 10 presents the performance measures, which include eastbound and westbound travel times, network-wide throughputs, average vehicle delays, and average stops from the evaluation of these methods.

Table 10. Travel Times and Network-Wide Performance Measures for 170E Controller HILS

Transition	Case	Travel Times (S.D.)		Network-Wide Performance Measures (S.D.)		
		Eastbound (sec)	Westbound (sec)	Throughput[a] (veh)	Avg. Delay (sec/veh)	Avg. No. of Stops (stops/veh)
a.m. – midday	170-1	118.3 (6.7)	111.4 (7.7)	2293 (48.5)	77.4 (5.0)	2.6 (0.4)
	170-2	123.2 (8.3)	117.5 (9.1)	2318 (57.1)	74.2 (6.3)	2.7 (0.5)
	170-3	120.0 (10.9)	114.6 (11.5)	2305 (72.56)	75.3 (6.7)	2.8 (0.5)
midday – p.m.	170-1	125.8 (7.5)	119.3 (8.5)	2565 (58.5)	72.5 (5.0)	3.1 (0.6)
	170-2	123.2 (7.1)	120.7 (9.0)	2571 (58.5)	72.5 (4.2)	3.1 (0.5)
	170-3	123.7 (6.8)	121.3 (7.8)	2566 (47.7)	72.2 (4.6)	3.0 (0.5)

[a] Defined as the number of vehicles leaving the network during the analysis period

The performance measures produced by the change from the a.m. TOD plan to the midday TOD plan showed faster travel times but higher average vehicle delay than those from the midday TOD plan to the p.m. TOD plan. A statistical analysis using the ANOVA test indicated that no significant differences exist among Shortway transition cycles at an alpha level of 0.05. Thus, Shortway with any number of transition cycles can be recommended as a TOD transition method. For the comparison among the three controllers, the transition methods providing the lowest average network delay (Case 170-2 for a.m. to midday and Case 170-3 for midday to p.m.) were chosen.

2070 ATC Traffic Controller

The five transition methods shown in Table 2 for the 2070 ATC controller were evaluated using the well-calibrated VISSIM-based HILS. Table 11 presents the performance measures, including eastbound and westbound travel times, network-wide throughputs, average vehicle delays, and average number of stops, from the evaluation of these methods.

The performance measures produced by the change from the midday TOD plan to the p.m. TOD plan showed faster westbound travel times and similar eastbound travel times but higher average vehicle delays than those from the a.m. TOD plan to the midday TOD plan, which is different from what the experiments using the 170E controllers showed in the previous section.

For the comparison between different transition methods (i.e., Smooth, Add Only, and Dwell), an ANOVA analysis based on average network delay time indicated that statistically significant differences exist among these transition methods. A statistical test was also conducted to compare the average network delays of Cases 2070-1 (Smooth) and 2070-2 (Add Only). The results showed that no significant differences in the a.m. to midday transition, while a significant difference was found for the midday to p.m. transition. Thus, Smooth was selected as the best transition method in the 2070 ATC controller.

Table 11. Travel Times and Network-Wide Performance Measures for 2070 ATC Controller HILS

Transition	Case	Travel Times (S.D.)		Network-Wide Performance Measures (S.D.)		
		Eastbound (sec)	Westbound (sec)	Throughput[a] (veh)	Avg. Delay (sec/veh)	Avg. No. of Stops (stops/veh)
a.m. – midday	2070-1	146.1 (18.5)	132.5 (8.0)	2306 (43.2)	74.5 (7.9)	2.6 (0.4)
	2070-2	141.9 (21.6)	142.9 (18.0)	2311 (38.3)	79.4 (6.8)	2.8 (0.5)
	2070-3	140.0 (10.8)	143.9 (18.6)	2301 (39.9)	82.8 (8.0)	3.0 (0.6)
	2070-4	134.9 (9.8)	143.7 (19.6)	2312 (35.7)	82.1 (7.1)	2.8 (0.4)
	2070-5	138.6 (9.9)	144.2 (14.8)	2292 (42.4)	86.8 (7.7)	3.0 (0.5)
midday – p.m.	2070-1	147.9 (9.7)	129.8 (8.1)	2479 (31.3)	99.2 (5.1)	4.9 (0.9)
	2070-2	139.3 (9.7)	125.4 (4.2)	2467 (57.5)	102.3 (5.8)	4.4 (0.7)
	2070-3	133.3 (11.2)	115.9 (6.0)	2442 (52.8)	110.5 (11.4)	5.4 (1.9)
	2070-4	140.5 (15.1)	128.8 (12.9)	2422 (45.8)	116.5 (9.0)	5.3 (1.1)
	2070-5	146.3 (20.5)	121.2 (11.7)	2429 (41.1)	115.4 (6.4)	5.3 (1.1)

[a] Defined as the number of vehicles leaving the network during the analysis period

In the comparison among the three selected dwell times for the Dwell transition method, no statistically significant differences were found. For the comparison among the three controllers, the transition method providing the lowest average network delay (Case 2070-1) was chosen.

ASC/3-2100 Traffic Controller

The eleven transition methods shown in Table 2 for the ASC/3-2100 controller were evaluated using the well-calibrated VISSIM-based HILS. Table 12 presents the performance measures from the evaluation of these methods. These include the eastbound and westbound travel times, network-wide throughputs, average vehicle delays and average number of stops.

The performance measures produced by the change from the midday TOD plan to the p.m. plan showed slower westbound travel times and similar eastbound travel times but higher average vehicle delays than those from the midday TOD plan to the p.m. TOD plan, which is similar to what the experiments using the 2070 ATC controllers showed in the previous section.

For the comparison among the transition methods evaluated in this section, an ANOVA test using average network delay was conducted. The results indicated that there were no statistically significant differences among transition methods used for both transition periods.

Thus, it can be concluded that any transition method works as well as any other transition method available in the ASC/3 controller. However, for the comparison among the three controllers, the transition methods providing the lowest average network delay (Case ASC/3-8 for a.m. to midday and Case ASC/3-4 for midday to p.m.) were chosen.

Table 12. Travel Times and Network-Wide Performance Measures for ASC/3-2100 Controller HILS

Transition	Case	Travel Times (S.D.)		Network-Wide Performance Measures (S.D.)		
		Eastbound (sec)	Westbound (sec)	Throughput[a] (veh)	Avg. Delay (sec/veh)	Avg. No. of Stops (stops/veh)
a.m. – midday	ASC3-1	147.7 (10.5)	148.4 (18.9)	2335 (47.1)	73.3 (4.1)	2.8 (0.4)
	ASC3-2	148.8 (10.6)	145.7 (18.3)	2334 (33.6)	72.9 (4.9)	2.7 (0.5)
	ASC3-3	149.7 (10.2)	149.5 (18.0)	2323 (40.8)	75.1 (2.8)	2.9 (0.3)
	ASC3-4	148.8 (10.0)	147.7 (18.7)	2321 (45.4)	73.5 (4.0)	2.8 (0.3)
	ASC3-5	143.4 (7.3)	139.7 (12.1)	2303 (38.5)	72.4 (2.9)	2.7 (0.3)
	ASC3-6	141.3 (9.9)	139.4 (12.3)	2312 (28.7)	73.7 (4.8)	2.7 (0.3)
	ASC3-7	144.2 (7.0)	137.9 (9.8)	2321 (34.8)	74.8 (3.2)	2.7 (0.2)
	ASC3-8	140.1 (10.3)	140.7 (11.5)	2314 (28.0)	72.1 (4.0)	2.7 (0.3)
	ASC3-9	137.2 (10.0)	133.1 (8.4)	2325 (49.1)	74.1 (3.2)	2.8 (0.4)
	ASC3-10	133.4 (6.6)	133.5 (9.0)	2328 (48.2)	73.7 (4.4)	2.6 (0.2)
	ASC3-11	133.0 (8.0)	132.1 (6.2)	2322 (41.6)	73.9 (4.9)	2.6 (0.3)
midday – p.m.[b]	ASC3-1	143.0 (10.4)	144.8 (22.7)	2561 (39.9)	83.6 (7.1)	3.8 (0.9)
	ASC3-2	140.3 (10.9)	145.9 (17.5)	2553 (63.4)	81.9 (5.5)	3.4 (0.5)
	ASC3-3	137.4 (11.5)	153.7 (23.1)	2553 (54.3)	83.8 (7.4)	3.7 (0.7)
	ASC3-4	134.4 (13.6)	146.8 (14.5)	2572 (57.3)	80.9 (6.1)	3.4 (0.7)
	ASC3-5	141.4 (16.7)	153.7 (19.9)	2540 (50.4)	85.9 (6.5)	3.5 (0.6)
	ASC3-6	145.0 (19.6)	149.0 (18.0)	2549 (56.2)	87.1 (8.2)	3.7 (0.8)
	ASC3-7	146.3 (18.6)	154.5 (22.6)	2536 (47.6)	87.8 (7.6)	3.6 (0.8)
	ASC3-8	140.2 (18.4)	146.8 (16.9)	2540 (64.5)	83.7 (5.9)	3.4 (0.6)
	ASC3-9	130.3 (9.1)	137.1 (17.0)	2547 (52.1)	84.6 (8.2)	3.6 (1.0)
	ASC3-10	131.0 (15.4)	131.1 (10.9)	2550 (47.9)	81.8 (4.6)	3.2 (0.4)
	ASC3-11	129.7 (10.0)	129.7 (18.9)	2550 (54.7)	84.7 (5.8)	3.5 (0.6)

[a] Defined as the number of vehicles leaving the network during the analysis period
[b] The number of replications of HILS runs for the transition from midday to p.m. was forty.

Comparison Among Three Controllers

In this section, the performance of each controller during TOD transition operations is compared. Table 13 presents the best cases for each controller in the two TOD plan change scenarios. As shown in the table, the transition operation in the 170E controller produced significantly faster travel times in both directions through the two TOD change scenarios. In addition, it showed less average delay in the transition between the midday TOD plan and the p.m. TOD plan and similar average delay in the transition between the a.m. TOD plan and the midday TOD plan. The comparison between the 2070 ATC and ASC/3-2100 controllers presents better performances in most MOEs except for the westbound travel time for the transition from the midday TOD plan to the p.m. TOD plan due to the faster start of transition operations of the ASC/3-2100 controller.

Table 13. Comparison Among the Best Cases From the Three Controllers

Transition	Case	Travel Times (S.D.)		Network-Wide Performance Measures (S.D.)		
		Eastbound (sec)	Westbound (sec)	Throughput[a] (veh)	Avg. Delay (sec/veh)	Avg. No. of Stops (stops/veh)
a.m. – midday	170-2	123.2 (8.3)	117.5 (9.1)	2318 (57.1)	74.2 (6.3)	2.7 (0.5)
	2070-1	146.1 (18.5)	132.5 (8.0)	2306 (43.2)	74.5 (7.9)	2.6 (0.4)
	ASC3-8	140.1 (10.3)	140.7 (11.5)	2314 (28.0)	72.1 (4.0)	2.7 (0.3)
midday – p.m.	170-3	123.7 (6.8)	121.3 (7.8)	2566 (47.7)	72.2 (4.6)	3.0 (0.5)
	2070-1	147.9 (9.7)	129.8 (8.1)	2479 (31.3)	99.2 (5.1)	4.9 (0.9)
	ASC3-4	134.4 (13.6)	146.8 (14.5)	2572 (57.3)	80.9 (6.1)	3.4 (0.7)

[a] Defined as the number of vehicles leaving the network during the analysis period

Because the 170E controller has more limited functionality and capability, it was not expected to have outperformed the 2070 ATC and ASC/3 controllers during the TOD plan transitions. To determine the reasons for the 170E's success, two additional tasks were conducted. These included (i) an analysis of individual turning movement delays at a critical intersection and (ii) further analysis of actual transition operations being performed by the 170E controller.

First, Table 14 summarizes the intersection-specific average vehicle delay by turning movements at the critical intersection, which was the busiest intersection among the four intersections, of the transition scenario from the a.m. TOD plan to the midday TOD plan. Further investigation indicated that the transition operation conducted by the 170E controller produced less average vehicle delay by providing more capacities to phases 2 and 6, which are coordinated phases, over other phases. This is the reason why the transition operation generated by the 170E controller produced much better eastbound and westbound travel times with smaller average vehicle delay.

Table 14. Average Vehicle Delay by Phase at the Critical Intersection

Movement	Average Vehicle Delay (sec/veh)		
	Case 170-2	Case 2070-1	Case ASC3-8
Eastbound left-turn	112.6	84.6	82.9
Eastbound through	19.6	26.3	26.0
Eastbound right-turn	9.8	13.1	11.7
Northbound left-turn	73.7	64.8	69.3
Northbound through	68.4	57.5	64.4
Northbound right-turn	14.7	14.8	14.3
Westbound left-turn	119.4	88.8	87.9
Westbound through	20.0	24.6	28.6
Westbound right-turn	6.4	6.5	9.3
Southbound left-turn	76.9	69.7	68.9
Southbound through	68.2	58.4	63.2
Southbound right-turn	34.1	34.8	26.6

Second, in an attempt to identify the reason the 170E controller showed faster travel times with similar average vehicle delay for the transition from the a.m. TOD plan to the midday TOD plan shown in Table 13, especially, and lower average vehicle delays on phases 2 and 6 with higher delays on other phases shown in Table 14, the research team recorded the display screen of the QuicLoad program, which is the communication program between a computer and the 170E controller for monitoring the operations of the controller and transmitting data. It should be noted that the research team placed maximum recalls to all phases in order to avoid the effects of gap-outs during the transition operations for this specific experiment.

Table 15 summarizes the information extracted from the recorded screens, which includes the marks of the master timer and the local timer of the 170 controller representing the critical intersection with major signal status changes according to the real timer. In addition, during the transition from the a.m. TOD plan to the mid-day TOD plan, TOD timing plans are supposed to change at 16:31:00 based on the Shortway transition method with three transition cycles. Note that the offset of the midday TOD timing plan is 136 seconds, which is the difference between the local timer and the master timer. As shown in Table 15, the 170 controller starts the transition from the a.m. TOD plan to the midday TOD plan when its master timer reaches zero mark after its predetermined TOD break point, which was explained earlier. The transition was completed through three transition cycles, which lasted 188, 98 and 60 seconds, respectively. Unlike what was explained in the manual of the 170E controller (*2*), force-off points of all phases were not adjusted by the same percentage change to maintain the same relative phase split during transition, especially in the third transition cycle as shown in Table 15. As such, the controller shows the green indication of only phases 2 and 6 for 150 seconds in the first cycle after achieving coordination. In other words, phases 1, 3, 4, 5, 7 and 8 were skipped even though the maximum recalls of these phases were set active in that cycle. Due to the resulting operation shown in the 170E controller, the critical intersection produced less average delays on phases 2 and 6 but higher average delays on other phases over the cases using the ASC/3-2100 and 2070 ATC controllers. In addition, the eastbound and westbound travel times from the cases using the 170E controller showed less travel time with the same reason.

Table 15. Operation of the 170E Controller during the Transition from A.M. to Midday

Real Timer (hh:mm:ss)	Signal Status	Local Timer (sec)	Master Timer (sec)	Remark
16:31:00	Phases 2&6 are on green	51	29	TOD break point
16:33:59	Phases 3&7 start green	20	209	
16:34:00	Phases 3&7 start yellow	21	0	Start of the first transition cycle
16:34:08	Phases 4&8 start green	29	8	
16:34:50	Phases 1&5 start green	71	50	
16:35:21	Phase 6 starts green	102	81	
16:35:23	Phase 2 starts green	105	83	
16:37:07	Phases 2&6 are on green	209	187	
16:37:08	Phases 2&6 are on green	0	158	Start of the second transition cycle
16:37:09	Phases 2&6 are on green	1	129	Adjust of the master timer
16:37:17	Phases 3&7 start green	9	137	
16:37:31	Phases 4&8 start green	23	1	
16:37:48	Phases 1&5 start green	40	18	
16:38:02	Phases 2&6 start green	54	32	
16:38:45	Phases 2&6 are on green	97	75	
16:38:46	Phases 2&6 are on green	0	76	Start of the third transition cycle
16:38:55	Phases 3&7 start green	9	85	
16:39:15	Phases 4&8 start green	29	105	
16:39:33	Phases 1&5 start green	47	123	
16:39:45	Phases are on all-red	59	135	
16:39:46	Phases 2&6 start green	0	136	Start of coordination with proper offset values
16:42:12	Phases 2&6 are on green	149	135	

Note: The real timer may show up to 1 second discrepancy from the local timer and master timer due to the delay through the communication between the computer and the controller.

Based on Tables 10 through 13, it was found that the resultant performances of the transition operations during the change of TOD timing plans are significantly different depending on the selected controller. This result is caused by the difference in the starting time of adjusting cycle length and offsets, and the way of adjusting force-off points during the transition operation.

CONCLUSIONS

- *Emergency vehicle preemption has a significant impact on coordinated signal systems.* Based on the comparisons between the base cases and the EVP cases for each of the time periods, it is evident that EVP increases congestion significantly. For instance, in the 170 controller off-peak study, a single EVP call on the northbound approach case caused 21% and 18% increases in average EB and WB travel times, respectively. Average individual travel time for the entire network also increased by 17%.

- *The location in the local cycle timer of the EVP call is a significant factor in EVP and transition operations.* It affects both the length of time for the preemption phases to begin timing and the amount of delay experienced during the transition period.

- *The transition method used by the controller can have significant impacts on traffic network conditions.* Shortway/Smooth generally outperformed the others (e.g., five to seven percent average network delay savings over Dwell in the 170 off-peak case). This is consistent with previous research in which Smooth or a similar method outperformed Dwell in most cases. In the 170 controller, the Dwell method did not always return to coordination, thus causing severe disruptions to coordination for a substantial amount of time.

- *The exit phases specified to time after preemption are very important to network performance and traffic operations.* From the 170 controller experiments, although the 170 could not specify exit phases, the HILS runs using a lead-lag cross street phase sequence showed approximately three percent less average network delay than those using a lead-lead cross street phase sequence for the off-peak case. The 2070 experiments then showed the benefits of the ability to specify particular static exit phases. It outperformed the 170 controller in the northbound EVP cases (fourteen percent and six percent average network delay savings for the off-peak and peak volume cases, respectively) and eastbound EVP cases (eight percent and eleven percent average network delay savings for the off-peak and peak volume cases, respectively). The ASC/3 runs showed the potential advantages of programming exit phases but doing so dynamically with respect to the location in the local cycle timer that the EVP call is made. Although the northbound EVP case did not show benefits, the ASC/3 improved average network delay by two percent in the eastbound EVP case.

- *In the comparison of the TOD transition methods in the three controllers, the 170E controller outperformed the 2070 and ASC/3 controllers in most of performance measures for two transition scenarios.*

- *The number of transition cycles for the Shortway transition method in the 170E controller is critical.* In the 2070 controller, the Smooth transition method produced less average delays in both transition scenarios, but resultant travel times showed different trends. In the ASC/3 controller, there was no dominant transition method through eleven cases in both travel times and network-wide average vehicle delay.

- *The 170E controller performed the transition operation in a manner favorable to the coordinated phases, resulting in the better network-wide performances. However, it resulted in larger delays for the non-coordinated phases.*

RECOMMENDATIONS

1. *VDOT should carefully consider decisions to allow preemption as the impact of preemption is very significant*. This study found that 17% increased network delay (or 9 additional seconds per vehicle) for a single NB EVP call during off-peak hour under 170 controller.

Thus, careful consideration should be given before allowing preemption to other service vehicles such as police cars.

2. *VDOT's NVSTSS should continue to implement the Shortway transition method with three cycles. The use of lead-lag cross street phase sequencing should be considered if it could adequately accommodate pedestrian crossing times*. In addition, Dwell should be avoided because it does not always return the signal controller to coordination.

3. *VDOT's NVSTSS should consider the feasibility of upgrading the firmware of the existing 170 controller to allow the selection of exit phase at the end of preemption*. This is because the benefits of the 2070 or ASC/3 controller appear to be coming from the exit phase feature.

4. *When VDOT decides to upgrade its traffic controllers, they should upgrade them to ASC/3 controllers over 2070 controllers.* This is because the dynamic exit phase feature available in ASC/3 controller has great potential to improve the EVP operations, especially with the deployment of Vehicle Infrastructure Integration. However, VDOT should consider additional factors including the maximum number of timing plans, ability to connect to existing central signal system, etc. before making a decision about future upgrades.

COSTS AND BENEFITS ASSESSMENT

Assumptions

For the benefit-cost analysis, several assumptions were made. To ascertain the benefits of using the advanced 2070 or ASC/3 controller over the 170 controller, the number of daily EVP calls were estimated based on a week's worth of field data records. As shown in Table 16, approximately 0.20 EVP calls per peak hour, and 0.25 EVP calls per off-peak hour were observed from the Northern Virginia Smart Traffic Signal Systems Preemption log data on five weekdays between May 7 and 11, 2007. Additionally, it is assumed that 50% of all EVP calls came from a cross street (i.e., NB scenario) and 50% came from the major street (i.e., EB scenario). Finally, it is also assumed that the maintenance costs of 170, 2070 and ASC/3 controllers were similar.

Table 16. Pre-emption Frequency in Northern Virginia Smart Traffic Signal Systems

	Number of total EVP calls for five weekdays	Number of Intersections with Preemption	Average EVP call per intersection per period	Average EVP call per direction (i.e., NB or EB) per hour per intersection
Off-Peak (9am – 4pm: 7 hours)	1243	143	1.22	0.14
Peak (6am – 9am; 4pm – 7pm: 6 hours)	875	143	1.74	0.10

Estimation of Annual Delay Savings

This analysis used the total delay time calculated in the VISSIM HILS simulation, shown in Table 17, to estimate the delay savings of the 2070 or ASC/3 controller over the 170 controller. It was assumed this difference in delay was incurred per EVP call and per TOD transition. The daily delay was then estimated based on the assumed number of daily northbound and eastbound EVP calls. This value was then multiplied by 261 normal workdays per year to obtain the yearly delay savings. The resultant total annual delay savings at the four-intersection test site was 5,304 vehicle-hours per year.

Table 17. Benefits Assessments under Best TOD and EVP Strategies

Scenario	Period		Total Delay (vehicle-hrs)		Benefits of 2070 or ASC/3 Controller Annual Savings (vehicle-hrs per year)	Note
			170 Controller	2070 or ASC/3 Controller		
TOD	AM Peak to Midday		48	48	0	AM Peak (6am-9am) to Midday (9am-4pm)
	Midday to PM Peak		52	58	(1566)	Midday (9am-4pm) to PM Peak (4pm-7pm)
EVP	Off-Peak	NB	65	56	2302	7 hours (9am to 4pm)
		EB	65	60	940	
	Peak	NB	124	118	1279	6 hours (6am to 9am; 4pm to 7pm)
		EB	129	114	2349	

Estimation of Annual Benefits and Costs

To calculate the annual benefits achieved by upgrading from the 170 controller to the 2070 controller, a cost of $17.02 per person-hour of travel was used, per the *2005 Urban Mobility Report*. Assuming one person per vehicle, after multiplying by the annual delay savings, the yearly benefit of upgrading controllers at the four-intersection test site was calculated to be $90,274 (= 5304 vehicle-hours × $17.02).

To calculate the total cost, costs were estimated for the signal controller upgrade. The U.S. Department of Transportation estimates between $2,400 and $6,000 in 2005 dollars (U.S. Department of Transportation ITS Joint Program Office, 2007). Using a conservative cost of $6,000 per controller upgrade, the total cost of upgrading controllers at the four-intersection test site is $24,000. Thus, an estimated total saving for just one year for four signalized intersections is $66,274. The savings for 143 EVP preemption locations in the Northern Virginia region could be over $9.4 million (= $66,274 annual savings × 143 locations), if a simple extrapolation method is used.

ACKNOWLEDGMENTS

The authors acknowledge Joonhyo (John) Kim and Seli James Agbolosu-Amison from the Center for Transportation Studies at the University of Virginia for providing their efforts for analyzing the results of the HILS runs; the authors also acknowledge Nhan Vu, Ling Li, and Hari Sripati for their support in obtaining preemption data and discussions for existing EVP operations.

REFERENCES

BI Tran Systems, Inc. *QuicLoad User's Manual.* Sacramento, CA, 2000.

Bullock, D., and Catarella, A. A Real-Time Simulation Environment for Evaluating Traffic Signal Systems. In *Transportation Research Record 1634.* Transportation Research Board, Washington, DC, 1998, pp. 130-135.

Cohen, D., Head, L. and Shelby, S.G. Performance Analysis of Coordinated Traffic Signals During Transition. Paper presented at the 86th Annual Meeting of the Transportation Research Board, Washington, DC, 2007.

Federal Highway Administration. *Traffic Signal Preemption for Emergency Vehicles: A Cross-Cutting Study.* Washington, DC, 2006.

Kirby, R.F. Memorandum to Transportation Planning Board: Meeting the Goals of the Traffic Signal Optimization Transportation Emissions Reduction Measure. December 10, 2003. http://www.mwcog.org/uploads/committee-documents/9FpeWg20031212094744.pdf.

McCain-NIATT. *Controller Interface Device (CID II): User Manual Version 2.0*. McCain Traffic Supply, May 2002.

Nelson, E. J. and Bullock, D. Impact of Emergency Vehicle Preemption on Signalized Corridor Operation: An Evaluation. In *Transportation Research Record 1727.* Transportation Research Board, Washington, DC, 2000.

Obenberger, J. and Collura, J. Transition Strategies to Exit Preemption Control: State-of-the-Practice Assessment. In *Transportation Research Record 1748/* Transportation Research Board, Washington, DC, 2001.

Obenberger, J. and Collura, J. Using the "Software-in-the-Loop" Simulation Methodology to Evaluate Traffic Signal Transition Strategies Employed to Exit Preemption Control. Paper presented at the 86th Annual Meeting of the Transportation Research Board, Washington, DC, 2007.

Park, B. and Qi, H. Development and Evaluation of Simulation Model Calibration Procedure. *Transportation Research Record 1934.* Transportation Research Board, Washington, DC, 2005.

Park, B., Won, J. and Yun, I. Application of Microscopic Simulation Model Calibration and Validation Procedure: A Case Study of Coordinated Actuated Signal System. In *Transportation Research Record.* Transportation Research Board, Washington, DC, 2006.

Planung Transport Verkehr AG. *VISSIM 4.10 User Manual*. March 2005.

Schrank, D. and Lomax, T. *2005 Urban Mobility Report*. Texas Transportation Institute, College Station, 2005.

Shelby, S.G., Bullock, D., and Gettman, D. Transition Methods in Traffic Signal Control. Paper presented at the 85th Annual Meeting of the Transportation Research Board, Washington, DC, 2006.

U.S. Department of Transportation ITS Joint Program Office. ITS Costs: Unit Costs (Adjusted)- Equipment Costs for Roadside Control (RS-C). http://www.benefitcost.its.dot.gov/its/benecost.nsf/SubsystemCostsAdjusted?ReadForm&Subsystem=Roadside+Control+(RS-C). Updated July 11, 2007.

Yun, I., Best, M., and Park, B. Evaluation of Emergency Vehicle Preemption Strategies on a Coordinated Actuated Signal System Using Hardware-in-the-Loop Simulation. Paper presented at the 86th Annual Meeting of the Transportation Research Board, Washington, DC, 2007.

APPENDIX A

PROS AND CONS OF THREE CONTROLLERS USED IN THIS PROJECT

Operations	**Performance Pros/Cons**	**McCain's 170 Controller**	**Econolite 2070 Controller**	**Econolite ASC/3 Controller**
EVP Operations	Performance	Not Good	Good	**Best**
	Pros	No clear advantage	Allows selection of exit phase at the end of preemption	In addition to exit phase, *logic processor* allows the selection of dynamic exit phase
	Cons	No exit phase selection option	A selected exit phase is fixed for the entire operation	No clear disadvantage
TOD Transition	Performance	**Best**	Good	Good
	Pros	Transition favors coordinated phases	No clear advantage	Potential improvement with *logic processor*
	Cons	No clear disadvantage	No clear disadvantage	No clear disadvantage