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Criteria for the Selection and Application of Advanced Traffic Signal Control Systems

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16. Abstract

The Oregon Department of Transportation (ODOT) has recently begun changing their standard traffic signal control systems from the 170 controller running the Wapiti W4IKS firmware to 2070 controllers operating the Northwest Signal Supply Corporation's Voyage software. Concurrent with this change in standard signal control systems, ODOT has taken the opportunity to install test sites with adaptive signal control systems and evaluate advanced features in the Voyage software.

The evaluation of advanced features and adaptive signal control systems has led to a series of questions about how to measure performance, when to apply a given feature and, when should one system be preferred over another. To answer these questions a survey of literature and practicing professionals was conducted to determine the current state of the practice regarding conventional and adaptive signal control systems. The survey of practitioners indicated that practitioners in general were seeking answers regarding when and how to implement adaptive systems. Similar questions were found in literature, with the addition that the FHWA's Model Systems Engineering Documents for Adaptive Signal Control Technology added questions regarding whether existing systems had potential performance gains available through feature enablement.

This knowledge was used to create an evaluation framework to guide practitioners in evaluating the performance of their current systems. A decision support framework based on decision tree logic and queuing theory models was built on top of the analytical framework to analyze the existing system for features that may improve performance. The decision support framework also provides a means of estimating the performance of different control strategies given the existing conditions.

As a means of evaluating the various systems and selected features, the research team created a series of simulation models in VISSIM 5.30. These simulations were controlled via external logic emulating the signal control logic of the various systems and features. In total, 4,536 simulation cases were examined. The results of these simulations were used to calibrate the decision support and queuing model logic.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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Executive Summary

The Oregon Department of Transportation (ODOT) has recently begun changing their standard traffic signal control systems from the 170 controller running the Wapiti W4IKS firmware to 2070 controllers operating the Northwest Signal Supply Corporation's Voyage software. Concurrent with this change over in standard signal control systems, ODOT has taken the opportunity to install test sites with adaptive signal control systems and evaluate advanced features in the Voyage software. The major questions ODOT is asking regarding these systems are:

- How do you evaluate an adaptive or advanced feature system?
- How well do they perform?
- When should the systems be applied?
- What the benefits of the systems are when applied to specific corridors?

This project seeks to answer those questions by seeking answers from a variety of sources. The project began with a thorough literature review. A review of the available literature found that most evaluation criteria and methodologies were based around before and after studies. Typically, an adaptive system would replace the existing system with performance measured before and after the signal system change.

The overwhelming majority of system evaluations found were binary comparisons. These studies were found to be of limited use for several reasons. The first is that the comparisons are binary, with just two systems compared, limiting the research team's ability to generalize the results across multiple systems. Second, additional changes, such as adding lanes or other capacity improvements also occurred between the initial evaluation and the final evaluation. Finally, the pre-existing system was rarely re-timed prior to the evaluation, leaving many questions about the benefits seen in the adaptive evaluation. The basic question left by many of these system evaluations can be boiled down to whether the performance of the existing system would be comparable, given a re-timing and examination of unused existing features. This question features quite prominently in the Federal Highway Administration (FHWA) *Model System Engineering Documents for Adaptive Signal Control Technology Systems*.

To get a better picture of the state of the practice, the research team conducted a survey of traffic engineers asking them detailed questions about their practices, signal system compositions, and the challenges they face. Responses were received from engineers in 23 states and 2 Canadian provinces with wide ranges in system compositions, sizes and areas of responsibility. The results of this survey were informative. The majority of respondents indicated that they currently operated TS1 and 170/170E based systems and many were looking at upgrading to 2070/2070N based systems. Most comments indicated upgrades to software were being driven by central management system changes, communications compatibility, controller hardware compatibility and lack of support for legacy systems. In fact, system performance was rarely cited as a reason to upgrade systems.

The survey also provided information regarding the evaluation and selection of signal control systems. Respondents indicated that their primary performance measures are travel time, number of stops, citizen complaints and congestion observation via camera. The most interesting part of these responses is what is not used. Respondents frequently received no data from their systems or did not trust it. The most trusted tool practitioners used in evaluating their signal control system's performance was Synchro.

Upon conclusion of the literature review and evaluation of the survey responses, the research team began directly addressing the research's core questions. The first step was to select a series of performance measures that could be used to evaluate the performance of conventional and adaptive traffic control systems. A key constraint on the performance measures and evaluation framework was the feasibility of practitioners being able to collect the required data, practically. The research team selected phase/movement and intersection saturation, day-to-day and period-to-period variability, queue length, corridor travel, intersection delay, arrival on green percentage and number of stops as the primary measures of performance. This seems like a rather large set of performance measures to ask practitioners to collect. However, the research team considered this and derives the performance measures from more standard and accessible data available to practitioners such as 15 minute volumes, intersection geometric data and other practitioner focused sources.

One of the greatest challenges in this research is the collection of data and the quality of data available to the research team. The limited number of advanced and adaptive signal control systems in use and the varying data collection methodologies used by those systems prevented easy comparison between the systems. The differences in sensor configuration, data types and intervals collected all contributed to the general difficulty of selecting appropriate performance measures as well as creating an evaluation framework that could fairly evaluate different systems.

The next task faced by the research team was to select a logical framework upon which to model the process of modeling the performance of the various traffic signal control systems. The decision tree framework and queuing theory based models were selected to drive the selection of signal control features and project system benefits. The decision tree framework allows for straightforward implementation that end users can follow when they wish to understand why a given feature or strategy is being recommended. Queuing theory based models are used in the analytical portions of the decision tree logic. The benefit of queuing theory models is that they are well understood in practice and can be modified to suit the various control strategies and the impacts of specific system features. Queuing model simplicity also contributes an insensitivity to nuances in data collection methodologies, intervals and other factors that could skew more complex analyses.

An ongoing challenge in this research has been the sheer number of possible intersection and corridor configurations. When one considers the combinations possible just considering the number of approach lanes, left turn lanes and right turn lanes on each approach, the problem becomes clear. The number of factors that influence traffic performance at an intersection and on a corridor is staggering. Equally as challenging is the operation of the signal control system, itself. Each system, conventional and adaptive has its own optimization strategy, and individual features may have their own strategies as well. Understandably, the companies producing the various signal control systems consider the algorithms behind their signal control systems and features to be confidential.

After creating the decision and modeling framework the research team created a series of simulation models to test the modeling framework and calibrate criteria in the decision tree. The simulation models were created in VISSIM 5.30 and included external logic programmed in C# to control the intersection signals. External logic was created to simulate the operation of each system in the study. Although the adaptive system control algorithms were not publicly available, there is sufficient information available to create algorithms that behave similarly and can be adjusted to mimic performance seen in field data collected for the project. In total, 4,356 simulation cases were considered.

To aid practitioners in applying the analysis and decision frameworks developed in this research, the research team has created a Microsoft Excel application to perform the analyses, run the queuing models and execute the decision tree logic. This application is intended to aid practitioners in selecting additional features to enable on their current systems as well as providing a short list of candidate systems to examine more closely when considering a signal control system change.

1.0 INTRODUCTION

Modern traffic control systems span a wide range of control strategies. These strategies vary from fixed time to actuated to adaptive with wide ranges in between. Currently, a well-established body of research and practical knowledge regarding the appropriate application of fixed time and actuated control strategies exists to guide engineers in conventional system selection. Unfortunately, there is no correspondingly well-developed body of knowledge regarding the application of adaptive control strategies. This leaves traffic engineers without a uniform selection process and without guidance in determining which systems to implement in their jurisdictions. To remedy this, the "Developing a Performance Measurement Framework and Selection Guidelines for Advanced Traffic Signal Systems**"** project was commissioned by both the Oregon Department of Transportation (ODOT) and Transportation Northwest (TransNow), U.S. Department of Transportation (USDOT) University Transportation Center for Federal Region 10.

The goals of this project are to examine the current state of the practice regarding conventional and adaptive signal control systems, determine what, if any, analytical frameworks and measures of effectiveness exist for signal control system evaluation, analyze the problems faced by practitioners in the field, develop a decision support framework and deploy an application incorporating lessons learned for practitioners to apply in signal control system selection. To achieve these goals, the following tasks are undertaken. First, a literature review is conducted to examine the current state of the practice and identify existing analytical frameworks and measures of effectiveness (MOEs). Second, a survey of transportation professionals is conducted to identify measures of effectiveness and analytical methods used in practice as well as identifying the most common challenges faced by practitioners. Third, an analytical framework, including measures of effectiveness and decision support logic, is developed. Fourth, the analytical framework models are calibrated using field and simulation data. Finally, the analytical framework and decision logic are encoded in a Microsoft Excel application for distribution to practitioners.

The remainder of this report is organized as follows:

- Section 2.0 covers the literature review with specific coverage of signal systems of interest to the Oregon Department of Transportation, signal control system measures of effectiveness, and analytical procedures.
- Section 3.0 details the survey results with emphasis on analytical methods used by practitioners and the challenges they face in selecting signal control systems and operating their current systems.
- Section 4.0 outlines the measures of effectiveness decision logic developed by the research team to aid practitioners in selecting signal control systems.
- Section 5.0 describes the simulation experiments conducted to augment the existing field data used in calibrating the analytical models outlined in Section 4.0.
- Section 6.0 shows the Microsoft Excel application developed to aid practitioners.
- Section 7.0 concludes the report.

2.0 LITERATURE REVIEW

The first step in preparing installation guidelines and evaluation criteria for conventional and advanced signal systems is to review system manuals, previously published reports, and comparison studies. There are three traffic control system categories of interest for this study. The first category covers conventional systems such as those with local firmware control using time-based coordination or free operation plans (*Gordon and Tighe, 2005*). The first category assumes isolated operation with no local or central master control. The next category includes conventional control systems such as time of day or traffic responsive (*Koonce et al., 2008*). These systems include communications to local or central master control and may include more advanced local firmware features, such as dynamic maximum times, actuated control and more. The last category is adaptive signal control systems, which are capable of adjusting cycle length, splits, and offsets dynamically for optimal control. In addition to the operational principles of these signal control systems, the state of the practice regarding evaluation methods and traffic control systems selection criteria is also reviewed. System evaluations and comparison studies will be summarized at the end of this section.

2.1 CONVENTIONAL SIGNAL CONTROL SYSTEMS

Fixed time control and actuated control are two common signal control strategies among conventional signal control systems. Fixed time control is widely used because it does not require traffic sensors. Actuated control is often implemented on isolated systems and requires field traffic detection to operate properly. Both control strategies may be implemented in controllers with only basic firmware.

The W4IKS firmware produced by Wapiti Micro Systems and the Northwest Signal Systems's Voyage firmware are two examples that can be used to implement basic signal control strategies. The W4IKS firmware can operate on model 170 controllers (*Wapiti Micro Systems Corp, 2011*) while the Voyage firmware is designed for 2070 and NEMA controllers (*Northwest Signal Supply, Inc., 2008*).

W4IKS combines the computational engine required to operate the signal in fixed time or actuated modes with a flexible interface that allows engineers to input customized control parameters. While the W4IKS firmware is flexible, it is also constrained by the platform it is designed to operate on (*Wapiti Micro Systems Corp, 2011*). The model 170 controller has very limited memory and storage capacity. The model 170 specification was also not originally designed to accommodate communications. Native communication capabilities were added with the model 170E specification. While the W4IKS firmware has served well, the platform is becoming obsolete and programming for the platform is more labor intensive than some other platforms. Transmission speeds and the ability to store and switch timing plans are also limited on the W4IKS firmware and the model 170 platform (*Wapiti Micro Systems Corp, 2011*).

The Voyage firmware is designed for the 2070(L) and NEMA (2070N, M1) platforms as described in the Voyage traffic controller software datasheet Version 1.6.0 (*Northwest Signal Supply, Inc., 2008*). Many agencies in Oregon are replacing 170/W4IKS implementations directly with 2070/Voyage. Voyage incorporates a user interface similar to that found in W4IKS. The 2070N and 2070 controller specifications used with Voyage offer dramatic improvements in memory, storage space, and communications. These improvements make the Voyage firmware more capable than model 170/W4IKS implementations.

2.2 ADVANCED CONVENTIONAL SIGNAL CONTROL SYSTEMS

To overcome the limitations inherent to isolated intersection controllers and facilitate corridor or network level control, many control strategies have been designed and implemented. Systems employing these strategies vary from simple closed loop systems, where intersection controllers are tied together to a local master, to more complicated centralized conventional control systems. The simplest systems, such as closed loop systems, are used to ensure corridor signal coordination and to implement simple corridor-wide timing plan selection (*Bullock and Nichols, 2003*). Other systems such as Econolite's ARIES and Peek's CLMATS are built upon the closed loop architecture to form a centrally administered traffic control system (*Bullock and Nichols, 2003*). More advanced central systems can collect data from intersection traffic detectors and then use the data to automatically select the optimal timing plans and adjust signal coordination parameters as needed (*Siemens, 2010*). These systems can also collect and store performance data for off-line analysis and for adjusting timing plans.

Advanced features such as various forms of priority, phase ordering, and phase skipping are also available in firmware applications. These advanced firmware features may be used to achieve effects similar to those of central system control without requiring communications between intersections or to a Traffic Management Center (TMC).

A particular form of central control, called traffic responsive, as embodied by the TransSuite software, is of interest to ODOT as a comparison case. The TransSuite software can communicate with both 170 controllers running Wapiti and 2070 controllers running Voyage (*TransCore, 2011*). Traffic responsive control uses a library of timing plans similar to a time of day system but changes between plans based on detector input (*FHWA, 2009b*).

2.3 ADVANCED SIGNAL CONTROL SYSTEMS

Conventional signal control systems are typically slow to respond and the timing plans used are not optimized by real-time input for a corridor or a network. These historical limitations led to adaptive control system developments over the past decades. Several adaptive control systems have been developed and deployed. These adaptive systems employ methodologies that use intersection detection data from a dedicated sensor array to calculate optimum cycle lengths, splits, and/or offsets. Each adaptive system uses different algorithms and optimizes different signal control parameters.

The primary advantage adaptive systems have over conventional central systems is their flexibility (*Gordon and Tighe, 2005*). Conventional systems that rely on selecting the best fixed time plan for the time of day or traffic conditions cannot cope with traffic conditions that were not anticipated in their timing plan libraries. Adaptive systems that can change their cycle lengths, splits, and phase orders can react to unexpected traffic conditions. Three advanced signal control systems, Sydney Coordinated Adaptive Traffic System (SCATS) (*Roads and*

Traffic Authority, 2011), Adaptive Control Software – Lite (ACS-Lite), and InSync are of particular interest to Oregon Department of Transportation (ODOT) and are reviewed here.

2.3.1 Voyage Advanced Features

The Voyage software used in conventional signal control is also capable of more complex signal control operations. Voyage's advanced features include phase reservice techniques such as late left turn and adaptive features such as adaptive phase split timing, among others. A number of these features have been implemented on Oregon's 99W. This research includes Voyage with advanced features enabled as a separate category of signal systems so that practitioners may judge what performance improvements may be achieved by implementing features already present in the Voyage software. In the following research, "Voyage Advanced" refers to Voyage implementations taking advantage of some or all of these advanced features.

2.3.2 SCATS

SCATS was developed in the late 1970's. The system was designed shortly after communications and computer technologies matured sufficiently to reliably operate traffic signals from a TMC. The SCATS system requires communications and central computing resources. SCATS has also been approved by the Federal Highway Administration (FHWA) for Intelligent Transportation Systems (ITS) deployment since the early 1990s in the United States (*Gettman et al., 2006*).

SCATS controls traffic at two levels. This two-tier control is used to determine the three principle signal timing parameters of traffic signal coordination: cycle length, phase split, and offset. The two levels are referred to as strategic and tactical. Strategic control determines suitable signal timings for the areas and sub-areas based on prevailing traffic conditions while tactical control handles individual intersection level control settings subject to the constraints imposed by the regional computer's strategic control.

SCATS allows cycle length to vary to meet traffic demand because, in general, increasing cycle time increases system capacity. Cycle length ranges from 20 to 190 seconds in SCATS, with the actual limits customizable by users. SCATS dynamically adjusts cycle time in the user-defined range to maintain the highest degree of saturation (green time utilization) possible in a coordinated group of signals.

"Phase split refers to the division of the cycle into a sequence of green signals for the competing movements at each intersection and must reflect the relative demands for green time on each approach"(*Roads and Traffic Authority, 2011*). The SCATS determination of phase splits tries to maintain equal degrees of saturation on competing (representative) approaches. However, control may be biased to favor principal traffic movements when demand approaches saturation.

Offset refers to the start time of main street green relative to the corresponding green interval start for a master intersection in the system (*Gordon and Tighe, 2005; Akcelik et al., 1998*). The pattern of offsets in a series of coordinated signals must be varied with traffic demand to minimize the stops and delay associated with travel through a network of signals. SCATS selects offsets based on free flow travel time and degree of saturation to minimize stops for the predominant traffic flows.

SCATS was designed to use stop bar detection. The system is optimized for fifteen-foot-long lane-by-lane loop detectors. The system can also use other loop sizes, depending on what is available, with proper calibration. SCATS is capable of using up to seven distinct stages labeled A through G with sub-stages available for lead-lag operations.

2.3.3 ACS-Lite

ACS-Lite is an FHWA sponsored adaptive traffic control system designed to be implemented on closed loop systems with current implementations adding support for networked operations. The system is designed for up to eight intersections tied together with one acting as master to coordinate the signals (*Gettman et al., 2006*). The system uses parallel control algorithms to improve urban intersection traffic conditions. It has been cooperatively developed into a deployable system by Siemens, McCain, Peek, and Econolite (*Gettman et al., 2006; Bullock et al., 2008; Shelby et al., 2008*). ACS-Lite aims to improve the quality of coordinated control while retaining existing systems with on-street masters and without requiring the installation of large numbers of additional detectors. The algorithm gradually adjusts the background Time of Day (TOD) plans to adapt to gradual changes in traffic conditions, but does not make real-time adjustments as traffic volumes change (*Gettman et al., 2006*).

The ACS-Lite system varies from vendor to vendor with some vendor-specific implementations but most versions incorporate traffic responsive capabilities and do not require additional traffic detector installations. However, the systems cannot currently adapt cycle length. Some vendors, such as Econolite, have also added central control compatibility to their ACS-Lite implementations (*Econolite, 2011).*

2.3.4 InSync

Surveillance video cameras and video image processors have been increasingly deployed over the past decades. Rhythm Engineering utilized the video detection capability and released InSync in 2009. InSync has been installed and tested in several locations in the United States (*Rhythm, 2010*). Most current installations are on arterial roads with up to 12 intersections. Larger installations do exist as evidenced by a survey respondent from Plano, TX who indicated that the city's system includes just over one hundred InSync controlled intersections. The InSync adaptive traffic control implementation is quite different from SCATS and ACS-Lite. InSync abandons the concepts of cycle length and phase sequence and instead serves movements in an optimized order while maintaining a dedicated green band. It continually evaluates whether a signal should remain in its current state or move to a different state, based on both the known demand of traffic at the intersection and predicted arrivals of platoons from other intersections. InSync has an installation philosophy that retains the existing traffic signal controller and other field equipment. Rhythm Engineering installs its own proprietary hardware box (see Figure 2.1) in the control cabinet to perform the adaptive calculations based on its own video sensor inputs and then commands the controller to activate the desired phases.

(Picture source: Rhythm Engineering Website at http://rhythmtraffic.com/wp-content/uploads/2010/06/IMG_0779_Smaller.jpg)

Figure 2.1: InSync processor box

2.4 SYSTEM SELECTION CRITERIA

One major goal of this research project is to identify appropriate selection criteria to be used in choosing an adaptive signal control system. Because of the large number of criteria that may be used to select signal control systems, it is important to choose accepted and proven criteria where available. This subsection summarizes the literature review on the selection criteria for advanced traffic signal systems in use by various agencies. Additional information from the survey is included to clarify observations from the literature review, when appropriate. The survey results will be examined in more depth in Section 3.0.

From the literature review, transportation agencies are found to share common views on traffic signal system selection and hence many criteria used in practice are quite widely used. Most criteria were developed for conventional signal control evaluations and are also applied to advanced signal control system evaluations. This appears to be so that direct comparisons can easily be made between before and after signal control system change with the same measures. Advanced traffic control system specific criteria exist, but they tend to be closely tied to the system being evaluated with little transferability among systems.

Survey respondents reported that they used a very limited number of performance measures with corridor travel time, volumes and splits being the most common. However, as many indicated that they did not currently use system derived performance measures as indicated that they did use them. Even more importantly, a majority of respondents indicated they did not trust the system outputted information. This lack of trust puts even more pressure on agencies to use simple and proven performance measures.

Typical traffic signal operational criteria include Measures of Effectiveness (MOEs) like Level of Service (LOS) (surrogate for average control delay per vehicle), number of stops, corridor travel time, queue length, cycle failures, etc (*Stevanovic*, *2010*). Cost is another area where many comparisons take place. This criteria category includes software costs, support contracts, installation costs, and training costs (*Selinger and Schmidt, 2010*). Compatibility criteria are generally less explicitly considered as such; instead, they are often obscured in cost or operational terms. For example, an intersection hardware and software that is not compatible with a new traffic signal control system will typically require additional equipment expenditures or operator training in order to implement the new system. An additional observation made by Stevanovic (*2010*) is that agencies adopting adaptive signal control systems require different personnel mixes than those operating conventional systems. The balance shifts from a maintenance heavy focus to an operational focus with agencies that fail to recognize the need to change focus often experiencing performance below expectations.

The compatibility of a given advanced traffic signal system with existing detection is an important factor to consider when upgrading traffic signal control systems. SCATS and ACS-Lite can both be used with loop detectors of varying sizes and configurations, though best results are achieved when lane-by-lane detection and system appropriate loop sizes are used. Standard loop designs (e.g., six feet advanced loops/zones and 20 to 40 feet stop bar loops/zones) have performed adequately for ACS-Lite in all field tests (*Gettman et al., 2006*). InSync was designed to use video detection only, but has a module that will allow it to include existing detection to supplement video detection.

Controller hardware and network compatibility is another important consideration when selecting advanced control systems. The ACS-Lite system was initially limited to the NEMA closed-loop traffic control systems manufactured by Eagle (SEPAC NTCIP v4.01b), Econolite (ASC/2 NTCIP), or PEEK (3000E with NTCIP translator hardware). Other controller models may be compatible with the ACS-Lite system in the future. This is considered an impediment to deployment, as described in "Adaptive Control Software – Lite (ACS-Lite) Implement Template" (*Gettman et al., 2006*). SCATS is compatible with most Type 170, Type 2070 and some NEMA controllers and cabinet configurations so long as communications are available and stable and the SCATS-specific firmware is loaded onto the controller. InSync has fewer inherent hardware limitations because the system has its own proprietary control box hosted in the same cabinet for decisions and simply uses the existing controller hardware as a means of controlling the signal lights (*Lowrie, 1992*).

2.5 EVALUATION METHODS

Signal performance measurement is very important because it quantifies the performance of an existing traffic control system and identifies any weakness it may have. A plethora of studies have been conducted on the evaluation of traffic signal systems (*Batanovi, 1986; Bloomberg et al., 1997; Andrews et al., 1997;Abdel-Rahim et al., 2006; Hawkins et al., 2009; Kosmatopoulos et al., 2006; Martin, et al., 2006*). However, each of these studies mainly focused on a specific on-site system rather than providing guidelines for selecting suitable signal control systems before implementation. The evaluation result is, to some extent, case-dependent and not spatially transferable. Some studies (*Shelby, 2004; Mudigonda et al., 2008*) used traffic simulation tools for more comprehensive evaluations on different control systems. However, the proprietary control algorithms may not be sufficiently released for accurate implementations in their simulation models. Therefore, the results may not be representative and convincing.

Several publications have served as guidelines for selecting traffic signal control systems over the past decades. For example, the Manual of Traffic Signal Design developed by the Institute of Transportation Engineers (*Kell and Fullerton, 1991)* determines the type of traffic control system based on volumes of minor and major streets. Lee and Lee (*2007*) proposed to select traffic signal control strategies at isolated intersections based on 24-hour volumes. The FHWA Traffic Control Systems Handbook by Gordon and Tighe (*2005*) suggests that the selection process should require self-examination, and consideration of life-cycle issues regarding system acquisition, operation, and maintenance. In general, the existing guidelines are too simple to provide any systematic and effective approach for selecting the advanced traffic control systems. Even though the Manual on Uniform Traffic Control Devices (MUTCD) (*2009a*) provides a more systematic approach, the selection criteria are specifically developed for pre-timed, semi-actuated, fully-actuated, and coordinated control systems. More advanced traffic signal systems, such as traffic responsive and adaptive signal control systems, are rarely covered in these practical manuals or handbooks.

The research most directly relevant to this proposal may be the study done by Mudigonda et al. (*2008*), in which a decision support tool was developed to evaluate different adaptive control strategies on transportation networks. Traffic simulation tools were effectively used in their work to retrieve the performance measures of various advanced signal control systems. Since the proprietary control algorithms are difficult to correctly implement in the simulation models, more details of the simulation approach are needed to fully understand the reliability of the evaluation results.

While reports such as the National Cooperative Highway Research Program (NCHRP) Synthesis 403 (*Stevanovic, 2010*) have looked at the issues of adaptive traffic control system evaluation and adoption, they have only reported on the state of practice, which is currently lacking a valid analytical framework. The lack of such a framework is likely due to the following difficulties. First, an advanced traffic control system is difficult to evaluate before it is fully implemented on-site because the control logic depends significantly on real-time traffic inputs. Second, little research has been done on developing a systematic approach to comparing performance measures of different advanced traffic signal systems. This may be because it is not practical to implement all advanced signal control systems at the same location and some of these systems are relatively new. Finally, the control algorithms stored in the advanced traffic control systems are typically proprietary and closely guarded.

To handle the difficulties mentioned, several efforts have been made to integrate microscopic simulation programs with traffic signal controllers to evaluate the performance of the propriety algorithms developed by various vendors (*Balke et al., 2000; Bullock and Catarella, 1998; Koonce et al., 1999; Engelbrecht et al., 1999; Husch, 1999; Koonce et al., 1999; Nelson and Bullock, 2000; Nelson et al., 2000*). The idea of hardware-in-the loop (HITL) simulation was developed by Bullock et al (*Bullock and Urbanik, 2000; Bullock et al., 2004*). Even though traffic simulation provides a means for virtually implementing all of the study algorithms in one intersection, sufficient technical details of the algorithms are required for correct implementations.

2.5.1 Comparison Studies

Many states in the U.S. have begun to install advanced traffic control systems to upgrade their conventional signal systems. Often this means an advanced traffic signal control system replaces a conventional central or closed loop control system. Reports covering these upgrades, correspondingly, tend to have data for only two systems, the original, conventional system and the new, advanced system. This limitation means that a number of reports are required to show the performance improvements that are possible using advanced signal control systems, a minimum of one report per system. Over the remainder of the section, the results of several case studies will be presented in order to give readers as accurate a picture of system performance as possible.

The comparison case studies presented here generally use performance measures such as corridor travel time and number of stops. Both of these performance measures are very dependent on the quality of timing plans in use of the comparison, i.e., a bad plan will cause excessive travel time and a correspondingly high number of stops. Unfortunately, comparisons are complicated by the fact that agencies generally do not expend the resources to retime their intersections prior to changing their signal control systems. Because the research team has no control over the conditions of the comparison, readers should note that improvement percentages are dependent on the quality of the timing plans, parameters and alignments in use before the signal systems upgrade. When incorrect plans, parameters and alignments are in use before the evaluation, the before and after evaluation performance improvements can be inflated. The NCHRP synthesis report (*Stevanovic, 2010*) indicated that when a well-maintained and timed conventional system is replaced by an adaptive system, it can be difficult to achieve performance improvements greater than ten to fifteen percent in any given performance measure.

2.5.2 SCATS

Beginning in 1992, Oakland County in the State of Michigan began converting their pre-timed coordinated traffic signal control systems to SCATS. There were 28 intersections in the test implementation. The sample data used to evaluate the project result was from a four-mile segment of M-59 from Pontiac Lake Road West to Pontiac Lake Road East consisting of seven signalized intersections. Table 2.1 shows the performance improvements seen on the study segment. Specifically, SCATS decreased the travel time by 6.7%, number of stops by 26.5%, queue length by 17.5%, total travel delay by 19%, fuel consumption by 5.1%, and increased the average travel speed by 7.0% (*Dutta and McAvoy, 2010*).

Table 2.1: Combined EB/WB weekday peak hour MOE comparison before/after SCATS in Oakland County, Michigan

Measure Of Effectiveness	Before	After	Change
Travel time (sec)	442.67	413.10	-6.68%
Travel speed (mph)	32.51	34.77	6.95%
Fuel consumption (gallons)	0.2269	0.2154	-5.07%
Number of stops	3.33	2.45	-26.43%
Total travel delay (sec)	158.04	127.93	-19.05%
Number of stopped vehicles	1289.96	1072.33	-16.87%
Maximum queue length	23.23	19.17	-17.48%

Source: *Martin and Stevanovic 2008*

The traffic signal control project in Park City, Utah changed the traditional TOD system to a SCATS system in 2005. All evaluations were from the 14 intersection signals along the corridor, and were collected between 7 and 9 AM (morning peak), and 4 and 6 PM (afternoon peak) on all weekdays, and noon and 2 PM (midday peak) on weekends under fair weather and dry pavement conditions. In general, the SCATS deployment in Park City, Utah has improved traffic operations. As shown in Table 2.2, the average travel time decreased by 5.8%, number of stops by 8.5%, and total travel delay by 15.5%. The travel times and delays on the major routes in the Park City network are always shorter with SCATS control than with the original TOD plans.

Table 2.2: MOE comparison before/after SCATS in Park City

MOE		AM NB	AM SB	PM NB	PM SB
Travel Time(seconds)	Before	907.3	895.8	888.0	951.3
	After	839.3	825.9	854.3	912.6
	Change	-7.5%	-7.8%	-3.8%	-4.1%
	Average change	-5.8%			
Stops	Before	7.8	7.2	6.0	8.5
	After	6.3	6.0	6.3	8.2
	Change	-19%	-16.7%	5%	-3.5%
	Average change	-8.5%			
Total Delay(seconds)	Before	335.0	307.4	305.4	375.5
	After	266.6	254.2	268.9	329.7
	Change	-20.4%	-17.3%	-12%	-12.2%
	Average change	-15.5%			

In March 2007, Gresham, Oregon changed their TOD plan system to SCATS at 11 intersections on Burnside Road. The study segment of four intersections along a 1.88-mile segment of Burnside Road showed an average reduction in travel time of 10.8% as shown in Table 2.3, although travel time increased in morning peak hours for the westbound direction (*Peters et al., 2007; Fehon and Peters, 2010*). In addition to the Gresham project, there are several other advanced traffic signal systems, including Voyage with advanced features and SCATS, deployed in Oregon under the ODOT Innovation Grant Program.

Table 2.3: Travel time comparison before/after SCATS in Gresham

Travel time (sec)		Before	After	Change	Average Change
East bound	8-10 a.m.	305	263	-19%	-10.8%
	12-2 p.m.	315	265	-16%	
	4-6 p.m.	373	314	-16%	
West bound	8-10 a.m.	226	248	10%	
	12-2 p.m.	321	294	-8%	
	4-6 p.m.	361	305	-16%	

By the end of 2010, there were 14 deployments of SCATS in the U.S. ranging from deployments of 11 signals up to 625 signals. SCATS has been installed in Oakland County, Michigan; Bellevue, Washington; Sunnyvale, California among others. There are also large installations consisting of thousands of signals in Sydney, Shanghai, and Hong Kong.

The SCATS system has been adding new features over time. Flashing yellow arrow, which allows left turns after yielding to pedestrians and other cars, is one of the more recent additions. The use of the flashing yellow arrow has reduced the left-turn delay from 38 seconds per vehicle to 16 seconds per vehicle on Factoria Boulevard in Bellevue, WA. Note that this delay reduction is in addition to the savings already realized by changing to SCATS.

2.5.3 InSync

Three of the current InSync deployments have been evaluated to determine their net impact on traffic operations within their respective corridors. Hutton et al. (*2010*) evaluated the replacement of an actuated system with the

InSync system and the evaluation results are summarized in Tables 2.4 through 2.6. In Lee`s Summit, Missouri, a 2.5 mile long corridor including 12-signalized intersections showed decreases in stops as shown in Table 2.4. The average stop reduction reached 95% under some conditions. Total delay decreased by 87%. Travel time, shown in Table 2.5, decreased by 18.8% (10.1% for northbound and 27.5% for southbound), which correlates with reductions in fuel consumption (*Hutton, et al., 2010; Siromaskul and Selinger, 2010*). Speed improvements are reported in Table 2.6.

Table 2.4: Number of stops along the corridor comparison before/after InSync in Lee`s Summit

Direction		**AM Peak**	**AM off peak**	**Noon peak**	**PM Peak**	**Night**
NB	Before	0.6	0.8	1.8	1.5	1.6
	After	0.7	0.4	0.6	0.7	0.3
	Change	17%	-50%	-69%	-57%	-81%
	Average Change	-48%				
SB	Before	3.9	4.6	4.7	2.6	1.8
	After	0.2	0.3	0.6	1.2	1.3
	Change	-95%	-95%	-88%	-56%	-31%
	Average Change	-73%				

Table 2.5: Travel time comparison before/after InSync in Lee`s Summit

Direction		**AM Peak**	**AM off peak**	**Noon peak**	**PM Peak**	**Night**
NB	Before	246 sec	247 sec	306 sec	292 sec	244 sec
	After	250 sec	234 sec	251 sec	248 sec	210 sec
	Change	1.6%	-5.3%	-18.0%	-15.1%	-13.9%
	Average Change	-10.1%				
SB	Before	343 sec	370 sec	392 sec	344 sec	251 sec
	After	233 sec	226 sec	245 sec	270 sec	232 sec
	Change	-32.1%	-38.9%	-37.5%	-21.5%	-7.6%
	Average Change	-27.5%				

Table 2.6: Travel speed (MPH) comparison before/after InSync in Lee`s Summit

direction		AM Peak	AM off peak	Noon peak	PM Peak	Night
NB	Before	37.6	37.5	30.4	32.2	38
	After	37.4	39.8	37.4	37.5	44.1
	Change	-0.4%	6.0%	23.2%	16.5%	15.9%
	Average Change	12.2%				
SB	Before	27.3	25.5	23.8	27.3	36.9
	After	39.8	41.0	38.3	34.8	40
	Change	45.8%	61%	60.9%	27.3%	8.4%
	Average Change	40.7%				

Note that the magnitude of the improvements seen in the previous tables far exceeds the 15% percent that would be expected according to Stevanovic (*2010*), particularly for southbound travel. The southbound improvement may be conflated with improved coordination for that travel direction. Southbound coordination improvement may be indicated by the asymmetric improvement in number of stops in Table 2.4, travel times in Table 2.5 and travel speed in Table 2.6 to more closely match northbound traffic.

2.5.4 ACS-Lite

In June 2009, Fulton County, Georgia changed eight intersections to the ACS-Lite system. The study data was collected at five adjacent intersections, from Fairburn Rd to I-285 on Cascade Road. Travel times, shown in Table 2.7, decreased by 15% and maximum queue length, shown in Table 2.8, decreased by 19.8% (*Wang, et al., 2010*). The results indicate that the ACS-Lite system effectively reduced the travel time on the arterial while simultaneously reducing queue lengths on side streets during peak periods.

Table 2.7: Travel time comparison before/after ACS-Lite in Fulton County

MorningPeak			
	Before	**After**	**Change**
EB: Fairburn to I-285 NB	67 sec	46 sec	-32%
WB: I-285 NB to Fairburn	122 sec	103 sec	-16%
EveningPeak			
	Before	**After**	**Change**
EB: Fairburn to I-285 NB	159 sec	136 sec	-14%
WB: I-285 NB to Fairburn	146 sec	136sec	-6%
Average of Both Peaks			
	Before	**After**	**Change**
EB: Fairburn to I-285 NB	113 sec	91 sec	-19%
WB: I-285 NB to Fairburn	134 sec	119 sec	-11%
Total travel time reduction	123 sec	105 sec	-15%

Table 2.8: Queue length comparison before/after ACS-Lite in Fulton County

MorningPeak			
Intersection	**Before**	**After**	**Change**
I-285NB	13.3	10.4	-21.8%
I-285SB	14.4	7.6	-47.2%
Utoy	14.9	11.3	-24.2%
Publix	2.4	2.5	0.4%
Fairburn	19.3	20.1	0.4%
EveningPeak			
Intersection	**Before**	**After**	**Change**
I-285NB	13.2	10.7	-18.9%
I-285SB	26.8	21.4	-20.1%
Utoy	17.2	17.3	0.05%
Publix	9.2	8.6	-6.5%
Fairburn	30.3	25.4	-16.2%
	Before	**After**	**Change**
Average of Both Peaks	16.1	13.5	-19.8%

The ACS-Lite installation in Gahanna, Ohio was implemented on Econolite NEMA hardware controllers and studied as a test bed. The improvements were then converted to a monetary savings using an hourly rate of $12.10 as a value of time for delay cost estimates and $2.25 as the per gallon price of gasoline. The ACS-Lite system was found to bring $88,500 in annual benefits from fuel savings and time savings at Gahanna, Ohio (*Gettman et al., 2006*).The ACS-Lite implementation in Houston, Texas was implemented on Eagle controllers and evaluated with the same time value and fuel costs. The resulting annual benefits were estimated to be $577,648 (*Gettman et al., 2006*).

2.6 COMPARATIVE STRENGTHS AND WEAKNESSES

In order to compare the overall characteristics of advanced traffic control systems such as ACS-Lite, InSync, and SCATS, surveys focusing on cost, maintenance, and reliability were conducted in 2009 and 2010 to compare the widely used adaptive signal control systems (*Selinger and Schmidt, 2010*). The objective of the surveys was to identify a short list of the technologies that practitioners should be considering for deployment on their own transportation networks. Some of the systems were eliminated because of lack of data. The three systems identified as strong installation candidates were SCATS, ACS-Lite, and InSync. These systems combine lower cost, decreased maintenance, and higher reliability. Table 2.9 shows a brief summary of strength and weakness of these three systems as identified by Selinger and Schmidt (*2010*) in *Adaptive traffic control system in United States, updated Summary and Comparison,* Readers should be cautioned that this table is quoted verbatim from the source report and that the original source surveys constitute a small sample size with only four responses per adaptive system. The small sample sizes allow for disproportionate influence by outliers.

Table 2.9: A comparison of cost, reliability, and maintenance among SCATS, ACS-Lite, and InSync

System	Strength	Weakness
ACS-Lite	Fastest installation and fine tuning time of the three	High downtime associated with communication
	Second lowest cost	The least operational benefits
	Ease of use and configurations	Adaptive software cannot change cycle length
		Short high volume periods are missed by the system
InSync	Lowest cost software platform	Video detection was commonly noted as a concern
	Lowest overall weekly maintenance	Communication was noted as a concern
	Lowest percent offline of three systems	
	Highest operational benefits by a large margin	
SCATS	Second Highest operational benefit	Highest cost
	Second Lowest installation and fine tuning hours per intersection	Highest average maintenance per week
	Second Lowest percent offline	

Source: Selinger and Schmidt (*2010*).

3.0 SURVEY OF TRANSPORTATION ENGINEERS

To expand upon the contribution of the existing literature and ensure that as many concerns as possible are addressed in the guidelines to be produced by the research team; the research team conducted a survey of city, county, state, and federal transportation engineers. The survey text is in Appendix A.

The survey covered numerous parts of the signal selection process and included several questions on available hardware, personnel, and communications assets as well as methodologies for determining signal timing and data collection. The responses to these questions are important to an advanced signal control system evaluation.

3.1 RESPONDENTS OVERVIEW

The survey was designed by the research team following discussions with local traffic operation engineers and members of the ODOT technical advisory committee (TAC) of this project. Considering the time and budget constraints, the survey was implemented as an online survey using the University of Washington's Catalyst WebQ tool.

The survey subjects were drawn from multiple sources, including relevant technical committees of the Transportation Research Board (TRB), the Institute of Transportation Engineers' certification list of Professional Traffic Operation Engineers (PTOEs), and authors of relevant publications. The various email lists were then compiled into a single list and sorted to include traffic operation engineers working in the public sector and eliminate consultants, academics, and others who are not responsible for signal system selection. The total number of persons surveyed was 486 with 430 in the United States and 56 in Canada.

A survey email with the Hyperlink to the online survey was sent to the survey population on April 27, 2011. The online survey closed in seven days. A total of 61 responses were received, six of which were eliminated due to unresponsiveness or quality of answers leaving fifty-five responses for analysis. Effective survey responses were from 23 states and two provinces. Table 2-10 below shows a breakdown of responses by state/province and agency type.

Table 3.1: Breakdown of survey respondents by State/Province

State/Province	City	County	State	Total
Arizona	1	1		2
California	2	1	1	4
Colorado	1	3		4
Florida		2		2
Georgia		1		1
Illinois	1			1
Louisiana		1	1	2
Maine		1		1
Minnesota			2	2
Mississippi		1	1	2
Nevada	2			2
New Mexico			1	1
New York			1	1
North Carolina	4		1	5
Ohio	1			1
Oklahoma	1			1
Oregon	3	1		4
South Carolina			1	1
Texas	5		1	6
Utah			3	3
Virginia		1	1	2
Washington	2	1		3
Wisconsin		1	1	2
Ontario, Canada	1			1
Alberta, Canada	1			1
Total	25	15	15	55

Survey respondents had been working in the field for an average of 15.6 years with a median value of 16 years (Figure 2.2). Survey respondents had responsibility for a wide range of signal system types and sizes. System sizes ranged from 35 to over 9000 signalized intersections as shown in Figure 2.3. The average system size was 954 signals with a median value of 215 signals. This range of system sizes was not very surprising when one considers that some respondents work for small cities and counties that do not have very many signals and other respondents are responsible for an entire state’s signal control systems.

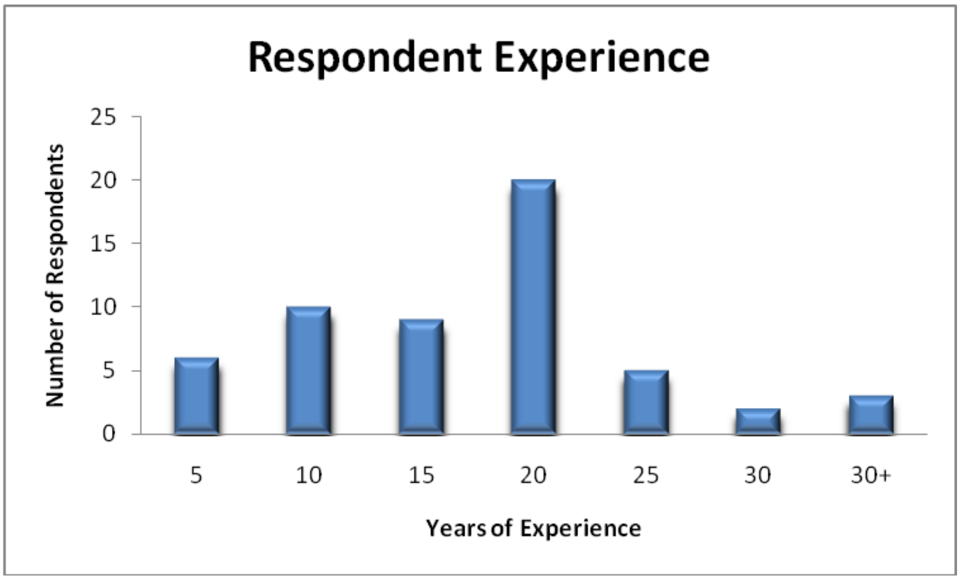

Figure 3.1: Experience level of respondents

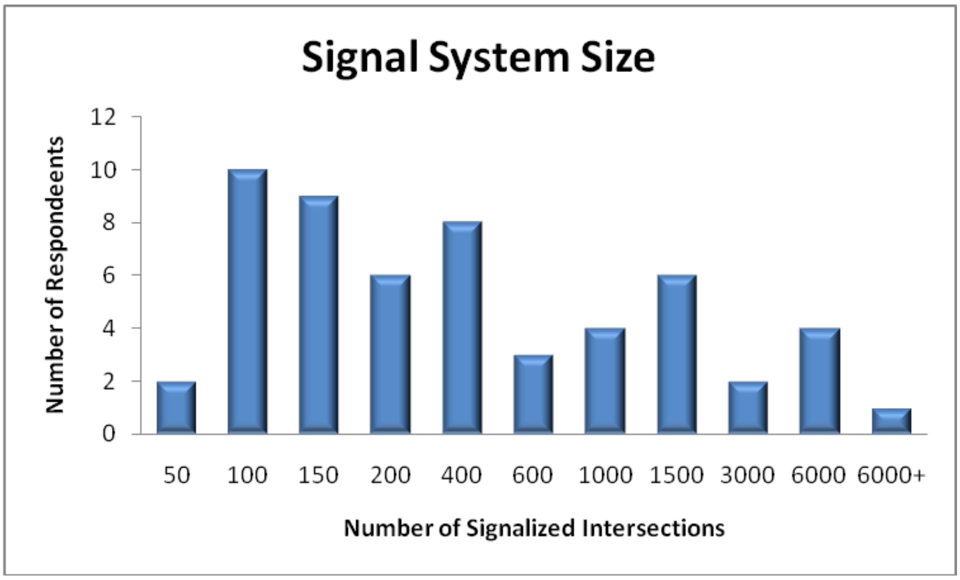

Figure 3.2: Size of signal systems administered by survey respondents

3.2 SYSTEM CHARACTERISTICS

Survey respondents were asked to indicate the systems currently in use by their agency and when their agency had last changed signal control systems. For the most part, respondents indicated that they were operating conventional centralized systems such as Siemens's i2 or TACTICS, Naztec's Street Wise or Econolite's Aries or Centracs as their primary systems. Respondents were asked to indicate if they were operating with the W4IKS or Voyage firmware or any of the adaptive systems previously detailed (ACS-Lite, InSync or SCATS). In total, eight out of fifty-five respondents operated the W4IKS firmware and five out of fifty-five operated the Voyage firmware. One fifth of respondents indicated that they were operating an adaptive signal control system such as SCATS, SCOOT, InSync, or ACS-Lite with another eight percent currently operating test installations. Many of these adaptive installations were small, with fewer than twenty intersections. The largest adaptive signal control installation reported by respondents was in Plano, TX with more than one hundred intersections running InSync. The cities of Bellevue, WA and McKinney, TX had installations of SCATS with 31 and 80 intersections, respectively, which were among the larger adaptive installations reported by respondents. Overall, less than a thousand intersections were reported to operate with advanced signal systems out of the 52,400 intersections run by survey respondents.

The predominant cabinet configurations are TS1 and 170E. Respondents commonly indicated that they were either currently upgrading or considering upgrades from 170 and 170E controllers to 2070 controllers. In many cases, the controller changes and other traffic control system changes were being pursued concurrently. Several respondents commented that the change to 2070 controllers was being pursued as part of a communications upgrade and/or National Transportation Communication Infrastructure Protocol (NTCIP) (*Joint AASHTO/ITE/NEMA Committee 2008*) compatibility upgrade. Often the existing software was old enough to not be NTCIP compatible. Communications upgrades and NTCIP compliance are a part of many of the traffic control system upgrades that respondents indicated had occurred in recent years or planned to execute in the future.

3.3 SYSTEM OPERATIONAL CHALLENGES

An important aspect of signal control system selection is picking the system that can best deal with the challenges being faced by the agency. Discovering the challenges commonly faced by agencies will inform decisions regarding signal control systems (survey question II-4 may be found in the Appendix). Survey respondents were given thirteen challenges and the option to choose "other" and write in any additional options. The predominant challenge faced by agencies is detector malfunction with over eighty percent of the respondents indicating that their systems were impacted. Over sixty percent reported that signal coordination is a challenge. A complete listing of the challenges identified can be found in 3.2.

Table 3.2: Challenges faced by respondents

Challenge	Frequency	Percentage
Detector malfunction	45	81.8%
Signal coordination	34	61.8%
Traffic saturation	27	49.1%
Field communications failure	25	45.5%
Variable traffic demand	23	41.8%
Pedestrian traffic	19	34.5%
Work zones	18	32.7%
Special events	12	21.8%
Emergency vehicle activity	11	20.0%
School traffic	11	20.0%
Controller programming	10	18.2%
Other:	10	18.2%
Weather	8	14.5%
Large vehicle effects	8	14.5%

The challenges that agencies face become less consistent after signal coordination with the next three challenges being identified by between 41 and 49 percent of the respondents. The third most reported challenge is saturated traffic. The fourth is field communications failure and the fifth is variable traffic demand.

It is troubling that so many practitioners identified malfunctioning detection as a challenge they face since adaptive systems are, in general, detector reliant. Adaptive traffic signal control systems require accurate detection in order for their algorithms to select the best signal timing parameters. Many such systems may be able to compensate for the loss of a few individual detectors; however, it would be expected, that as more detection fails, any adaptive system's performance would fall off dramatically.

On the other hand, that signal coordination was indicated as a challenge by sixty percent of respondents could bode well for adaptive systems. Adaptive systems such as SCATS, InSync, and ACS-Lite can all adjust their cycle parameters to traffic conditions while maintaining the coordination setup in their base plans. It may require additional effort at installation to build the required coordination, but the coordination should stay in effect while the systems adapt to traffic conditions.

Saturated traffic conditions are problematic for all signal control systems. The best a signal control system can do is to use time efficiently. Because adaptive systems can use the available time more efficiently than most other systems they may be able to improve a given roadway's capacity by wasting less time. This could reduce saturation and either allow shorter cycles to be used, or improve performance at the same cycle length.

Forty-five percent of survey subjects reported that field communications failures posed a challenge to their agency. For adaptive systems, field communications failure is problematic. SCATS, in particular, is communications reliant because all of the optimization and data collection occurs at a central server and communications loss will result in the controllers reverting to time of day control. It is also problematic for conventional central systems. It should be noted here that several respondents indicated they were upgrading from 170 to 2070 controllers to improve communications.

Variable traffic demand was the fifth most selected challenge at forty-two percent of respondents. This challenge is perfectly suited to adaptive traffic systems. Adaptive systems are designed to adapt to variable demand, which makes them ideally suited to solving this problem.

3.4 ADVANCED SIGNAL SYSTEM SELECTION CRITERIA

There are many criteria that may be used to select signal control systems. A number of these criteria were reviewed by the research team. The most relevant criteria were grouped into three categories: costs, system parameters, and performance measures. In order to better estimate survey respondents' true valuations of the various criteria, each criteria is presented twice for ranking.

The first time (survey question III-1), survey respondents were asked to select the five criteria they believed to be the most important in selecting an adaptive signal control system. Criteria were awarded points based on the order they were selected (five for first pick to one for fifth pick, zero otherwise). Points were then totaled across respondents. The aggregate ranking for each criterion can be found in Table 3.3. Each criterion is listed in the order it ranked. The category into which the criterion was placed is listed in the second column. Table 3.3

shows that cost and system parameters dominate signal system selection criteria with the first performance criteria ranked at eleventh place out of seventeen. The concern with costs and system characteristics over performance may explain why so many agencies have used the same signal control systems for decades. It would also explain why so few adaptive signal control systems are installed and being installed since an adaptive signal control system is more expensive and generally requires equipment, software or communications changes.

Table 3.3: Aggregate criteria rankings

Criteria	Category	Ranking
Installation/construction cost	Cost	1
System communication requirements	System	2
Controller brand/type compatibility	System	3
Initial license acquisition cost	Cost	4
Operating cost	Cost	5
Stability and durability	System	6
Controller software compatibility	System	7
Adaptability to changing traffic conditions	System	8
Increased equipment maintenance cost	Cost	9
Hardware upgrade cost	Cost	10
Corridor travel time	Performance	11
Signal status data logging and resolution	System	12
Intersection level of service	Performance	13
Number of vehicle stops	Performance	14
Cycle failure	Performance	15
Training cost	Cost	16
Queue length	Performance	17

The second time, survey respondents were asked to rank criteria within each category (survey questions III-2, -3, -4). For example, survey respondents were asked to rank corridor travel time, intersection level of service, number of vehicle stops, cycle failure, queue length, and other criteria from most important to least important in evaluating adaptive traffic control systems.

The research team expected that the respondents would rank criteria similarly between the per category rankings from survey questions III-2, III-3 and III-4 and the order criteria from that category ranked in the combined criteria rankings seen in Table 3.3. The combined rankings were intended to provide information to show the relative importance of the various categories. The combined category rankings Tables 3.4, 3.5 and 3.6 show the rankings for each criteria group and the criteria ranking within the combined rankings. The number in parenthesis is the ranking for criteria when the combined ranking order is only considered within one category.

The research team intended to determine what characteristics are truly desired from a new adaptive control system and what characteristics are desired in response to the shortcomings of current systems. This was intended to de-convolute current problems from future system selection. For example, when replacing a system that has had constant communication problems it is natural to rank stability and quality of communications highly. The question was whether a given criteria has been ranked highly because of current problems or because of its import in selecting a new system.

While there were differences between the per category rankings and the aggregate criteria rankings, only a few are really noteworthy. Most of the ranking changes observed for questions III-2, III-3 and III-4 were minor fluctuations of criteria order between criteria that scored within a few points of each other in question III-1. In question III-2 hardware upgrade costs was ranked tenth in Table 3.3, the fifth cost criteria in that list, while it was ranked third when cost criteria were considered separately. Initial license acquisition cost decreased from the combined list where it was fourth ranked overall and the second cost criteria, compared to the fourth ranked cost criteria in question III-2. This pair of discrepancies may be indicative of how costs are considered by respondents. Considering hardware and other costs as part of a larger project, or as individual signal system costs, can cause different results. In question III-4 stability and durability ranked first versus its sixth overall and third system criteria placement in question III-1. Communications requirements dropped from second overall and first system criteria to fourth in question III-4. This swap is probably related to current problems versus desired characteristics with so many respondents indicating that communications are a problem for their current system and it being perfectly logical for stability and durability to be very highly ranked.

Table 3.4: Cost criteria rankings

Criteria	Ranking	Combined
Installation/construction cost	1	1 (1)
Operating cost	2	5 (3)
Hardware upgrade cost	3	10 (5)
Initial license acquisition cost	4	4 (2)
Increased equipment maintenance cost	5	9 (4)
Training cost	6	16 (6)

Table 3.5: Performance criteria

Criteria	Ranking	Combined
Corridor travel time	1	11 (1)
Intersection level of service	2	13 (2)
Number of vehicle stops	3	14 (3)
Queue length	4	17 (5)
Cycle failure	5	15 (4)

Table 3.6: System criteria

Criteria	Ranking	Combined
Stability and durability	1	6 (3)
Controller brand/type compatibility	2	3 (2)
Controller software compatibility	3	7 (4)
System communication requirements	4	2 (1)
Adaptability to changing traffic conditions	5	8 (5)
Signal status data logging and resolution	6	12 (6)

3.5 SYSTEM EVALUATION METHODS

Another goal of this research is to identify methods that are suitable for evaluating traffic conditions and determining their usability in evaluating signalized intersections for conversion to advanced signal systems. Of particular interest are evaluation methods that practitioners are familiar with and that can be compared to existing conventional system evaluations. It is important that some evaluation methods used to evaluate advanced signal systems be applicable to conventional systems so that stakeholders can evaluate performance gains unambiguously.

Adaptive systems have been historically difficult to test and simulate accurately due to the dynamic nature of cycle lengths, splits, and phase sequence order. Traditional evaluation methods may not be able to accurately predict measures of effectiveness such as control delay for adaptive systems. The evaluation difficulties extend into the realm of simulation, as most of the control algorithms are proprietary and not available publicly for emulation.

Corridor travel times, number of stops, citizen complaints, and congestion observation via video surveillance are the dominant performance measures reported in the survey. Travel times and number of stops can be combined with traditional traffic measures such as counts and directional volumes for traffic simulations. These performance measures can be used to virtually test the various systems.

A disturbingly high number of respondents indicated that they receive no information from their systems, do not use that information, or did not trust the information they did get. Thirty percent of respondents indicated they do not receive useful data from their systems. Thirteen percent responded that they do not trust the data they do get and thirteen percent do not use the data they get. Combined, over half of the respondents do not have a data feedback cycle from their systems with which to monitor or improve operations.

This is disturbing because of its implications for signal system operations and selection. These users would have no information to do the expected analysis and system performance monitoring. These users may have to use other means, such as complaints received, travel time runs, video camera observations, and periodic studies to check their system’s performance. Approximately twenty-five percent of respondents indicated that they were examining the inputs from their systems for reliability. Almost all of the remaining respondents are in the process of evaluating their new systems. Among them, several respondents indicated that they were specifically evaluating the data provided by their systems.

Pre- and post-implementation studies showing the performance gains achieved by the installation of new traffic control systems are the dominant evaluation method. This is somewhat problematic from an absolute comparison standpoint because other changes are often concurrently implemented, such as signal retiming or road realignments. Before and after type studies conflate the benefits of the new signal system with the other work done at the same time making it difficult to isolate the gains made due to signal control improvements.

3.6 OTHER OBSERVATIONS

Survey respondents often included additional data in their answers that allows for more insight into what is going on in practice. On average, survey respondents indicated that their jurisdictions had changed signal systems in the last five years. Note that this average ignores agencies that have never changed their signal systems or did not indicate a timeframe (8/55 respondents). One third indicated that they were in the process of changing their conventional signal control systems, either installing a new central control system or updating from a previous generation of central system to a more current vintage of system (i.e. from Siemens i2 to TACTICS). Support stoppages for current software systems and obsolescence of hardware, particularly Siemens i2 and Type 170 controllers, were cited as reasons to upgrade by survey respondents.

Approximately one-third of respondents indicated that their agency is involved in a regional coalition to enhance signal system compatibilities and streamline management. There was not a specific question asking whether a given agency was part of a coalition; however, several respondents indicated that their agency had elected to change systems for regional compatibility reasons or were considering such changes.

Approximately one-third of the respondents was in the process of changing conventional signal control systems or will start the process in the near future. Many respondents indicated that their current software was no longer supported by their vendor. The ceasing of support for the Siemens i2 system was particularly mentioned as a reason to upgrade or begin making plans to upgrade. Fifteen percent of respondents indicated their conventional system changes are being forced by the vendors choosing to no longer support a given product or the obsolescence of their hardware (predominantly model 170 controllers).

Overall, the results make sense and form a coherent narrative. A practitioner’s first concern is how much it will cost to do any sensor installations and intersection upgrades. The second set of concerns is compatibility with the controllers and communications practices used by the agency. Determining whether existing equipment can be used is effectively a cost question. If existing equipment must be replaced, than new equipment must be purchased, adding to the costs. Licensing and operating costs are then considered.

3.7 SURVEY CONCLUSIONS

Survey respondents were very constructive and candid in providing their remarks, often including additional information that proved useful in analyzing results. Many of the problems respondents face are very similar to the problems this research is trying to solve. The interest in this project is indicated by the high interest in the survey results. Ninety percent of respondents requested a copy of the survey results. Over a quarter of respondents also indicated that they were currently operating test installations, planning test installations, or otherwise examining adaptive signal systems. A number of respondents were also examining upgrades to their conventional central systems. As a result of the number of survey respondents considering conventional central system upgrades, it would be advisable for further research to include such systems at least as a baseline for comparison.

4.0 DECISION TREE LOGIC DESIGN FOR ADVANCED SIGNAL SYSTEM SELECTION

Intersection and signal system performance are controlled and constrained by many factors. Everything from the angle of the roads meeting at the intersection to the speed limit and number of lanes in the intersection has an impact, as well as many more factors. It would be prohibitively expensive and time consuming to research every factor inherent to intersection performance. Also, it would be a useless tool for practitioners if there would be an equally prohibitive number of input parameters they would need to provide to use the model. To make the task more manageable on both ends, the research team focused only on the key factors affecting intersection performance and used data relatively easy for practitioners to collect.

4.1 SIGNAL CONTROL SYSTEM CONSTRAINING FACTORS

A number of factors influence signal system timing and system performance. A small selection of critical factors are discussed here. These factors are commonly encountered in the field and constrain signal system performance. The presence or absence of these constraints can also impact the suitability of different signal control systems at specific intersections. Geometric factors, such as number of lanes dedicated to each movement are considered under input data in Section 4.2.

4.1.1 Crossing Arterials

When evaluating an advanced signal control system implementation on a corridor, it is important to know how constrained the system may be. A corridor with only minor cross streets will be able to dedicate its green time mostly to the major corridor. As side street demand increases, there will be more competition for the intersections' green time resources. When side street demand exceeds corridor demand it, instead of the main corridor, can drive green signal time allocation.

The different operational methods used by each system will also be impacted differently by the presence of a crossing arterial. A fixed time implementation will only be as good as the data used to create the timing plan(s) and the consistency of traffic. Different systems will be more or less constrained by the competing demands of crossing arterials. An advanced or adaptive control system installation may be able to manage traffic fluctuations better and hence improve intersection performance.

Crossing arterials pose different challenges for the different adaptive systems. SCATS, which was designed to operate in an urban network is able to accommodate a crossing arterial relatively easily into its tactical and strategic operations, including the prospect of coordinating SCATS signals between corridor and arterial via marriage, the linking of intersections into coordinated groups. InSync, on the other hand, uses a green band on the corridor; provisions for crossing arterial progression were not found in the published materials.

4.1.2 Corridor Saturation

The saturation of a corridor, as represented by the volume to capacity ratio (v/c), indicates how heavily traveled the corridor is relative to its carrying capacity. Typically, measuring volume at an intersection is straightforward with tube counters or video recordings being common methods. Advance sensors at intersections also provide data that can be used to estimate the v/c ratio. Some agencies, such as the City of Bellevue, WA have even added loop detectors at their intersections to form count lines. Such permanent sensor emplacements provide the same data as a tube counter but can provide it continuously instead of just the few days or weeks a tube counter would be deployed.

Capacity can depend on the quality of signal operations, which is troublesome for evaluation purposes. A corridor may have its capacity reduced through poor signal operations. When examining a corridor, capacity issues may be affected by multiple factors, including the signal control system itself, which can be difficult to separate without in depth statistical analysis.

Measuring capacity at an intersection is more complex. A road without a traffic signal, such as a freeway, can operate with hourly volumes exceeding 2000 passenger cars per hour per lane (pcphpl). Once a traffic signal has been added to that same road the startup and stop delays as well as clearance time will decrease the capacity. In an ideal world, the capacity would be equal to the base capacity times the fraction of effective green time allocated to that road. The capacity effects of startup and clearance losses, which will be incurred each cycle, will be a function of cycle length, with shorter cycles incurring proportionately more startup and clearance time losses than longer cycles.

4.1.3 Directionality of Traffic

The traffic throughput of an intersection approach is directly affected by the allocation of green time at that approach. If traffic is strongly biased to one movement then signal timing can be adjusted to give that direction more time and minimize green time given to low demand movements. As traffic on various movements increase, the green time at that intersection must be divided among more movements.

The best-case scenario is that the majority of the traffic travels one direction, or complementary directions, through the intersection. For example, a strong northbound through movement with minimal demand on other movements, except possibly the northbound left or southbound through, would be a strongly directional flow. The flow may change over the course of the day, with a morning and evening commute, for example.

The worst-case scenario would be traffic that frequently changes primary direction and traffic demand that varies significantly from direction to direction. Most systems require multiple cycles to change their cycle parameters, such as offset, cycle length, phase order, etc. With frequently changing primary traffic flows, some systems will continually be adapting to the changes without actually reaching an optimal operational state.

4.1.4 Consistency of Traffic

Traffic can vary over the course of the day. The variability of traffic from one interval to the next can have an impact on operational efficiency, particularly for adaptive signal operations. Likewise, traffic that varies from day-to-day can determine the operational efficiency of fixed time signal control systems.

Traffic that is consistent day-to-day can be handled well by fixed time signal control. The more consistent traffic is day-to-day the better fixed-time plans will work. The number of plans required for fixed time to work best will be determined by how consistent traffic is period-to-period. As day-to-day variability increases, traffic responsive signal control will become more effective and efficient than fixed time control.

Figure 4.1 shows 15-minute traffic volumes for southbound through traffic at the intersection of NE 8th St. and 148th Ave. NE in Bellevue, WA (intersection 49) during May 2011. This figure shows very consistent traffic with relatively minimal variation day-to-day. Compared across days, the average standard deviation is twelve vehicles per 15-minute interval and the peak standard deviation is thirty-two vehicles per interval. Figure 4.2, taken from data gathered at 148th Ave. NE and SE 28th St., shows a very different picture with two different traffic patterns. The difference between the two patterns is whether Bellevue College is in session or not. The data spans from July, when school was in session, to September, when school was out. Fixed time plans designed using data in August would be completely ineffective during the peak travel days seen in July where over three times the volume could be seen in a given interval. Depending on the plans designed for traffic responsive operations, traffic responsive control is also likely to have trouble with such large volume swings.

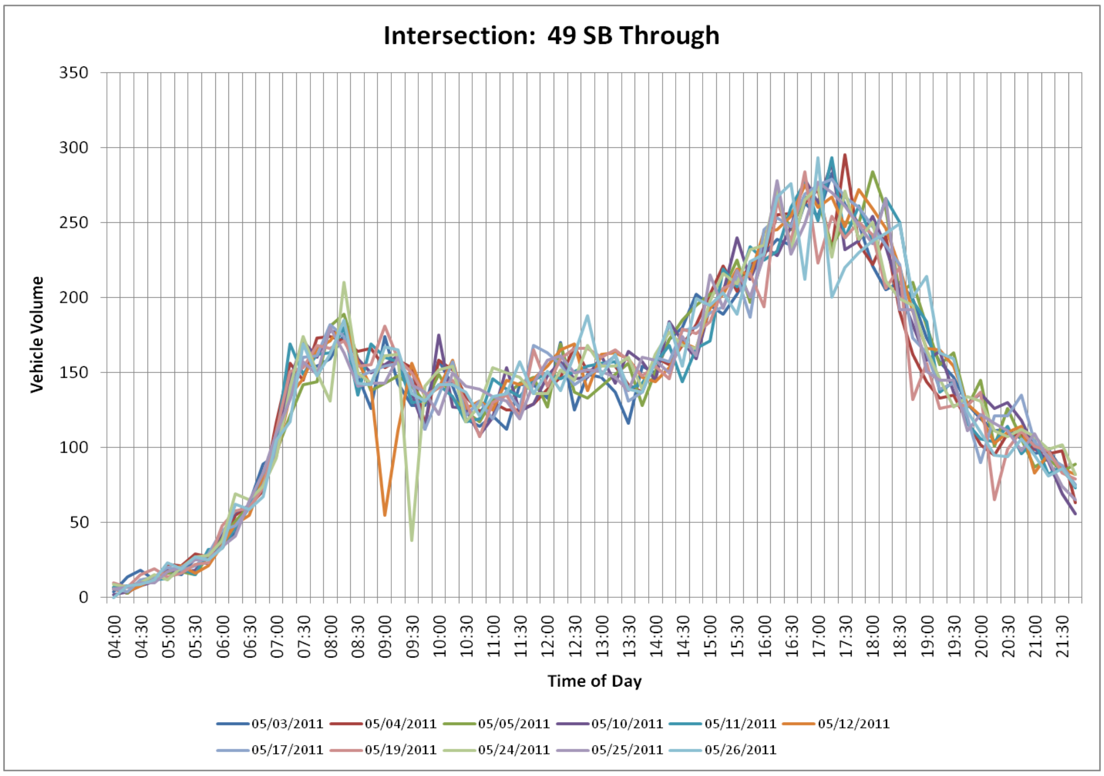

Figure 4.1: Daily southbound traffic (T,W&Th), NE 8th St. and 148th Ave. NE, Bellevue, Washington

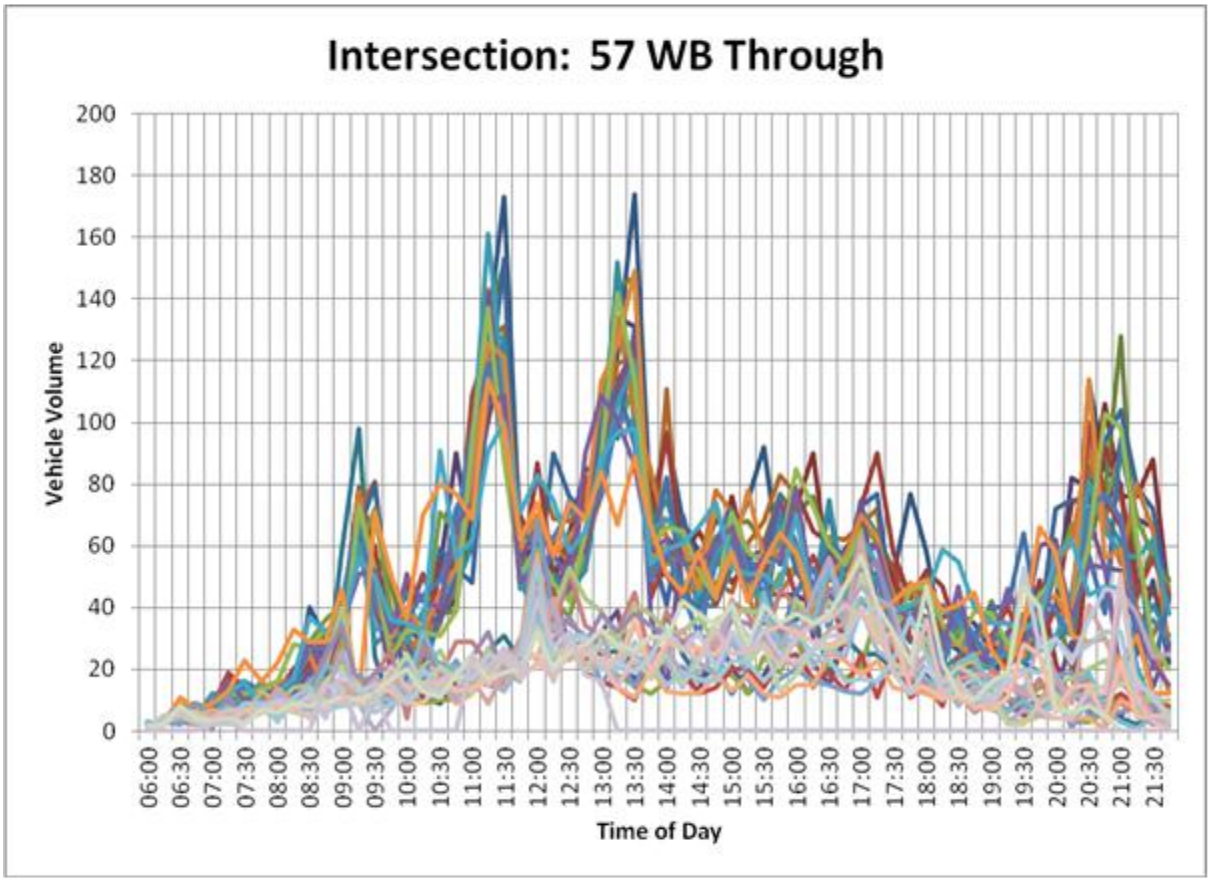

Figure 4.2: Daily westbound traffic (T,W&Th), 148th Ave. NE and SE 28th St., Bellevue, WA., July to September 2011

Day-to-day variability is not the only measure of variability that is important. As period-to-period variability increases, fixed time and traffic responsive signal control will become less effective. Fixed time plans need to be made longer to accommodate more traffic variation during a given period, or more plans are required to cover the given range of traffic conditions. Traffic responsive control's effectiveness is determined by how much efficiency is lost changing between plans and how many plans are needed to cover the traffic conditions.

Figure 4.3 shows the intersection of NE 8th St. and 116th Ave NE in Bellevue, WA. Note particularly, the variations in volumes seen from 2 pm (14:00 on the chart) to 6 pm (18:00 on the chart). From 15-minute interval to 15-minute interval, the traffic volume can vary over 100 vehicles. Variation at shorter time intervals can be equally as dramatic, as seen in Figure 4.4. Even adaptive signal control systems may have difficulty adapting quickly to such high variations.

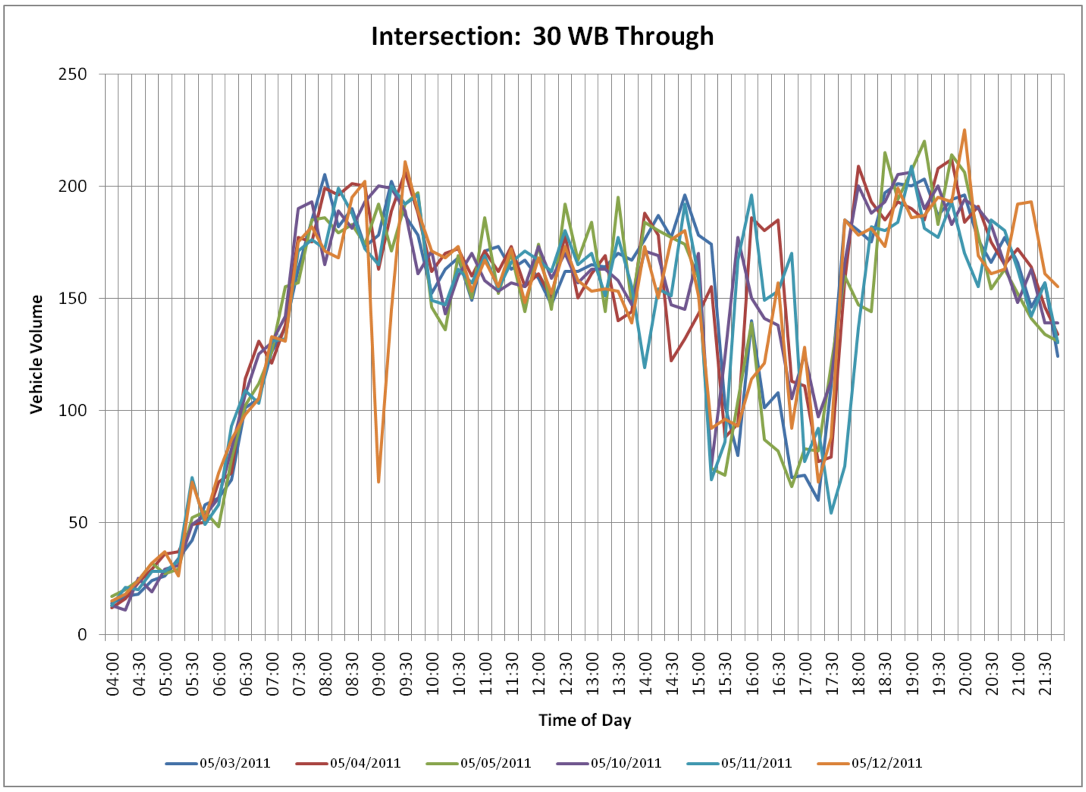

Figure 4.3: Daily westbound traffic showing variation by 15-minute intervals, NE 8th St. and 116th Ave NE, Bellevue, WA

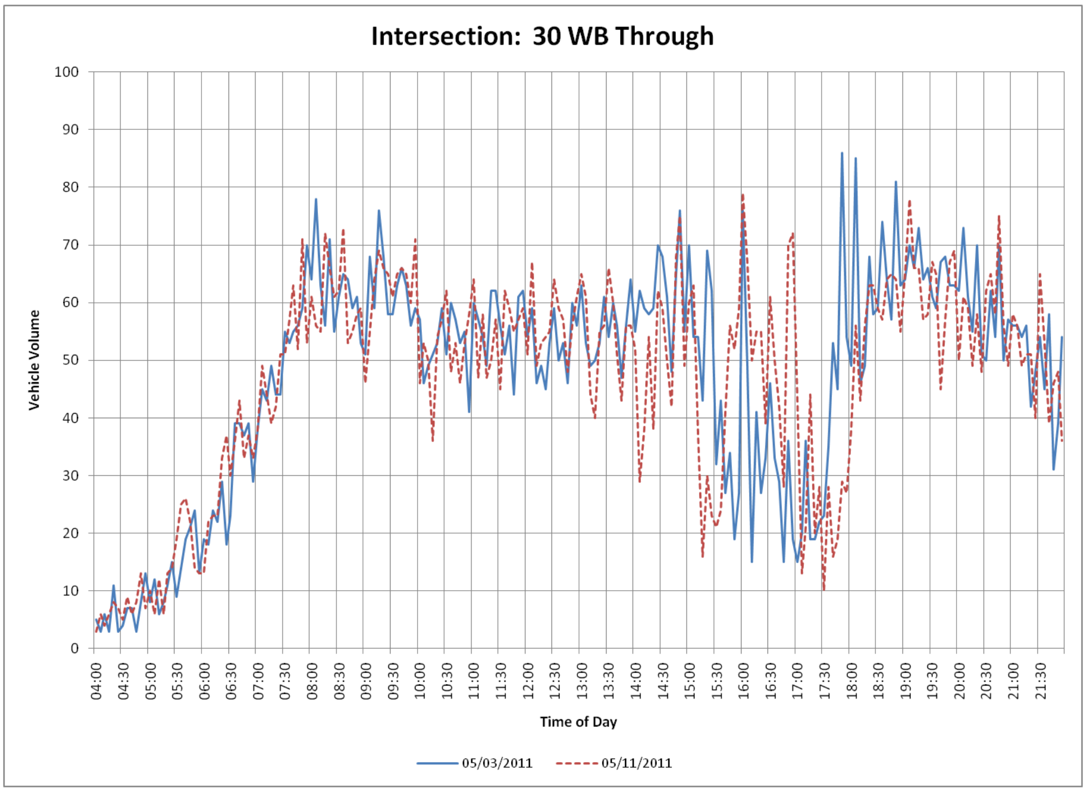

Figure 4.4: Daily westbound traffic showing variation by five-minute intervals, NE 8th St. and 116th Ave NE, Bellevue, WA

4.1.5 Proportion of Conflicting Movements

Another constraint on signal control operations is conflicting movements. A conflicting movement is a movement that crosses another movement and would cause vehicles to collide if both movements were allocated green time at the same time. A northbound through movement and a southbound left-turn movement are conflicting movements while the north and south through movements are not. The traffic demands for these conflicting movements can control signal operations.

At low left-turn demand and medium to low opposing through demand, it is common to see left turns served by permissive left turn (green ball) signal where drivers must find acceptable gaps in oncoming traffic in order to turn left. As left-turn or opposing through demand increases, the left turn will generally be served as a separate, protected (left turn arrow), movement. Separating the left turn into its own protected phase requires allocating time specifically to that phase, which can require increasing cycle length. Increased cycle length generally incurs more delay for minor movements because they must wait longer between green times.

4.1.6 Other Considerations

Obviously, no list of questions can be complete and there are many factors that will be unique to any given corridor. However, some questions are likely to come up in an evaluation. While these questions may or may not influence signal system selection, they are sure to influence implementation.

4.1.6.1 Intersection Spacing

The space between intersections can be used to hold traffic queues. In the case of closely spaced intersections, there may not be sufficient space between intersections to hold traffic released at an upstream intersection without blocking the intersection. The spacing of intersections both on the corridor and off should be examined. This is particularly true of intersections near major crossing arterials and highway interchanges where large volumes of traffic may be passing through. The uniformity of intersection spacing can affect progression.

4.1.6.2 Signal ownership

Which agencies own and operate a given traffic signal, or group of traffic signals can be very important. Even though a given system may be a better performance choice, if a neighboring agency is already operating a different signal control system, it may make more sense to standardize on a single system for a corridor or region instead of having a different signal control system for each corridor or section of corridor.

The maintenance and operations of different systems requires additional resources, compared to operating a smaller subset of systems. Similarly, the ability to share maintenance and operations resources is important. The value of being able to share technician and engineering expertise should not be underestimated.

4.1.6.3 Highway interchanges

Highway interchanges can have a large effect on corridor performance. Interchanges can represent large traffic flows, sources of variability and bottlenecks. Depending on corridor configuration and demands, a highway interchange can easily represent one of the larger traffic flows on a corridor. Incidents on highways and freeways can also affect corridors at interchanges. Traffic to and from a highway interchange, can represent a capacity bottleneck with ramp metering slowing traffic from the corridor to the highway, or demand from the highway exceeding intersection capacity.

4.1.6.4 Overlaps

With the wide variety of possible intersection designs and operational strategies, it is common for traffic engineers to "overlap" phases. Typically, overlaps are used for non-standard vehicle movements and for non-automobile movements. Pedestrian movements are commonly assigned to overlaps, as are right-turn-only signals and movements at more than four-way intersections. For corridors that make use of overlaps it is important that any signal control system being considered has the requisite overlap capabilities to operate the signal.

4.1.6.5 Transit Priority

Transit signal priority has been implemented on many corridors. When those corridors are having their signal control systems upgraded, it is important to assess the compatibility of new signal control systems with the existing transit signal priority system. A similar assessment should be made for corridor upgrades that will include adding transit signal priority.

4.1.7 Intersection Classification

The wide variety of intersection geometries, lane configurations, and conflicting movements possible at any given intersection on a corridor make it difficult to design an analytical procedure capable of adequately addressing each contingency. A series of classifications and generalizations serve to reduce the complexity of the analysis for individual intersections and corridors. These classifications and generalizations focus on selecting the important data that differentiates intersections. The majority of the classification work stems from analysis of the constraining factors previously identified.

4.1.7.1 Intersection Geometry

The first classification is to simplify the geometry of an intersection. Given the variations in crossing angles of intersection approaches, numbers of lanes, presence of left turn bays, number of approaches, etc., there are a very large number of potential intersection configurations. By reducing the geometry options to the number of approaches (up to four) and the number of lanes assigned to each movement on the approach the analyses can be narrowed to an achievable scope.

4.1.7.2 Linking Segments

The segments that link intersections also have traits that need to be characterized. There may be nothing but road between two intersections, possibly through areas of light development, commercial development, heavy development, or other development. Other development of interest includes schools, stadiums, malls, etc. that can have large traffic demands at varied intervals. Also of interest are other control types on the segment, such as stop signs or pedestrian signals that may influence traffic flow.

4.1.7.3 Traffic demand

Intersection traffic demand also needs to be classified for some analyses. Traffic can vary in volume, directionality, and variability. Some strategies are better applied to highly directional traffic than others. Others are applicable to certain volume conditions. By classifying traffic demand patterns, particularly by time of day and day of week, checks about whether certain features should be enabled can be greatly simplified. This is especially beneficial for features that can be enabled and disabled by time of day. Consider enabling phase reservice, for example, when capacity restrictions prevent large platoons but demands are high, a particularly common occurrence for metered highway ramps. During peak periods, phase reservicing can be enabled to deal with queuing and congestion. Then phase reservicing can disabled for the rest of the day to simplify coordination. With interval level classification it is much easier to identify when to enable and disable such features.

4.2 INPUT DATA

Performing the desired in-depth analysis of individual intersections or a corridor that is needed to recommend the implementation of a particular traffic control system requires a significant amount of data collection work. The necessary datasets fall into many categories but can be roughly broken down into geometric, counts, and control categories. In designing the analytical framework, efforts have been made to minimize data collection cost and analytical complexity.

4.2.1 Geometric Data

Geometric data outlines the fixed features for the corridor. This includes the number of lanes on intersection approaches, speed limits, and saturation flow rates. These factors determine the capacity, or how many vehicles can pass through the intersections per hour. Further information includes approach configuration, and possible right-of-way conflict data and the length of road segments linking intersections, both of which impact progression on a corridor. Additional information such as capacity restrictions caused by freeway ramp meters or out of jurisdiction signals is also important and impacts decisions about certain features like phase re-servicing.

4.2.2 Pneumatic Tube and Wapiti Data

Sample data from pneumatic tube counts and the W4IKS software (as operated by ODOT on the 99W corridor) were obtained by the research team. These two datasets proved remarkably similar in character. Both data sets consist of volume data. Pneumatic tube count volumes are recorded in terms of axle strikes, which must be converted to vehicle counts and aggregated into fifteen minutes before use. The W4IKS data provided to the research team came from the 99W corridor prior to the installation of 2070 controllers and the Voyage software. It consists of volume data from twelve channels, each of which may include more than one loop detector, aggregated in fifteen-minute intervals. When more than one loops wired together in one channel, corrections must be made to ensure the quality of volume data. The method used in this study was developed by Wu et al. (2010).

For both volume collection methods, relatively accurate volumes can be obtained for each fifteen-minute time period. However, neither of the above data collection methods provides control data. Also, there is no indication of saturation during the interval from these two data sources. These omissions greatly inhibit analyses of signal performance. Only very basic analyses may be conducted with just the tube counts or W4IKS data.

4.2.3 Voyage Data

The Northwest Signal Supply Company's Voyage software is the new default software for all ODOT signal installations. The Voyage software is coupled with new standard hardware in the form of a 2070 controller. Both hardware and software represent a remarkable increase in capability over the Wapiti W4IKS software and 170 hardware of the previous standard.

Voyage collects a great deal of data about volumes and signal operations. Three information groups are of the most interest, detector data, MOE data, and coordination data (if coordination is enabled). The three data types are further described below.

4.2.3.1 Detector Data

Voyage can collect detector data from up to 64 detector channels in user defined periods. This data is count data similar to tube counts or that collected by W4IKS. The collection periods are user selectable, given that they divide into 60 minutes. This makes the acceptable periods 1, 2, 3, 4, 5, 6, 10, 12, 15, 20, 30, and 60 minutes. Typically, ODOT configures Voyage to collect count data in 15-minute periods. So the research team uses fifteen minute interval volume as standard input.

4.2.3.2 MOE Data

MOE data is collected similarly to the detector data with the collection period being a user defined period divisible into 60 minutes. The MOE data includes performance measures such as the number of times each phase was served during the collection interval, the number of max outs, gap outs, and force offs for each phase during the interval and the average green time for each phase during the interval. Several of these Voyage MOEs are used in the MOE calculations explained in Section 4.4. Once again ODOT data supplied to the research team for analysis was collected in fifteen-minute intervals.

4.2.3.3 Coordination Data

Coordination logs are collected per cycle and include phase termination type, end of phase time, platoon ratio, and arrival on green percentage. Phase termination type details how the phase terminated, i.e. gap out, max out, not served, etc. The end of phase time is the time in seconds at which the phase ended during the cycle. The platoon ratio indicates how well grouped the platoon is, i.e., whether traffic is arriving as a contiguous platoon or random arrivals.

4.3 PERFORMANCE ANALYSIS

In order to classify system performance and define system evaluation criteria, several performance measures have been selected. These performance measures constitute the Measures of Effectiveness (MOEs) that are used in the analytical framework used to create the decision tree. The MOEs measure different aspects of signal system performance.

4.3.1 Level of Service and Delay

The Highway Capacity Manual 2010 (*TRB, 2010*) defines Level of Service (LOS) by estimating the delay incurred due to signal control. This delay may be due to long cycles, poor progression, or a number of other reasons not directly related to the geometric factors of the intersection. It is important to note that while the

HCM 2010 provides equations to estimate the control delay used to determine LOS (*TRB 2010*), the control delay cannot easily be directly determined through field measurement.

Often other measures of delay are used in practice. Corridor travel time relative to the free flow travel time is probably the most used field measure of delay. Many traffic studies and implementation reports rely on travel time as a means of measuring system performance improvements. For minor cross-street traffic, it is common to see stopped delay used to measure performance. Stopped delay measures the time vehicles are stopped waiting for the signal to turn green.

4.3.2 Queue Length

Vehicles stopped at an intersection form a line that can block other vehicles from entering or crossing a roadway. Queues for left turns that exceed the available left turn bays tend to back into the main travel lanes and pose a blocking and safety problem for oncoming traffic. Queue lengths can also become an issue when intersections are closely spaced and queues can back from one intersection to another. Because of this, the length of the queue formed by vehicles waiting at an intersection can be a very important MOE. Queue length may also reflect other MOEs with corridors that experience larger delays likely having larger queues. Queues may also be a symptom of poor progression with vehicles constantly being trapped between traffic signals.

4.3.3 Progression

The progression of traffic through a green signal at one intersection, to arrive at the next during the green signal has a large impact on delay and queuing. By properly timing signals, it is possible to progress traffic through several intersections in a row. One of the limiting factors for progression is that progression generally requires that traffic signals are coordinated so that green signals are properly offset and provided with a similar length of time to enable vehicle platoons to traverse the coordinated intersections without stopping. Depending on intersection spacing and link speed, the offsetting of signal timing can make it difficult to impossible for traffic to progress in opposing directions.

Measuring the quality of progression can be challenging. There are many potential measures of progression, including number of stops, queuing length, and percent arrival on green. Arrival on green represents the percentage of vehicles arriving at an intersection while their movement has a green signal. To avoid over-representing delay and queuing, arrival on green has been selected to measure the quality of progression.

4.3.4 Data Analysis

This project requires the collection and analysis of large amounts of data. The large volumes of data are necessary in order to cover as large a number of possible implementation scenarios as possible. The systems included are implementations of Voyage (time of day and actuated control, with advanced features when possible), TransSuite, SCATS, ACS Lite, and InSync. This requires that data be collected for a minimum of six corridors just to represent each system in the evaluation. Ideally, field data would be collected from several implementations of each system. However, the number of systems currently in operation and the availability of data make data collection a challenging task.

Data has been collected from several sites in Oregon and Washington. Currently the Smart Transportation Applications and Research Laboratory (STAR Lab) of the University of Washington (UW) has data from Bellevue, WA, Washington County, OR, Portland, OR and ODOT. Bellevue, WA has provided data from 38 intersections running the SCATS traffic control system. Washington County has provided data on three systems. The first system is a corridor running InSync on Cornell Road that includes data from the basic Voyage implementation that was in place before InSync. The second is the SCATS installation on the Tualatin-Sherwood Road. The third is the TransSuite system with a basic Voyage implementation on NW 185th Ave.Portland, OR. Additionally, ODOT provided data on their Voyage Advanced implementation on 99W.

Data collection on the ACS-Lite systems has been hampered by their relative rarity and the lack of any in Oregon. Utah DOT has kindly agreed to provide data once their evaluation has been completed, but that is the only data that has been confirmed as available at this time. Advanced feature implementations of Voyage are also rare with the 99W implementation being the only example with data currently collected by the research team.

4.4 MEASURES OF EFFECTIVENESS

Before implementing the analytical logic, performance analysis of the current system under various corridor and flow conditions that occur must be conducted. Toward this end, a series of MOEs have been developed to analyze intersection performance and corridor conditions. These MOEs can then be used in the decision tree logic to differentiate performance cases and recommend strategies to improve performance. After the initial analysis, predictions regarding performance of candidate systems can be made and features examined using the decision tree logic detailed in Section 4.5.

4.4.1 Saturation

Saturation, as measured by the volume to capacity ratio, has a long history in traffic performance measurement. From a logical perspective, it is to be expected that trying to push increasing volumes of traffic across a saturated corridor or through a saturated approach would have performance penalties. Similarly, lower saturation values would be expected to have better and more robust performance, i.e., be less likely to experience cycle failure and congestion. From a control perspective the saturation on a corridor would impact decisions about running actuated, traffic responsive, or time of day plans.

4.4.1.1 Phase Saturation

The volume on each approach relative to the capacity of the approach can indicate issues with demand and supply. Similarly, using cycle information to determine how much green time a given movement gets during a cycle allows for an analysis of whether a given movement is getting an appropriate portion of the cycle's green time. Figures 4.5 and 4.6 jointly show the green time adjusted saturation levels for each movement at the 99W and Greenburg Rd. intersection on May 16, 2011. Of particular note are the saturation levels for phases 1 and 5, which are at or above 1.0. These data are from after the activation of coordinated late left turn at the Greenburg Rd. intersection. The research team believes that the data may not accurately reflect phase time served during coordinated late left turns, which may explain the high saturation values for the left turn phases. The volumes served and the numbers of phase services reported do not seem to be consistent. Left turn phases are reported to have been at low green times, for example 12 seconds, but at higher than expected volumes. The volumes indicate that vehicles would have to be served at an average of one per second or more. This is probably a limitation to the internal data structure of the system where the reserved left turn green time is recorded over the original green time.

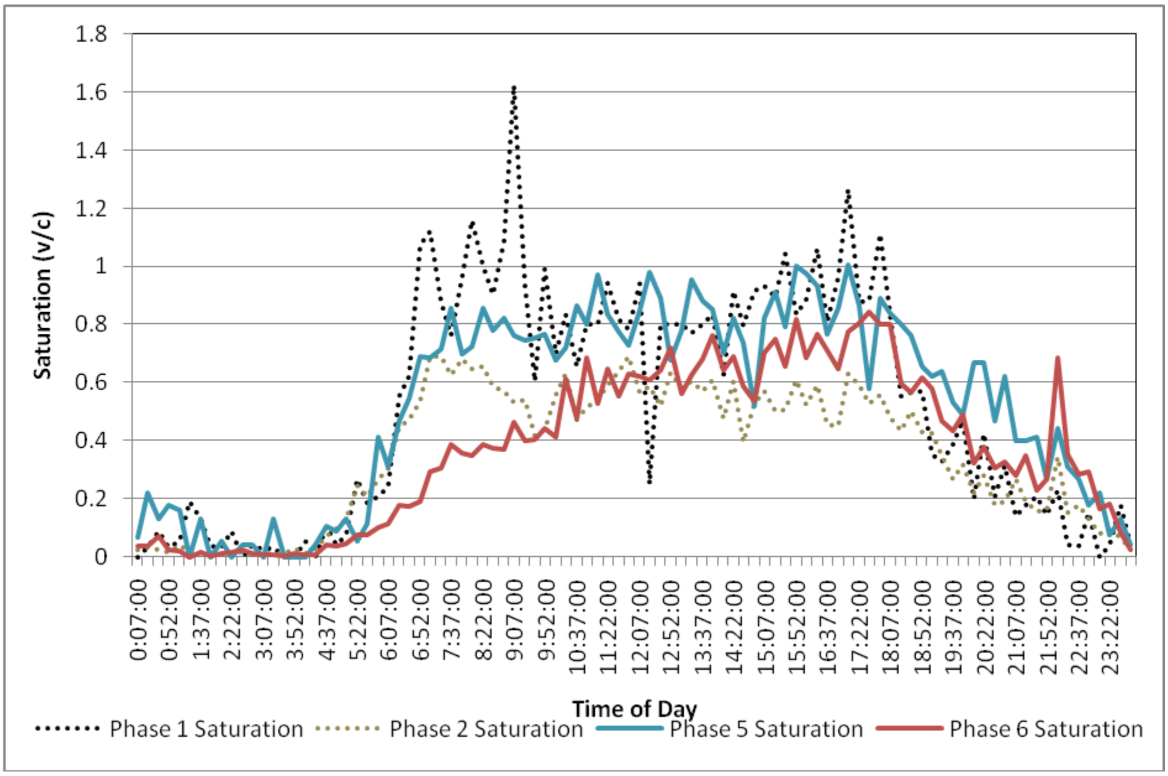

Figure 4.5: Mainline saturation by phase at Greenburg Rd. on Monday May 16th, 2011

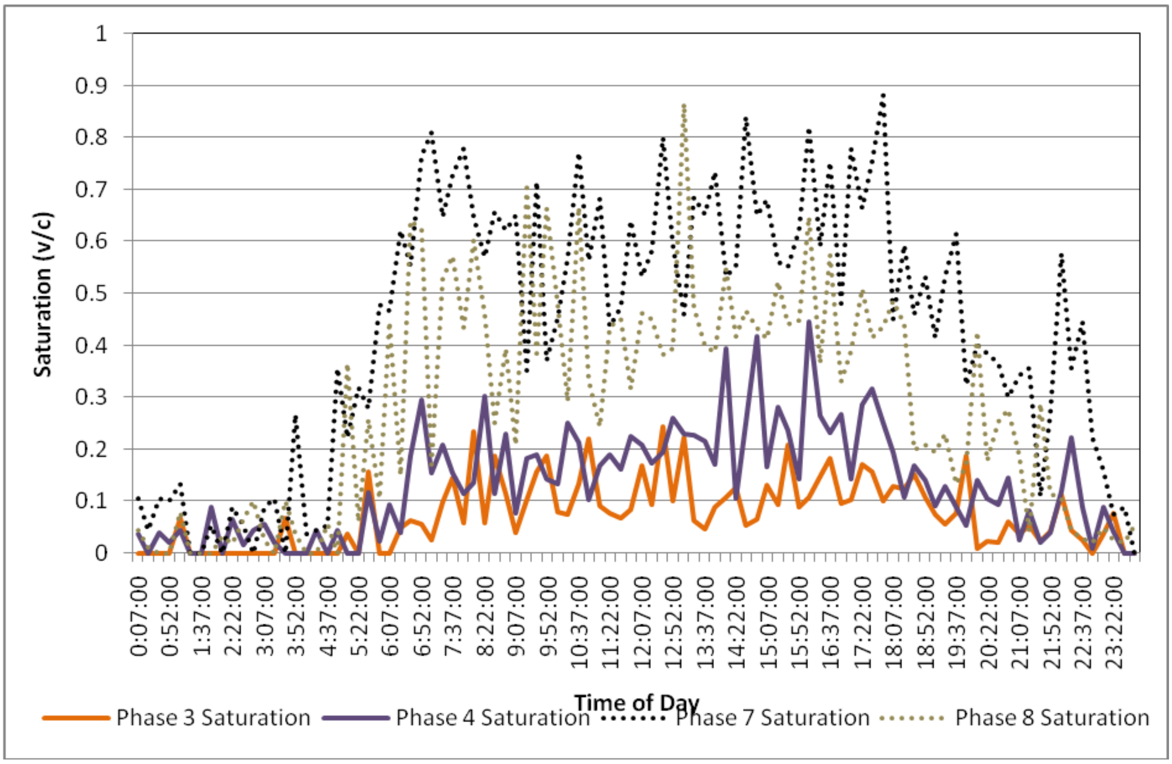

Figure 4.6: Cross street saturation by phase at Greenburg Rd. on Monday May 16th, 2011

4.4.1.2 Intersection Saturation

Each intersection will only be able to handle a certain amount of traffic given its geometric design and control plan. For a four-leg intersection, there are a couple of combinations that are likely to dominate. These combinations can be broken down into standard phasing patterns just like in a cycle. The patterns repeat for the main and cross streets, so the main street will be discussed here, but the patterns are combinations for both the main and cross streets.

Using NEMA phasing, the main street phasing patterns would correspond to movements 2/6 with permitted left turns, 2/6 with lead-lead or lag-lag left turns, 2/6 with lead-lag, and 2/5 plus 6/1. Each combination represents a different case for maximum intersection saturation. If left turns are particularly low, they do not require a separate left turn phase and thus the saturation of the left turn phase would not be counted against total intersection saturation. For the lead-lead or lag-lag cases the left-turn movements should have approximately the same saturation values. When left turn volumes are different enough, the lead-lag option allows for larger differences in left-turn phase times.

The goal of measuring intersection saturation is to determine how appropriate different signal control strategies would be for that intersection. Additionally, some strategies may be unsuitable for implementation under certain traffic conditions, or they may require additional consideration during implementation. For example, delay equalization strategies, such as those employed by InSync, which rely on accurately detecting vehicle arrivals to calculate delay, may require additional consideration on saturated corridors where queues can extend past detectors.

4.4.1.3 Cycle Failure

While cycle failure is not solely dependent on the volume to capacity ratio, it can be an important measure of signal performance. When cycle failure occurs there are three likely causes. The first is that demand outstrips capacity. The second is that the approach is not given enough green time. The third is that progression from the previous intersection is poor causing vehicles to arrive at the end of the green band and/or causing the pre-existing queue not to clear before new vehicles arrive.

Detecting cycle failures with occupancy data is relatively easy. Unfortunately, tube count, W4IKS, and Voyage data do not include occupancy measures. Voyage data does include average phase service times and max out counts for each phase. When a phase is maxing out and has a high average green time it may be experiencing cycle failures. Figures 4.7 and 4.8 are for phase 5 at the Greenburg Rd. intersection on Saturday May 14th, 2011 and Monday May 16th, 2011, respectively.

Note that on Saturday there are a larger number of max outs and the average green time hovers near twelve seconds with an average of three max outs per fifteen minute interval. Compare that to the data for Monday where the average green time can exceed fifteen seconds and at most two max outs occur. The primary difference between the two days is the max plan in effect. On Saturday, the maximum phase time for movement 5 is fifteen seconds versus twenty to twenty-two seconds for the Monday plans. The cycles on Saturday are at 130 seconds while the Monday cycles vary between 120 and 140 seconds. This would tend to indicate that the weekend plan may be in need of adjustment.

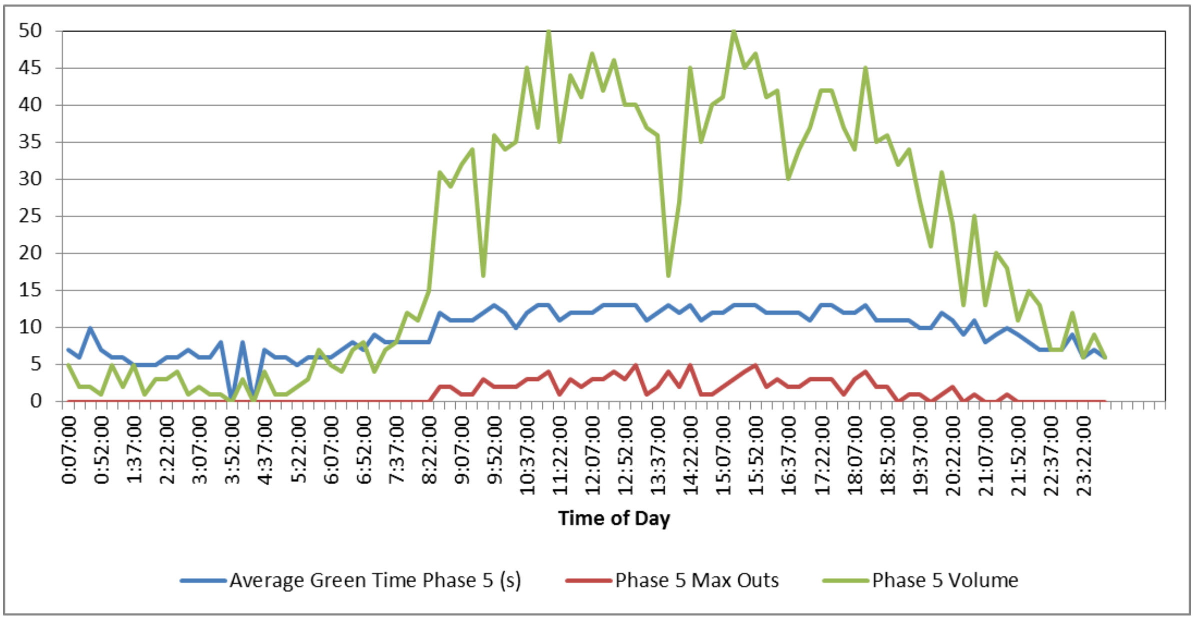

Figure 4.7: Cycle failure analysis for Greenburg Rd. on Saturday May 14th, 2011

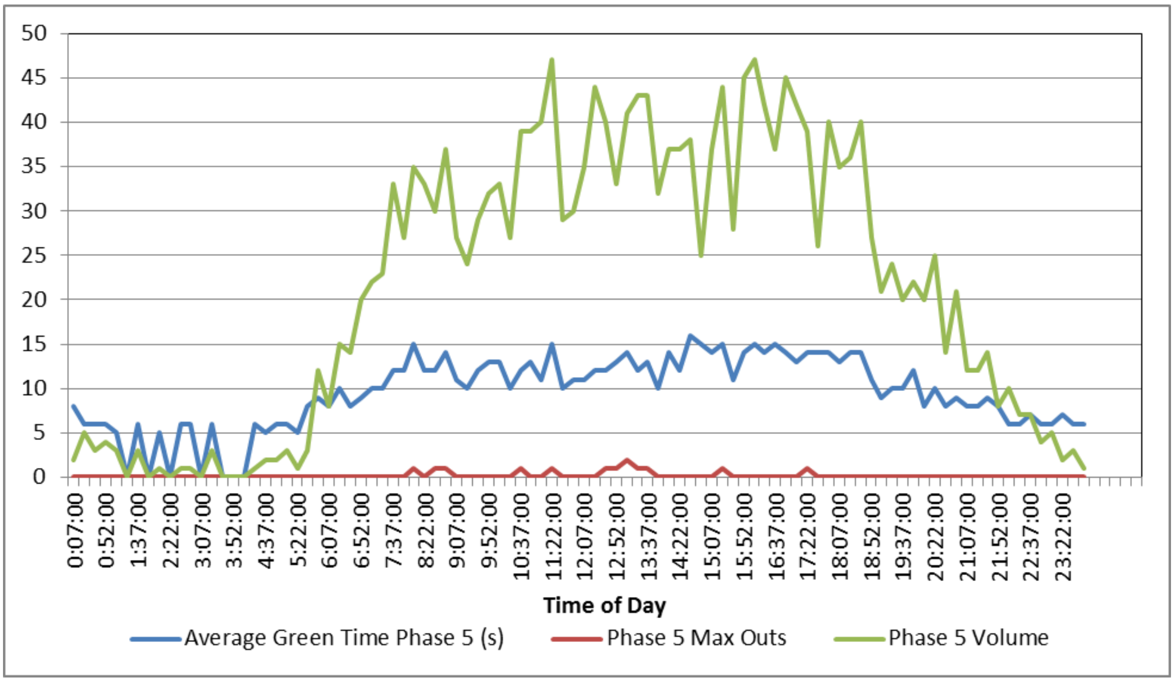

Figure 4.8: Cycle failure analysis for Greenburg Rd. on Monday May 16th, 2011

4.4.2 Variability

Traffic variability is important in determining whether or not an adaptive signal control system is warranted. Measuring the variability of traffic requires a high level of data collection, particularly the day-to-day variability measurements. The less variability in general there is the more suitable conventional systems like time of day plans would be. Conversely, as variability goes up, adaptive systems are likely to perform better and are hence recommended.

The actual execution of the variability analysis is somewhat troublesome. Common tools, such as Microsoft Excel, can execute a period-to-period analysis with relative ease, but a particular data arrangement template must be followed and data consistency must be ensured. Achieving a compatible data arrangement to the template can mean a fair amount of manual work, particularly when data are missing or have different starting or ending times. The difficulty only increases with day-to-day analysis. Tools such as Microsoft SQL or custom programs are much better suited to executing the day-to-day analysis since they can match up data from, for example, each Monday from a month of data, with greater ease.

4.4.2.1 Day-to-Day Variability

Day-to-day variability is measured such that an interval is compared against that same interval on the next week. For example, the period on Monday, May 16th from 7:00 AM to 7:15 AM would be compared to the same time period on Monday, May 23rd. Day to day variability provides insight into how appropriate time of day plans would be to the intersection or corridor. Day-to-day variability can be quantified most easily through standard statistical measurements such as mean and standard deviation. Note that day-to-day variability can also be considered amongst different days for systems which operate the same plans across multiple days of the week. Day-to-day variability is discussed here in terms of specific day of week in case settings are different for specific days.

4.4.2.2 Period-to-Period Variability

Period-to-period variability measures the difference between consecutive periods. For example, the period on Monday, May 16th from 7:00 AM to 7:15 AM would be compared May 16th from 7:15 AM to 7:30 AM. As period-to-period variability increases, more adaptive control strategies may be warranted. Period-to-period variability is measured using the average of the difference between consecutive periods and the average of the absolute value of the difference between consecutive periods.

The reason for this selection is that the direction and magnitude of the change are both of interest. The average value of the change will indicate whether a net increase or decrease in traffic is occurring and the average of the absolute value of the difference gives a measure of the total changes occurring between intervals. The ratio of the average to absolute value of the average change ranges from -1.0 to 1.0 and indicates a consistent net decrease in traffic at minus one, a net increase at plus one, and random changes at zero.

4.4.3 Queuing

Queuing can have large impacts on intersection performance. This is particularly true when queuing of through traffic results in blocking access to a left-turn bay or when spillover from a left-turn bay blocks through movements. If queuing is a problem, optional strategies such as phase re-service may be effective. Figure 4.9 show the queue lengths recorded at the Greenburg Rd. intersection for the main street phases. Figure 4.10 shows the queue lengths for the cross street phases. Queue lengths, particularly for phase 6 at just before 5 PM may indicate blockage of the left turn bays. Phase 8 may have similar problems throughout the day.

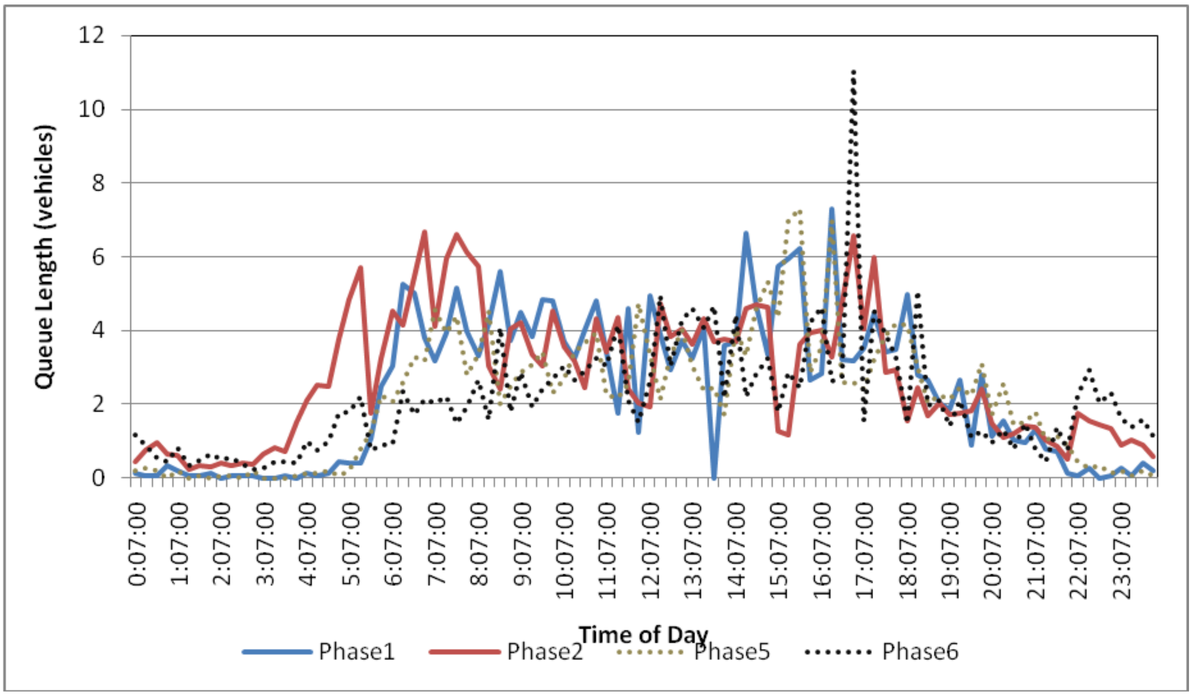

Figure 4.9: Queue lengths by phase for Greenburg Rd. on Monday May 16th, 2011

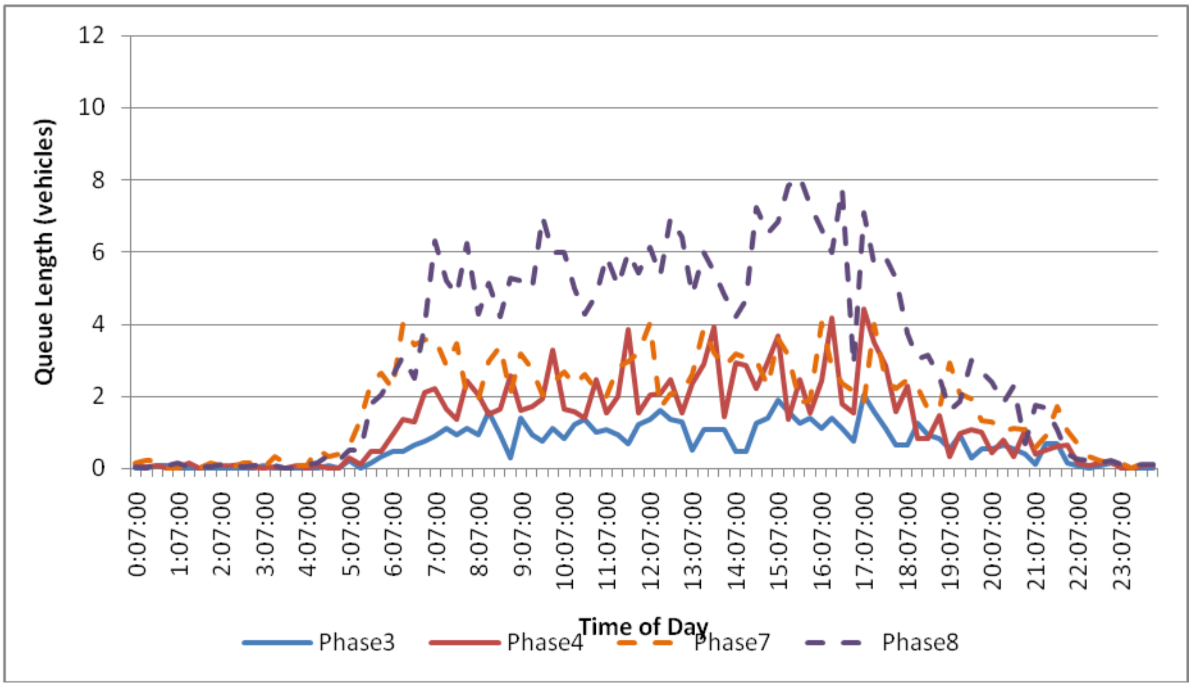

Figure 4.10: Queue lengths by phase for Greenburg Rd. on Monday May 16th, 2011

4.4.4 Travel Time

Travel time along a corridor is one of the most important measures of performance for practitioners. Intersection delay is another important measure directly related to corridor travel time and level of services. These two measures are inter-related, as intersection delay increases, corridor travel time would be expected to increase, except when intersection delay increases are limited to side streets only.

4.4.4.1 Corridor Travel Time

Corridor travel time is traditionally measured directly either through video observation or by floating car methods. These methods are unavailable in the current analytical framework since all of the information collected thus far is being examined after the fact, instead of in an active traffic signal system study. Instead a synthetic travel time estimation approach has been developed to test the framework. This travel time is determined using the arrival on green percentage from the coordination data provided by the Voyage software and the link geometry and speed data. While this travel time estimation approach provides meaningful and quantified measures of travel time for analytical usage, it is also expected to be of limited accuracy compared to field measurements of travel time. The analysis is constructed to use real travel time data when available.

4.4.4.2 Intersection Delay

Intersection delay is another field data measure that is synthesized for analytical usage and relative comparison. The arrival on green percentage is collected for each approach by the Voyage software. By examining the arrival on green percentage for each approach, it is possible to estimate the number of vehicles that arrived on red and were therefore delayed. Because of the granularity constraint of the data, i.e. arrive on green or not, it is impossible to calculate when vehicles arrive during the red interval. The delay is calculated as though vehicles arrive halfway through the red time since random arrivals would have an average arrival time halfway through the red interval.

$$TT = \sum_{i=1}^{n} \frac{L_i}{V_i} + \sum_{i=1}^{n} \frac{r_j}{2\left(1 - \frac{AOG_{kj}}{100}\right)} \qquad \text{4-1}$$

Where *TT* is the estimated travel time, V_i is the travel speed for segment i,L_i is the length of segment i, r_j is the red time of intersection j and AOG_{kj} is the arrival on green percentage for phase k of intersection j. Where segment i connects to an approach of intersection j and phase k serves the majority of the movement.

4.4.5 Progression

Progression can have a positive or negative effect on a corridor's traffic. When progression is good, vehicles will arrive after the existing queue has cleared with sufficient green time remaining for the platoon to traverse the intersection. When progression is at its worst, vehicles will arrive just after the green time ends and thus wait the entire red time until they are allowed to traverse the intersection. One measure of progression is the arrival on green percentage, which is directly measured by the Voyage software. Another measure is the number of stops, which can be estimated from the arrival on green data.

4.5 DECISION TREE LOGIC

The next step after the MOEs have been determined in the analytical phase is to determine where improvements can be made and what those improvements are. To accomplish this, decision tree logic has been proposed as a means of deciding which systems and features applicable to the intersections and corridor. The decision tree logic is implemented in a Microsoft Excel application that incorporates the data analysis functionality necessary to navigate the decision tree.

4.5.1 Feature Selection

After reviewing the FHWA systems engineering documents and reviewing how some of the study systems have changed from version to version, the research team decided to change how strategies, features, and systems were represented in the decision tree logic and analytical framework. The primary change was to make strategy and feature selection a la carte. Instead of creating the decision tree logic necessary to recommend suites of features, with all of the combinations, decision branches and calibrations that would entail, each feature has its own decision tree logic that is only as complex as it needs to be. Presenting each feature separately will also make application of the FHWA's system engineering approach easier, because unused features of the existing system could be evaluated.

Along with the change to a la carte selection for features and strategies, the research team decided to make all features generic, rather than system or brand specific. This decision was made for multiple reasons. The first is that the control algorithms for Voyage, SCATS, ACS Lite and InSync are all proprietary, so the research team has not been able to do exact tests on these control systems. Therefore, representing the performance of a branded system with generic results would be inappropriate. The second reason is that system features and performance can change by version. A specific branded analysis that was well tuned could be invalidated by the next version change.

An additional limitation is the timescale of data available for the analysis. Most of the data ODOT made available and most of the data available to its practitioners is in 15 minute increments. At this scale many details are lost. For adaptive and actuated systems, it is particularly important to use high frequency data because they react to smaller fluctuations than time of day and traffic responsive systems. This data gap necessitated additional modeling and additional assumptions.

4.5.2 System Representation

With features and strategies being represented in generic form, the question of how to represent a given system such as time of day control is natural. A given system is represented by a feature matrix that indicates which features are available through the system and any incompatibilities between features. This way, new systems can be added to the decision tree without having to completely recreate the decision tree or redo the research. Similarly, new features can be added with less work than if each combination had to be researched again.

4.5.3 Example Decision Tree

Figure 4.11 shows a simplified example of the decision tree logic as applied to coordinated late left-turn strategy selection. The decision steps in this simplified tree are to check for cycle failures, if cycle failures are frequent then look at the saturation level of the left turn movement. For moderate and high left-turn saturation levels look at the opposing through movement saturation. If the opposing through movement is heavily saturated then coordinated late left turn is not recommended. For less saturated opposing through movements the next step is to look at the concurrent through movement. If the concurrent through movement has low saturation coordinated late left turn is not recommended. For medium-high saturation of the concurrent through movement, coordinated late left turn may or may not be beneficial, but for high saturation of the concurrent through movement, coordinated late left turn would be recommended.

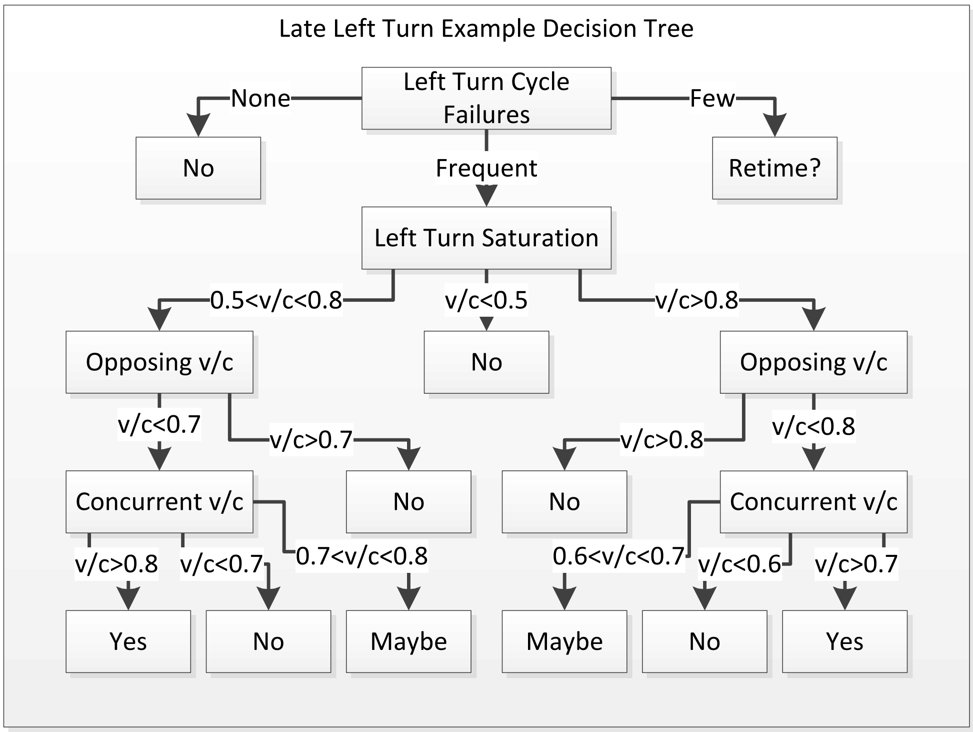

Figure 4.11: Example decision tree logic for coordinated late left turn

This simplified example examines coordinated late left turn as a queuing solution. As executed, the logic has more gradations. The decision tree for each specific operational objective, such as reducing left turn delay, would appear different. Each step of the decision tree is devoted to a logical step in the process. The first step is identifying if a problem exists, in this case cycle failures and high left turn demand in an interval. The next step is determining whether the chosen feature should be applied. For coordinated late left turn the application conditions are high left-turn saturation, moderate to low opposing through traffic, and heavy concurrent through traffic.

These conditions stem from the principles on which coordinated late left turn works. For the coordinated late left turn to be served there must be demand for the left turn after the first service. To have opportunity to be served the opposing through movement must gap out and the concurrent through must still be in service with sufficient time remaining to serve the left turn again.

4.6 CONTROL STRATEGY

The principles on which green time is allocated at an intersection can have large impacts on intersection and corridor performance. Some operating principles apply to all movements, such as the decision to implement time of day control; others may only impact a single movement, such as phase reservice. Operational strategies can be broken down into many different groups. Three strategy groups are local control strategy, left turn strategy, and phase reservice.

The local control strategy dictates the cycle length and primary distribution of green time amongst the various phases active at an intersection. The local control strategy can have varying degrees of intelligence. A number of common strategies are discussed in the following sections.

4.6.1 Time of Day

Time of day control is the most classical signal control methodology. It has not appreciably changed from its earliest uses in mechanical timer driven signal control. Under time of day control a fixed timing plan is loaded into the signal controller for each period of the day. In practice, it is common for there to be four to six timing plans used at an intersection over the course of a day. These plans generally represent an night time plan (or free operation depending on the system), a morning plan, mid-day plan and evening plan with one or two extra plans for peak period traffic, if needed.

Time of day control is typically used where congestion is high and predictable, such as central business districts. In these areas the benefits of coordination can outweigh inefficiencies in green time allocation. Also, because these areas are frequently saturated, some types of control, such as actuated, can be pressed to their maximum green time allocations which results in de facto fixed time operations.

Time of day control is often built into signal controller software making its use “free”. Central control software is often used for administration, but it is not absolutely necessary. Time of day control is unique in that it does not require vehicle detection to operate. Newer implementations tend to incorporate some features from actuated control such as gap outs and phase length changes to accommodate pedestrian crossings where the corresponding vehicle phase would be too short to allow for safe crossings.

The tricky part of time of day and traffic responsive control is transitioning from one plan to the next. There are a number of methods to do this including dwell, add, subtract, shortway and more (Shelby, et al., 2006). Each strategy has its best application to achieve transition from one plan to the next. The major difficulty in transition is the need to change offsets for the coordinated phase(s) from one plan to the next. The more severe the offset change, the more difficult the transition can be.

In general, fixed plans such as those used by time of day and traffic responsive control have been well modeled. The Highway Capacity Manual (HCM) 2000 (TRB, 2000) provides methods for calculating timing plans and analyzing performance. The HCM 2000 method of creating timing plans is based on finding a cycle length that is suitable for the intersection and movement saturations. Details may be found in Chapter 16 of the HCM 2000. These equations were used as the starting point for developing timing plans for time of day and traffic responsive control.

4.6.2 Actuated

Actuated signal control uses a ring and barrier structure along with detection to control traffic. The phases are numbered with even numbers assigned to through movements and odd numbers assigned to left turns. A figure from the FHWA Signalized Intersections: Informational Guide (FHWA, 2012) is presented as 4.12, below. This figure shows that phases that conflict are either in the same ring, as phases 1 and 2 are, or are across a barrier from each other in the case of phase 1 and phases 3, 4, 7 and 8. Since rings advance independently until reaching a barrier, phase 1 can be served with phases 5 or 6. Phases 2 and 6 would both need to be finished in order to cross the barrier and serve phases 3 and 7.

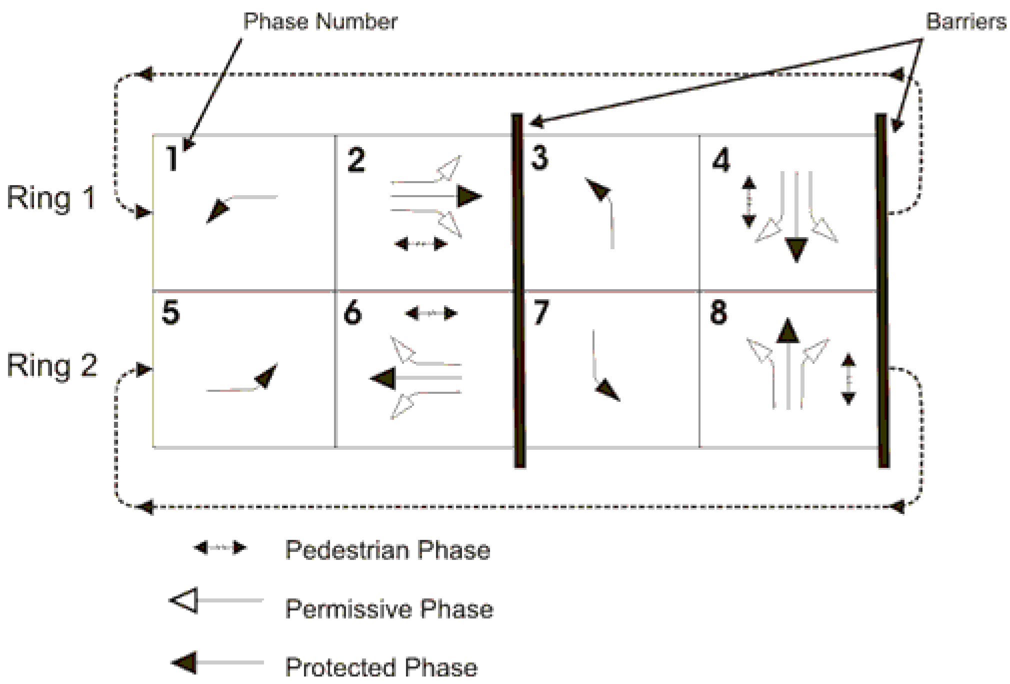

Figure 4.12: NEMA Phasing Diagram (FHWA, 2012)

Under light traffic conditions actuated control can quickly serve movements and minimize delay compared to strategies like time of day control. When traffic become heavier, it is more likely that vehicles will arrive and trigger extension time until the maximum green time is reached. For very heavy traffic, actuated control behaves like a fixed time plan based on the maximum green times.

One downside to isolated actuated control is that it may unnecessarily stop approaching vehicles. This behavior can impact corridor performance by increasing the number of stops vehicles have to make. To reduce this problem, it is common to have actuated control intersections “rest” in the corridor’s primary movement phases, typically through movements. Another technique is to set up coordinated actuated control where the maximum green times and force off settings are used to keep the beginning time of the coordinated phases aligned along the corridor. This means that some point in the cycle is fixed and offset at each intersection just like a time of day plan, but the rest of the cycle behaves like any other actuated control system.

4.6.3 Traffic Responsive

Traffic responsive control is basically a hybrid of time of day control and actuated control. Traffic responsive control uses a library of timing plans like time of day control but selects a timing plan based on system detector data from the corridor. Typically similar plans are used for both time of day and traffic actuated control, the difference is that the traffic responsive system will not implement the plans until traffic conditions match certain conditions. In practice, traffic responsive operation allows for a more tailored response than time of day control. Plans that may be necessary to meet high peak period demand but cause extra delay in minor movements can be moved into and out of only when needed.

One of the downsides to traffic responsive operations is that it can be difficult for some systems to make transitions between timing plans. The transition can take anywhere from one cycle to several minutes to complete depending on how different the current and new plans are and what movements are coordinated. This transitional period can be detrimental to coordination and even cause congestion while a corridor's signal's realign. This behavior makes it very important to choose the right transition criteria when setting up a traffic responsive system. It also limits traffic responsive systems' suitability to variable traffic demands.

4.6.4 Adaptive: Saturation Equalization

Adaptive control systems such as SCATS and ACS Lite use the saturation of intersection detectors to determine how green time should be allocated between movements (*Roads and Traffic Authority, 2011; Shelby, et al., 2008).*In addition, SCATS uses the total saturation of all voting detectors at the intersection to determine if the cycle length should increase or decrease. ACS Lite updates the base timing plan in use on the corridor every ten minutes based on information from system detection and the timing plan library. The chief differences between the two control strategies is the period necessary for cycle lengths to change and the degree a movement allocated time is allowed to change per cycle.

Note that while the term saturation has been used here referring to the detectors for both ACS Lite and SCATS, the two systems are actually using subtly different measures. SCATS uses the degree of saturation which is a relative measure related to the gaps between vehicles rather than the occupancy of the detector. ACS Lite uses occupancy directly. Since occupancy and headways can be difficult to predict, particularly from count data, the research team is using saturation as a surrogate measure that can reasonably be determined from volume, provided queues and congestion are accounted for.

4.6.4.1 Fast Occupancy

Unfortunately SCATS' algorithms are not published. The plain English version of their algorithms is available, however. Since the costs of directly simulating SCATS through purchasing software and hardware were prohibitive, an alternate solution was needed. To solve this problem the research team began creating an algorithm based on the plain English description of the SCATS local control algorithms. This algorithm is not SCATS, but it is intended to be close enough to get an idea about whether the assumptions being made in modeling for the rest of the project are valid.

4.6.4.2 Slow Occupancy

As with SCATS, the research team did not have access to the algorithms governing the ACS Lite system. Similarly, the costs of hardware in the loop or direct purchase of simulation software was prohibitive. Instead, the research team created a substitute algorithm that mimics the local optimization of ACS Lite. This algorithm is not ACS Lite and is intended only to be used to aid in model validation. The major differences between the fast occupancy and slow occupancy programs are that slow occupancy cannot change cycle length dynamically, can only reallocate a maximum change of ten seconds from the base timing plan and requires five cycles for each iteration of the time allocation process.

4.6.5 Adaptive: Delay Equalization

The InSync system is the third and final system considered by ODOT. InSync uses video detection to detect queues and estimate the number of vehicles waiting at a signal (Rhythm Engineering, 2012). The system optimizes local operations by trying to minimize delay. It does this by counting the vehicles on each movement every five seconds and then adding that number to a delay total. In this way one vehicle waiting ten seconds is equivalent to two vehicles waiting five seconds. The local optimization engine then tries to minimize the total delay. Global optimization sets up green tunnels along the corridor that ensure progression along the corridor.

Adaptive systems that optimize based on delay, such as InSync, can be analyzed in a manner similar to those optimizing based on saturation. However, this analysis does require additional computational work. Estimating how an adaptive delay equalization control system would work on a corridor requires modeling the arrival rate of vehicles at each approach of each intersection. Data limitations, particularly for side streets and major sources and sinks of traffic limit model accuracy.

As with the previous adaptive systems InSync's algorithms are not published. There was not even an option to purchase a simulation package at the time of the research, so simulation of InSync was always going to need to be via external control logic. Once again focus was on the local optimization engine for replication. Actually executing the algorithms required modification of the base simulation model in order to replicate InSync's detection methodology.

4.7 FEATURES

The research team has examined a number of system control features available to the various signal control systems. Northwest Signal Corporation has been very helpful with regard to the Voyage system's features and operations. The research team has sought to include as many features as practical in the analysis both for use by practitioners in getting the most performance out of their systems and to accommodate the FHWA's system engineering approach which requires the examination of the existing system's options before changing signal control systems.

The detail level of the analysis, essentially set at a 15 minute level by the available data, limits the research team's ability to model a number of features. This is especially true for features that rely on instantaneous data. For example, Voyage includes a feature; lane by lane gap out, to allow gap outs under actuated operations to be enacted either at either an approach or individual lane level. With this feature disabled, a gap out occurs when there is a gap across all lanes used by the movement. When the feature is enabled, a gap out occurs when a gap occurs in any lane used by the movement. This feature is intended to address situations where queuing or lane utilization is impacting intersection performance. Unfortunately, it is very difficult to address lane utilization and gap sizes from 15 minute data. This has led the research team to focus on features that directly impact green time allocation, such as left turn strategies and phase reservice techniques.

4.7.1 Left Turns

Between intersection layout and coordination demands, there can be an unexpected importance in how left turns are handled at an intersection. Left turns can broadly be broken into three categories with sub-categories. Left turns could be prohibited, permitted, or protected at an intersection. Prohibited left turns are actually a trivial case for intersection layouts and progression since they do not require accommodation in the layout or consideration for coordination. Permitted left turns allow vehicles to make left turns when opposing traffic permits and require drivers to exercise safe driving habits in selecting appropriate gaps during which to execute their left turns. Protected left turns have a dedicated left turn signal and phasing that allows left turns to be made without interference from opposing traffic.

Protected left turns are indicated by green arrows and typically have dedicated left-turn lanes. Protected left turns are typically phased adjacent to the opposing through movements. If the left turn is phased before the opposing through movement it is a leading left turn and if it is phased after the opposing through movement it is a lagging left turn. Protected left turns are phased as lead-lead (both left turns proceed the mainline phase), lead-lag (one left turn proceeds the mainline phase and the other follows), or lag-lag (both left turns follow the mainline phase) depending on the controlling agencies policies. Changes between leading and lagging lefts may also be changed based on time of day or coordination plan.

Permitted left turns can be signaled with either green balls or flashing yellow arrows with the same effect on driving. Oncoming left turning vehicles must yield to opposing traffic but may make their turns without stopping. Typically, green ball signals are used where there are no dedicated left turn lanes. Flashing yellow arrows are often used at locations with dedicated left turn bays and protected left turn signals. Typically such an intersection operates with flashing yellow arrow permitted left turns during off peak hours and protected operations during peak hours if turning volumes warrant. An additional operational method is to serve the left turn as permitted, using the flashing yellow arrow, and, if vehicle remain at the end of the through movement service, serve the remaining left turn vehicles in a lagging protected phase.

Generally, permitted left turns are not coordinated since their probabilistic nature precludes the definite scheduling inherent to coordination. Protected left turns are another story. Coordination can play a large role in determining whether leading or lagging lefts are used at an intersection. For intersections with concurrent arrivals from adjacent intersections, either leading or lagging lefts may be used depending on how the other phases in the cycle are operated. When arriving vehicles are not concurrent, for example, if upstream traffic will arrive before downstream traffic, then a leading left can be used on the approach with earlier arrivals and the later arrivals can have a lagging left turn. This allows traffic from both movements to get their through movement time when they arrive and lets left turn traffic traverse the intersection with a minimum of delay. Other reasons to choose between concurrent lefts and lead-lag left turns is if the demands are dramatically different or if queuing is a problem. Additionally, strategies such as phase reservice may require leading left turns.

4.7.2 Phase Reservice

Phase reservicing is a technique that may be applied across a number of the study systems. Phase reservicing is when a phase that has already been given green time once during a cycle is given green time again at a later point in the same cycle. Phase reservice is generally used when queues or discharge rates are causing problems. For example, a left turn has particularly high demand and commonly overflows the left turn bay, blocking through traffic. By serving that left turn twice during the cycle, excessive queuing may be reduced or even prevented. Or a metered freeway ramp has a limited discharge and the left turn demand exceeds the queuing capacity of the ramp. By splitting the left turn volume into two smaller platoons and allowing time to discharge between platoons, more vehicles may be served and queuing reduced.

Some control strategies natively use phase reservice as part of their basic control strategy. For example, actuated control that rests in a phase can behave as though it were programmed for phase reservicing. Another example is InSync with its lack of a delineated cycle. It simplifies some analyses if one assumes that InSync is simply applying phase reservice to its control strategy rather than trying to apply an arbitrary cycle.

Beyond generic phase reservice, there are two conditional phase reservicing control logics that should be covered. The first is the TS2 conditional service specification as detailed in NEMA TS2-1998 v02.04. The TS2 conditional service specification requires that the controller serve an odd numbered phase after normal service has finished provided there is enough time on the concurrent through phase for an additional service of the odd numbered phase. The specification also requires a conditional service minimum green time and that even phases may be conditionally served after a conditional service of an odd phase. The odd phase cannot be reserviced after the even phase has been reserviced, which prevents infinite phase reservicing. Logically conditional service is only practical on leading phases since the phase must complete and have a call on it again before the concurrent movement completes its service.

Northwest Signal Supply Inc. has created a similar feature for their software which is called “coordinated late left turn”. It operates in a similar manner to the TS2 specification but has one important difference. The TS2 specification for conditional phase reservice results in a required barrier crossing after the conditional service. Coordinated late left turn checks for opposing phase calls after the left turn has received late left turn service. If there are no opposing calls the system is allowed to return to the coordinated phases. Coordinated late left turn can only be activated for leading left turns and is only recommended for use on one left turn at a time on each side of the barrier.

4.8 IMPLEMENTATION

There is a logical dependence and order of operations to the process of evaluating the existing control and determining the best features or system to implement on a corridor. First, the existing data must be analyzed, then problems identified followed by evaluating possible features. The analysis framework‘s purpose is to compute the MOEs described in section 4.3. Once the MOEs have been calculated, performance problems and user goals can be examined using the decision tree logic described in Section 4.5.

Finally, a parameter estimation methodology is needed to quantify parameters for the selected features or system. The parameter estimation methodology is of dual use. It is intended to fine tune an existing configuration or determine which features or systems would offer the best performance improvement. Then the analytical framework can generate new MOEs for the expected performance of the new system configuration. These new MOEs can then be used by the decision tree logic until a stable feature set is determined both locally and corridor-wide. The entire process is diagramed in Figure 4.13.

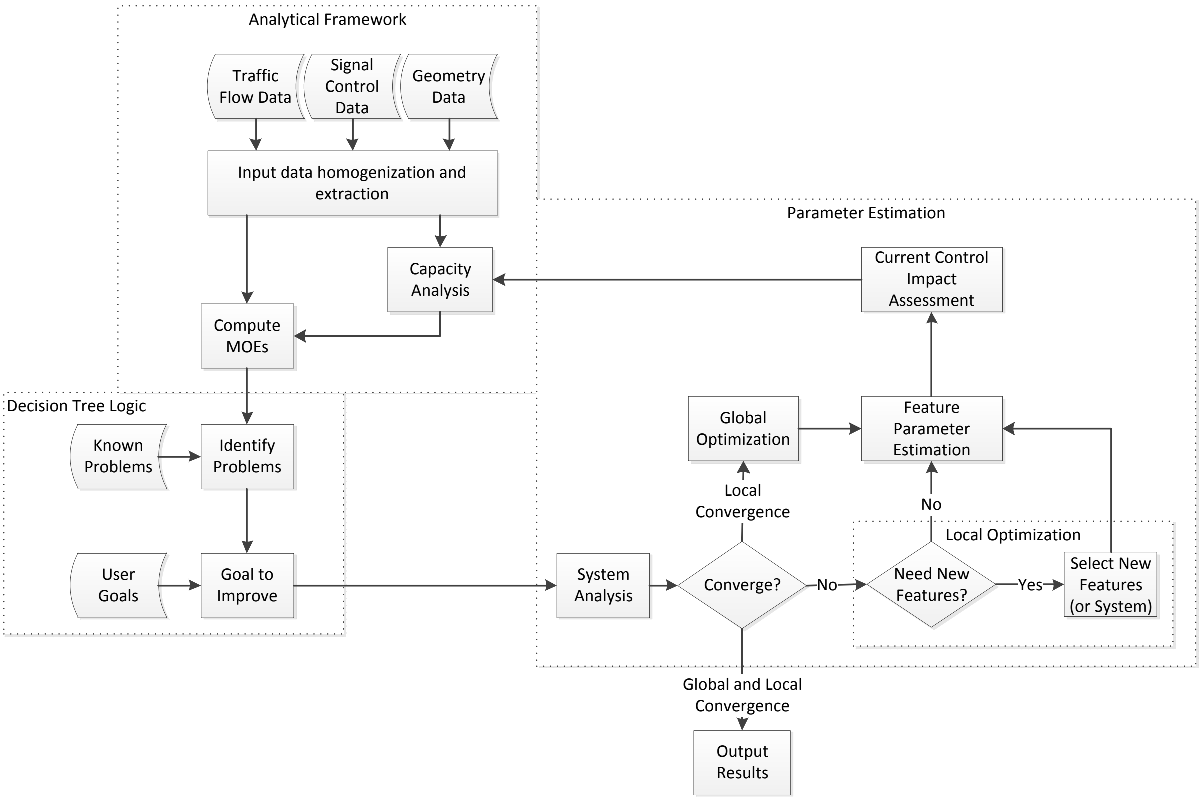

Figure 4.13: Analysis framework, decision tree and parameter estimation logic diagram

4.8.1 Analysis Framework

The analysis framework is designed to take input data, format it for analysis, and calculate MOEs. The data is formatted so that different input data may be used to the extent possible. For example, volume data is aggregated into per phase volumes for analysis so that data from tube counts, W4IKS and Voyage may be used interchangeably. Obviously, only data that is present can be formatted, aggregated, or analyzed. This means that some analyses may not be possible given certain input data, or that simple models may be used to estimate missing data.

To the extent possible, the analytical framework has been test executed in Microsoft Excel. Some analyses, including the variability analysis were executed in a combination of Microsoft SQL and C# programming. In order to reduce the required software, a number of the more complicated analyses are being incorporated into a single program for final deployment.

The final deliverable this program reads input data from selected systems or specified formats. Once the data is read, an output file will be created for import into an Excel workbook that contains the remainder of the analytical framework, the decision tree logic, and the parameter estimation methodology. From this point the decision tree logic can be executed.

4.8.2 Decision Tree Logic Execution

The first step of the decision tree logic is for the analysis framework MOEs to be evaluated. Initial performance problems can then be identified for presentation to the user. The user can choose which performance problems to focus on and force the selection of performance problems that were not detected in the initial analysis.

The next step is the selection of improvement goals. Given the presence of certain performance problems, a set of improvement goals may be recommended. The user can then choose which performance goals to use. From this point, parameters must be estimated to determine whether performance goals can be met.

4.8.3 Parameter Estimation

After performance problems and improvement goals are identified, the first step is to examine whether the current system configuration is capable of meeting the performance goals. If not, the next step is evaluating whether the unused features of the existing system can be activated and improve performance. If further performance improvement is required, other systems are then evaluated, starting with base configurations.

The estimation methodology attempts to satisfy performance goals at each intersection locally and then proceed to a corridor-wide optimization. This way, different features can be enabled at different intersections to optimize corridor performance. Features can also be recommended based on time of day, day of week, and features of the intersection. For example, if intersection and corridor conditions warrant the use of conditional left turn phase reservice at an intersection from 7 AM to 9 AM Monday through Friday and from 10 AM to 1 PM on Saturday, then conditional left turn phase reservice can be recommended for those times and performance analyzed as though the feature were active.

4.8.4 Decision Tree Calibration

In the construction of the decision tree logic and analysis framework, the research team has striven wherever possible to make use of field data. Using field data to determine thresholds in the decision tree logic allows for greater confidence in predicting performance than simulation or traffic flow theory based models since the field data represents what actually is happening. Large amounts of field data from several corridors and intersections in multiple jurisdictions have been collected, offering the research team a comparatively broad view of traffic signal control performance.

The downside to field data is that field data is only applicable under the conditions it is collected. For example, two intersections have exactly the same geometry, flow, and phasing parameters, but one intersection is the most heavily trafficked on its corridor while the other is an average intersection on the corridor. Changes to the first intersection would be expected to impact the entire corridor to a much greater extent than changes to the latter. A field data based analysis of one intersection would have misleading results when applied to the other. This leads to a situation where field data from each signal control system should be collected under all possible traffic and geometric conditions. Such data collection efforts would be prohibitive at best, leading the research team to look into other means of calibration and self-calibration.

The large number of MOEs developed in the analytical framework is one attempt to reduce the uncertainty inherent to predicting which features or systems will improve performance on a corridor. The various MOEs were developed intending to directly detect as many different geometric, flow, and operational traffic conditions as possible. By directly detecting queuing, congestion, variability, etc. it reduces the calibration burden for the decision tree logic. Instead of trying to calibrate a flow model to predict when a left turn movement would experience queuing or cycle failure, those events can be detected directly from the raw data wherever possible.

Some features, particularly ones that operate in a probabilistic manner are more difficult to calibrate. Conditional left turn phase reservice is one example of a probabilistic feature. If the conditions are met, then an additional left turn movement is served, otherwise the phase terminates normally and does not recur until the next cycle. This means that the frequency of reservice and the operating capacity of the left-turn movement are not constant. To better predict how such features may operate, microscopic traffic simulation models such as VISSIM can be used.

Conditional left turn phase reservice is a feature that can be a double edged sword if it is not used properly. In order to serve the coordinated late left turn, the opposing through movement, phase 6 in this example, must gap out while phase 2 continues service. Without coordinated late left turn in operation, phase 6 could remain in green as long as phase 2 did not terminate. When several vehicles take advantage of late left turn, the large delay reduction experienced by the left turn vehicles overrides the small delay incurred on phase 6, which should be lightly trafficked by the time it gaps out and allows coordinated late left turn to be serviced. If too few vehicles make left turns then it is possible for enough vehicles to be delayed by the termination of phase 6 to outweigh the delay reduction experienced by the left turn.

As part of the research a VISSIM model was created for the 99W corridor to test whether custom logic representing coordinated late left turn operations could be implemented in the model. The simulation has been expanded and the input data used updated. Data from Thursday May 19, 2011 has been used as input data for an updated model. The model will be further developed for the next task in the project, however the coordinated late left turn simulations have already been tested and providing preliminary results on the benefits of coordinated late left turn.

These results are detailed in the following charts. Figure 4.14 shows the volumes on the through and left turning movements on 99W at Greenburg Road. There are several important details to note about the data. First, for most of the morning, until approximately 9:30 AM, the phase 2 traffic is heavier than the phase 6 traffic. This is important to coordinated late left turn service efficiency. Second, phase 5 left turn traffic fluctuates in a range of five to ten percent of the phase 2 traffic levels. In other words there are a relatively small number of left turning vehicles to experience delay reductions, which means that small changes in the number of left turn vehicles in an interval can skew the delay.

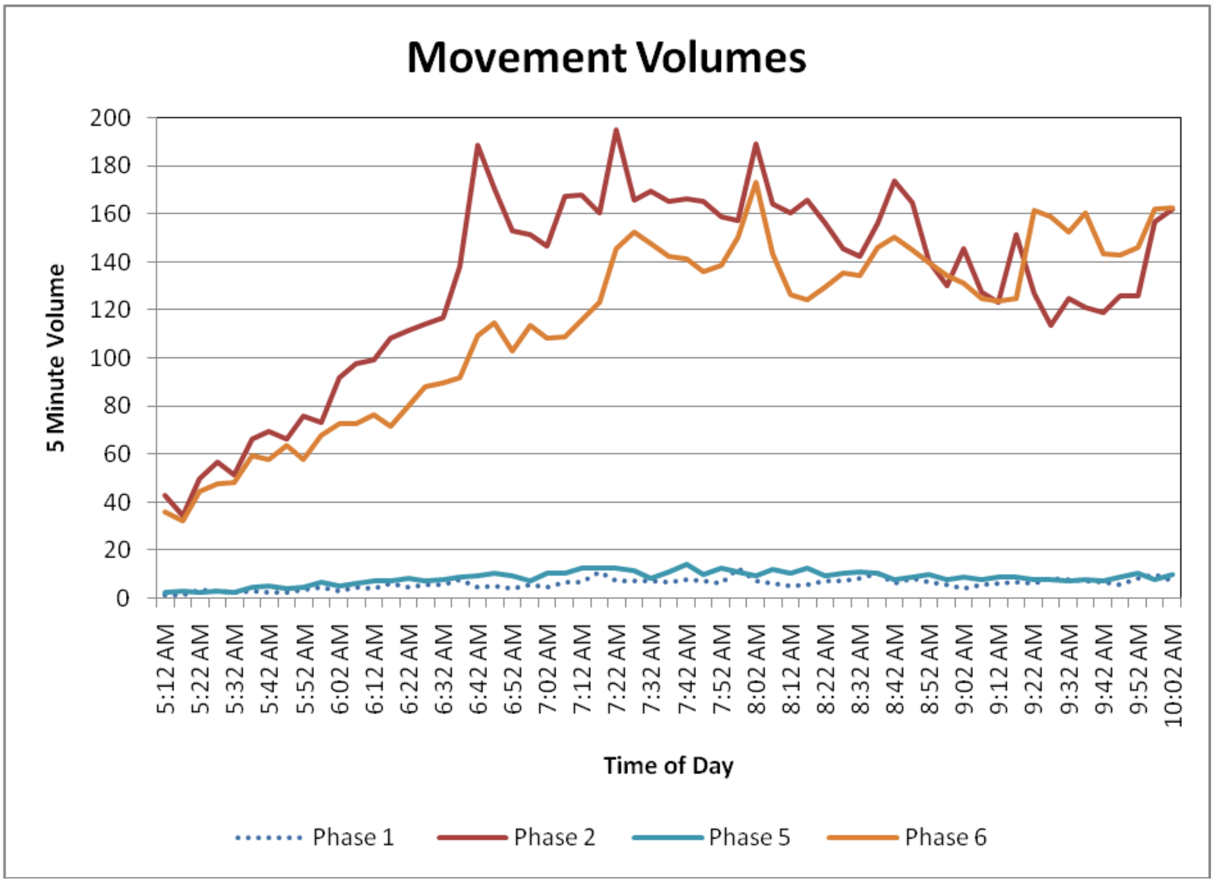

Figure 4.14: Five-minute volumes at 99W and Greenburg Road by phase

Figure 4.15 shows the left turn average delay on 99W at Greenburg Road. The base case is for coordinated actuated control without late left turn. This case is represented by the solid line. The dotted line shows the delay for the phase 5 left turn under coordinated late left turn operations. For the left turning vehicles, the delay savings is obvious. The phase 5 left turn saves thirty seconds of delay for the majority of the morning. This is not an unexpected result. The real question is whether that left turn delay reduction comes at the cost of increasing delay for the rest of the intersection.

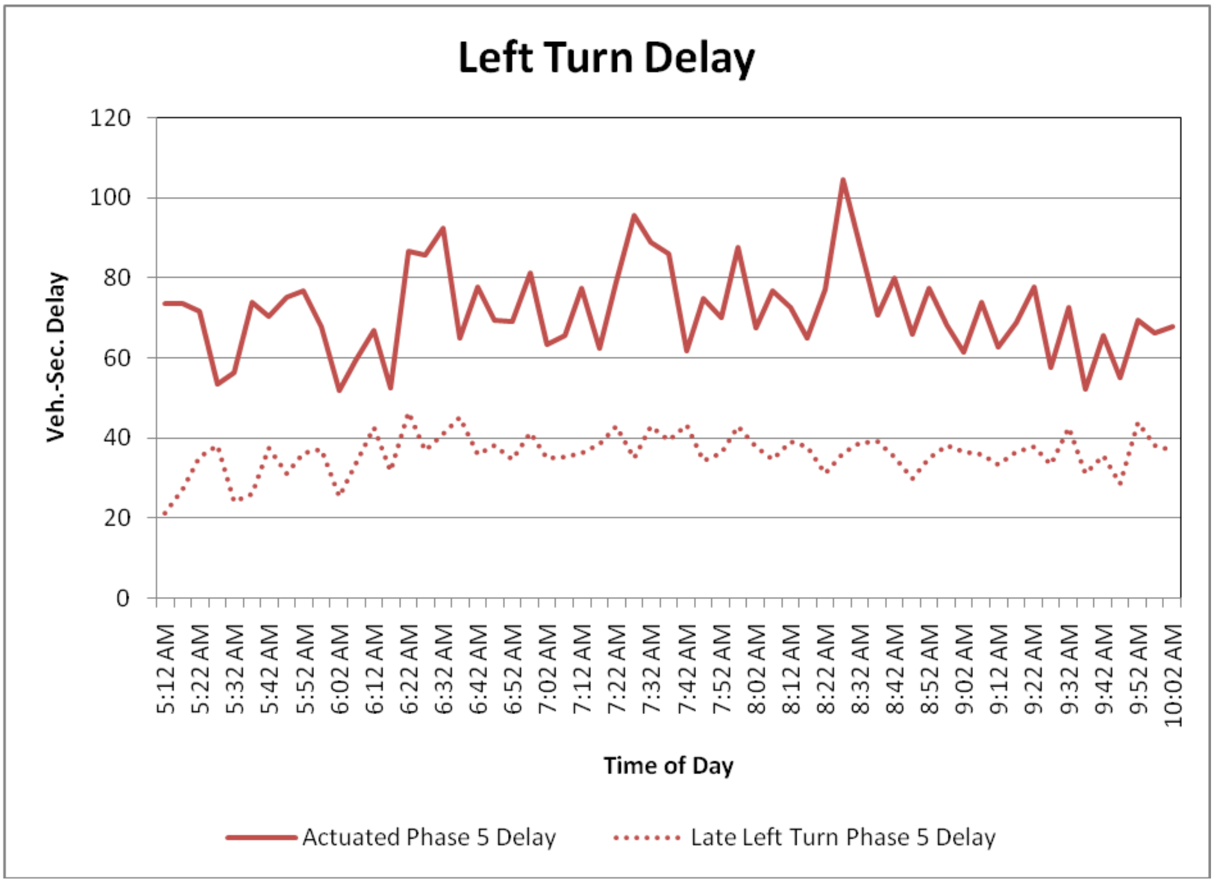

Figure 4.15: Left-turn delay under actuated control with and without coordinated late left turn

Figure 4.16 shows the average delay incurred for the 99W through movements (phases 2 and 6) plus left turns (phases 1, 2, 5 and 6), and the total intersection average delay at Greenburg Road. Solid lines are used to represent the coordinated actuated control base case and dotted lines represent the results with coordinated late left turn enabled. For the period up to approximately 9:30 AM coordinated late left turn average delay is consistently lower than the base case. For the period after 9:30 AM performance suffers, and a quick look at Figure 4.13 will show why. Until 9:30 AM, phase 2, which phase 5 relies on for coordinated late left turn service, has a greater volume than phase 6. After 9:30 AM phase 6 has greater demand than phase 2. Once this reversal takes place, coordinated late left turn would be expected to be served less often. The left turn delay results in Figure 4.15 show that performance decreases after 9:30 AM. Coordinated late left turn would also be expected to incur greater delay penalties for phase 6 as the traffic ratio with phase 2 decreases. An examination of the phase 2/6 data in Figure 4.15 indicates this is happening more frequently and the left turn delay reduction is no longer compensating for it.

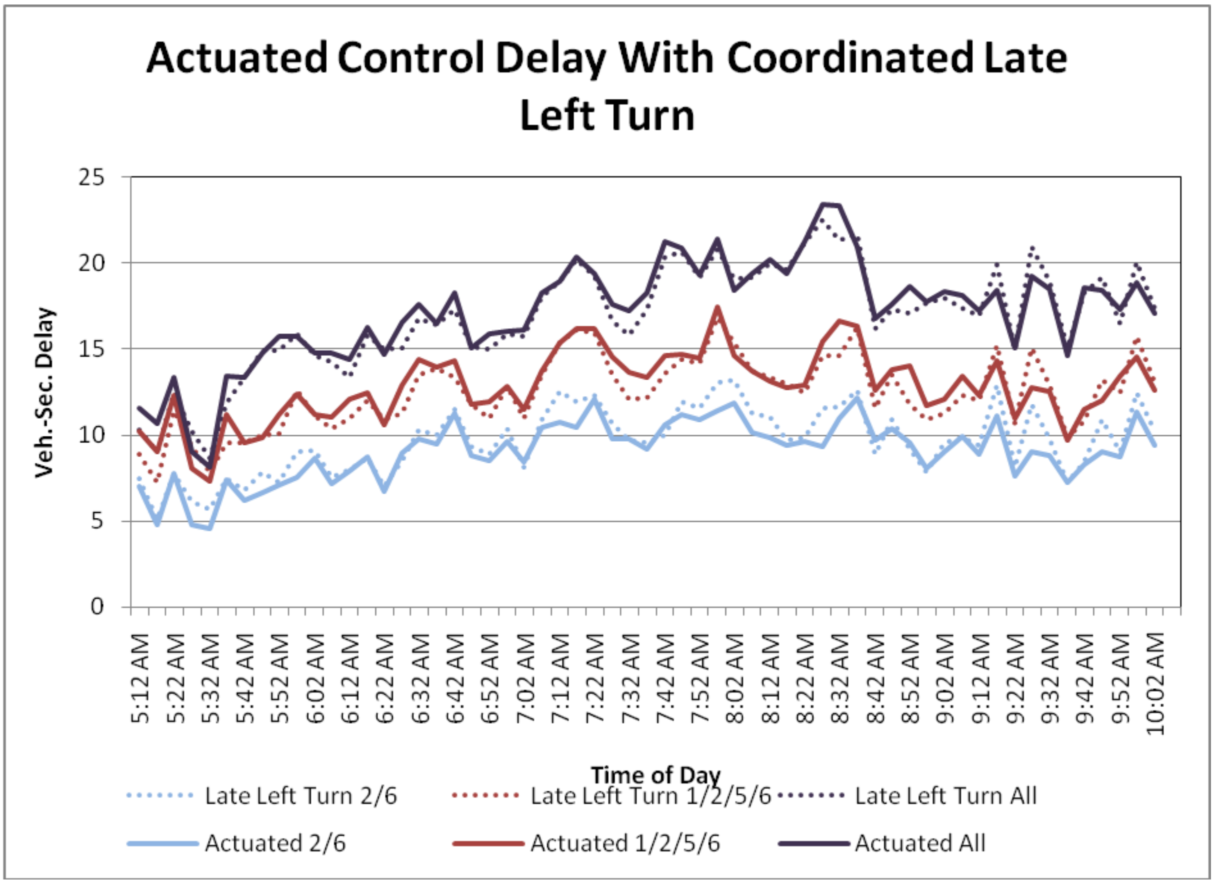

Figure 4.16: Average Vehicle-Seconds of Delay by Movement Group

From simulations like these and knowledge of the operating principles of the various study systems and features, it is possible to calibrate the decision tree logic. To a lesser extent, it is also possible to check if enabling one set of features would cause conditions to change in such a way as to cause conditions that would interfere with another feature. During parameter estimation such checks can be made and any contra-indicated feature combinations flagged.

For other features and strategies it may be impractical to simulate the results. This is particularly true for the adaptive signal control algorithms of SCATS, ACS Lite, and InSync. Because the algorithms are proprietary and the costs to create simulations are prohibitive, these control strategies cannot be directly simulated. The strengths and weaknesses of the algorithms can be predicted, to an extent, based on the public information regarding the algorithms. These estimates of performance may not be completely accurate, but absolute accuracy is not necessary given the macroscopic scale of the corridor analysis and other simplifying assumptions inherent to the analyses.

When field data and simulation are both impractical, or the behavior involved is simplistic, existing traffic flow theory will be applied. Examples include queuing behavior and lost time during a cycle. Traffic flow theory has been developed for decades and offers insight into a number of topics. For those odd cases where traffic flow theory does not exist or the existing models are determined to be inadequate, new models will be needed.

5.0 SIMULATION EXPERIMENTS FOR THE FUNDAMENTAL INTERSECTION AND CORRIDOR TYPES

In order to identify the advanced traffic signal system that best fits a particular corridor or intersection, measures of effectiveness (MOEs) must be quantified for all the alternative systems. To develop such a tool that quantifies the MOEs, relationships between the MOEs and traffic, geometric, and control variables must be established. However, existing research has not covered all these relationships. To fill the gaps, simulation experiments are needed to collect data for the desired analyses. Therefore, this part of the research focused on the implementation of traffic signal control logics and evaluation of their impacts in a simulation environment. Performing the experiments in a simulated environment offers several major benefits. The first, and most important to this project, is the relaxation of data constraints. It has been widely recognized as a very difficult and expensive task to collect a quality dataset from the field, particularly for evaluating advanced traffic signal control systems. Even though field data are collected, they are often subject to quality problems as well as the limitations in observable scenarios. Through properly designed and calibrated simulation models, data collection can be much easier and efficient. Simulation also offers the benefit of controlling traffic conditions for a thorough investigation of scenarios of interest, which is nearly impossible in the field. The last major benefit of simulation is repeatability. An experiment in the field cannot be easily repeated with the same test conditions, but in simulation it is simply a matter of restarting the simulation. Therefore, simulation experiments are employed in this study to collect measures of effectiveness for intersections with various traffic demands, lane configurations, and control strategies.

The simulation software chosen is PTV Vision's VISSIM software (PTV America, 2012) version 5.3. VISSIM is one of the most widely used microscopic simulation programs and models the behavior of individual vehicles on a simulated network. It is designed so each simulated vehicle makes driving behavior model-based decisions each time step of the simulation. VISSIM allows users to change driver behavior model parameters in order to calibrate model performance to their specifications. VISSIM also enables external programs to control model parameters, such as driver behavior model factors and network features such as signal control status through an external communications framework called the Component Object Model (COM) interface.

Since the advanced traffic signal control features of interest for this project are not available through the built-in functions of VISSIM, customized external modules are needed to implement these control features for simulation experiments. The research team used Microsoft C# and .NET framework 4.0 to the program external control modules to interface with VISSIM for this project. The external control modules, containing the signal control logic, can read and send commands to VISSIM model components via the COM interface. With these external control modules, customized control logics can be simulated.

5.1 EXPERIMENTAL DESIGN

5.1.1 Design Factors

To measure the performance of traffic signal control systems and provide selection guidelines for practitioners, a number of factors must be considered. These factors can roughly be broken down into intersection geometric, corridor, traffic, and control factors. A short list of examples can be found in Table 5.1.

Table 5.1: Example Factors

Intersection Geometric	Corridor	Traffic	Control
Approach Lanes	Intersection Spacing	Volume	Phase Order
Left Turn Lanes	Access Points	Turning Movements	Overlaps
Right Turn Lanes	Highway Ramps	Variability	Coordination
Symmetry	Choke Points	Truck Percentage	Pedestrians

There are many more potential factors for evaluation than are listed in Table 5.1. If just the listed parameters were tested with three values for each factor, there would be 3^{16} or 43,046,721 combinations. Simulating this number of combinations is not feasible given the resources allocated to the research. Therefore, a more limited set of experimental factors must be identified as described in the subsection below.

5.1.2 Core Test Cases

To ensure the reliability of the simulation analysis results and make the best use of limited resources, all factors are carefully screened so that the most important ones are included in the simulation experiments. Efforts are also made to ensure that the selected factors are properly represented in the simulation environment. For example, simulation of access points on corridor segments would require significant additional modeling and calibration work to create two functional intersections with all the routing and turning movement calibrations required to make the various turns into and out of the access point function. Additionally, such a simulation would be more computationally burdensome, with the signal control logic being required to operate two sets of traffic signals instead of one. With these limitations in mind, a number of simplifying assumptions were made. These are:

- All signals are operated as 8-phase intersections with leading left turns.
- The VISSIM traffic composition default of two percent heavy vehicles is used.
- The intersection approaches are symmetrical.
- Vehicle traffic dominates intersection performance.

Several factors were deemed to require more effort to simulate than the results would justify, either from modeling, performance or calibration concerns. Pedestrians would introduce several factors, including pedestrian crossing demand, pedestrian crossing times, and yielding behavior. Most of the corridor factors introduce similar numbers of additional factors. Access points, for example, introduce the need to generate traffic into and out of the links as well as calibration of routes and turning behaviors. Similarly, intersection spacing has a direct impact on progression and attendant signal timing issues. Because of these concerns, methods other than simulation were pursued for modeling of these factors.

The factors deemed to be of the greatest initial importance are traffic volumes, turning movements, coordination, approach lanes, and right turn lanes. From these factors a variety of test cases were developed. Some assumptions were used to reduce the test cases in a reasonable manner. For example, it was assumed that right turn lanes would only be used when right turn movements were high. Similarly, intersection configurations were assumed to be symmetric across the main street and symmetric across the cross street. Table 5.2 shows the factors modeled and the specific values tested.

Table 5.2: Core Test Cases

Test Factor	**Factor Values**	**Number of Values**
Volume Combinations (main:cross street in vphpl)	600:300, 900:300, 1000:300, 600:600, 800:600, 400:200	6
Turning Movements (through/right/left)	80%/10%/10%, 60%/30%/10%, 60%/10%/30%	3
Coordination	Random, Platooned	2
Approaches (main:cross street approach lanes)	3:2, 2:2, 2:1	3
Total Combinations		108

The values in Table 5.2 for the volume combinations are expressed in terms of vehicles per hour per lane (vphpl) on the main street and cross street respectively. Turning movements are expressed in percentages of through traffic, right, and left, respectively. Figure 5.1 shows the various lane configurations used for the different approach and turning movement values. Coordination is either inactive with vehicles arriving as they are randomly generated by VISSIM or coordinated to form platoons using upstream signals. Approaches are reported as the ratio of main street approach lanes to cross street approach lanes. For example, the 600:300 volume combination applied to the 3:2 approach configurations and using the 60%/30%/10% turning movements represents the volume conditions reported in Table 5.3.

Table 5.3: Test Conditions

Movement	**Main Volume**	**Cross Volume**
Through	1080	360
Right	540	180
Left	180	60

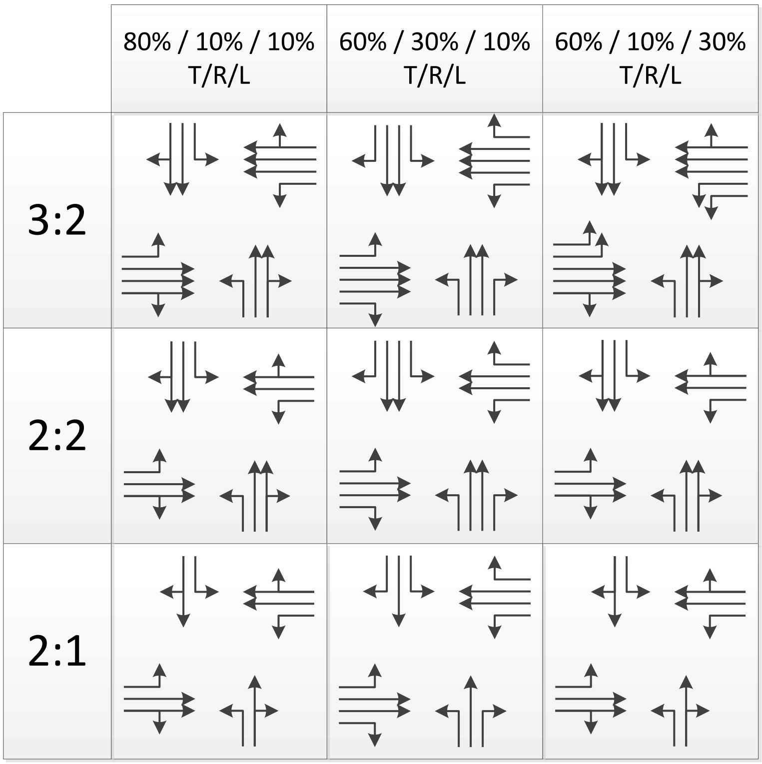

Figure 5.1: Lane Configurations by Approach Configuration and Turning Movement Bias

5.1.3 Capacity for Future Improvements

The budget and timing constraints limited the number of scenarios the research team can investigate. However, the methodology framework developed in this task certainly allows future add-ons to enhance the analytical capability and result reliability. The research team intends to continue to expand simulation coverage as much as possible before project termination. Important features, such as left turn phase reservice are not properly applied to traffic conditions with equal opposing and concurrent volumes. Therefore, the inclusion of asymmetrical volumes is of the highest priority. Alternate phasing orders and strategies are another important area deserving additional consideration.

5.2 VISSIM MODEL DEVELOPMENT

5.2.1 Model Creation

In order to simulate the various test cases, a series of VISSIM models were created. These simulation models reflect the intersection geometries shown in Figure 5.1. Key points in model creation include the simulation of right turn on red and the proper operation and calibration of driving behavior where conflicting vehicles interact, such as on free right turns with traffic.

5.2.2 Data Collection

Since the main focus for simulation is the collection of data to supplement field data for use in calibrating other models, most of the focus is on simulation data collection. VISSIM simulation enables a number of different detection and data collection systems. These include simulated (loop) detectors, queue counters, travel time measurements, and delay counters. Each element is visible through the COM interface, however, only the detectors are truly helpful since the other measurement systems have their own quirks.

5.2.3 Simulated Detectors

VISSIM's simulated detectors operate like conventional loop detectors with additional features built in that are particularly useful given the computational overhead inherent to communicating over the COM interface. VISSIM detectors provide the standard presence measurement used by real world signal controllers, but they also provide headway between vehicles, measured in seconds since the last car passed over the detector. Detector placement for the simulated intersections is as follows, six foot detectors at 4 feet from the stop bar and advance detectors 165 feet (50 m) upstream of the stop bar detectors. The stop bar detection is slightly unusual with a six foot diameter loop instead of a twenty foot long loop. This is because the consistency of simulated traffic negates many problems with stopping too early and the other features of the simulated detector, such as headway detection, function better with shorter detectors.

The delay optimization based traffic signal control strategy required a different detection setup. The delay based optimization strategy roughly implements InSync's local optimization strategy, which is discussed in the next section. The key point from a simulation model perspective is that InSync counts vehicles in the queue and checks queue length (Rhythm Engineering, 2012). In order to emulate this input a number of strategies were attempted. The one that proved most successful in simulation is shown in Figure 5.2. It consists of ten 20 foot long detectors in each lane.

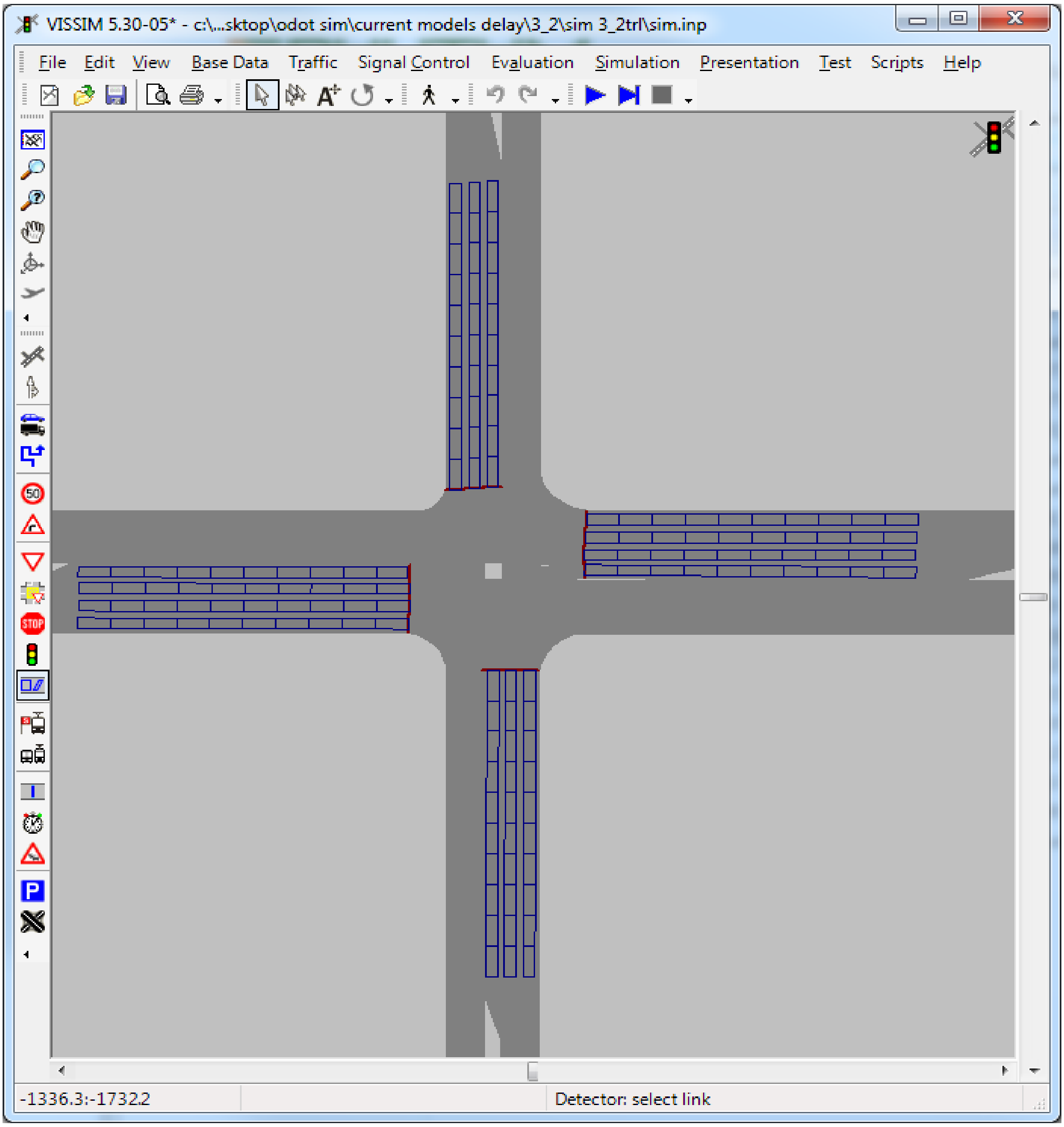

Figure 5.2: Detector Placement for Delay Optimization Strategy

5.2.4 Queue Counters

VISSIM also includes the ability to place queue counters on the network. In this case, queue counters are placed immediately before the stop bar to measure traffic queued at the signal. A queue counter reports the average and maximum queue length during each user specified interval, 30 seconds for this research. Queue counters also report the number of stops within the queue. The number of stops is presented as a total and does not necessarily coincide with the number of vehicles in the queue. This is because vehicles join the queue when their speed drops below a threshold speed, 3.1 mph, and leave it when their speed increases beyond another threshold, 6.2 mph. This means that vehicles can nearly stop, join the queue and leave it again without being recorded as stopping. Changing the thresholds can manipulate this behavior, but not truly eliminate it, so it must be considered in any analysis.

5.2.5 Travel Time

Travel time is a set of data collectors incorporated into VISSIM. Travel times are measured from a start point to an end point on the network. Once a vehicle crosses the starting line, VISSIM begins tracking its travel time until it crosses the end point. Travel times are collected at user specified intervals which is 30 seconds for this research. Travel time is averaged for all vehicles crossing the end point during a 30-second interval. If no vehicles cross the endpoint during an interval, then a travel time of zero is reported.

5.2.6 Delay

Delay is another function of travel time data collection that can be enabled in VISSIM. Delay can be reported two ways, and both are used in this research. The first is at user specified intervals just like travel time and queue counters. In this mode, average delay is reported for each interval with additional information that includes the average time stopped and average number of stops. The second method of reporting is the raw data. In the raw data, each vehicle that enters the travel time segment and the delay it experiences during its trip is recorded.

5.2.7 Calibration

Calibration is a very important step for any simulation research. At the intersection level, calibration efforts are dedicated to deciding parameter values of the driver behavior models. There have been numerous papers detailing strategies for selecting the optimal calibration parameters. One paper, by Brian Park and Maggie Qi (Park and Qi, 2005), has recommended a calibration procedure and parameter values used by other studies. Given the similarity of their case study work to this project, the research team chose to use their parameter values directly for this study.

The VISSIM simulation software is capable of utilizing two different driver behavior models when simulating traffic. The manual suggests utilizing the Wiedemann 1974 model (Wiedemann, 1974) for urban simulation and the research team followed this suggestion. The Wiedemann 1974 model and other VISSIM behavior model factors provided by Park and Qi (2005) and used to calibrate these simulation models may be found in Table 5.4.

Table 5.4: Default and Calibrated VISSIM Driver Behavior Parameters

Parameter	Default	Calibrated	Model
Average Standstill Distance	6.6	12.6 feet	Wiedemann 1974
Additive Part of Safety Distance	3	5	Wiedemann 1974
Multiplicative Part of Safety Distance	3	5.3	Wiedemann 1974
Look Ahead Observed Vehicles	2	4	General Following
Maximum Look Ahead Distance	820	706 feet	General Following
Minimum Gap Time	3	4 sec	Priority Rules
Minimum Headway	16.4	65.6 feet	Priority Rules

One parameter that was not addressed by Park and Qi was the waiting time before diffusion. VISSIM occasionally has vehicles get into situations where a desired lane change or other behavior, such as yielding can cause a vehicle to stop in place for indefinite periods of time. Since stopped vehicles generate queues and block other vehicles, VISSIM tracks them for a time and if they remain deadlocked for longer than the waiting time before diffusion parameter VISSIM removes the vehicle from the network. Unfortunately, the queues that such vehicles leave behind are not magically corrected. This can lead to rather significant disruptions. The default value for waiting time before diffusion is 200 seconds. This was found to be too long. This time was lowered to one minute, which was found to be the best compromise between diffusing legitimate vehicles and not diffusing deadlocked vehicles quickly enough.

5.3 DATA COLLECTED

Table 5.2 details the distinct test cases created for each signal control system (time of day, traffic responsive, actuated, fast occupancy, slow occupancy and delay optimization) being evaluated. With each system being subjected to 108 test cases, large amounts of data have been collected. Each intersection generates twelve travel time and delay measurements and eight queue counters per test at a rate of one record each 30 simulation seconds and a raw delay entry per vehicle that enters the network. Even reducing these numbers to averages presents a staggering amount of data.

The data itself is stored by VISSIM in text files. The research team has written programs to read the raw files and upload the data to a database for analysis purposes. Millions of rows of data have been collected. Because of this volume of data, it is impractical to display even a small fraction of it in this report. Instead, a selection of charts showing some interesting results is presented here.

The first chart shows the impact of platoons on signal performance. Figure 5.5 shows the average vehicle-seconds of delay data for each movement at an actuated control intersection under random arrivals and strong platoons. Delay is measured in vehicle-seconds, the total number of seconds each vehicle waits, added together, so that small delays on high demand movements are accounted for with the same relative weight as long delays on low demand movements. The intersection in question is configured as a 2 lane approach main street with left turn lane and a 1 lane approach plus left turn lane cross street. The data was collected under the 600 vphpl main street and 300 vphpl cross street volume condition.

The impact of platoons on vehicle delay is quite clear in Figure 5.3. Delay decreases by over 80 vehicle-seconds for the east and west bound through movements. Likewise, delay is reduced for the cross street when it receives progression and platooning. Cross street delay was reduced by 15 vehicle-seconds on average.

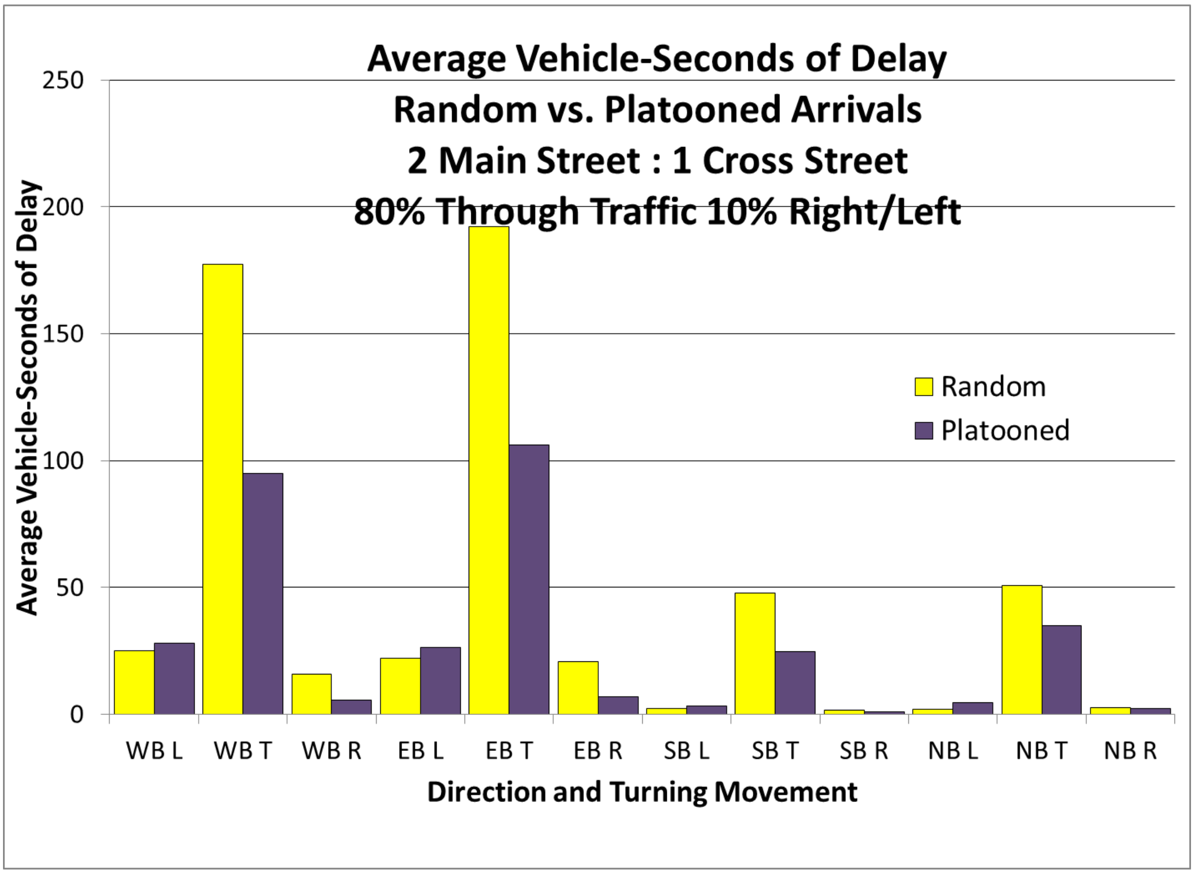

Figure 5.3: Average Vehicle-Seconds of Delay by Movement at 2:1 Intersection Under Actuated Control with 600:300 vphpl Input Volumes

The second chart, Figure 5.4, gives an idea of the performance difference between actuated control and fast occupancy based control algorithm. The test intersection and volume levels are the same as the previous intersection. For this comparison both systems are operating with platooned arrivals. The fast occupancy control strategy created by the researchers is able to adjust its cycle length and splits within relatively wide margins, which gives the system greater flexibility than the actuated system to respond to traffic arrivals.

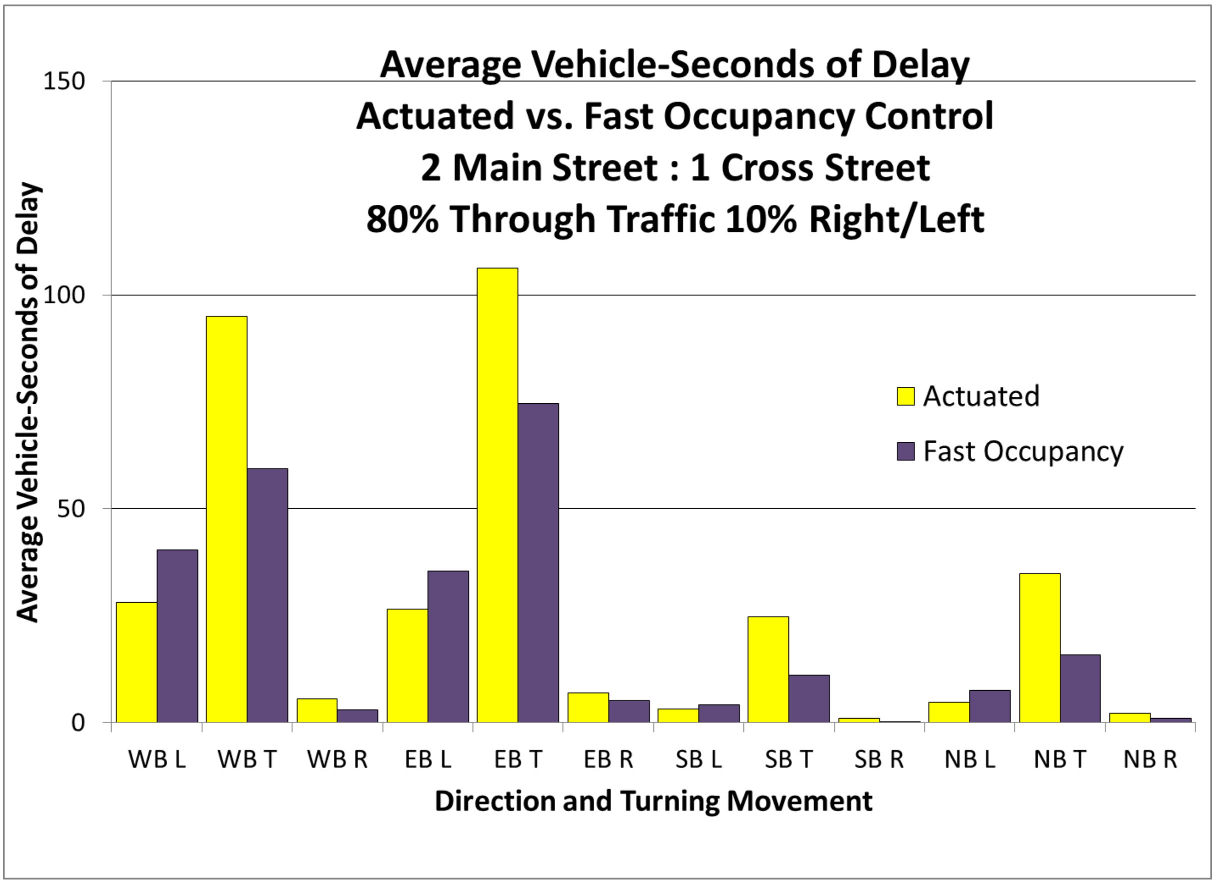

Figure 5.4: Vehicle-Seconds of Delay for Actuated Control vs. Fast Occupancy Algorithm Under Platooned Arrivals

The simulation data collected thus far is useful for two reasons. The first is that the research team can setup simulations to test model accuracy by providing exact conditions to test the models on. The second is that simulation data can be used to calibrate models when behavior is uncertain. It is for this reason that many of the test cases are near saturation. Intersections that are approaching saturation have the greatest unpredictability and the greatest need for accurate modeling.

5.4 PLANNING MODELS

5.4.1 Background Information

The primary goals of this research are the production of an analysis framework for practitioners to use in analysis of signal control systems and guidelines for the selection of advanced signal systems. Part of the analysis framework and the subsequent guidelines is a set of background models that aid in determining performance measures. These models, based on queuing diagrams and arrival and departure curves, begin with simple assumptions and then build successively more complex structures as needed to accommodate the behavior of complex systems.

The simplicity of the models' individual components helps keep complexity at manageable levels. For example, the delay model is based off of a conventional arrival and departure model. Figure 5.5 shows example deterministic arrival and departure curves with the height of the shaded area representing the number of vehicles that have arrived on the approach. The slope of the upper line indicates the uniform arrival rate, q_a, of vehicles on the approach. The lower line that originates at point r is the departure line, with its slope indicating the saturated discharge rate, q_s, of the approach. The vertical thickness represents the total queue length on the approach and the width of the shaded area indicates the delay experienced by an individual vehicle. In the figure, *r* indicates the termination of the phase's red indication and *C* represents the total cycle length.

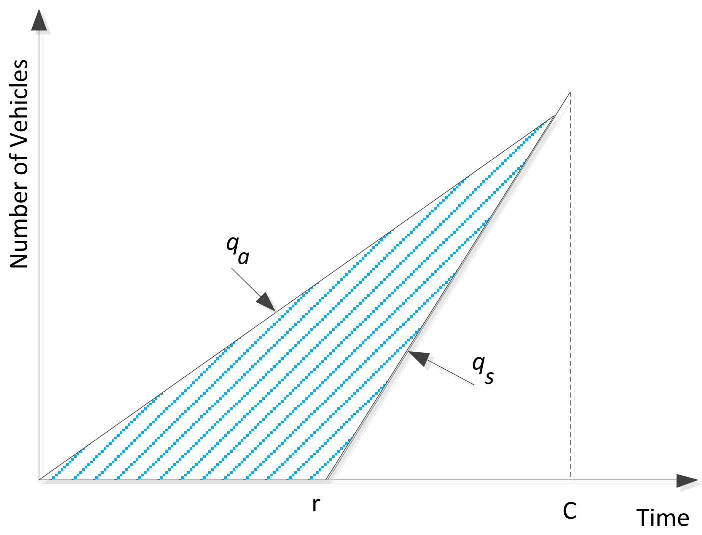

Figure 5.5: Arrival and Departure Curves with Uniform Arrival Rate

The simplicity of the models' basis belies their utility in analyzing advanced signal systems. The arrival and departure curves are not restricted to linear equations. They can also be probabilistic in nature to account for adaptive signal control systems and features such as conditional phase reservice. For systems, such as InSync, that rely on queue length and delay to choose the next phase, the queues and delays for each approach can be used to determine the next phase. Similarly, the proportion of the discharge line that is under the shaded area represents the proportion of green time that experiences saturated flow, which can be used to estimate occupancy which, affects systems such as ACS Lite and SCATS.

Similarly, features such as conditional phase reservice, which are probabilistic in their activation, can have their activation rate modeled based on when the queue line intersects the discharge line. The corresponding opposing through lane arrival and discharge curves can then be modified based on feature activation probability. Other factors such as coordination and platoons can also be modeled. A platoon arrival is simply a different arrival rate into the queue which can be represented by using different arrival curve slopes.

With the number of model extensions that have been designed and added to the base model, the model process would be unwieldy to execute by hand. Instead, the research team has been developing an Excel application to contain the analysis process. The overall process is shown in Figure 5.6. Users input basic traffic flow and intersection geometry data into the application and select operations parameters such as signal control strategies and system features. Estimated MOEs are then output for the user to evaluate.

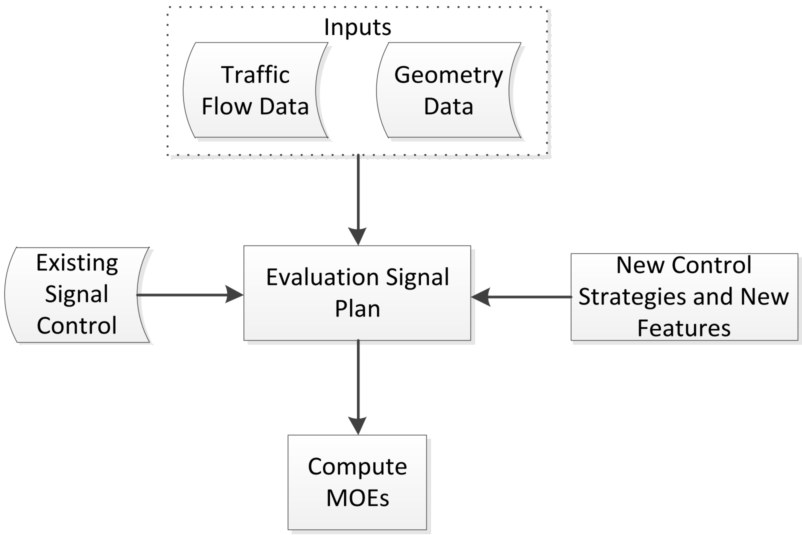

Figure 5.6: Analysis Process

5.4.2 Performance estimation based on Arrival and Departure rates

Vehicle delay can be estimated, both on an individual and on average basis, from the queuing diagram method shown in Figure 5.6. For an isolated intersection, assume that the vehicle arrival rate is uniform, as shown in Figure 5.6, then the area of the shaded triangle is the total delay in one cycle for that phase and the average delay for each vehicle can be defined as

$$\bar{d} = 0.5r \cdot (\overline{q_a}t)/(\overline{q_a}C) = 0.5r \cdot t/C \quad (5.1)$$

where r is the effective red time; *t* is the time needed to clear the queue in one cycle; $\overline{q_a}$ is the average arrival rate; and *C* is the cycle length. Assuming that the intersection does not congest, the total vehicle arrivals should equal the total vehicle departures. This gives us Equation 5.2.

$$\overline{q_a}t = (t - r)q_s \quad (5.2)$$

where q_s is the saturation flow rate. The departure flow rate, q_d, is assumed to be the saturation flow rate while a queue exists. After the queue has discharged, the departure rate will reduce to the arrival rate. Rearranging (5.2), the estimation of *t* can be

$$t = rq_s/(q_s - \overline{q_a}) \quad 5.3)$$

The total number of stops can be calculated from the number of vehicles stopped in the queue

$$N_s = tq_d = rq_sq_d/(q_s - \overline{q_a}) \quad (5.4)$$

The average number of stops

$$\overline{N_s} = tq_d/Cq_d = rq_s/C(q_s - \overline{q_a}) \tag{5.5}$$

The maximum queue length

$$Q_{max} = rq_d \tag{5.6}$$

The saturation for phase i

$$Sa_i = Cq_d/q_s(C - r) \tag{5.7}$$

For the coordinated intersections, the percentage of vehicles which arrive on green and can go through the intersection without any delay will be determined by how strong the coordination is. Assume that the percentage of vehicles passing through the intersection without stopping is P_{d0}. The average number of stops is then trivial to calculate

$$\overline{N_s}^c = 1 - P_{d0} \tag{5.8}$$

As shown in Figure 5.7, the shaded area is the total delay in one cycle, the average delay for each vehicle under coordinated conditions can be defined as

$$\bar{d}^c = 0.5r(1 - P_{d0}) \tag{5.9}$$

The maximum queue length

$$Q_{max} = rq_{ar} \tag{5.10}$$

where q_{ar} is the arrival rate during the red time. When the corridor is well coordinated, q_{ar} is much smaller than the average uniform arrival rate $\overline{q_a}$. Note that the saturated flow rate is the same as in the isolated intersection case.

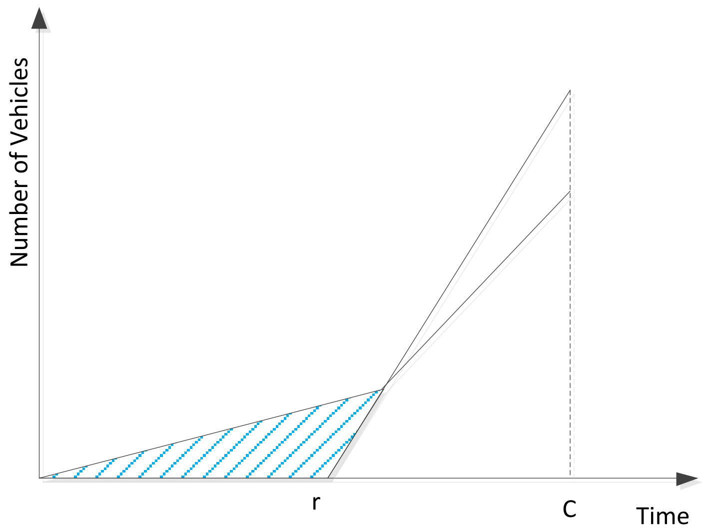

Figure 5.7: Arrival and Departure Queuing Diagram for a Coordinated Intersection

5.4.3 Model Extensions for Adaptive Systems

Actuated systems and adaptive systems, like SCATS and InSync, can skip phases when there are no vehicles waiting on that phase. This can complicate delay estimation and requires additional modeling to identify the probability of a phase being skipped. This adds steps and complexity to the analysis process.

When traffic volumes are low, the arrival pattern can be modeled as random arrivals with a Poisson distribution. Using this distribution, it becomes possible to quantify the probability of arrivals or no arrivals during a cycle. These probabilities can then be used to determine if a phase will be skipped in the modeling. For phases *i* and *j* the probability of no arrivals on both phases is

$$p_{ij} = \exp(-\overline{q_a}_i C) \cdot \exp(-\overline{q_a}_j C) \tag{5.11}$$

For a single phase to have no arrivals would simplify to $p_{ij} = \exp(-\overline{q_a}_i C)$. If *i*=3 and *j*=7, then the optimal cycle can calculated using the HCM 2000 methodology would be

$$C_{37} = 16X_c/(1 - \max(Sa_1 + Sa_2, Sa_5 + Sa_6) - \max(Sa_4, Sa_8)) \tag{5.12}$$

where Sa_i is the saturation rate for phase *i*; max is the maximum function getting the maximum value and X_c is the critical volume to capacity ratio as defined in Chapter 16 of the HCM 2000. The green time for each phase can be allocated based on the saturation rate. For example, the green time for phase 6 is

$$g_6 = C_{37} \cdot \frac{Sa_6}{Sa_5+Sa_6} \cdot \frac{\max(Sa_1+Sa_2,Sa_5+Sa_6)}{\max(Sa_1+Sa_2,Sa_5+Sa_6)+\max(Sa_4,Sa_8)} \tag{5.13}$$

After calculating a cycle length that reflects the actual cycle that the actuated or adaptive system will serve, it is possible to determine the delay, number of stops and other parameters as previously defined in equations 5.1 through 5.10.

5.4.4 Model Extensions for Conditional Left Turn Phase Reservice

For features, such as Conditional Left Turn Phase Reservice (CLTPR), the left turn phase, like phase 5 in Figure 5.8,can be served a second time when the opposing through movement gaps out.

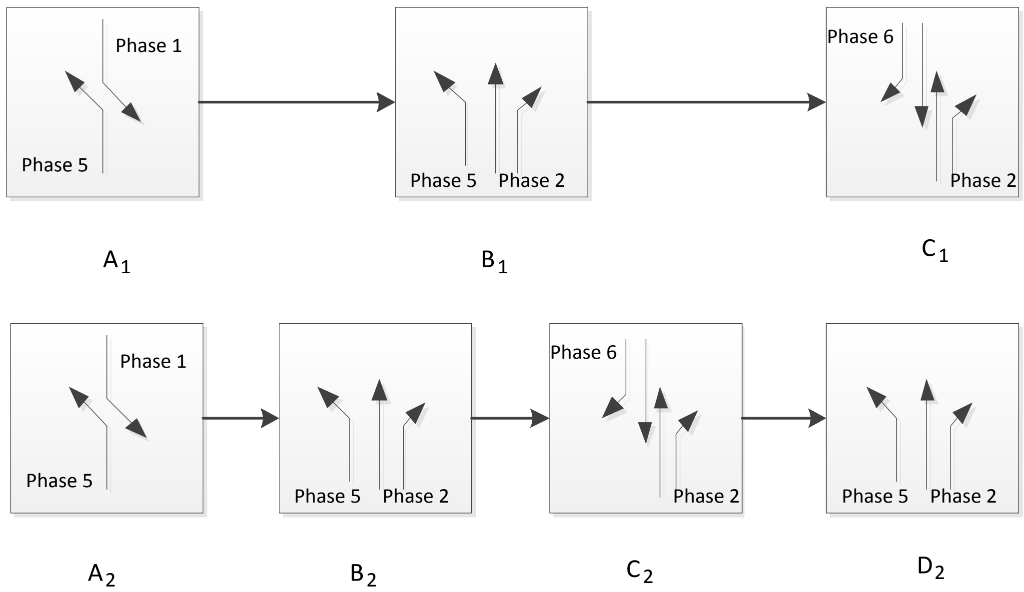

Figure 5.8: Traditional Actuated Control and CLTPR

A quick examination of CLTPR shows that it is more likely to trigger when volumes are directionally biased. Directionally biased traffic is more likely to cause conditions where one through movement requires significantly more time to serve than the other. The long service time on one through movement gives the other through movement an opportunity to gap out which allows the left turn concurrent to the heavy through movement to be served again.

Assuming the following:

- Phase 2 is the dominant through movement main street phase. That is Volume 2 > Volume 6 and by implication Volume 5 > Volume 1
- Green time allocation for the cross street phases is unaffected. Phases 3, 4, 7 and 8 are unaffected by phase 1 or phase 5 CLTPR
- The cycle length is unaffected by CLTPR

The delay experienced by phase 5 becomes

$$D_{L2} = \frac{1}{2} q_{a5} (1 - \frac{q_{a5}}{q_{s5}})(r_2^2 + g_2^2) \tag{5.14}$$

where q_{a5} is the arrival rate for phase 5; q_{d5} is the departure rate for phase 5. Figure 5.9 shows the conventional left turn delay and queuing case.

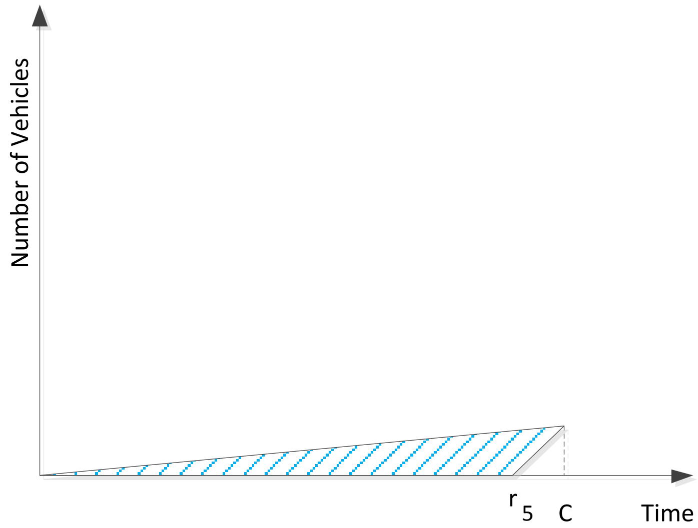

Figure 5. 9: Arrival and Departure Queuing Diagram for Phase 5 Under Traditional Actuated Control

For CLTPR, when the phase 5 left turn is served twice, the total delay for phase 5 is the shaded area in Figure 5.10 and defined as

$$D_{L1} = \frac{1}{2} q_{a5} (1 - \frac{q_{a5}}{q_{s5}})(r_2^2 + g_2^2) \tag{5.15}$$

where r_2 and g_2 are the red time and green time for phase 2. Note that the area of the triangles is smaller for phase reservice, indicating less total delay. The widths of the triangles are shorter indicating less individual vehicle delay and the heights of the triangles are lower indicating shorter queues.

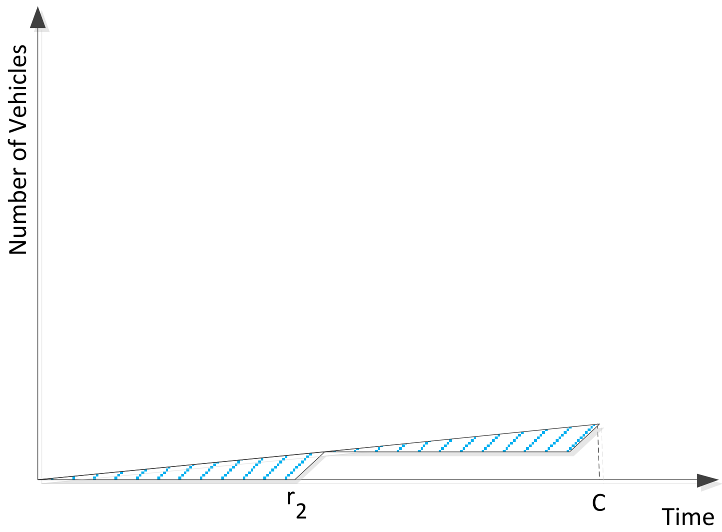

Figure 5.10: Arrival and Departure Queuing Diagram for Phase 5 Under CLTPR

The total delay for phase 6 under traditional actuated control is the shaded area in Figure 5.11 and defined as

$$D_{T1} = \frac{1}{2} q_{a61} r_2^2 + \frac{1}{2} q_{a61} r_2^2 \frac{q_{a61}}{q_{s6} - q_{a62}} = \frac{1}{2} q_{a61} r_2^2 (1 + \frac{q_{a61}}{q_{s6} - q_{a62}}) \tag{5.16}$$

where q_{a61} and q_{a62} are the arrival rate for phase 6 during the red time and green time respectively.

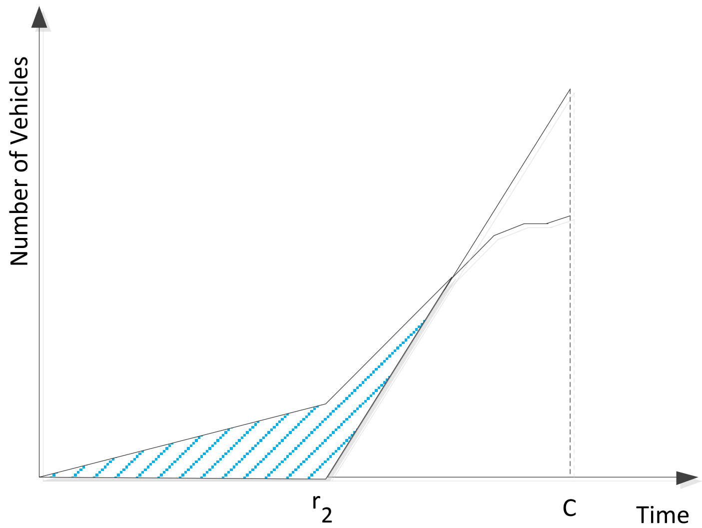

Figure 5.11: Arrival and Departure Queuing Diagram for Phase 6 Under Traditional Actuated Control

The total delay for phase 6 under CLTPR is the shaded area in 5.12 and defined as

$$D_{T2} = \frac{1}{2} q_{a61} (r_2 + \Delta t)^2 \left[1 + \frac{q_{a61}}{q_{s6} - q_{a62}}\right] \tag{5.17}$$

where $\Delta t = Y + Ar$ is the lost time when switching from phase 6 to phase 5. Note that under CLTPR, phase 6 can begin accumulating a queue before the traditional beginning of the cycle for that phase. This leads to increased individual and average delay. The question is whether the delay savings for phase 5 outweigh the delay penalties for phase 6.

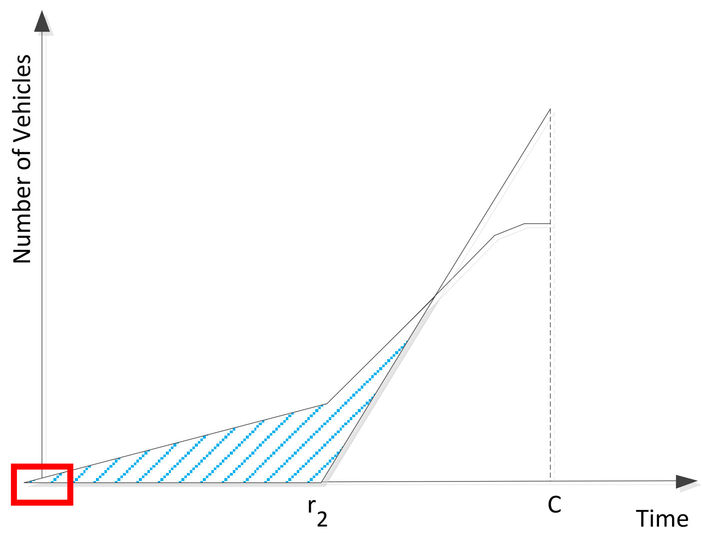

Figure 5.12: Arrival and Departure Queuing Diagram for Phase 6 Under CLTPR

For the other phases the delay is the same between traditional actuated control and CLTPR.

Assuming the following conditions for the main street:

- Only one left turn lane, and the saturation flow rate of the left turn lane is 1400 Veh/h/ln
- There are 3 through lanes for phases 2 and 6, and the saturation flow rate of the through lanes is1800 Veh/h/ln
- With coordination, q_{a62}=3q_{a61}
- 60% of green time is allocated to the dominant phase (phase 2) that is g2 = 0.6 C.

The estimation result is shown in Figure 5.13. The y-axis is the left turn volume and the x-axis is the opposing through volume. In area A, CLTPR has a smaller total delay and in area B traditional actuated control has a smaller total delay. One can conclude that:

- CLTPR tends to perform better when the left turn volume is higher; and
- CLTPR tends to perform worse when the opposing through volume is higher.

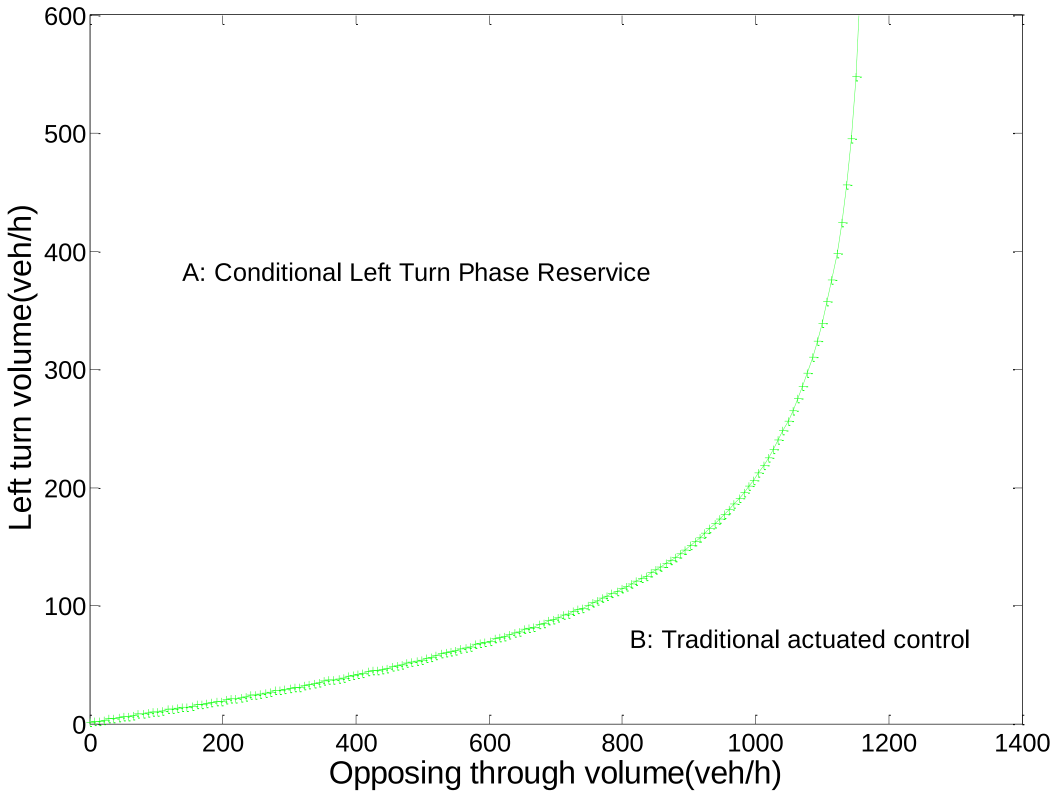

Figure 5.13: Application Conditions for CLTPR

5.5 PLANNING MODEL VALIDATION

The purpose of the simulation work, described previously, is to provide known and controlled data points that can be used in validating the models. Field data is useful in such an endeavor, but the number of unknown and uncontrolled factors can cause issues and make tracking down errors and incorrect assumptions more difficult. Figure 5.14 shows the operational concept of the model system. In this concept, the model's inputs can be broken down into four categories of data. The first is constants; these constants are fixed for a given set of conditions and must be predetermined. The second is geometric data such as the number and configuration of an intersection's lanes, saturation flow rates and other constant parameters that are associated with individual intersections. The third is cycle data that is tied to timing plans, feature selection and operational choices such as phase order, green time allocation, left turn treatments, etc. The final category is interval data. Interval data include volumes, turning rates, arrival on green percentage and other data that can vary from interval to interval. The models for each control system vary in specific assignment of variables to each group and so must be validated separately. For example, the model for fast occupancy can change its cycle length each cycle and so includes cycle length and green time in the interval data instead of in the cycle data.

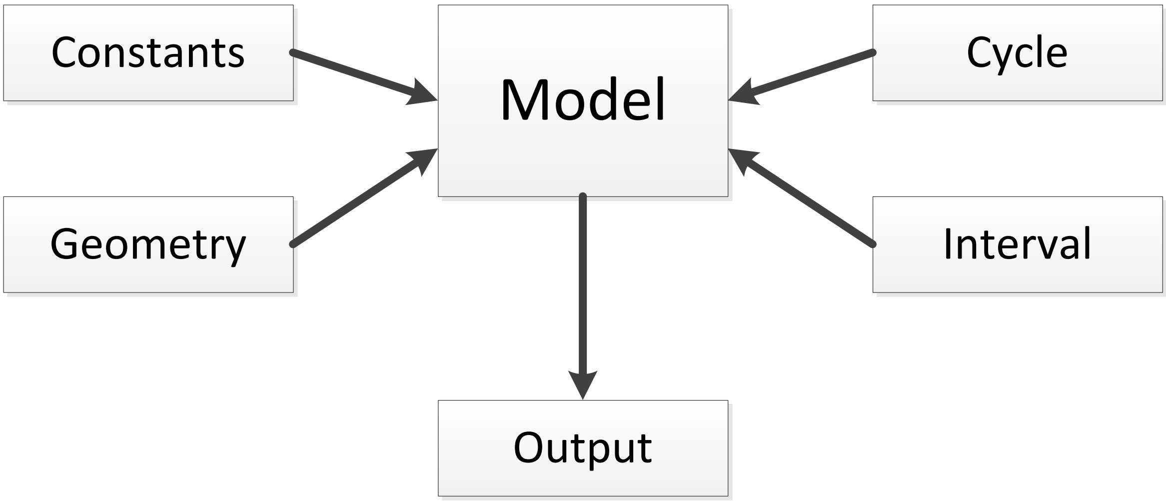

Figure 5.14: Model Operational Concept

It is important that the models provide accurate and representative data for analysis. In order to validate the models the research team compared the model outputs to the simulation output data. The following tables show the validation for the average number of stops by phase for the time of day control strategy applied to a 3:2 intersection under 600:300 vphpl approach volume (1800:600 vph approach volume) and 80%/10%/10% (T/R/L) turning movements under random arrivals (Table 5.5) and platooned arrivals (Table 5.6).

Table 5.5: Number of Stops by Phase for Random Arrivals

Random	Simulation	Model	Difference	Error (%)
Phase 1	1.86	1.22	0.64	34.50
Phase 2	10.94	11.86	-0.92	-8.41
Phase 3	0.43	0.45	-0.02	-5.00
Phase 4	4.54	4.29	0.25	5.59
Phase 5	3.59	1.51	2.08	57.91
Phase 6	10.36	11.05	-0.69	-6.63
Phase 7	0.48	0.44	0.04	7.95
Phase 8	4.32	4.18	0.14	3.21

Table 5.5 shows the average number of stops by phase for both the simulation data and the model output. The error values shown in the table are defined relative to the simulation data. The research team has defined 20% error as the acceptable margin of error for the models to be useful as planning tools. The percent error for Phase 1 and Phase 5 are much larger than 20% and are cause for concern. The research team examined the data and observed the simulations and determined that given certain random seeds VISSIM's randomly generated traffic was occasionally generating heavy traffic that would cause cycle failures. For Phase 5, in particular, three of the seven of the chosen simulation random seeds produced very high traffic flows for the left turns. The research team plans to correct this problem in two ways. The first is running an additional set of simulations with different random seeds to mitigate the impacts of outlying random seeds. The second is to increase the model logic surrounding cycle failure and queuing to alert users when output values may be suspect or need to be subjected to increased scrutiny for cycle failure. It should be noted that, in spite of the high error rates for Phase

1 and Phase 5 the overall error for the intersection is 16% and still below the 20% error threshold, though improvements can definitely be made.

Table 5.6: Number of Stops for Platooned Arrivals

Platooned	Simulation	Model	Difference	Error (%)
Phase 1	1.43	1.47	-0.05	-3.17
Phase 2	3.63	3.24	0.39	10.77
Phase 3	0.51	0.58	-0.07	-13.32
Phase 4	0.97	1.08	-0.11	-11.27
Phase 5	1.84	1.78	0.06	3.08
Phase 6	2.83	3.07	-0.24	-8.58
Phase 7	0.53	0.57	-0.04	-7.61
Phase 8	1.44	1.06	0.38	26.31

Table 5.6 shows the data for the same experimental conditions under platooned arrivals. Platoon arrivals are timed to arrive a few seconds after the green indication on the through movement so that they will pass through without stopping. Phase 8 shows a rather large percent error that is a combination of simulation random effects and the small total value involved. Upon closer examination, two of the seven random seeds produce traffic patterns that are almost perfect for stopping Phase 8 traffic.

For planning purposes, this level of accuracy should provide sufficient information and accuracy to achieve the goal of recommending a short list of systems for further consideration. The current level of accuracy is also sufficient to make recommendations about which features may be worth implementing at a given intersection. Given the quality of input data expected from tube counters, manual counts and intersections with tied together loop detectors, it is unlikely that the models will prove to be the limiting factor for accuracy.

6.0 EXCEL APPLICATION

In order to make it easier to use the models and improve convenience and accuracy, the models and extensions are being packaged into an Excel application. Currently, the application includes three components: data input (Figure 6.1), control strategy input (Figure 6.2) and individual intersection feature selection (Figure 6.3).

The data input screen allows users to input geometric data such as the number of lanes available to each phase, as well as pocket sizes for queuing calculations. Users can also enter saturations flow rates by phase. For coordination calculations, users are able to enter an assumed Arrival On Green (AOG) fraction to represent the quality of platoons achieved by the existing system.

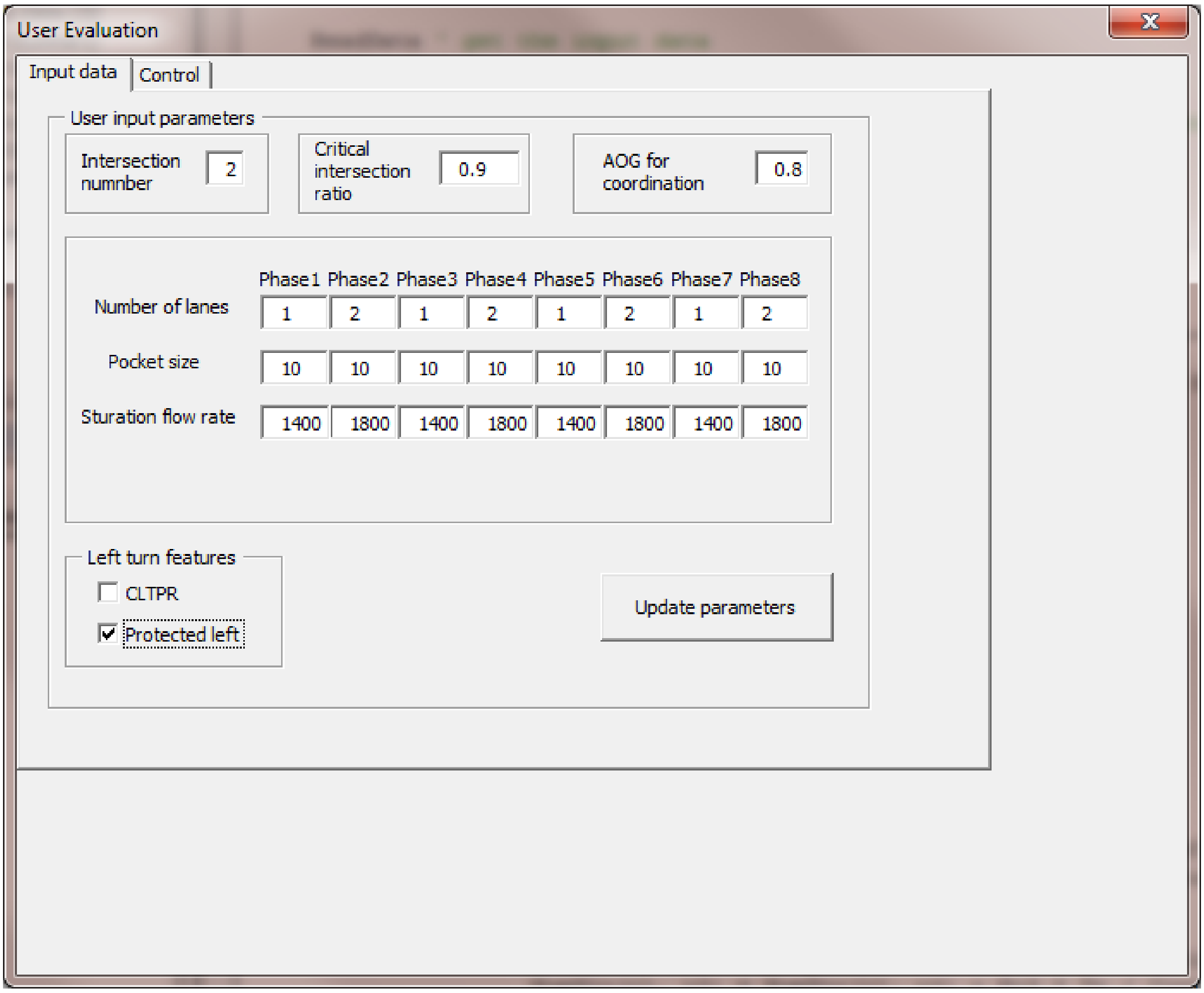

Figure 6.1: Input Data in Excel Application

After the basic data has been input into the system, users can then move on to selecting control strategies. Users can perform the evaluation on their existing system and also use the models described previously to examine what might be expected of another signal control system. This allows users to identify which systems are better suited to their conditions in the event they wish to change signal control systems. Alternatively, the tools may be used to determine if a signal control change is warranted based on performance.

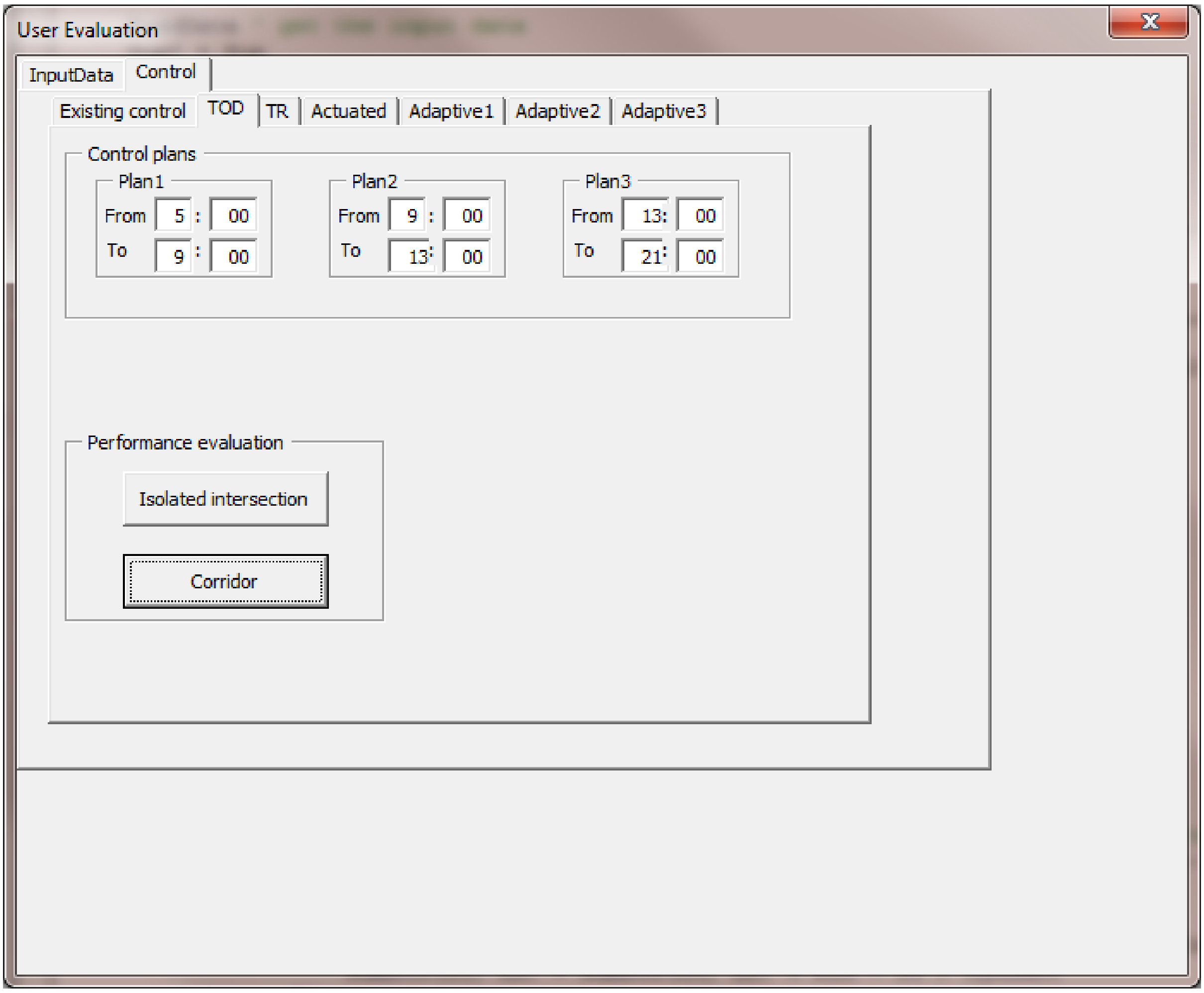

Figure 6.2: Control Strategy Input in Excel Application

The final step in the current version of the Excel tool is selecting features such as phase reservice from the available features. Features that are not compatible with the selected system are not electable. This component is intended to aid practitioners in selecting additional features of their existing system to enable as well as identifying useful features in candidate systems.

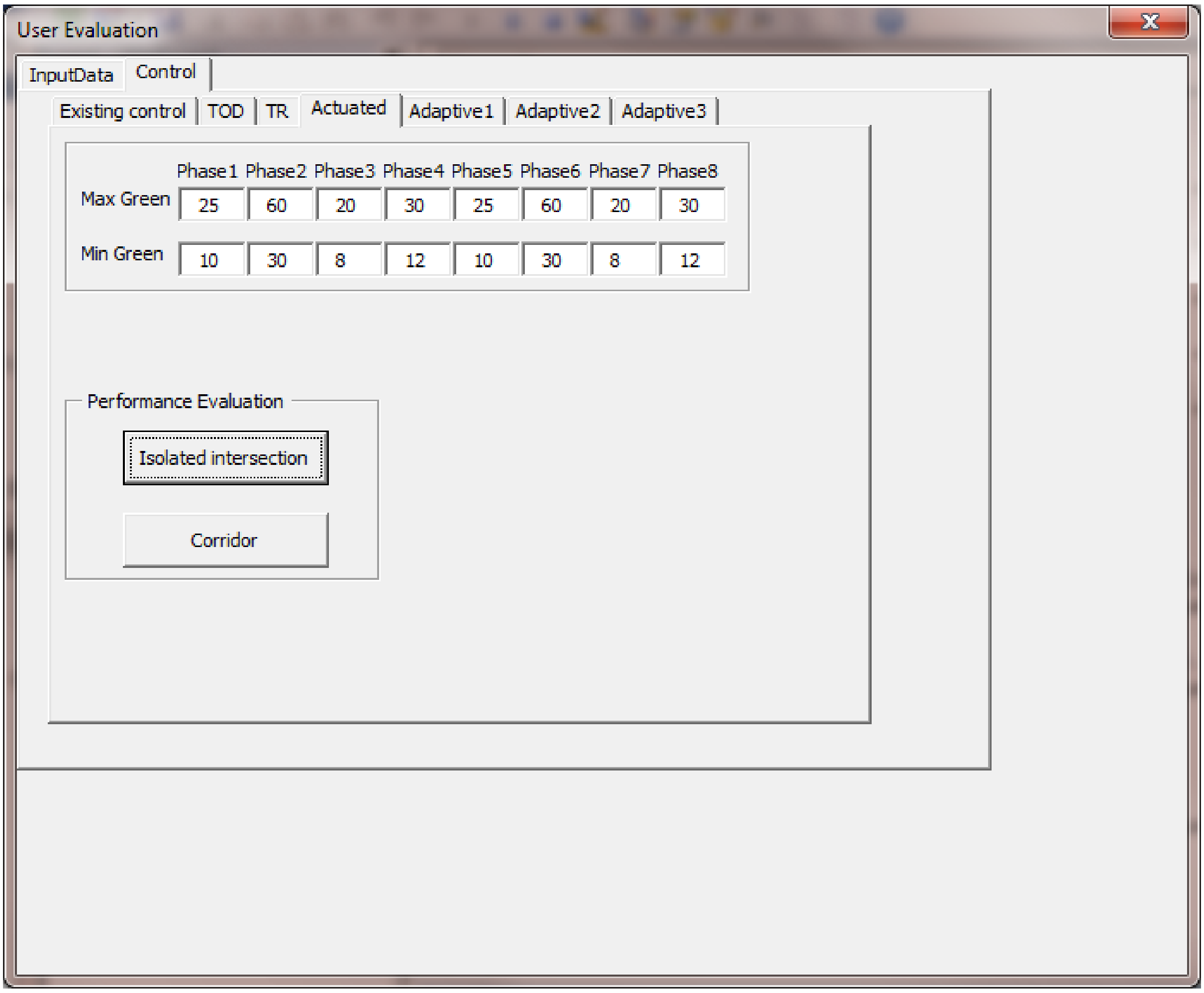

Figure 6.3: Feature Configuration in Excel Application

7.0 CONCLUSIONS

The project began with a thorough literature review. A review of the available literature found that most evaluation criteria and methodologies were based around before and after studies. Typically, an adaptive system would replace the existing system with performance measured before and after the signal system change. The overwhelming majority of system evaluations found were binary comparisons. These studies were found to be of limited use for several reasons. The first is that the comparisons are binary, with just two systems compared, limiting the research team's ability to generalize the results across multiple systems. Second, additional changes, such as adding lanes or other capacity improvements also occurred between the initial evaluation and the final evaluation. Finally, the pre-existing system was rarely re-timed prior to the evaluation, leaving many questions about the benefits seen in the adaptive evaluation. The basic question left by many of these system evaluations can be boiled down to whether the performance of the existing system would be comparable, given a re-timing and examination of unused existing features. This question features quite prominently in the Federal Highway Administration (FHWA) *Model System Engineering Documents for Adaptive Signal Control Technology Systems*.

To get a better picture of the state of the practice, the research team conducted a survey of traffic engineers asking them detailed questions about their practices, signal system compositions, and the challenges they face. Responses were received from engineers in 23 states and 2 Canadian provinces with wide ranges in system compositions, sizes and areas of responsibility. The results of this survey were informative. The majority of respondents indicated that they currently operated TS1 and 170/170E based systems and many were looking at upgrading to 2070/2070N based systems. Most comments indicated upgrades to software were being driven by central management system changes, communications compatibility, controller hardware compatibility and lack of support for legacy systems. In fact, system performance was rarely cited as a reason to upgrade systems.

It has been a very challenging task to compare quantitatively the performance of different traffic signal control systems. Existing studies focus mainly on case studies based on data collected from particular systems implemented at some specific locations, making it difficult to compare across alternative systems. To fulfill the goals of this research project, the research team developed a quantitative framework and its Excel implementation to quantify the performance of each major traffic control feature associated with the advanced traffic signal systems of interest. This framework combines existing mathematical models with simulation findings to enable quantitative evaluations on identified control features.

The selection of decision factors is crucial for the success of this analysis approach. The varied nature of the systems being evaluated makes determining MOEs fairly across all systems challenging. Through the literature review and preliminary analysis, a small number of MOEs, which include delay, arrival on green percentage, and queue length, were identified for further consideration.

Tremendous efforts have been made to simulate control features under various traffic and geometric conditions using VISSIM. Through the COM interface provided by VISSIM, the research team successfully simulated all the identified control logics using customized external control modules. Various data, including delay, queuing, speed, etc, were collected from the 4,536 hours of simulation experiments.

With the support of these simulation results and existing literature, the research team has been able to develop delay, queuing, and probabilistic models capable of handling various signal control systems, including time of day, traffic responsive, actuated, and adaptive systems. These models were calibrated with field and simulation data and enhanced by adding conditional and probabilistic elements to increase their applicability and accuracy. The models are capable of predicting vehicle delay, number of stops, and queuing.

The modeling effort and the project in general have been focused on developing a practical set of criteria for advanced traffic signal selection and an effective supporting tool for practitioners to easily follow the criteria. This supporting tool, which was developed in Excel, allows practitioners to make use of the models based on commonly available data types and without having to program the models or execute them by hand. The tool is intended to be easy to use and provide swift quantitative feedback on system performance.

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APPENDIX: SURVEY FORM

Survey for Advanced Traffic Control System Selection

Dear Sir or Madam,

We are performing research for the Oregon Department of Transportation on criteria for the selection and application of advanced traffic signal systems. Advanced signal systems include adaptive signal systems and the more complicated options available for conventional signal systems. As a part of our research, we are soliciting your input regarding your experiences with both conventional and advanced traffic control systems. We are interested in the traffic signal systems currently used by your agency and how you configure, operate and evaluate them.

The goal of this research is to provide guidance to traffic engineers regarding when to install advanced signal systems, what benefits to expect and what impediments might be encountered.

We would like to thank you for your participation in this survey. We will be happy to share survey results with you.

Sincerely,

Yinhai Wang, PhD
Professor and Director
Civil and Environmental Engineering
University of Washington
Seattle, WA98195-2700

Tel: 206-616-2696

Email: **yinhai@u.washington.edu**

Mailing Address:
STAR Lab
University of Washington
112 More Hall
Box 352700
Seattle, WA98195-2700

Would you like to receive a copy of the survey results?Yes_____ No_____

PART I: Background Information

I-1. Please provide the following:

Name: ___________________________________

Title: ___________________________________

Employer: ___________________________________

Email: ___________________________________

I-2. How long have you worked in traffic signal operations?___________

I-3. At your agency how many FTEs work on each of these aspects of signal operations?

______ Signal timing

______ Controller programming

______ Central system management

______ Signal/controller/detector maintenance

______ Other (please specify) ____

______ Total signal operations staff

I-4. What role do you play in your agency's traffic signal control systems management? (1-2 sentences)

I-5. What systems are you familiar with? (Check all that apply)

□ (Check□ (Check
□ (Check □ACSLite
□CInsync □nsyncek all that apply

I-6. When was the last time your agency changed its traffic signal control systems, and why? (1-2 sentences)

Part II: Current Signal Control Systems

II-1. How many signalized intersections are under your agency's supervision? ______________

II-2. Please indicate how many intersections are operated with the following systems:

_____ SCATS	________ Voyage
_____ Wapiti	________ ACSLite
_____ Insync	________ Other ________________________

II-3. Please indicate how many of the following controllers are used in your signal operations:

______ 170	______ TS 1
______ 170E	______ TS 2
______ 2070	______ ATC as TS 2 or TS 1
______ ATC 2070	______ Other (Please Specify)

II-4. What factors are the most challenging for your agency to deal with in traffic signal control? Check all that apply.

☐ Variable traffic demand	☐ Special events
☐ Emergency vehicle activity	☐ Traffic saturation
☐ Work zones	☐ Large vehicle effects
☐ School traffic	☐ Detector malfunction
☐ Signal coordination	☐ Field communications failure
☐ Pedestrian traffic	☐ Controller programming
☐ Weather	☐ Other (please specify)

II-5. What kind of procedures or guidelines does your agency follow for signal control software upgrades? (2-3 sentences)

II-6. What performance measures are generated by your current signal control software? Does your agency generate additional performance measures? What are they? (2-3 sentences)

II-7. Do you trust the performance measures generated by the traffic signal control software your agency is currently using? Why? (2-3 sentences)

II-8. What methods and/or software do you use to fine tune signal timings or optimize traffic signal control software configurations? (2-3 sentences)

PART III: Advanced Signal Control System Selection Criteria

III-1. Please pick the five factors you believe to be the most important in selecting a signal control system and indicate their order of importance from 1 (most important) to 5 (least important).

___ Stability and durability
___ Installation/construction cost
___ Hardware upgrade cost
___ Operating cost
___ Training cost
___ Intersection level of service
___ Number of vehicle stops
___ Queue length
___ Cycle failure
___ Increased equipment maintenance costs
___ Controller software compatibility
___ System communication requirements
___ Corridor travel time
___ Initial license acquisition cost
___ Signal status data logging and resolution
___ Adaptability to changing traffic conditions
___ Controller type/brand compatibility
___ Other (please specify) ____________

III-2. Please rank from 1 (most important) to 6 (least important) the following cost factors by importance for selecting an advanced signal control system.

___ Initial license acquisition cost (excluding yearly renewals)

___ Installation/construction cost (new sensors, communications, etc.)

___ Hardware upgrade cost (controllers, servers, etc.)

___ Operating cost (personnel, power, license renewal, etc.)

___ Increased equipment maintenance cost (additional equipment, servers, etc.)

___ Training cost (travel, consultants, seminars, etc.)

___ Other (please specify) ________________________

III-3. Please rank from 1 (most important) to 5 (least important) the system performance aspects your agency requires the selected advanced signal control system to improve.

___ Intersection level of service

___ Number of vehicle stops

___ Queue length

___ Cycle failure

___ Corridor travel time

___ Other (please specify) _______________

III-4. Please rank from 1(most important) to 6 (least important) the system characteristics that are the most important to your agency?

___ Controller brand/type compatibility

___ System communication requirements

___ Stability and durability

___ Adaptability to changing traffic conditions

___ Signal status data logging and resolution

___ Controller software compatibility

___ Other (please specify) ____________________________

III-5. If your agency is currently operating advanced signal systems, how do you evaluate system performance? (1-2 sentences)

III-6. If your agency is currently operating advanced signal systems, did you do pre- and post-implementation evaluations? Can you provide links to or copies of the original data and results?

III-7. If you have any other comments you would like to give the research team, please provide them below.