CRITERIA FOR THE SELECTION AND APPLICATION OF ADVANCED TRAFFIC SIGNAL SYSTEMS

Final Report

SPR 729

Oregon Department of Transportation

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by

Yinhai Wang, Professor
And
Jonathan Corey, Yunteng Lao, Kristian Henrickson, and Xin Xin
Graduate Research Assistants
Smart Transportation Applications and Research Laboratory
University of Washington
Seattle, WA 98195

for

Oregon Department of Transportation
Research Section
555 13th Street
Salem OR 97301

and

Federal Highway Administration
400 Seventh Street, SW
Washington, DC 20590-0003

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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. To assist ODOT's engineers in selecting when and which systems to evaluate more closely, a methodology frame work has been developed and implemented in a Microsoft Excel based evaluation tool. This framework uses queuing models and simplified control logic to estimate corridor performance. Selected additional features have also been enabled to allow engineers to evaluate the performance benefits that may be realized through enabling them with the existing systems.

Finally, to compare performance across different systems and different measures of effectiveness, the research team implemented a cost to benefit ratio calculation. This calculation encompasses performance measures produced by the evaluation model as well as external data regarding existing equipment, required upgrades, and additional costs such as those associated with retiming operations. By including as many cost factors as practical, the methodological framework and its Excel-based implementation may offer a means to make the selection of systems to evaluate as simple and straightforward as possible.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	G	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°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 to evaluate an adaptive or advanced feature system?
- How well do they perform?
- When should the systems be applied?
- What are the benefits of the systems when applied to specific corridors?

This project seeks to answer those questions by looking at information 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. This evaluation methodology is problematic because it requires implementing a system before it can be evaluated.

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. This leaves a basic question that 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) requirements for the systems engineering process documented in the *Model System Engineering Documents for Adaptive Signal Control Technology Systems* to be executed as a prerequisite for federal funding of adaptive signal control systems.

To get a better picture of the state of the practice, in April 2011 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.

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 prevents easy comparison between the systems. The disparate optimization goals of the various systems also make direct comparison more difficult because certain performance measures are targeted by the systems. For example, SCATS tries to maintain saturation at approximately 80%, so comparing systems on just saturation could put SCATS at a disadvantage. 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.

An ongoing challenge in this research has been the sheer number of possible intersection and corridor configurations. When one considers the combinations possible just from the number of approach lanes, left turn lanes and right turn lanes on each approach, the problem becomes quite complicated. The number of factors that influence traffic performance at an intersection and on a corridor level 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.

With the support of field and microsimulation observations and existing literature, the research team developed a probabilistic queuing model to support the analysis of various signal control systems, including time of day, traffic responsive, actuated, and adaptive systems. This queuing model is designed to produce common measures of effectiveness, such as delay, queue length, and saturation. The queuing model was combined with a logical intersection geometry model and various candidate adaptive signal control models to create a complete signal control system performance evaluation framework. 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 for varied signal control systems.

After performance modeling was completed, the next question to be answered was how to compare two systems with different operational goals and how to score different performance measures such as average number of stops versus average delay. The most generally applicable and equitable evaluation method the research team could devise to compare the various systems and performance measures was a cost to benefit ratio analysis. This analysis method allows multiple performance factors as well as important operational factors such as labor hours required to operate the system to be considered simultaneously. The cost to benefit ratio analysis method allows systems to be compared as complete systems; including installation costs, required hardware, licenses, operations requirements and performance characteristics.

The cost to benefit ratio analysis methodology is built upon a series of models. These models are a queuing model to estimate delay, queue length, and other performance measures; a logical model to represent intersection and segment configurations; and a signal control model to implement the various signal control strategies. The interaction of each of these models with input data produces the performance estimates used to generate expected benefits.

To aid practitioners in applying these models, an Excel based application has been developed. This application is designed to help practitioners input data into and configure the models. The application is designed to automate the model application process and format the model output data for use in the cost benefit analysis. To improve the applicability of the model and simulate the effects of random traffic, the traffic volume inputs and departure headways are randomized using the Monte Carlo Method and the gamma distribution. This randomization helps to truly test signal control system performance by changing the arrival and departure patterns the signal control logics must react to.

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 currently available 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 (UTC) for Federal Region 10. Since project inception, TransNow has ceased to operate and the Pacific Northwest Transportation Consortium (PacTrans) has taken over as the Region 10 UTC.

The goal of the project was to develop a planning level tool capable of indicating the suitability of a given traffic signal control system to a selected corridor. This planning level tool is designed to use readily available data, such as 15 minute volume and turning movement counts combined with available information regarding the various systems’ control logic. This was a challenging task for several reasons. First, the project touches on numerous subject areas, such as signal control methodologies, traffic flow theory and numerous practical issues. Second, predicting system performance at the planning level without requiring excessive information, calibration or programming from the users presents a major challenge. Third, typical predictive research uses microsimulation software for safety and operational analyses (*Yang et al. 2000 and Drummond et al. 2002*), but the stated project goal of developing a planning tool to be executed in Microsoft Excel precludes the research team from developing a microsimulation based tool.

The project covers six signal control logics, three conventional and three adaptive. The three conventional systems are fixed time, basic actuated and actuated with advanced features. These conventional control logics are available from multiple systems and vendors. It is possible for the same controllers and software to run more than one of these control strategies. Adaptive signal control systems of interest include Rhythm Engineering’s InSync system, the Adaptive Control System (ACS) Lite system and the Sydney Coordinated Adaptive Traffic System (SCATS).

ODOT is specifically interested in the capabilities of the Voyage software supplied by Northwest Signal Supply as they compare to existing Wapiti W4IKS software installations and adaptive systems. This interest stems from the fact that ODOT has purchased a statewide license for the Voyage software making it “free” for ODOT to use. An additional consideration in the interest regarding the performance of Voyage is the Federal Highway Administration’s (FHWA) Systems Engineering guidelines, which must be followed if federal funds are used in the system deployment. Systems engineering requires agencies to examine enabling or disabling existing system features before pursuing system replacement (*FHWA 2012*). This makes evaluation of the performance of Voyage as compared to other candidate systems of clear interest to ODOT.

As a means of narrowing the focus on this broad topic of signal operations, performance evaluations, measures of effectiveness, costs, and numerous other subtopics, it is helpful to distill the questions posed by this research. These questions include:

- What are the primary operational and system challenges faced in the field?
- How is performance measured?
- How can systems that produce different data and have different operational goals be compared?
- What are the constraints that need to be considered during signal system selection?

The research team began by conducting a literature review looking at the operation methodologies used by each of the considered control systems, existing comparison studies and identifying common Measures Of Effectiveness (MOEs) as a starting point for answering the questions posed by this research. This information may be found in the literature review in Chapter 2.

While a respectable volume of literature exists for some aspects of the project, there are several areas where academic literature and professional concerns may not overlap or are not current. The relative rarity and new nature of some systems may also make literature scarce. To mitigate these issues and attempt to more tightly identify how systems are monitored and evaluated in the field, the research team conducted a survey of transportation engineers to identify the issues they face and how they evaluate their systems. The findings of this survey are presented in Chapter 3.

An important part of the modeling and performance estimation process is to understand how each system behaves and how to estimate performance. The research team undertook a series of simulation experiments to test implementations of the various signal control strategy logics. The simulation experiments also looked at ways to measure performance. One set of simulation results is detailed in Chapter 4.

Based on the results of the literature review and the survey, the research team developed a modeling framework to evaluate signal control system performance. This model was designed to be capable of supporting multiple signal control strategies while being able to report relevant MOE information for each system. The details of this model are discussed in Chapter 5.

Selecting a model upon which to base the evaluation framework is only the first step in producing an evaluation framework. There are numerous conditions, parameters and restrictions that any given intersection and signal control system operates under that must be fed into the model or used to control model inputs and outputs. Because of limitations in Excel, from model resolution and due to proprietary algorithms for several of the systems of interest, the research team implemented simplified versions of the adaptive algorithms. Because these simplified algorithms only approximate the intended systems, instead of replicating their complete logic, the research team decided to rename the control algorithms to prevent misrepresentation of the intended systems. These and other aspects of the evaluation framework are covered in Chapter 6.

An intermediate goal of the project is to develop a methodology for the selection of a signal control system. In order to compare systems across wide operational conditions and with different operational goals, it was necessary to select a common comparison standard. The research team decided that a cost to benefit ratio would be the most applicable comparison method. The details of the cost to benefit ratio calculation may be found in Chapter 7.

Developing an operational model and comparison methodologies were intermediate steps to the ultimate goal of developing an application capable of quantifying a given control systems' impact. The Excel application builds upon the model discussed in Section 6 and the evaluation framework presented in Section 7 to create a complete system. More details can be found in Chapter 8.

This research identified a number of considerations that do not necessarily fall into a performance category. Other considerations may not have a quantifiable cost to be considered in the cost to benefit analysis. These considerations are discussed in Chapter 9.

Finally, this research project has covered several large topic areas. During the course of the research project, several interesting conclusions have been reached. A number of opportunities for future research and development have also been identified. These are presented in Chapter 10.

2.0 LITERATURE REVIEW

The first step in preparing installation guidelines and evaluation criteria for conventional and advanced signal systems is to review existing evaluation methods, selection criteria, system manuals, 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*). This 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. System evaluations and comparison studies will be summarized at the end of this chapter.

2.1 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, proprietary control algorithms are generally not publicly released, limiting accurate implementation in simulation models. Therefore, the results may not be representative of actual system performance, particularly where advanced features are concerned.

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.

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. These difficulties are compounded by the differences in data reported by each system. 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 at one intersection or on one corridor, sufficient technical details of the algorithms or significant vendor support are required for correct implementations. An additional consideration of simulation and HITL simulation techniques is the applicability of such methods across multiple corridors and the calibration efforts required to calibrate a system to each corridor.

The research most directly relevant to this project may be the work done by Mudigonda et al. (*2008*), in which a decision support tool was developed to evaluate different adaptive control strategies on transportation networks. The tool is based on a Geographic Information System (GIS) base with rule based logic for evaluating the various signal control systems. Mudigonda et al. had difficulty with the lack of readily available signal control logic for proprietary systems. Their solution was to program logic into their system that was similar to the adaptive systems being evaluated.

2.2 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 Chapter 3.

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, responses were fairly evenly split between those that indicated they did not use system derived performance measures and those that indicated they did use them. Even more importantly, a majority of respondents indicated they did not trust the system generated outputs. This lack of trust puts even more pressure on agencies to use simple and proven performance measures.

From the literature review of evaluation methods and the survey results, transportation agencies are found to share common views on traffic signal system selection criteria and hence the small subset of selection 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.

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, 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 variants called Tesla and Fusion that will allow it to include existing detection to supplement video detection (*Rhythm 2012*).

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 corresponding cabinet configurations so long as communications are available and stable and the SCATS-specific firmware is loaded onto the controller (*Lowrie 1992*). InSync has fewer inherent hardware limitations because the system has its own proprietary control box, see Figure 2.1, hosted in the same cabinet for decisions and simply uses the existing controller hardware as a means of controlling the signal lights (*Rhythm 2012*).

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

Figure 2.1: InSync processor box

2.3 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 Northwest Signal Supply'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*), and has recently been adapted for the 2070(L). ODOT is replacing 170/W4IKS implementations directly with 2070/Voyage as part of their system modernization.

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.

2.3.1 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, "advanced actuated control" refers to Voyage implementations taking advantage of some or all of these advanced features.

2.4 ADVANCED CONVENTIONAL SIGNAL CONTROL SYSTEM IMPLEMENTATIONS

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 (currently licensed by ODOT), 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*).

2.5 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 fixed timing plans by 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. SCATS and InSync are currently deployed in Oregon.

2.5.1 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 control. 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 a high degree of saturation (green time utilization) in a coordinated group of signals.

The SCATS system adapts its phase splits according to traffic conditions. In the words of the Roads and Traffic Authority (*2011*), "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." 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.

2.5.2 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).*

2.5.3 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 (see Figure 2.1) in the control cabinet to perform the adaptive calculations based on its own video sensor inputs and network data from other intersections in the system and then commands the existing controller to activate the desired phases.

2.6 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 this 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 differences in 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 by the previous system in 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 pre-existing 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 with adaptive systems greater than ten to fifteen percent in any given performance measure.

2.6.1 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 permitted 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.

2.6.2 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 Table 2.4, Table 2.5, and Table 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 corridor 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 2.5and travel speed in Table 2.6 to more closely match northbound traffic.

2.6.3 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*).

2.7 OREGON ADAPTIVE SIGNAL CONTROL EXPERIENCE

2.7.1 InSync

City of Hillsboro and Washington County installed InSync on a 1.7 mile section of Cornell Road from Butler Street to NE Brookwood Parkway in Hillsboro, OR as a pilot of the InSnyn technology. The pilot included 9 intersections along a busy suburban corridor and was funded through a Department of Energy ARRA grant. Hathaway et al. (*2012a*) performed an evaluation of the new installation. Prior to the installation of InSync, the existing time of day system was retimed to enable a fair comparison of the existing system and the InSync installation.

The evaluation found that corridor travel times improved in both directions during the AM peak period and the midday off peak period. The PM peak period showed significant eastbound improvement (49 second reduction) with a very small reduction (3 seconds) in westbound travel time.

One caveat noted for the travel time measurements is that eastbound delay measurement may have been impacted by the sampling location which did not capture delay incurred while waiting for the eastbound tunnel. The authors noted that eastbound delay was likely overestimated by 5 to 10 seconds. Delay at three sampled intersections increased slightly overall. Overall, the InSync system represented an improvement in operations over the existing time of day system.

2.7.2 SCATS

As an additional component of the Oregon DOT's adaptive signal control systems testing two SCATS installations were implemented, one on the Tualatin-Sherwood Road and the other on US 97 and OR 126 at Bend, OR and Redmond, OR. The Tualatin-Sherwood Road installation begins at Teton Avenue and terminates at I-5. The US 97 installation stretches from Bend, OR (2 isolated intersections)to Redmond, OR (4 Intersections). The OR 126 installation is co-located with the US 97 installation in Redmond, OR. The OR 126 installation consists of a pair of intersections on a couplet of one way streets that intersects US 97 and two additional intersections beyond the one way couplet. The sites, Tualatin-Sherwood Road and US 97/OR 126, were last retimed in 2010 and 2008, respectively.

The Tualatin-Sherwood Road corridor serves commercial and light industrial areas off of I-5 including businesses such as Kmart. Hathaway and Urbanik (*2012*) found that travel times decreased by approximately ten seconds for both east and west bound traffic in the AM peak, approximately 30 seconds each direction in the non-peak, and by 23 seconds for westbound traffic and 50 seconds for eastbound traffic in the PM peak. Total intersection average delay for selected intersections changed less than ten seconds, except for a 29 second average delay reduction at Martinazzi Avenue.

The analysis of SCATS operations on the Tualatin-Sherwood Road revealed a number of important trends. First, SCATS ran at generally higher cycle lengths than the preceding time of day system. Second, SCATS had been set up to preferentially serve the mainline over side street movements, increasing delay for side street movements and reducing the level of service ratings from D to E for some movements during the AM peak period. Third, SCATS made improvements in mainline progression through its adjustments of offsets. Some of the improvements were quite remarkable with reductions in mainline phase failures from over 40 per hour to fewer than 10.

Additional lessons were learned regarding the Teton Avenue intersection, which generally operated independent of the main corridor. Because of the proximity of a UPS distribution center, a high minimum green time was set to prevent gapping out of the side street phase when trucks were present. During other times, this resulted in unnecessary time allocation that reduced efficiency at the intersection. After the analysis, Washington County staff adjusted the system to use advance detection to address truck traffic issues. Overall, Hathaway and Urbanik (*2012*) found that SCATS is most appropriately applied to high volume corridors, based on their analysis of which intersections saw improvements in operations.

The evaluation for the Bend and Redmond SCATS installations Hathaway et al. (*2012b*) was a little different from other evaluations in that it included an analysis of traffic during the Deschutes County Fair. This evaluation looked at the AM off peak period, midday period, PM peak period and the Deschutes County Fair. During the AM off peak period SCATS slightly increased travel times, 4% westbound and 2% eastbound, along OR 126, but also significantly reduced the cycle length from 80 seconds to 40 seconds. During the midday period SCATS resulted in minor improvements (3%-6%) in corridor travel times, but did so by reallocating cycle failures from mainline movements to side streets. PM peak period improvements to travel time were more significant with westbound OR 126 experiencing a less than 1% increase in travel time versus decreases of 6-9% for the other travel times.

Operations during the Deschutes County Fair are perhaps the most interesting. The travel times on US 97 decreased by 13% on NB US 97, 14% on SB US 97, 5% on WB OR 126 and 9% for EB OR 126.

Overall, Hathaway et al. (*2012b*) found that the SCATS system allocates more time to the mainline, potentially at the expense of side streets. They also commented on the significant upfront costs in financial terms and staff time. Other observations by the research team indicated that having engineering staff in charge of the SCATS servers rather than IT is advantageous and that working with the vendor staff (TransCore) during setup makes maintenance easier in the long run.

2.7.3 General Observations

All three of the test installations resulted in per intersection costs near $50,000. Each evaluation also made particular note of detector quality being important to the success of the system. The various corridors seem to see average improvements on the order of 5-10% with peak improvements of approximately 12-14%. Both SCATS and InSync may trade increases in side street and minor movement delay for mainline performance due to the timing policies selected for implementation.

2.8 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 3.1 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 3.1). Survey respondents had responsibility for a wide range of signal system types and sizes. System sizes ranged from 35 to over 6,000 signalized intersections as shown in Figure 3.2. 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.

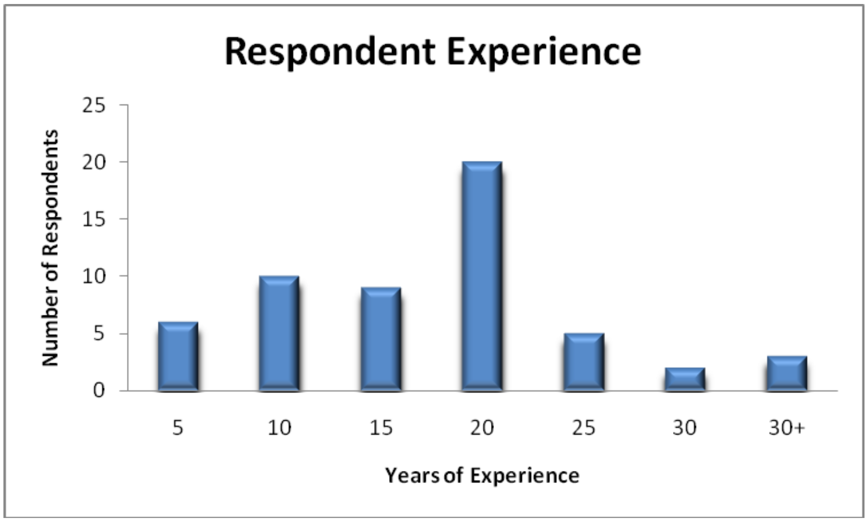

Figure 3.1: Experience level of respondents

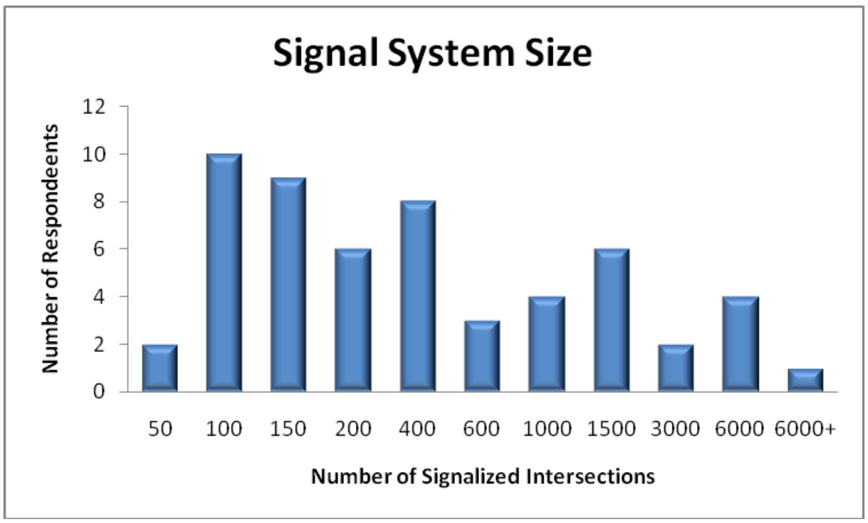

Figure 3.2: Size of signal systems administered by survey respondents

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 i2, TACTICS, Street Wise, 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) (*NTCIP 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 Table 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 forty-one and forty-nine 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 almost 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 can 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 criterion 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 explains 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 generally more expensive and requires equipment, software, and/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 within category rankings presented in Table 3.4, Table 3.5 and Table 3.6 show the rankings for each criterion group and the criterion 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 criterion has been ranked highly because of current problems or because of its import in selecting a new system.

While there were differences between the within category rankings and the aggregate criteria rankings, only a few differences 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. Communication 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.

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 received no information from their systems, did 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 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. 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).

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.

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 COMMENTS

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 SIMULATION

One of the challenges to implementing the evaluation methodology is to recreate the various signal control logics and ensure they work. Some of the signal control logics are complicated enough that, even if the proprietary algorithms were available, it would be impractical to implement all of their features in an Excel application. This is particularly true for the adaptive algorithms. The goal of implementing the various strategies in simulation was to find the minimum required feature set necessary to replicate the control logics.

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 were needed to implement these control features for simulation experiments. The research team used Microsoft C# and .NET framework 4.0 to 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 as demonstrated by Zhang et al. (*2008*) and Zhang el al. (*2009*).

4.1 EXPERIMENTAL DESIGN

4.1.1 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 4.1.

Table 4.1: 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. However, 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 are identified as described in the subsection below.

4.1.2 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. Including these elements in the simulation would also make the simulation less general and transferable. With these limitations, 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 geometrically.
- Vehicle traffic dominates intersection performance.

The goal of these simulations is to ensure that the algorithms used to represent each control logic function as intended. Some of the logics like fixed time control, are quite simple and easy to implement. Conversely, the algorithm representing InSync, proved to be challenging to implement in a believable manner. Specifically, getting the detection scheme to approximate InSync's video based queue detection and delay estimation algorithms proved to be significantly more difficult than the more conventional detection strategies used by the other systems.

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 to a reasonable number. 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 4.2 shows the factors modeled and the specific values tested.

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. (Note that a simplified pedestrian logic is included in the Excel application.) 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. Looking at the use case for the Excel application as a planning tool, it was deemed unlikely that engineers would have sufficient data to accurately account for access point traffic during their preliminary analyses. 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.

Table 4.2: 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 4.2 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, in the order of through traffic, right, and left. Figure 4.1 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 4.3.

Table 4.3: Test Conditions

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

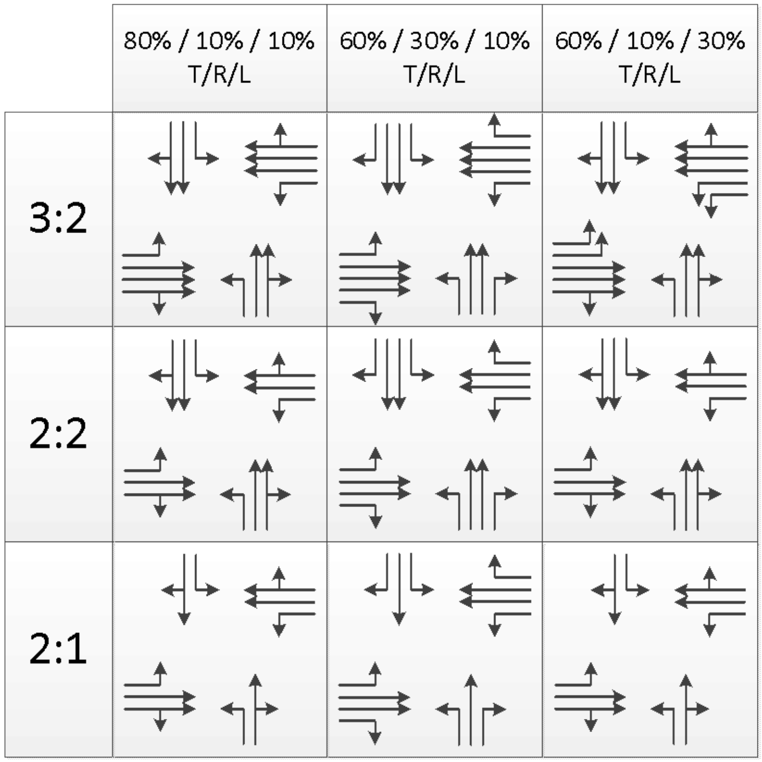

Figure 4.1: Lane Configurations by Approach Configuration and Turning Movement Bias

4.1.3 Simulation Notes

The research team pursued official simulation software for each of the various systems. VISSIM incorporates signal control logic functions capable of simulating fixed time and actuated control. VISSIM Simulation packages exist for SCATS and ACS Lite, but not for InSync. The research team pursued these simulation packages, but the costs to implement them were prohibitive and the restrictions inherent to their use were unacceptable. For Example, the SCATS simulation package effectively requires a total system implementation with central server, central system license and vendor configuration for each intersection. To keep all of the system evaluations on common ground, each of the control logics was implemented using C# and the COM, even though fixed time and actuated control could be implemented through VISSIM.

4.2 VISSIM MODEL DEVELOPMENT

4.2.1 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 4.1. 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.

4.2.2 Data Collection

Since the main focus for simulation is the collection of data to supplement field data for use in calibrating the queuing and evaluation 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 in this case since the other measurement systems have their own quirks.

4.2.3 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. Note, that the intersections were configured for a design speed of 35 mph.

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 4.2. It consists of ten 20 foot long detectors in each lane. Because InSync uses video detection to estimate queues there are a number of potential detection issues regarding camera viewing angles, camera height, apparent vehicle size and other video detection error related factors such as occlusion that can't be adequately represented in simulation.

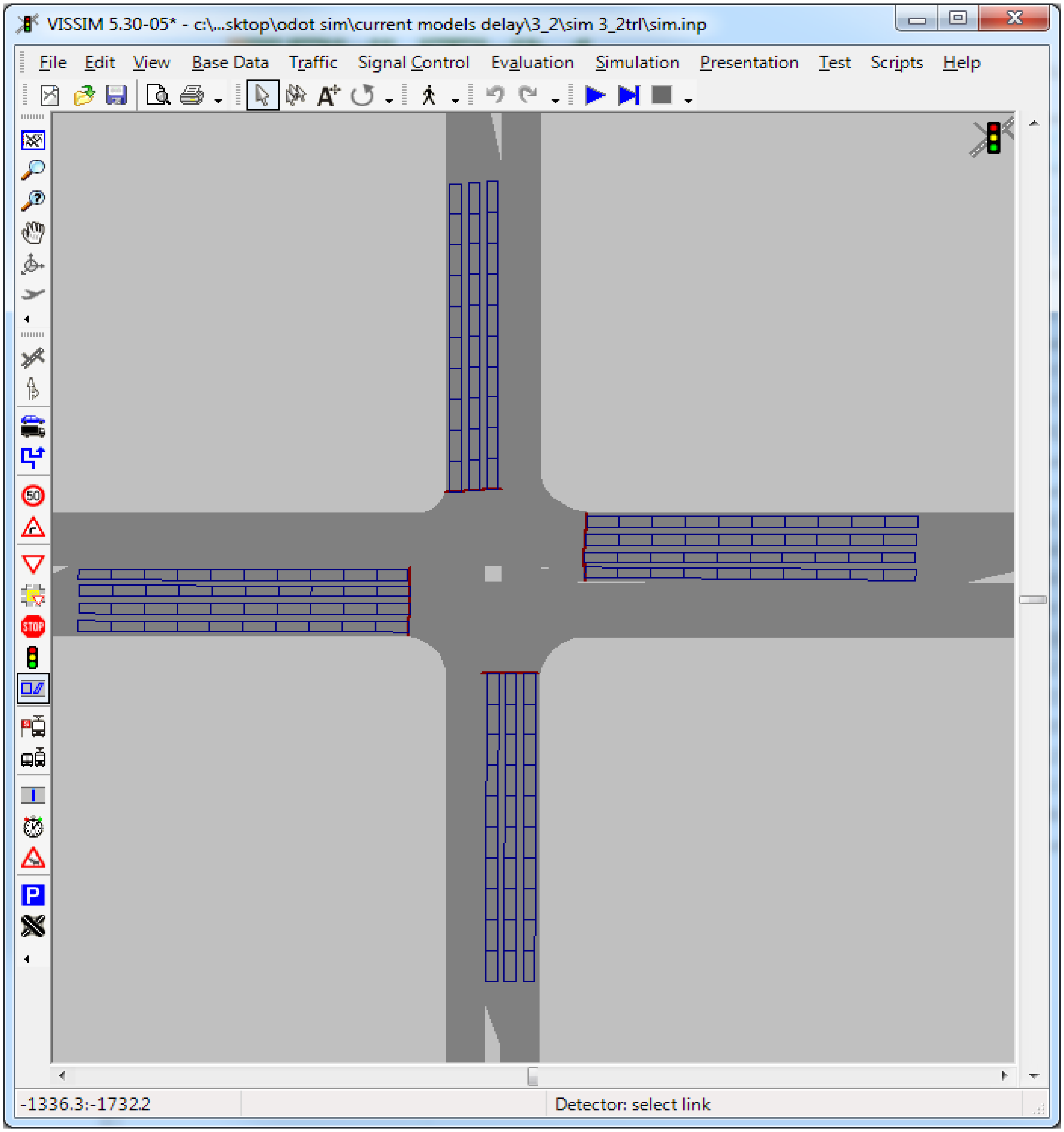

Figure 4.2: Detector Placement for Delay Optimization Strategy

4.2.4 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.

4.2.5 Travel Time

Travel time is measured by 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.

4.2.6 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.

4.2.7 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 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 4.4.

Table 4.4: 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 (*2005*) 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. This most commonly occurs with permissive turns where a vehicle stops and then can't accelerate fast enough to make it through gaps in oncoming traffic. 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.

4.3 DATA COLLECTED

Table 4.2 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 4.3shows 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 4.3. 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.

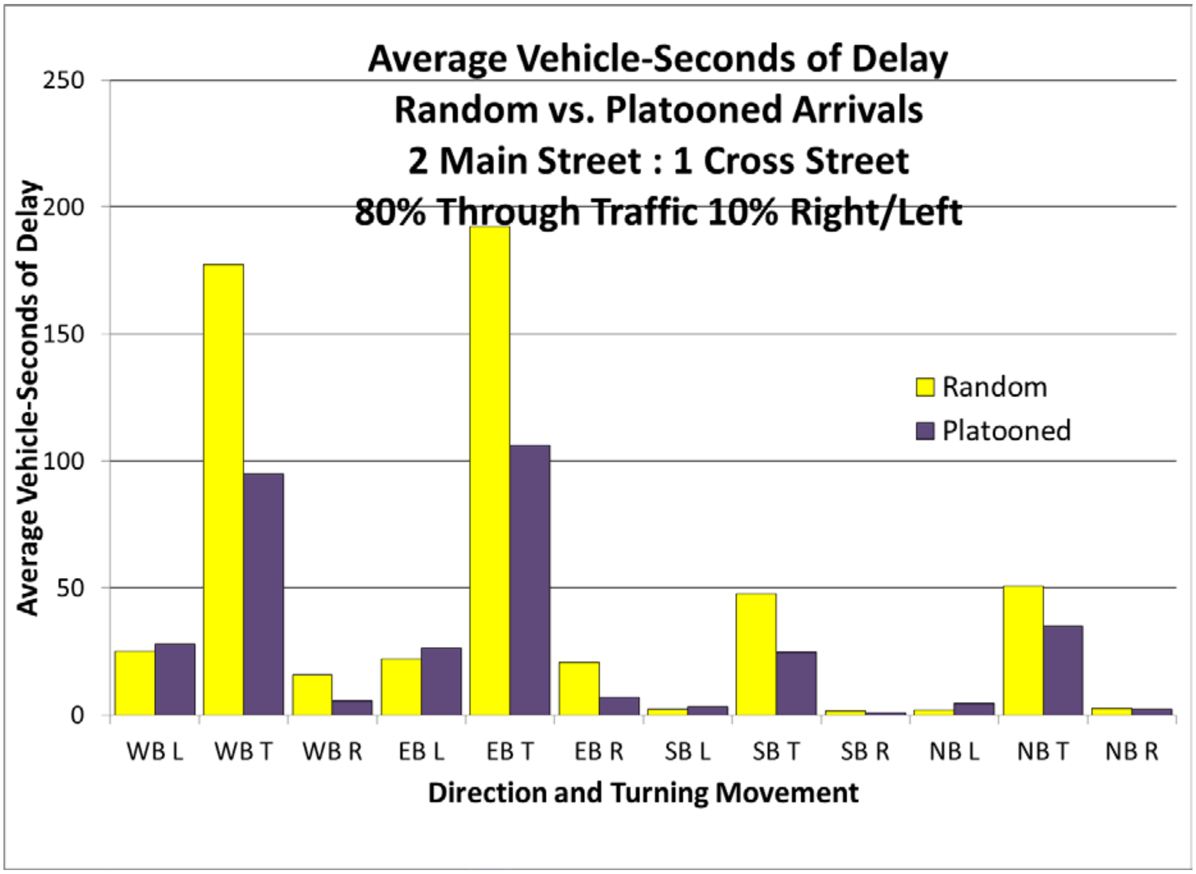

Figure 4.3: Average Vehicle-Seconds of Delay by Movement at 2:1 Intersection Under Actuated Control with 600:300 vphpl Input Volumes

Figure 4.4 gives an idea of the performance difference between actuated control and the SCATS-like 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. An examination of the two algorithms showed that fast occupancy gained its performance benefits from being able to adjust its maximum times to serve peaks in demand. This resulted in fewer cycle failures and the commensurate delay.

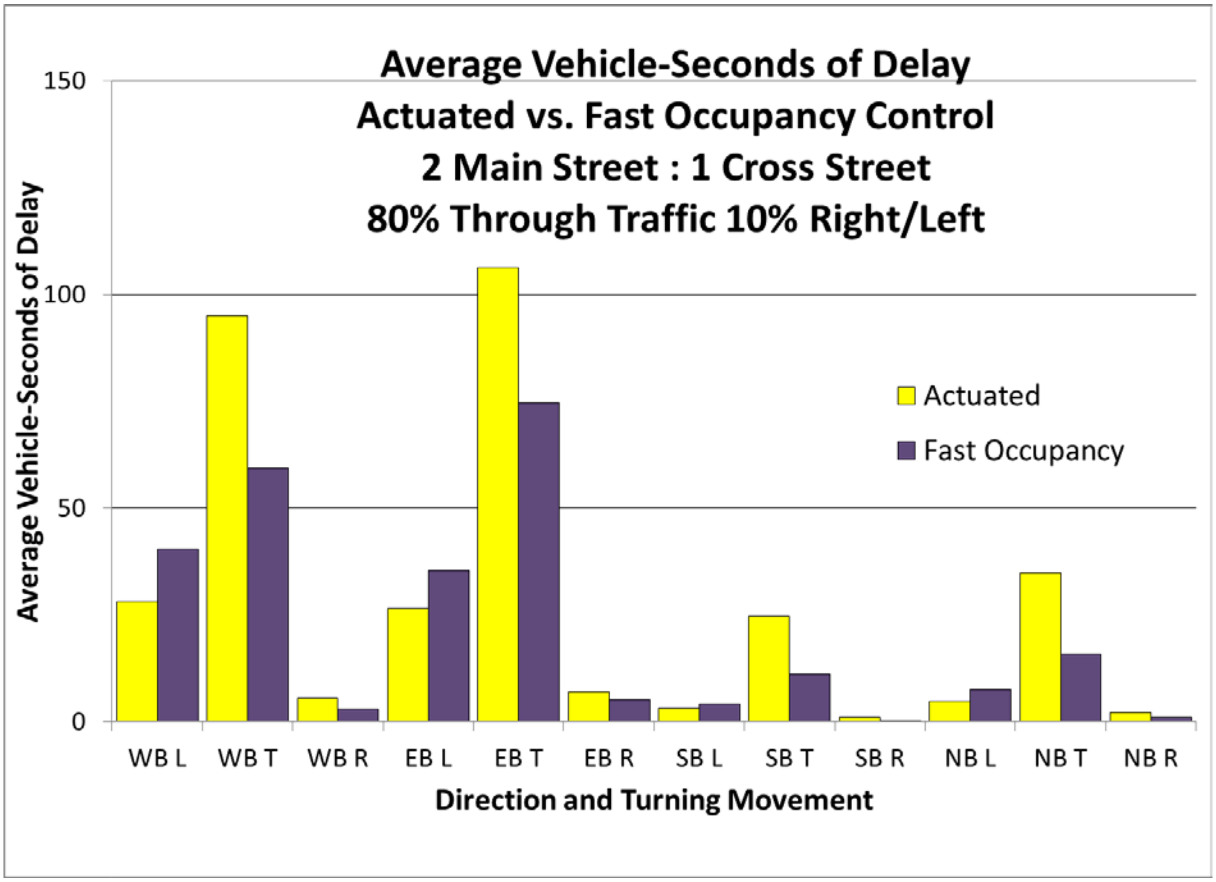

Figure 4.4: Vehicle-Seconds of Delay for Actuated Control vs. Fast Occupancy Algorithm Under Platooned Arrivals

The simulation data collected 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.

5.0 MODEL LOGIC

With the limitation imposed by ODOT that the final tool be implemented in Microsoft Excel and the limitations of microsimulation tools regarding undisclosed algorithms, the research team chose to build on queuing models. Queuing models have been used in transportation to predict intersection performance and predict measures of effectiveness such as average and total delay (*Ruskevich 2011, Mannering et al. 2007*). There are numerous queuing models that may be applied to an intersection and several different terminologies surrounding them. For clarity, the terminology that will be used for the remainder of this report will follow Kendall's notation (*Kendall 1953*). Kendall's notation denotes a queuing system in the form of Arrival Type/Service Type/Number of Servers. In the notation the arrival and service distributions are described by the letter D when the distributions are deterministic and the letter M when the distributions are stochastic. A few example stochastic distributions are the Poisson and Gamma distributions. So a queue with deterministic arrivals and deterministic departures with one server would be a D/D/1 queue. If arrivals were to be regarded as following a Poisson distribution, but departures were still deterministic, the queue would be denoted M/D/1 instead. A third letter, G, is used to denote the use of a general distribution, i.e. no special assumptions about the distribution of arrivals or departures.

Looking at traffic patterns inherent to corridor operations there are some different ways to apply queuing theory based on the assumptions made regarding vehicle arrival and departure patterns. For this project, the research team is assuming that saturated flow has a uniform distribution with upper and lower bounds. Similarly, arrivals from outside the network are assumed to be Poisson distributed with exponentially distributed headways except when the traffic flow is saturated. Note that while arrivals from outside the network are considered to be Poisson distributed the arrival rates used to generate the specific distributions used will be varied based on expected arrivals from upstream.

A sampling of queues and queuing cases can be found in Table 5.1, below. In the model each queue has servers up to the number of lanes dedicated to that movement (denoted by # Table 5.1). An interesting queue to look at is the free right turn on red queue. It uses Poisson arrivals and looks at the headways of conflicting vehicles to determine when to serve a vehicle, if it wishes to turn right, otherwise it reverts to a deterministic departure rate of zero until the light turns green. Side street left and right turning vehicles likewise have service distributions based on thresholded exponential distributions to simulate gap acceptance behavior (*Ragland et al. 2006*).

Table 5.1: Example Queues

Case	Queue	Arrivals	Departures
Red Light (Through Traffic)	M/D/#	Gamma	0
Red Light (Free Right Turn)	M/M/1	Gamma	Headway>Min. Gap, 0
Green Light With Queue	M/M/#	Gamma	Departure headway
Arrival on Green	M/D/#	Gamma	Infinite or Arrival Rate
Side Street Permitted Left Turn	M/M/#	Gamma	LT Arrival headway > Sat. Headway and Through Headway > Min. Gap

The distribution of headways and arrivals is important to consider when side street and permitted left turn traffic is included in the analysis. An average or uniform headway assumption would lead to the conclusion that there are no windows for vehicles to make turns onto the main street after traffic reaches a threshold volume where the average gap is smaller than the acceptable gap. In reality, vehicles are not so evenly distributed and there will be usable gaps even with traffic flows high enough for the average gap to be unacceptably small.

5.1 MONTE CARLO METHOD

The Monte Carlo Method (MCM) was published by Metropolis and Ulam (*1949*) as a means of solving complex problems with difficult probabilistic and combinatorial aspects. One example used in their description of the method is a game of solitaire. Computing the probability of winning a game of solitaire is a surprisingly difficult endeavor because the order of cards in the deck and the individual stacks, as well as the order of plays all impact the probability of winning. The solution proposed by Metropolis and Ulam (*1949*) was to simply "play" a sufficiently large number of games that the law of large numbers would dictate that their computed solution would be close to the actual probability of winning a game of solitaire.

Applying this concept to the problem of predicting traffic signal system performance and the queuing theory discussed previously, the research team has created a methodological framework applicable to Excel that can be used to not only compute average benefits, but also examine the variability of those benefits as well. Through the use of randomization and explicit or assumed variabilities, the proposed framework can be used to measure the performance of varying traffic flows and arrivals on the performance of the signal system. Another important benefit is that adding variability to the system may expose particularly good or bad operational conditions. As an example, consider how performance could be expected to vary when operational conditions are near to saturation. If average performance and deterministic traffic flows are used, the estimated performance could be quite different from observed performance where traffic flows may be oversaturated at times.

5.2 PERFORMANCE ESTIMATION

Vehicle delay can be estimated, both on an individual and on average basis, from the queuing diagram method shown in Figure 5.1. For an isolated intersection, assume that the vehicle arrival rate is uniform, as shown in Figure 5.1, 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

$$\bar{d} = 0.5r \cdot (\overline{q_a} t)/(\overline{q_a} C) = 0.5r \cdot t/C \tag{5-1}$$

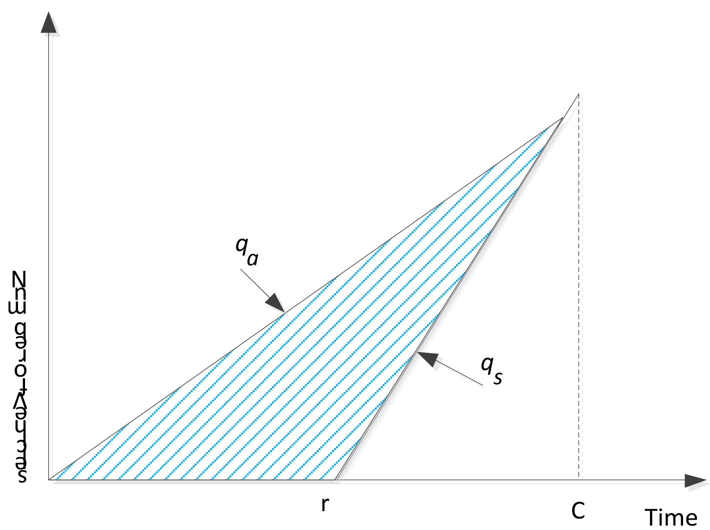

Figure 5.1: Arrival and Departure Curves with Uniform Arrival Rate

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.

$$\overline{q_a} t = (t - r) q_s \tag{5-2}$$

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

$$t = r q_s / (q_s - \overline{q_a}) \tag{5-3}$$

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

$$N_s = t q_d = r q_s q_d / (q_s - \overline{q_a}) \tag{5-4}$$

The average number of stops

$$\overline{N_s} = t q_d / C q_d = r q_s / C(q_s - \overline{q_a}) \tag{5-5}$$

The maximum queue length

$$Q_{max} = r q_d \tag{5-6}$$

The saturation for phase *i*

$$X_c = Cq_d/q_s(C\text{-}r)Sa_i = Cq_d/q_s(C\text{-}r)Sa_i = Cq_d/q_s(C-r) \tag{5-7}$$

For 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. Assuming 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 5.2, 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

$$Q_{max} = r q_{ar} \tag{5-10}$$

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.

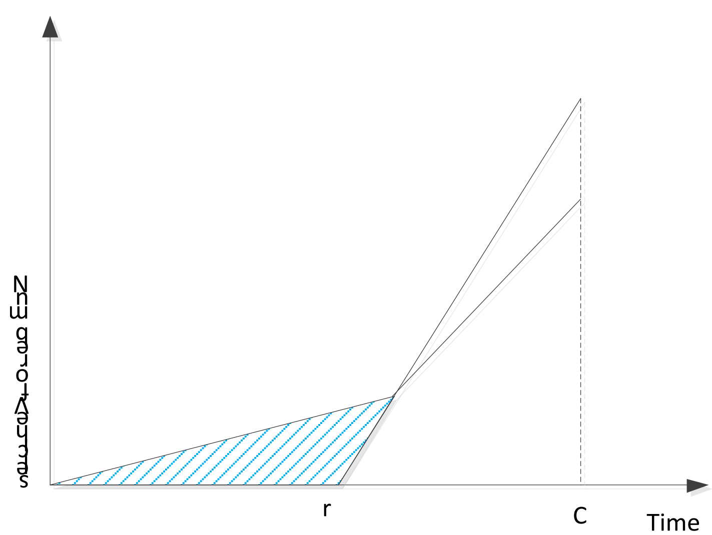

Figure 5.2: Arrival and Departure Queuing Diagram for a Coordinated Intersection

When these methods are applied to an Excel spreadsheet with MCM varied arrivals and departures calculated based on small discrete time steps, there are subtle changes to the equations. Queuing for example can be implemented in the form of Equation 5-11.

$$Q_{i,j} = Q_{i-1,j} + \sum q_{a\,i,j} - \sum q_{d\,i,j} \qquad \textbf{(5-11)}$$

Where $Q_{i,j}$ is the phase j queue in interval *i*. This value is determined based on the *i*-1 interval's queue for phase *j*, $Q_{i-1,j}$, plus the sum of arrivals for phase *j* during interval *i*, $\sum q_{a\,i,j}$, and minus the departures for phase *j* during interval *i*, $\sum q_{d\,i,j}$. Using the arrival distributions and MCM described previously in the Excel spreadsheet will impact the queue by changing the arrival and departure rates. Specifically, arrivals and departures will not form straight lines. They will be stepped as arrival and departure information is processed each time step in the model. By looking at the average and maximum values the research team can gather the relevant performance data and identify intervals with problems such as queues blocking upstream intersections.

Another important aspect of the implementation in Excel is that significant amounts of data need to be collected just to emulate the various control strategies. For example, the number of vehicles in the queue is important to running InSync's optimization algorithm because it seeks to minimize total vehicle-seconds of delay per phase (*Rhythm Engineering 2012*), which requires knowledge of how many vehicles are waiting in the queue during any given interval to calculate. There are corollaries for the other systems as well, such as needing the phase saturation levels for ACS Lite's algorithm (*Gettman et al. 2006*). Because many of the performance measures need to be calculated for operational reasons it is fortunate that it is relatively trivial to gather fairly complex performance data from the model.

For example, the queue length is a function of the number of vehicles waiting in the queue and the number of lanes available to store those vehicles. If 12 vehicles are in a movement's queue and that movement has two lanes associated with it, there would be an expected queue length of 6 vehicles. Similarly, there would be a 4 vehicle queue for three lanes. Total vehicle delay measurement becomes a time integral calculated as the sum of the number of vehicles in the queue during each interval multiplied by the interval length. Average delay is total delay divided by the number of vehicles passing through the queue. Incidentally, the number of vehicles passing through the queue is also the throughput or volume measured for that phase.

Figure 5.3, below, shows an example queuing diagram using one second intervals and random arrivals (solid blue line) and departures (dashed red line). The queue length, assuming a single lane for queuing, is shown with the dotted green line. The total delay incurred by the queued vehicles is represented by the purple dash-dot line. In this case 12 vehicles arrive over 30 seconds and depart over 15 seconds. During that time, a maximum of 4 vehicles reside in the queue at any given moment and a total of 36 veh.-sec. of delay are incurred. This works out to an average delay of 3 seconds per vehicle. Saturation can be calculated by dividing the number of vehicles discharged during the green interval by a user supplied saturated flow rate. For this example, the queue is served by two lanes. We will use 1,800 vehicles per hour per lane as the saturated flow rate. Using these numbers, the queue discharged at a rate of 0.8 veh./sec. which is 80% of the saturated flow rate of 3,600 vehicles per hour (2 lanes at 1,800 veh./hr./ln.), which works out to 1 veh./sec. Vehicles arriving after the queue has cleared are immediately discharged and do not add to the queued vehicles or vehicle delay. Note that the synthetic saturation would be expected to be different from a loop detector's occupancy reading as vehicle lengths and speeds are not being used to calculate saturation.

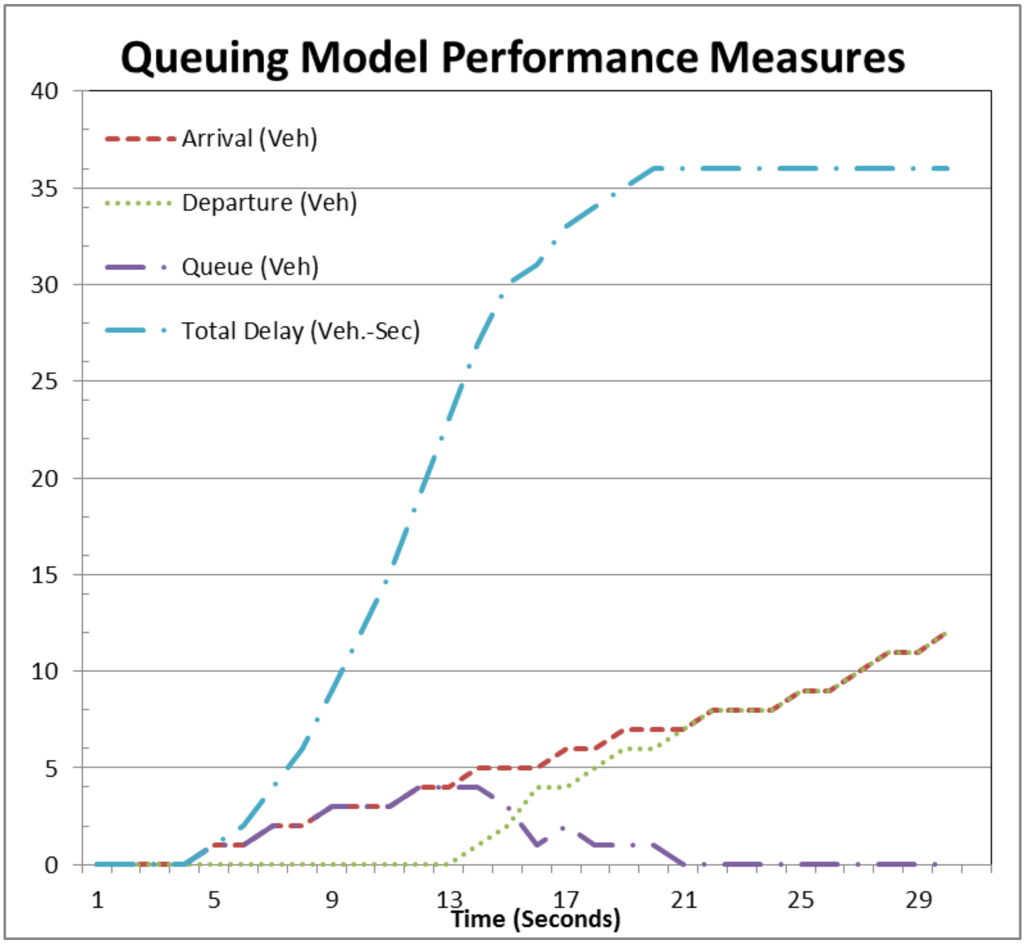

Figure 5.3: Arrival and Departure Diagram for Discreet Time Intervals with Queue Length and Total Delay

5.3 NETWORK CONSTRUCTION

When estimating the performance of a traffic signal system, it is important to accurately represent the network that the system will be deployed upon. To this end, the queuing model and MCM will be used on a network consisting of major intersections, minor intersections and segments. Major intersections are signalized and accept data inputs for all movements at the intersection as well as pedestrian crossing counts. The approaches to major intersections may also have lane layouts that are different from their connecting segments. Segments span from stop bar at an upstream intersection to the stop bar at the downstream intersection and may have a different number of lanes in the upstream and downstream directions. Minor intersections are located along segments between intersections. Minor intersections serve to allow the system to correct for volume differences between volumes headed downstream from a major intersection and those observed at the downstream intersection. If volumes increase downstream than the volume added at a minor intersection will be positive and vice versa. This volume leveling function also serves to break up platoons.

Network construction is an essential function of the queuing and evaluation logic that is built into the Excel application. Each queue needs to be linked to an arrival source and departure sink. By default, each intersection has twelve queues, one each for through, right and left movements on four approaches. Different choices regarding intersection geometry enable or disable different queues. For example, a right turn queue would be linked to a through movement queue if there is not a right turn only lane and right turns are allowed. If right turns are prohibited, the right turn queue would be completely disabled. Similarly, a T-intersection would disable the unused approach queues. Additional construction logic is required to link queues to departure lanes, an eastbound left turn, a westbound right turn and a northbound through movement all discharge to the northbound segment associated with that intersection. These linkages are used to determine if permitted movements may discharge and what volumes are seen at downstream intersections.

5.4 TRAFFIC SIGNAL CONTROL

To apply this queuing model methodology to signal control system evaluation, each queue must be assigned to a signal control during network construction. The signal control logic seen by each queue is very simple. The control logic either gives the queue a “red light” during which no vehicles may discharge, a “green light” which indicates that traffic should discharge at the saturation flow rate, or a “permitted” indication which requires the queue to wait for a sufficient gap in conflicting movements before discharging a vehicle.

Note that the walk signal is not tracked in a directional manner. Specifically, the system does not track whether the pedestrian is crossing east to west or west to east. This is important because permitted movements receive a “red light” when they would intersect a crosswalk during the walk signal. This means that permitted lefts and rights will not discharge while the relevant crosswalks are receiving the walk signal. Also note that as implemented, all crosswalks are outside of the right turn lane, so right turns will always be affected by crosswalks.

Similarly, the traffic signal control logics need to have input from the queuing model in order to drive their logic. For example, under actuated control the existence of a queue can be interpreted as a presence call. Saturation and delay are other model outputs that can be used by control logics. The control logics responsible for controlling which queues get which indications at which times and how they allocate those indications will be discussed in Chapter 6.

6.0 SIGNAL CONTROL SYSTEM EVALUATION MODEL

The queuing model discussed in Chapter 4 forms the theoretical heart of the analytical engine implemented in the Excel application. However, it does not represent the sum total of the logic needed to operate the analytical engine. There are numerous other factors, such as intersection configuration and specific control logic details that must also be input and enforced.

There are three aspects of the analytical model that will be discussed in this chapter. The first aspect is the required input data. The second is the signal control logic. The final aspect is the output data generated by the model. Each aspect builds upon the queuing model. The input data controls which queues are active and what vehicle flows are present. The signal control logic controls queue service. Finally, the output data is gathered from the queuing model.

6.1 REQUIRED MODEL 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, volume, and control categories. In designing the analytical framework, efforts have been made to minimize data collection cost and analytical complexity.

6.1.1 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 the length of road segments linking intersections, both of which impact progression on a corridor. As was briefly discussed regarding model network construction in Section 4.3, there is a respectably large amount of data needed regarding details such as exclusive right turn lanes, approach lengths, existence of pedestrian crosswalks, etc.

6.1.2 Volume Data

Volume data is a required input for evaluating the performance of a signal control system. Due to the variation in how the various systems record data and what data they record, it became obvious that a single, basic format was needed. It would have proven burdensome to require data not collected by more basic systems, as well as counterproductive in light of the project's goal of determining whether to replace such a basic system with a more advanced implementation. Additionally, the project was intended to develop a planning level tool, not a microsimulation model which would require such detailed data.

To make the evaluation methodology as accessible as possible, the research team and TAC decided that 15 minute interval through, right and left volumes as well as pedestrian actuations per 15 minute interval would be used. This standard of volume data collection can be met very easily by basic data collection methods, such as tube counters. With ODOT currently using the Wapiti W4IKS and Northwest Signal's Voyage software at the majority of their intersections, it should be easy for practitioners to gather sufficient input volume data.

There are two concerns to address when using automatically collected data from the existing signal control systems. The first concern regards a set of W4IKS data provided to the research team that 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. These tied together loops pose a problem. When multiple loops occupy the same detector channel, the channel will only add one volume count to the bin when any of the tied together loops are occupied. This is not a problem for one loop, but may result in two vehicles counting as a single vehicle when two loops are tied together. The more loops that are tied together, the greater the potential impact on the reported volume as more simultaneously arriving vehicles are miscounted. Wu et al. (*2010*) developed a probabilistic method for correcting the volume counts based on the probability of one or more vehicles arriving at the same time given the current volume level.

The other concern of note when using detector data is that combined movement lanes or channels have a single volume record. This means that it may be impossible to accurately discern the number of right turning vs. through movements for a combined through and right turn lane from detector data alone. This problem becomes more acute for combined through, right and left turn lanes. While such lanes may not be common on the mainline of the corridor, they would be expected to occur on side streets. In these cases it may be necessary to use tube count data or to split detector data based on previous tube count results.

6.1.3 Timing Plan Features

There are a number of frequently implemented traffic signal control techniques that the evaluation logic implements in addition to the control logics. These include right turn overlaps and two varieties of left turn phase reservice. These features have specific requirements for implementation in the field and in the evaluation logic.

6.1.3.1 Right Turn Overlaps

Right turn overlaps allow right turns to get green lights out of the normal sequence and separate from their corresponding through phase. Using Figure 6.1 as an example, the phase 2 right turn can be overlapped with the phase 3 left turn. This is allowed because the two movements do not conflict. However, there are implementation requirements. The overlapped right turn requires a separate right turn lane and a separate signal head to give independent right turn control. Because of these requirements, the selection of right turn overlaps is made during intersection geometry data input, rather than during timing plan creation. It is assumed that a right turn overlap is always used when the intersection is configured to be able to do so. Overlaps may be implemented with any signal control logic.

6.1.3.2 Left Turn Phase Reservice

Left turn reservice comes in two varieties, fixed and conditional. Fixed reservice will always reserve the left turn phase while conditional reservice looks at a combination of opposing and concurrent through traffic conditions to determine whether to bring up the left turn phase again. It should be noted at this point that conditional phase reservice is a NEMA specification (*NEMA 1998*) that may be incorporated into numerous systems. Voyage software includes a feature called coordinated late left turn that operates slightly differently (*Northwest Signal Supply 2009*). Specifically, the NEMA standard requires the barrier to be crossed after left turn reservice while coordinated late left turn is allowed to return to the coordinated phases if there is no demand for other phase service. Under most traffic conditions there should be little difference between the two algorithms because traffic demands should be high enough to put some demand on opposing phases, which causes coordinated late left turn to behave the same as the NEMA specification.

Left turn phase reservice is available to all conventional control logics, and the fast occupancy and slow occupancy adaptive logics. The delay optimization control logic has no need of phase reservice techniques because it does not follow a fixed phase order or adhere to a cycle length. Conditional left turn phase reservice is only available to the advanced actuated control logic.

Left turn phase reservice, conditional or fixed, requires that the left turn in question be a leading left turn. This is so that the left turn can be served a second time before crossing the barrier. A conventional phasing diagram for comparison with the left turn phase reservice diagram is provided as Figure 6.1. An example NEMA phasing diagram for left turn phase reservice may be found in Figure 6.2. When reservice occurs, it changes which phases can cross the barrier. In Figure 6.1 phases 2 and 6 were required to terminate before the barrier could be crossed and phases 3, 4, 7, and 8 served. For left turn reservice of phase 5, as shown in Figure 6.2, phases 2 and 5 can cross the barrier. For conditional reservice of phase 5, phases 2 and 5 could cross the barrier if the left turn is reserved, otherwise phases 2 and 6 would be required to cross the barrier.

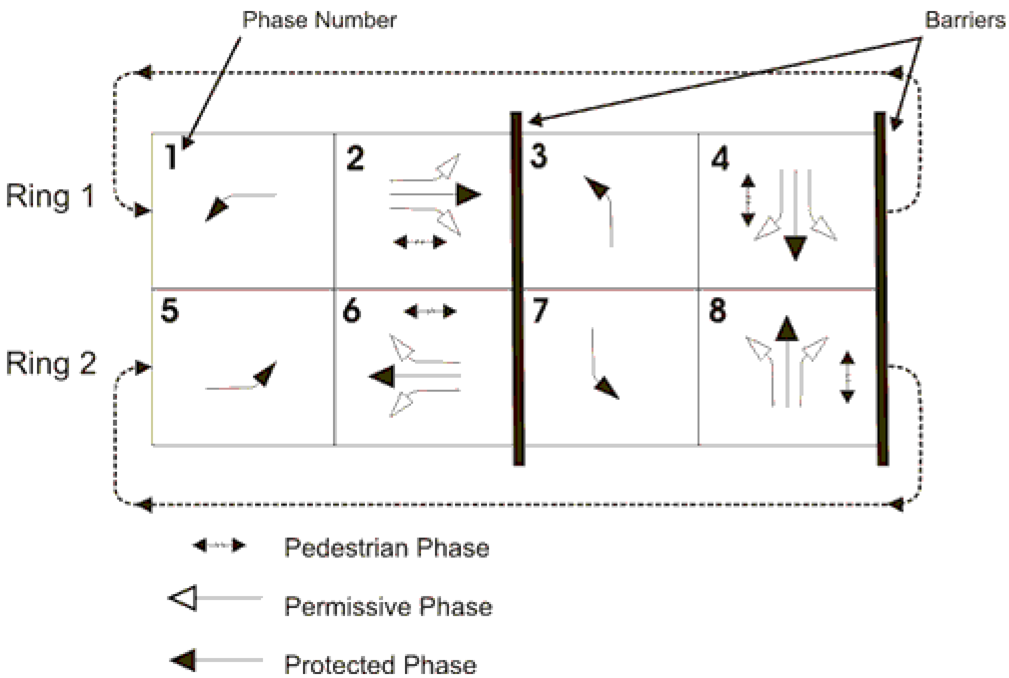

Figure 6.1: NEMA Phasing Diagram (*FHWA 2012*)

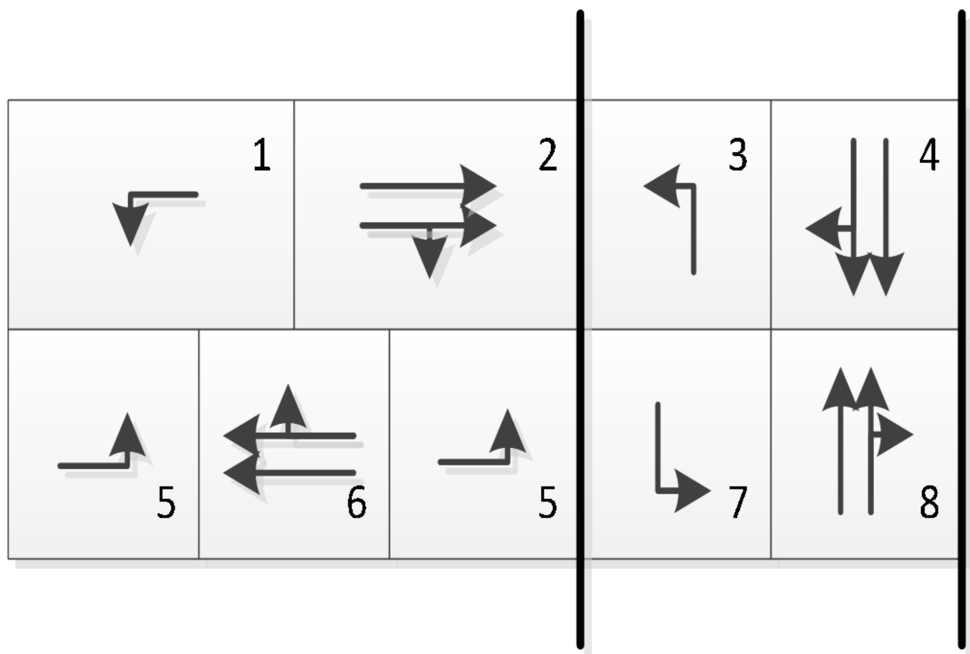

Figure 6.2: Left turn phase reservice

6.2 OPERATING CONSTRAINTS

There are numerous operating constraints that the signal control logics must adapt to. These include phasing issues and preferences and pedestrian impacts among others. In general these constraints enforce restrictions on phase orders, service times and whether certain movements are valid.

6.2.1 Pedestrian Phase Impacts

Pedestrian service is a commonly encountered constraint on signal control. When considering a corridor, it is common for the corridor phases to enjoy longer relative service times and for the corridor to be the larger of the two streets at an intersection. This tends to make pedestrian crossings of the cross street simple, because the shorter crossing distance is associated with the longer allowed time to cross. Pedestrians crossing the corridor, however, present a problem. In general, streets crossing the corridor require less time to serve their vehicle demands and more time is required for pedestrians to cross the larger street. In this case more service time needs to be allocated to the cross street phases in order to properly serve the pedestrian movement

6.2.2 Phasing

There are a number of geometric design details that influence phasing. These influences may restrict which phase orders can occur, or they can prevent certain phases from existing. There are two major constraints specific to intersection geometry that were taken into account in the application, restricted phasing and T intersections.

Restricted phasing is used when two movements that would normally be compatible with each other are for some reason incompatible. Typically this occurs with left turns where the intersection geometry would cause opposing left turns to occupy the same space. Since these two left turns can no longer be phased together, a number of restrictions come into play. First, the relevant left turns are restricted to lead-lag phasing since the two left turns cannot be served simultaneously as they would in lead-lead or lag-lag phasing. Second, the concurrent through phase is required to be served for a minimum time between the leading and lagging left. The new NEMA phasing pairs for phases 1, 2, 5, and 6 under restricted phasing are 1 and 6, 2 and 6, and 2 and 5. Note that 1 and 5 is no longer valid.

Another common phasing restriction is the T-intersection. Currently, T intersections are only supported for side streets; there is no option to implement a T-intersection where the corridor ends in a T-intersection. With T-intersections one of the side street approach legs is removed. This means that there is no volume input from those phases, any movement that would turn into the affected leg is deactivated and so on.

Using Figure 6.1, consider removing the phase 3/8 leg of the intersection as an example. Phases 3 and 8 cease to exist because that leg has been removed. The phase 1 left turn has nowhere to go and is eliminated. Phase 4 is reduced to right turns only and phase 2 right turns are not allowed. This restricts the available phases and which phases are allowed to start a cycle. In this case phases 1, 3 and 8 have been eliminated which reduces the 16 possible starting phases to 2 (2457 and 2467). This reduces the valid phase pairs dramatically as well, now only 2 and 5 and 2 and 6 are valid for the first side of the barrier and only 4 and 7 are valid for the second.

6.3 IMPLEMENTED CONTROL LOGIC

This is the core piece of the research which everything else either builds upon or supports. In total there are three conventional and three adaptive control logics implemented in the computational engine. This will give practitioners significant control over the evaluation process. The flexibility afforded by the multiple signal control systems should make it easier to evaluate diverse signal control systems and some advanced features can be enabled on advanced implementations.

Because of the proprietary nature of several of the algorithms and the limitations of Excel, it was not possible or practical to implement complete control algorithms for each system and system feature. It would have also been prohibitive in terms of data entry and possibly contrary to the goal of having a planning level model to have delved into such fine details. Because these systems are either simplified versions or translations of the plain English descriptions of the systems, the research team believes it is important to descriptively name the control strategies distinctly from their ideological parents to prevent confusion about what signal control logic is being used.

6.3.1 Control Phasing

Figure 6.1 shows a typical NEMA phasing diagram. To eliminate confusion as much as possible, the research team decided to adopt NEMA phasing notation for all systems. For convention, phases 2 and 6 are the corridor phases and phases 4 and 8 are used for the cross street. For consistency phase 2 travels in the ascending intersection number direction. For an east-west corridor with intersections numbered from east to west, the phasing would be as shown in Figure 6.1. For a north-south corridor numbered from north end to south end, phase 2 would be the southbound direction and phase 6 the northbound direction.

An important fact to consider that may not be evident to readers unfamiliar with NEMA phasing is that certain phases may be active at the same time while others are prevented from acting together. For example, phase 1 (the westbound left turn in Figure 6.1), may be active at the same time as phase 5 (the eastbound left turn) or phase 6 (the westbound through). Phase 1 may not be active at the same time as phase 2 (the eastbound through) or any of the phases on the other side of a barrier; phases 3, 4, 7 and 8.

For leading left turns, as shown in Figure 6.1, the valid corridor active phase pairs are 1 and 5, 1 and 6, 2 and 5 and 2 and 6. These pairs are reached in the following manners. Phase pair 1 and 5 as leading left turns, start the process. Phase pair 1 and 6 would become active when phase 5 terminates before phase 1. Likewise, phase pair 2 and 5 becomes active when phase 1 terminates before phase 5. Phase pair 2 and 6 would become active in one of three ways; the first is if both phases 1 and 5 terminate simultaneously, the second is coming from phase pair 1 and 6 when phase 1 terminates and the third is from phase pair 2 and 5 when phase 5 terminates. Phase pair 2 and 6 is the only phase pair able to cross the barrier and begin the process again on the other side of the barrier with phase pairs 3 and 7, 3 and 8, 4 and 7 and 4 and 8. Phase termination is handled differently by each system and will be discussed in the following sub-sections. Please note that there are changes to these valid phase pairs and their order of appearance based on whether leading or lagging left turns are used and other control parameters, such as split phasing.

6.3.2 Conventional Control Logic

Conventional signal control logic covers fixed time, basic coordinated and advanced coordinated actuated operation. Each operation method is detailed below. The details of the two plan selection methods are also detailed below. Each of the three conventional systems, fixed time, basic coordinated actuated and advanced coordinated actuated is compatible with time of day and traffic responsive based plan selection. This means that there are effectively six combinations of conventional signal control logic and plan selection available for evaluation.

6.3.2.1 Fixed Time

Fixed time logic terminates phases when the planned amount of green time has been served. This makes the logic simple and predictable. Fixed time control is the most classical signal control methodology. It has not appreciably changed from its earliest uses in mechanical timer driven signal control. In practice, it is common for there to be four to five timing plans used at an intersection over the course of a day. These plans generally represent a morning plan, mid-day plan and evening plan with one or two extra plans for peak period traffic, if needed.

Up to five plans are available in the application. Each plan has an associated pedestrian plan option for use when the phase 4 or phase 8 pedestrian movements would require more time than the time normally allocated to those phases. It is assumed that phases 2 and 6, as corridor phases, will generally have sufficient green time to cover their associated pedestrian movements.

In general, fixed timing plans 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 can be found in Chapter 16 of the HCM 2000. These equations can be used as the starting point for developing timing plans for time of day and traffic responsive control.

6.3.2.2 Basic Coordinated Actuated

Many of ODOT’s intersections are currently operating with the W4IKS software on 170 controllers. Other corridors are using Voyage software on 2070 controllers, but have not had advanced features enabled, or are using plans directly translated from previous the W4IKS operated 170 system. While there are differences between the various basic actuated operations, they share sufficient similarities to be modeled as the same system at a planning level.

The specific control logic implemented in the application runs the coordinated phase pair (2 and 6) under fixed time operations and does not allow phases 2 or 6 to be omitted. Other phases are operated in a typical actuated manner where a minimum green time must elapse before the phase may be allowed to gap out and terminate or reach its maximum allowed green time and terminate. Phases 2 and 6 are allowed to stay green given no demand for other phases. In the application this behavior is called resting. Other phases may be ignored if there is no demand for them. This behavior is called omission in the application. To retain planned coordination, any excess time saved from other phases terminating early or being omitted is accumulated to the coordinated phases.

A final note about basic coordinated actuated behavior involves the gap out behavior. Under basic coordinated actuated operation gap out occurs when all lanes of an operating phase have a sufficiently large gap. This behavior is called simultaneous gap out, sometimes it is referred to as simgap. This gap out logic resets its countdown each time a vehicle passes over a monitored detector.

6.3.2.3 Advanced Coordinated Actuated

With ODOT's transition to Voyage software on 2070 controllers there is increased interest in exploring the impacts of various advanced features available in the new software. In general, the Voyage software operated 2070 running coordinated actuated plans behaves similarly to basic coordinated actuated with phases being served until minimum green time has been served and then either gapping out or maxing out to terminate the phase.

The major differences between basic coordinated actuated and advanced coordinated actuated are that advanced coordinated actuated actuates the coordinated phases (2 and 6), uses lane by lane gap out and can assign time freed up by early termination to serving pedestrian phases. Actuating the coordinated phases has potential impacts on mainline progression which are often mitigated by increasing the minimum green time on the coordinated phases to limit the possibility of premature gap out.

Lane by lane gap out checks each lane of a movement for gaps. Once a lane has gapped out under lane by lane gap out, it does not reset. This means that each lane can use the same gap out parameters instead of needing a different gap out parameter for each movement. Advanced coordinated actuated is also allowed to assign unused time to cover pedestrian calls for short phases which allows the advanced coordinated actuated control logic to have a chance of serving side street pedestrian calls without using an alternate pedestrian phasing plan.

6.3.2.4 Plan Selection

There are two common methods of timing plan selection, time of day based and traffic responsive (*Koonce et al. 2008*). Under time of day plan selection a timing plan (for fixed time or actuated control logic) is selected based on the current time of day. A given plan may be used multiple times per day and be used for extended periods. For example, plan

1 may be used from 7:00 AM to 8:30 AM and again from 9:30 AM to 11:00 AM. It should be noted that some fixed time operating systems completely lack detection and can only use time of day plan selection.

Traffic responsive plan selection uses a different selection principle. Instead of choosing a plan based on the time of day, traffic responsive plan selection uses representative detectors along the corridor to select the timing plan that will best serve current traffic conditions. Effectively, traffic responsive logic breaks down to a decision tree where thresholds are set for detectors or combinations of detectors. When a given set of thresholds are met, the system implements the timing plan set by the engineer for that set of conditions (*Koonce et al. 2008*).

There two commonly used sets of thresholds, volume and V+KO (or VPlusKO). Volume is as simple as it sounds with each detector reporting its volume, typically in terms of vehicles per hour. V+KO stands for volume plus a constant, K, times occupancy, O. This method is preferred where congestion may cause reduced volumes or queues. For reduced volumes, congested detectors will report higher occupancy from slow or stopped vehicles, offsetting the reduced volume during congestion. For queues, an upstream detector that should be beyond normal queues will begin to register increased occupancy when traffic is no longer free flowing over the detector. The occupancy factor prevents the traffic responsive system from reverting to lower volume timing plans or ignoring queuing when congestion occurs and more service may be required (*Koonce et al. 2008*).

The process of selecting which plans should be used at a given time of day or which detectors and thresholds to use in a traffic responsive plan selection can require a significant time investment in corridor observation. In the application, the difficulties associated with selecting appropriate detectors and thresholds would be compounded by the differences between synthetic occupancy and a measured occupancy from the field. To avoid significant differences between modeled performance and performance expected from traffic responsive plan selection, the application does not currently implement V+KO. Instead the application uses a simple volume based approach. This implementation simplifies user input as well as calculation and programming logic. The application implementation selects one intersection to serve as the master intersection with phase 2 and phase 6 volumes at that intersection being used to determine the appropriate plan.

6.3.3 Adaptive Signal Control System

Adaptive signal control systems use custom and often proprietary logic to adjust their timing parameters to current traffic conditions. The three systems being considered for this project are InSync, ACS Lite and SCATS. All three of these systems have proprietary algorithms that could not be implemented in the application. Instead, a series of basic adaptive control strategies have been created that are based on plain English descriptions of how each system works. These surrogate systems are named for their method of operation. Delay optimization was created based on InSync’s described operating principles. Slow occupancy emulates ACS Lite and fast occupancy imitates SCATS. For convenience and clarity the various algorithms are also indicated by the name of the intended system preceded by the word faux to indicate that the implementation is not a direct implementation of the proprietary algorithm.

6.3.3.1 Delay Optimization (Faux InSync)

The two core principles upon which InSync operates are green band progression and delay minimization when a green band is not scheduled. InSync optimizes delay across movements by counting approximately how many vehicles are present (using video detection) for each movement every five seconds and serving the movement group that has the most vehicle-seconds of delay (*Rhythm Engineering 2012*). For example, one vehicle that waits fifteen seconds will accrue as much delay as three vehicles waiting for five seconds. An important consideration is that Insync is not required to operate in cycles with consistent phase order like conventional systems.

The delay optimization strategy can reasonably represent InSync's delay minimization logic for serving phases outside of green bands. These algorithms, while proprietary, are straightforward and well described. The algorithms by which InSync creates a green band, however, are not described nearly as well. The research team has been forced to make a series of educated guesses and simplifications to integrate green band logic into the application.

The green band logic, as implemented, checks the ends of the corridor and determines when the end intersections wish to discharge their coordinated through movements. When an end intersection discharges its through movement, a series of calculations are made to determine what the offsets are between intersections. Another calculation estimates the required size of the green band based upon the measured delay at the intersections and user input minimum and maximum tunnel sizes. The logic then requires that each intersection be serving the appropriate through phase at the appropriate time and continue to serve that movement until the green band time has been exhausted, upon which, the intersection operations revert to serving the phase with the most delay, which may be the coordinated through movement. To prevent numerous small green bands from causing the system to become unstable, green bands are required to be spaced at least the minimum tunnel green time apart.

As an example, a four intersection corridor would generate a green band in the increasing intersection number direction when intersection 1 wants to serve its phase 2. From this point intersection 2 will be required to serve phase 2 at a time in the future equal to the travel time from intersection 1 to intersection 2. Intersection 3 is required to serve phase 2 at a time in the future equal to the travel time from intersection 1 to intersection 3, and so on. The intersections would be required to serve phase 2 for a number of seconds equal to the minimum tunnel green time specified by the user and then they revert to serving whichever local phases have the greatest delay, which may include phase 2. After the green band has expired at intersection 1, no new green band can be initiated until the minimum tunnel time has elapsed.

6.3.3.2 Slow Occupancy (Faux ACS Lite)

The ACS Lite system uses time of day based plan selection system to select an actuated control plan as a base upon which to perform its adaptive control logic. Once a plan has been selected, the ACS Lite system adjusts the maximum green times every 5-15 minutes (*Gettman et al. 2006*). ACS Lite can adjust splits separately for each intersection. The system is biased in favor of coordinated phases to help maintain progression.

The ACS Lite split optimization plan is quite straightforward, with phase splits balanced based on green time utilization. The determination of green utilization is based on phase saturation, which is a measure easily derived from the queuing model. From this point it is relatively simple to determine which phases need more time and which phases should donate time based on their relative saturation levels. The system is only allowed to make small changes to the plan each interval, which keeps the system from becoming unstable do to overreaction.

The offset calculator is more troublesome and impractical to implement in Excel. The offset calculator uses statistical measures to identify whether vehicles are arriving at downstream intersections during green indications. This would require more tracking and calculations than are practical to implement under the limitations of Excel.

In the application, the phase split balancing methodology is implemented. Each 15 minute interval split adjustments are recalculated based on the previous 15 minutes worth of data. Offsets are maintained according to the original timing plan under the assumption that the offsets should not appreciably change based differing splits within a fixed cycle length.

6.3.3.3 Fast Occupancy (Faux SCATS)

SCATS operates with two levels of control, tactical and strategic. Strategic control is focused on determining the correct cycle for a signal or group of signals. Tactical control looks to optimize the use of cycle time allocated by strategic control.

Strategic control focuses on cycle length and coordination. Cycle length is determined based on phase and intersection saturation. Coordination is created by observing the vehicle flows between intersections and uniting multiple systems under the same cycle length when those vehicle flows are high enough to warrant cooperative cycle lengths.

Tactical control allocates green time within a cycle. Phases may be terminated early based on low demand or skipped entirely when there is no requisite demand. Effectively tactical control acts as though the system were isolated with the exception that the coordinated phases cannot skip or terminate early, in order to maintain progression (*Roads and Traffic Authority 2011*).

In the Excel application, tactical control has been implemented according to the available plain English descriptions. Elements of strategic control, such as the logic to combine multiple intersections in a coordinated group and selecting appropriate cycle lengths, have been implemented. Once again it is the progression logic that is unavailable. A simplified progression logic has been implemented which chooses between increasing intersection direction progression, balanced progression and decreasing intersection number progression.

6.4 REQUIRED MODEL OUTPUT DATA

In order to perform the cost and benefit analysis to selecting the most appropriate systems to analyze in greater depth, certain performance measures must be output from the model and evaluation logic. These data include volumes, delay, queue lengths, number of stops and saturation.

Volumes are an important aspect of system performance to report. Volumes are an important tool for internal evaluation. Also certain performance indicators can be reported in different units for clarity and may require volume information to make the conversion. For example, the total delay and average delay can both be important measures of performance, but average delay requires knowing the number of vehicles delayed in order to calculate it.

Delay is another important measure of performance. Delay is also one of the performance aspects that is most visible to road users. Minimizing vehicle delay is a common optimization goal for traffic signal systems.

Queuing can lead to severe performance impacts as well as having safety implications. Queues that overflow left turn bays can put stopped vehicles in front of through movement traffic which may be flowing. This presents a collision hazard and is undesirable. Queuing from downstream intersections can prevent upstream intersections from operating well.

The average number of stops to traverse a corridor is a commonly used measure of performance that indicates how well progression is working on a corridor. Stops are another aspect of corridor performance that is readily apparent to road users.

Saturation is the final performance measure of interest for this research. When phases are under saturated, there is room to adjust phasing, timing or features used to reduce wasted time. Similarly, when phases are nearing or over saturated it may be necessary to adjust settings to add more time to the saturated phase.

7.0 COST AND BENEFIT ANALYSIS

One of the challenges faced by agencies selecting a new traffic signal control system is getting the best value for the money spent. This Cost to Benefit Analysis (CBA) can be based on many costs and consider numerous benefits. Typical benefits considered in the transportation field include travel time and vehicle costs such as fuel consumption (*VTPI 2009*). Numerous studies have looked at savings in travel time or delay and fuel consumption, and converted them into dollar costs for comparisons, typically reported as savings over the previous system (*DKS 2008, Dutta and McAvoy 2010, Gettman et al. 2006*). It can be surprising how rarely those same studies indicate the costs incurred. Of the three studies listed previously, Dutta and McAvoy (*2010*) indicate that a total of $12 million was allocated between county and federal sources; Gettman et al. (*2006*) indicate an expected system cost between $10,000 and $30,000 excluding infrastructure; and DKS (*2008*) breaks out the construction, design and integration, benefits evaluation, installation and annual costs.

There are a number of costs endemic to purchasing and installing a traffic signal control system. These costs range from the purchase of hardware such as controllers and communications equipment to licensing costs for controller and central system software. Often these costs are spelled out in purchasing contracts and are otherwise known in great detail. Also, agencies typically have supply contracts and a history of maintenance and installation projects that allow engineers to estimate equipment needs and costs.

There are other, less immediately visible, costs such as engineer and technician training that are often overlooked in the published reports. These costs can sometimes be troublesome to quantify depending on the agency's record keeping. With short funds and restricted hiring at many agencies, labor hours for planning, installation, project oversight and operations can no longer be excluded from cost considerations. This is especially true when staff levels play into the objectives and goals of implementing the traffic signal control system such as in Gresham, OR (*DKS 2008*).

Estimating operational benefits in the absence of microsimulation and in an Excel environment is a challenge. After examining many research paths, the research team decided to use a queuing based model (*Kelly 1975*) as the means to calculate system benefits. Combining the queuing model with a Monte Carlo Method (MCM) (*Metropolis and Ulam 1949*) allows the research team to calculate operational Measures of Effectiveness (MOEs) such as queue lengths, delay, etc. based on vehicle arrivals within the queuing model. By introducing variability via the MCM the research team is able to examine the reliability of the various measures through the use of different randomization of the inputs by the MCM.

One of the key aspects of CBA analysis is valuing the various costs and benefits in a common measure for comparison, with money typically used as the common measure. When costs are then compared to benefits, a cost to benefit ratio can then be established for the comparison of multiple projects that may or may not have much in common. In this research, values are attached to performance measures which are then used to calculate a cost to benefit ratio for users to apply to comparisons between systems. Because the values attached to numerous measures can change over time, the research team has made these values changeable by the end user. For example, the value of time spent waiting in a queue would be expected to vary by prevailing wage in the area. Likewise, a new union contract could change the valuation of a technician's time spent installing equipment.

The remainder of this report will detail the methodologies used to estimate benefits, perform CBA and the application of those methodologies in Excel.

7.1 BENEFIT CALCULATION

In this project, microsimulation was originally viewed as a possible means of examining signal control system performance. Once the research team examined the costs and requirements of using microsimulation, particularly for the simulation of the adaptive signal control strategies, ACS Lite, InSync and SCATS, it quickly became apparent that the project funding would not support purchase of the software and hardware necessary to directly simulate the candidate systems. Additionally, considering the wide scope of corridors to which the Oregon Department of Transportation (ODOT) may apply this methodology, it was clear that the detailed calibration work typical of microsimulation work (*Park and Schneeberger 2003*) would be impractical.

The high cost and the impracticality of calibrating simulations to all possible operating conditions led to the research examining queuing models as a viable alternative to simulation. Queuing models offer an implementable solution to one of the most challenging aspects of this research, calculating benefits based on low resolution data and without relying on further microsimulation efforts. Low resolution data is a significant obstacle in this research because adaptive systems optimize their cycle parameters based on real-time inputs. This means that small details, such as arrival pattern and distribution may have significant net impacts on performance. These kinds of details can be crucial to detailed operation, but are not commonly gathered and certainly not routinely or easily gathered in practice. To offset this data deficit the research team is applying the MCM to the queuing model in order to estimate the impacts of different arrival patterns and fluctuations in traffic flows into the corridor.

Low resolution data, in this case refers to volume data collected per movement, either via pneumatic time sensors or via older signal control detectors. In particular, the Technical Advisory Committee (TAC) requested that the data from existing intersections using 170 controllers and Wapiti firmware be considered by the methodology. Many of the existing traffic signals use a single detection channel per phase or movement, further degrading the data. A methodology exists that is designed to correct for the volume errors incurred through tying multiple lanes of detection into a single input channel (*Wu et al. 2010*).

The cost to benefit ratio analysis methodology is built upon a series of models. The analysis builds upon the models introduced in Chapter 5, which are a queuing model to estimate delay, queue length and other performance measures; a logical model to represent intersection and segment configurations; and, from Chapter 6, a signal control model to implement the various signal control strategies. The interaction of each of these models with input data produces the performance estimates used to generate expected benefits.

7.2 BENEFIT VALUATION

Like transportation agencies, there are two costs that matter to roadway users, time and money. One principle difference between user and agencies though, is that an individual user's time is spent in small chunks. This means that while time spent in traffic can be correlated to many stress indicators and frustration (*Stokols et al. 1978*); it can be difficult for users to see changes in lost time. Consider an average travel time savings of ten seconds over a two minute average trip. Now, consider the variability in the trip duration when individual trips can vary by over thirty seconds just by getting one more red light. Unless travel time savings are significant, it can be difficult for road users to notice improvements.

Because an agency cannot directly show increases in productivity due to reduced delay and it is difficult to show substantial individual time savings, it is typical for agencies to use a time value of money to put a value on the aggregate user time saved by a signal control system improvement (*DKS 2008, Dutta and McAvoy 2010, Gettman et al. 2006*). Users and agencies are also showing increasing interest in travel time reliability and users are willing to pay for it on the freeways (*Brownstone and Small 2005*).

Obviously time is not the only cost to users, they must pay for fuel and vehicle costs as well. The benefit gained by installing a new control system is defined as the benefit difference between the new system and the original system:

$$B = \sum B_n - \sum B_o \qquad \textbf{(7-1)}$$

Where $\sum B_n$ and $\sum B_o$ are the total benefits, valued in dollars, for the new control system and original system.

While it is easy to represent the total benefits in mathematical terms, it can be more difficult to value individual benefits. For example, how should travel time reliability on arterials be measured? Is the 85th percentile an appropriate choice? Or, should standard deviation be used? How should reliability be valued compare to average travel time? For freeway based work, these questions have a rapidly maturing body of research attempting to answer the questions (*Brownstone and Small 2005, Texas Transportation Institute and Cambridge Systematics 2006*). Work on arterial travel time reliability focuses on measures such as the buffer index, a measure of the difference between an average trip and the 95th percentile travel times (*Texas Transportation Institute and Cambridge Systematics 2006*). Data such as the buffer index can be calculated using the average travel times and the 95th percentile of travel times generated during MCM calculation.

7.3 COST ANALYSIS

One of ODOT's primary goals with regard to this project has been to enable them to determine which corridors may be good candidates for adaptive signal control systems. This general goal can be broken down into three specific questions. The first question is, would a new signal control system provide a performance benefit to the corridor? The second is, would that performance benefit be worth the time and money needed to realize it? Finally, which signal control system provides the most benefit compared to the time and money needed to install it? These three questions are at the heart of the CBA framework developed by the research team.

7.3.1 Cost Valuation

There are two types of costs that matter to transportation agencies, money and time. The interest in monetary costs is straightforward and simple to understand. While the conversion of labor time into monetary costs is a simple matter of determining the costs of an employee's wages and benefits, there are more subtle issues related to costs that agencies may need to consider. Increasing or decreasing the number of employees an agency employs is not instantaneous and entails a large number of other costs that can be hidden or not directly tied to projects. Examples of costs that can be tied to increasing the number of employees include availability of office space, computers, rest rooms, training needs and more. Costs associated with reducing employee count can include unemployment insurance, administrative costs, severance packages, retraining/reassignment costs and a number of negative outcomes due to bad attitudes and behavior (*Cascio 1991*). Table 7.1 summarizes some of the cost components related to implementing a signal control system broken out into engineering/tech costs, system costs, communication costs, and training costs categories.

Table 7.1: Cost Summary

Engineering/Tech Costs	System Costs	Communications Costs	Training Costs
Timing Plan Creation	License cost	Monthly Comm. Services	Engineer training cost
System Optimization	Maintenance cost	Intersection Comm. Hardware	Technician training cost
Controller replacement	Hardware cost	Trenching (for Comm.)	
Detector installation			
Detector validation			
Comm. Installation			

While the potential costs surrounding employees are varied and may be difficult for agencies to pin down, hardware costs and software costs and construction costs are much more concrete. Agencies such as ODOT have personnel trained to estimate the costs of projects and write the contracts governing their construction and implementation. Likewise, frequently purchased equipment such as controllers and detector hardware are often procured under contract at negotiated rates. These factors make establishing a total cost for hardware, software and construction relatively straightforward.

The research team decided to focus cost estimation on the engineer and technician activities directly related to the signal control system in an attempt to prevent confounding factors from influencing the results. An important aspect of this decision is that restricting the personnel costing decisions to those activities and costs most directly related to the signal control system will limit differences in cost attribution and make costs more defensible and definable under contestation. Additionally, since the focus is on traffic signal control system costs and not construction costs, only hardware and software costs directly related to signal control are considered. Construction of and maintenance for additional right of way, lanes, illumination and other features that are commonly incorporated into corridor upgrades are explicitly ignored.

Training and staffing costs are important to consider. Depending on the particular details of the purchase agreement, training may or may not be included in the contract along with other costs, such as licensing. Regardless of how training is contracted or paid for it will have two costs that factor into the CBA. The first is direct costs of the training session such as the cost of having training staff present the training, facilities costs, equipment costs, etc. The other major cost is in engineer and technician time. A day of training, even if the session is considered free or incorporated into the purchasing contract, will still cause a day of lost productivity for the engineering and technician staff, and their respective hours should be accounted as a cost in the CBA.

7.3.2 Cost Estimation

The total cost for implementing a control system is the sum of the cost for engineering/tech costs, system costs, communication costs, and training costs. That is

$$C_{total} = \sum_{i=1}^{n} \beta_i T_i + C_{sy} + C_{com} + C_{tr} \qquad \textbf{(7-2)}$$

Where β_i and T_i are the hourly rate and hours for the i^{th} kinds of work, respectively; n is the total kinds of work considered in the engineering/tech costs; C_{sy}, C_{com} and$C_{tr}$are the system costs, communication costs, and training costs, respectively.

It is important to note that the costs associated with each category have temporal and spatial variability. Work done today in Portland, OR will have different cost values than work done in Bend, OR ten years from now. This can be due to a number of factors, such as inflation, availability of contractors, expertise of personnel, etc. Because of the variable nature of the individual components of engineering, technician, system, communications and training costs, these data must be supplied by the user when performing the evaluation in order to produce accurate results..

7.4 COST TO BENEFIT RATIO CALCULATION

The end goal of a CBA is to determine the ratio of benefits to cost for each system being considered. The benefit-cost ratio (BCR) is often used for comparing different systems or projects to determine which projects have the highest positive impacts relative to their costs. The BCR is defined as the ratio between the total benefits and the total costs (*Shively 2012*):

$$BCR = \frac{B_n - B_o}{C_n - C_o} \qquad \textbf{(7-3)}$$

Where B_n and B_o are the total benefits in dollar for the new control system and original system; and C_n and C_o are the total costs in dollars for the new control system and original system.

It is important to note that the BCR is not a requirement that a specific project or system be funded. It is a decision making aid that will help choose between systems, but it cannot consider all of the factors involved. For example, it is possible for a system to have unacceptable performance in one or more areas, while still providing enough performance increases in other areas to generate a high BCR. Selecting such a system for implementation would be problematic, thus BCR cannot be used as the sole criteria in system selection. Engineering judgment will still be needed to determine if all aspects of the system and its performance will satisfy the needs and demands of the corridor.

8.0 APPLICATION

The goal of this research is to develop an analysis tool that practitioners can use to evaluate different strategies and systems for implementation on a given corridor. Given the number of systems available, it can be a daunting task to find the best system to implement on a given corridor. This application is intended to be used in preliminary analyses with limited data and effort. The results can then be used to create a short list of systems that should be looked at more closely. This will allow engineers to focus their efforts on the systems likely to produce the best results and free up resources to evaluate those systems more thoroughly.

8.1 APPLICATION FLOW

The Excel application is broken into three Excel spreadsheet files for convenience and usability. These files are the data input file where the corridor parameters, intersection geometries, segment characteristics, signal control system selection, signal timing parameters and simulation parameters for the evaluation are entered. The model file reads the data input file, runs the model simulation and generates outputs. The cost to benefit file reads the simulation outputs from one or two model files, takes user input for cost factors and generates a cost to benefit ratio. Figure 8.1 shows the startup window for the data input application. Help files have been integrated into the STATICS suite to help users input data correctly and understand why certain options may or may not be visible.

The various pieces were broken into different Excel files to aid in usability and control factors such as file size. The models and control logic represent the largest and also the most computationally expensive component of the process. By having the data input in a separate file from the model simulation file, it is relatively easy to try multiple simulations with different data. If the input data were integrated into the model simulation file, it would require changing the input data each time the simulation were to be run. Since it is a non-trivial task to enter geometric and timing data, unnecessary repetition of the work is to be avoided where possible. Storing and working with multiple, relatively large, files for a given corridor was also not considered to be an effective solution to working with multiple configurations. By separating the input data from the model file, it is possible for one model file to run any number of model simulations based on different input file data with the same model file. For similar reasons, the cost to benefit analysis was also split from the model file.

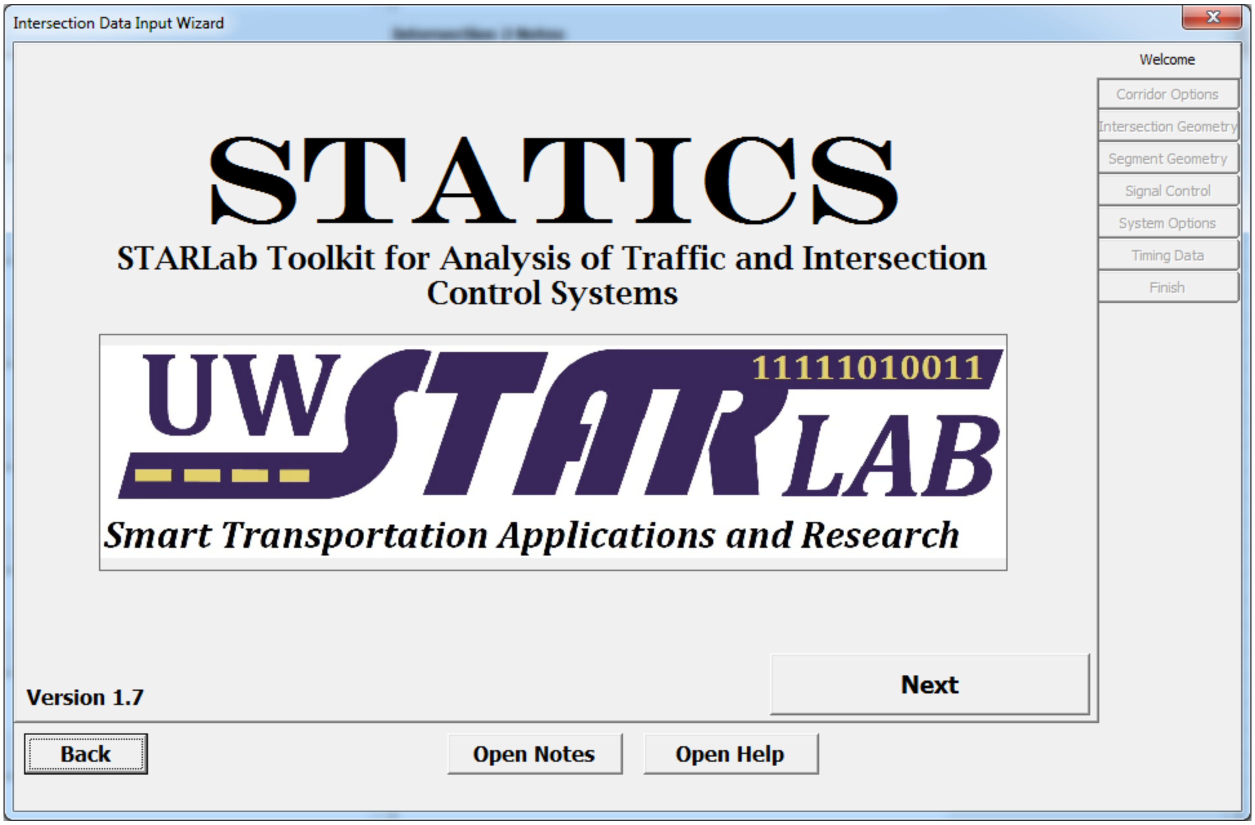

Figure 8.1: Application Startup Window

8.2 DATA INPUT FILE

The data input file starts with the startup screen seen in Figure 8.1. It then proceeds to a corridor setup screen. Following corridor setup is intersection geometry entry. The next screen is segment and minor intersection configuration.

After segment and minor intersection configuration the data input process moves on to signal control factors. The first signal control decision to be made is which system will be used in the evaluation. This is followed by entering system wide data such as schedules for time of day plans. After system wide data has been entered, the specific intersection timing data must be entered. Finally, the simulation parameters and simulation outputs are chosen.

8.2.1 Corridor Setup

The first step in the analysis, seen in Figure 8.2, is to determine how many intersections are being evaluated. The number of intersections selected at this point will determine how many intersections and segments are visible for the remainder of the process. It is also important to give some kind of a name to the project so that various files can be differentiated and confusion kept to a minimum. The Corridor Name and Evaluation Day fields are simple text blocks that are used by the application to track where and when the evaluation is taking place. Internally these fields are simple text and are not strictly required by the program, though they are highly recommended for human users. Clicking on the Change Constants button (The button name changes to Set Constants when pressed and changes are not committed until Set Constants is pressed) will make a set of controls visible (as in Figure 8.3) for users to enter simulation constants as discussed below. Clicking the Set Constants button commits the constant values.

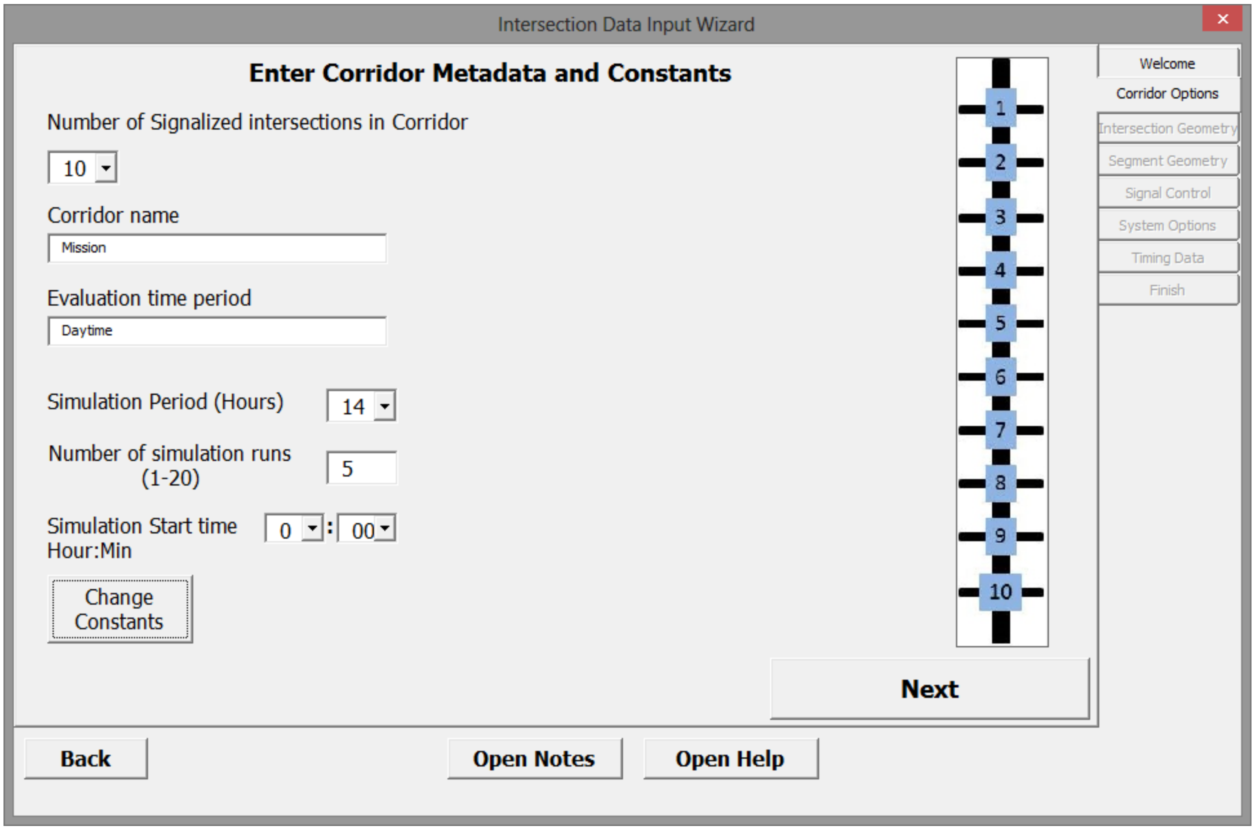

Figure 8.2: Corridor Metadata and Constants

There are a number of basic simulation constants that are required to make the queuing model work. These include saturation flow rates for through, right turn and left turn movements, acceptable gap times for turning vehicles and vehicle length and standstill distances. The saturation flow rates control the distribution of vehicle discharge times during green lights and, thus, influence the volumes served. Saturation flow rates are also used to determine movement and intersection saturation levels, which are used in performance reporting and some aspects of signal control. Gap acceptance behavior controls how vehicles are discharged during permitted movements. Specifically, a turning vehicle will wait until a gap larger than the set gap length is available in order to make a permitted turn. In the application, only a single right turn lane or shared through and right turn lane are considered, so only a single value is required to determine acceptable gaps for right turning vehicles. Left turning vehicles are somewhat more complicated to model under permitted control. Left turning vehicles may cross up to four opposing through lanes in the model, though practice may be more restrictive. The more lanes the left turning vehicle must cross the longer the vehicle will take to make the turn and the larger the gap that will be required. Finally, the vehicle length and standstill distance factors are used to determine the lengths of queues for performance measurement and occlusion purposes. Whether a queue backs up to the previous intersection or whether a turning movement bay backs up into the through lanes is an important consideration for performance evaluation.

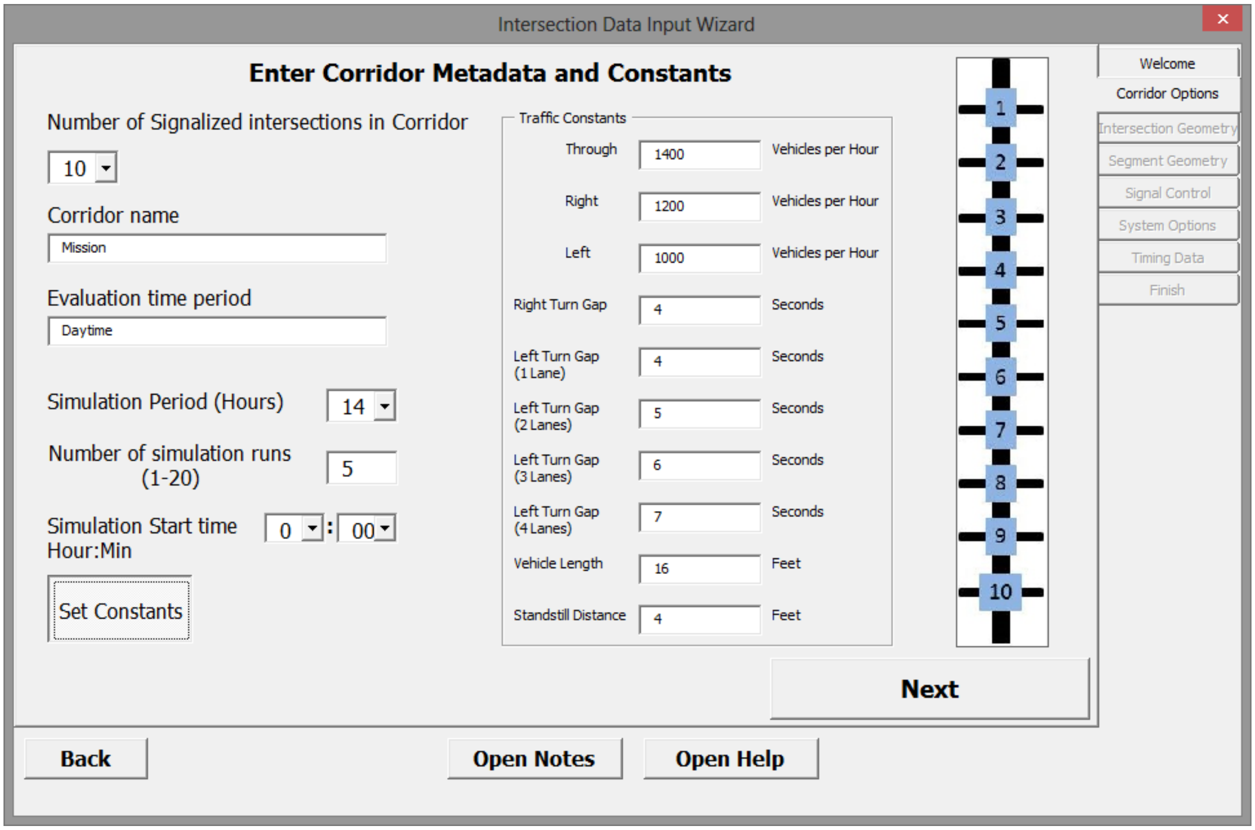

Figure 8.3: Simulation Constants Window

8.2.2 Intersection Geometry

Intersection geometry is a critical part of the modeling and signal control simulation process. As such, each intersection needs to have some rather extensive data input into the application in order for it to accurately model the intersection and its traffic. Each intersection's button in Figure 8.4 is linked to a pop up windowthat will collect the relevant data.

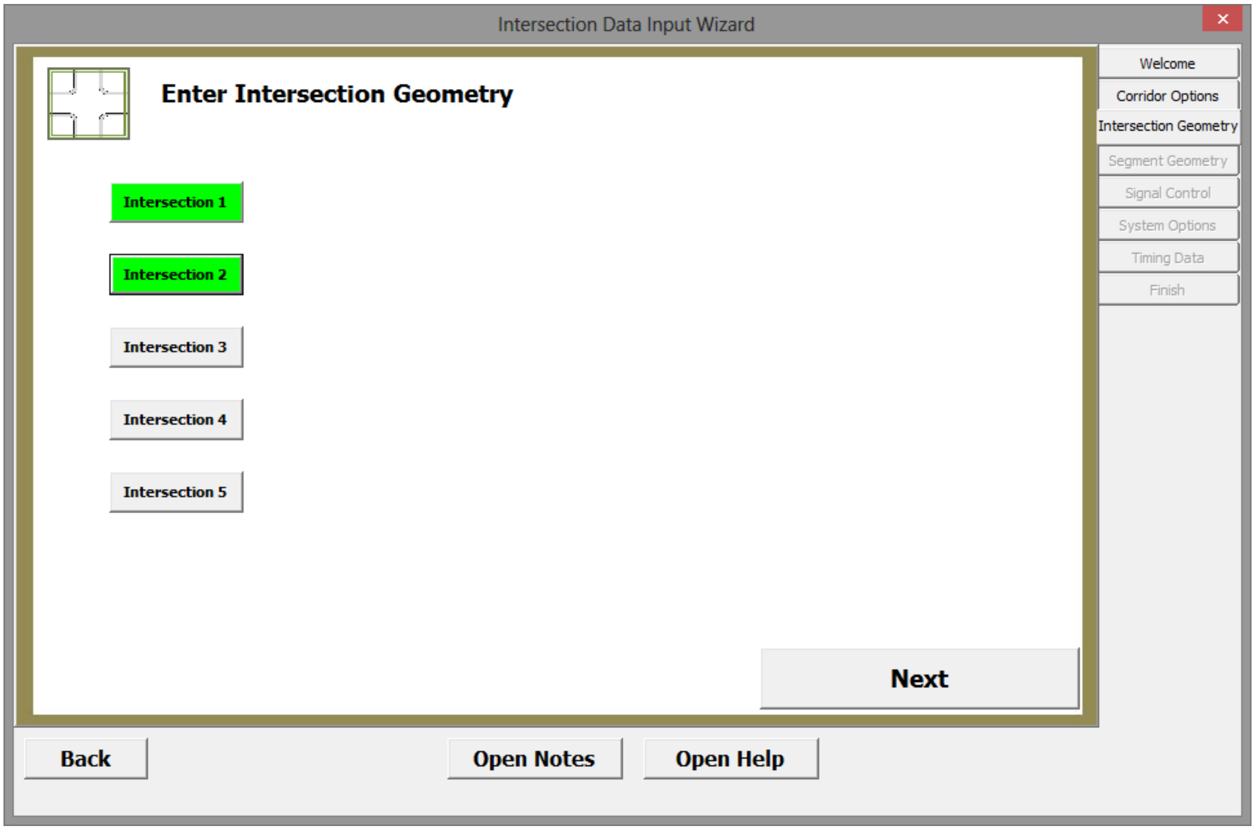

Figure 8.4: Intersection Geometry Screen

The intersection geometry entry window is the most complex window in the entire application. This is because there are a large number of geometric factors that define an intersection. When this window first opens for a given intersection, all of the controls are disabled except for the buttons in the Phasing Restrictions box as seen in Figure 8.5. These buttons control left turn phasing restrictions, T-intersection type and phasing. According to the standard phasing shown in Figure 6.1, phases 1 and 5 and phases 3 and 7 would normally be able to be served together.

Restricted phasing is used to prevent the two opposing left turn movements (phases 1 and 5 and phases 3 and 7) from being allowed to be served at the same time. Certain intersection geometric factors can cause the paths left turning vehicles would use to cross, this is particularly possible when there are two left turn lanes on one or both phases. Phasing restriction buttons enforce a minimum of six phase control for the 1/5 Restricted button and require the signal to operate in eight phase or six phase split modes mode when the 3/7 Restricted button is activated. These phasings are necessary to allow lead-lag left turns for the appropriate movements which allows the system to enforce a separation between the corresponding left turn phases.

The T-intersection buttons are mutually exclusive, only one may be active at a given time. When one of the T-Intersection buttons is selected, the opposite approach is removed. Its queue lengths are set to zero, its controls disabled, etc. For example, if the T-Intersection 3/8 button were selected, the T-intersection 4/7 button would be unselected if it were active. Also the Phase 4/7 Approach set of controls would be disabled, the phase 4 crosswalk deactivated (because the crosswalk is tied to its associated phase for timing), the left turn control type from the phase 2/5 Approach set of controls would be set to prohibited and Right Turn On Red (RTOR) would be disabled for the Phase 6/1 Approach, the Phase 6/1 Approach right turn control type would be changed to prohibited and the number of through lanes for the Phase 3/8 approach would be set to zero.

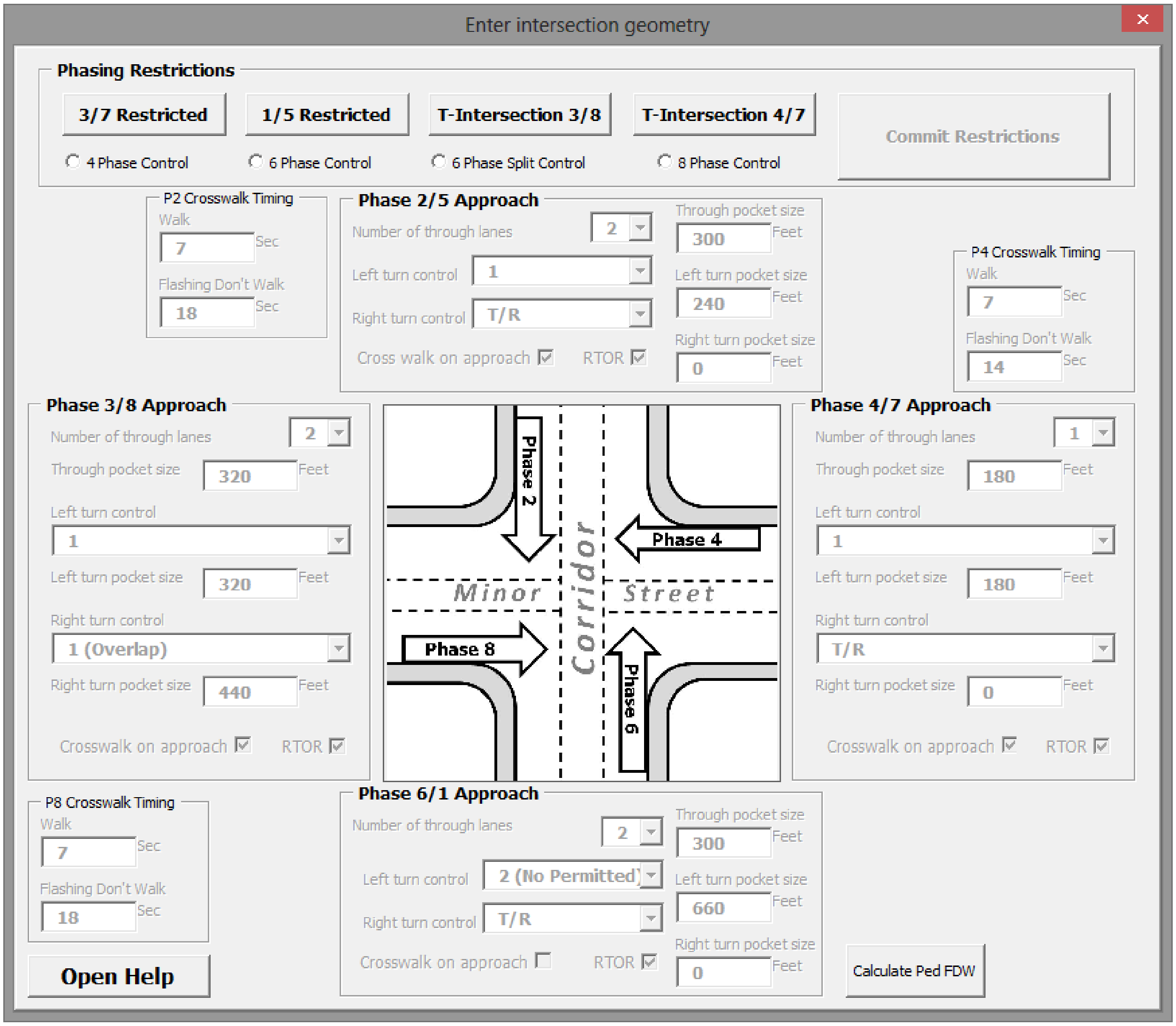

Figure 8.5: Intersection Geometry Entry Before Phase Restrictions Have Been Committed

When the appropriate phasing restrictions have been selected, the user must select the Commit Restrictions button. This allows all of the appropriate controls to be enabled and disables the phasing restrictions as seen in Figure 8.6. For each approach there are drop down menus for each movement on the approach to determine how many lanes are utilized by each movement and how they are operated. Left turn control allows for dual left turn lanes with the restriction that there are no permitted left turns in that configuration (which increases the intersection phasing), one left turn lane, no dedicated left turn lane but permitted left turns from a through/left turn lane and prohibited left turns. Right turn control allows one right turn lane with overlaps to allow the right turn phase to have a green light during the other street's left turn (for example, phase 2 right turn and phase 3 left turn), one right turn lane with permitted right turn operation, a through/right turn lane with permitted turns or prohibited right turns. If both T/L and T/R are selected at the same time with a single through lane, that lane will serve all three movements.

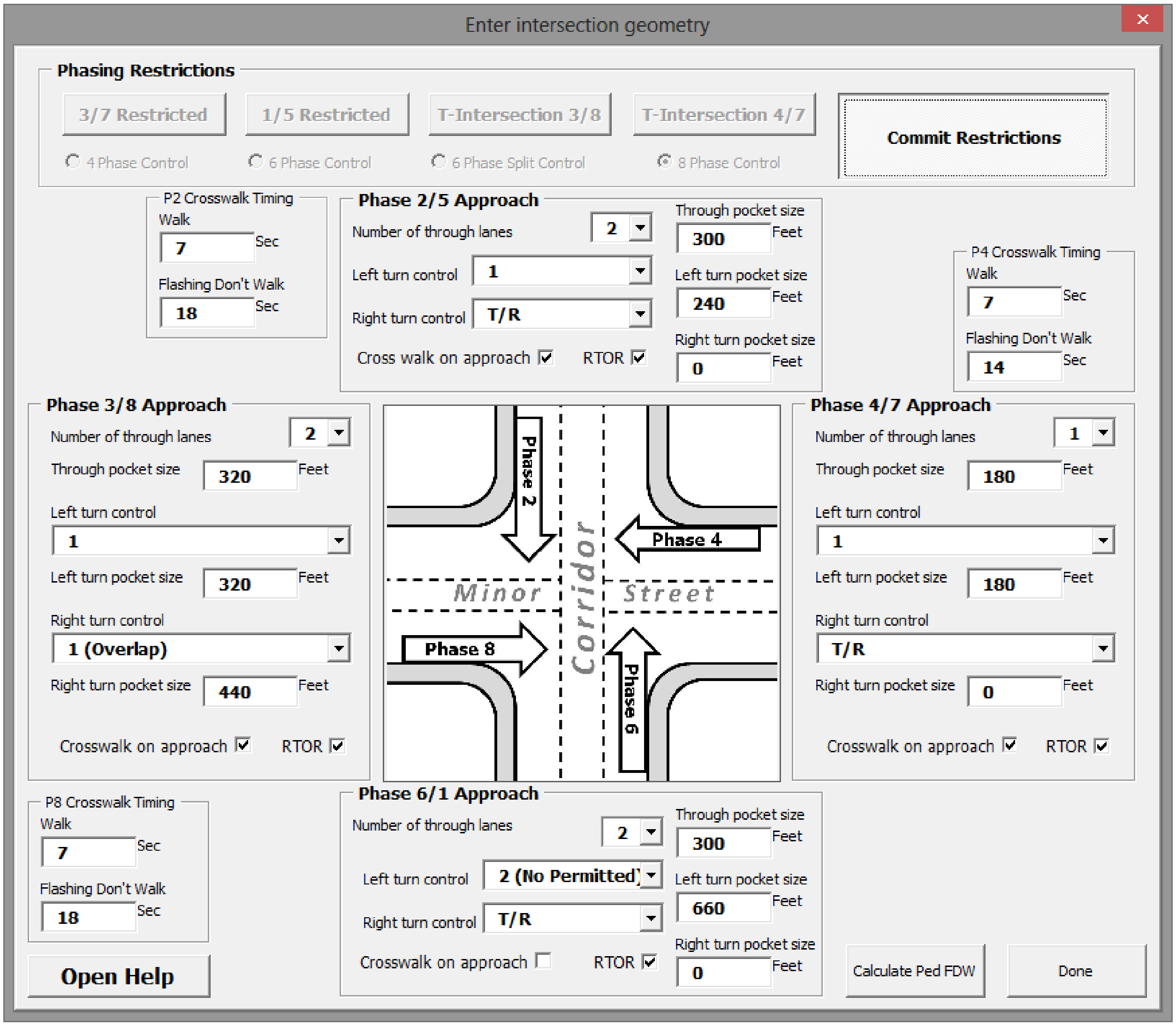

Figure 8.6: Intersection Geometry with Phasing Restrictions Committed

This affects queue length calculations, because the intersection may have limited storage for more vehicles than expected based on segment lane counts. There is also a text box for each turning movement to input the length of pocket sizes for storing turning vehicles. Each approach also has two checkboxes. The RTOR check box enables or disables right turn on red permitted right turns. The crosswalk on approach checkbox will enable or disable the appropriate Crosswalk Timing box. In the Crosswalk Timing boxes there are two text boxes, one for the walk time and the other for the flashing don't walk time.

8.2.3 Segment Geometry and Minor Intersections

Since segments between intersections are generally simpler geometrically than intersections, the data input windows are much simpler than those for intersection geometries. Segment geometry inputs may be seen in Figure 8.7. These inputs consist of a free flow speed, the segment length in feet and the number of lanes between each intersection pair. Segments are limited to up to four lanes in each direction with a minimum of one. Note that there will be one fewer segment than intersections, because segments only exist between intersections.

For each segment in Figure 8.7 there is a checkbox to input minor intersection characteristics. These minor intersections are unsignalized sources of traffic on the segment. They are used to balance traffic differences found in the data. For example, a total of 400 vehicles may be observed on an approach at an intersection during a 15 minute interval, but only 350 may have come from the appropriate through movement, right turn and left turn movements at the upstream intersection. This kind of discrepancy is relatively common in field data. Some of the difference comes from vehicles entering or leaving the segment between the two intersections. Other causes of difference include sensor errors, poor sensor placement, etc. To make the modeled volumes more closely adhere to observed volumes, the model system includes the concept of minor intersections to allow volumes to change between intersections. Minor intersections also play a part in platoon break up and are thus important to the modeling process.

Each segment may have up to 3 minor intersections along its length. These minor intersections are defined by their location. Their location is a simple distance measurement from the upstream (lowest number) intersection. Note that the minor intersection properties are the same for both directions of travel, but the volume added or subtracted between the intersections is directional. If traffic is lost going from intersection 1 to intersection 2 and gained from intersection 2 to intersection 1, then the volume difference will be subtracted from the traffic going from 1 to 2 and added to the traffic going from 2 to 1.

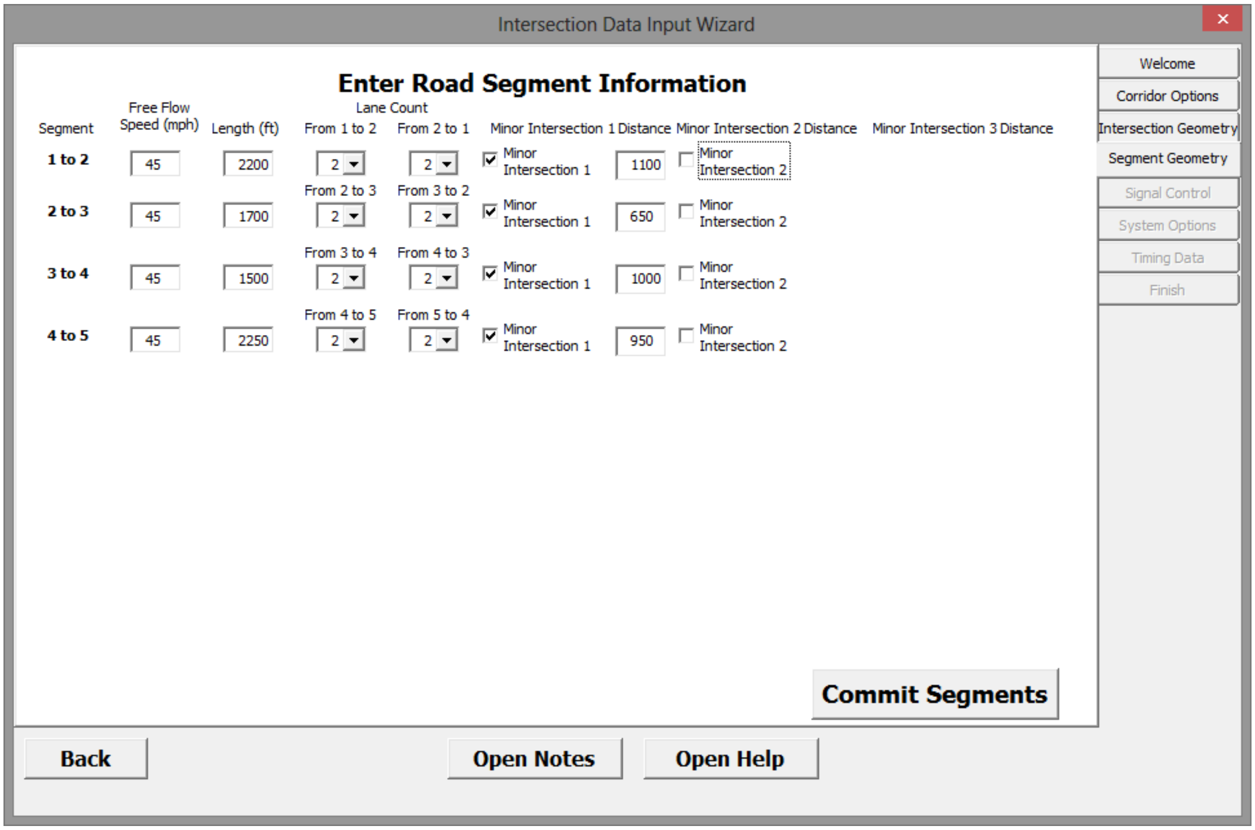

Figure 8.7: Segment Geometry Inputs

8.2.4 Signal Control

Ultimately, this project is all about the traffic signal control system selection that follows segment data input. Figure 8.8 shows the traffic signal control selection screen. There is a toggle button at the top of the screen that indicates whether adaptive or conventional systems are being evaluated. Clicking the toggle button will switch whether conventional or adaptive systems are enabled for selection. The conventional systems can operate with either time of day or traffic responsive plan selection. Choosing between the two options is done by selecting the desired strategy in the Plan Selection box. In Figure 8.9, Figure 8.10, Figure 8.11, and Figure 8.12 conventional systems are active and Fixed Time control has been selected with Time of Day plan selection. Note that an error message will pop up if a combination of conventional strategy and plan selection strategy or an adaptive system is not selected.

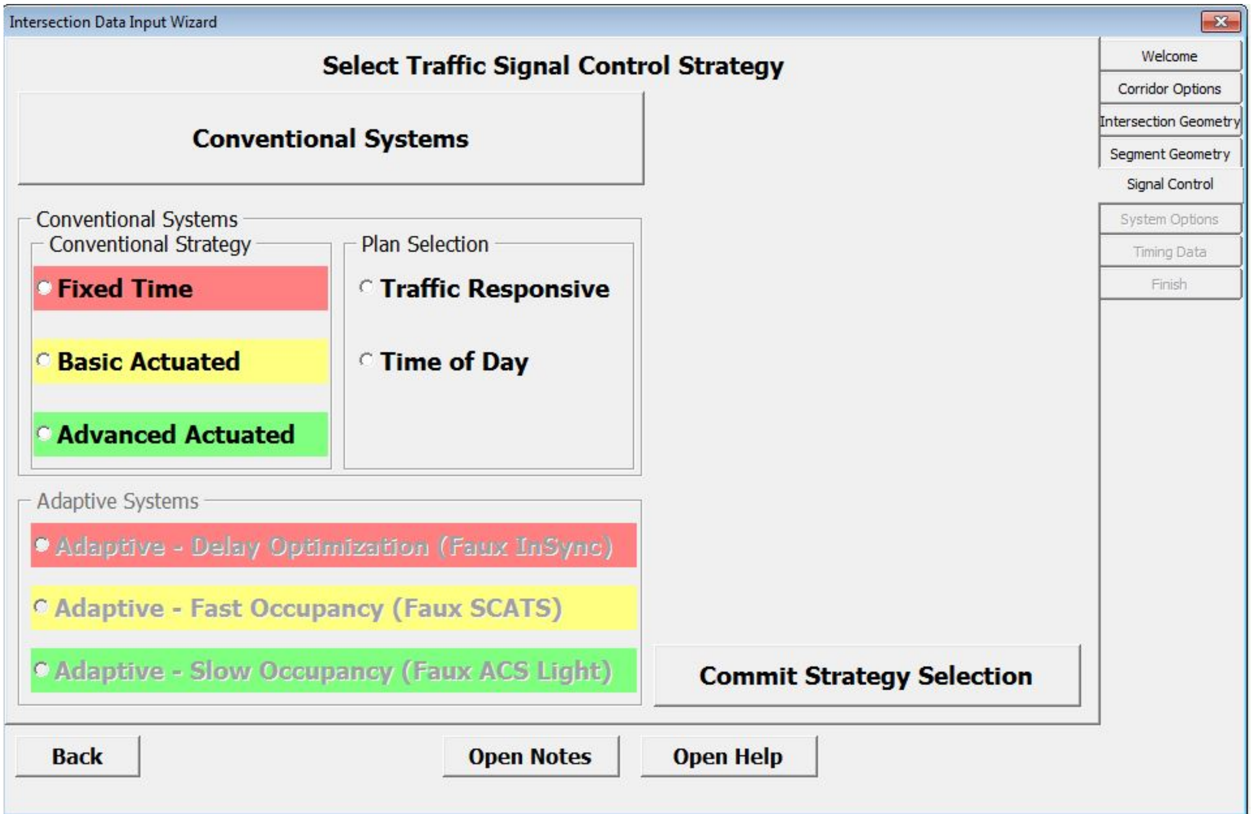

Figure 8.8: Traffic Signal Control System Selection

8.2.5 System Specific Information

Once a traffic signal control system is selected, there are some system level parameters that need to be entered. In Figure 8.9, the system options for fast occupancy signal control are shown. In operation, the selection of a signal control system causes only the relevant system level options to be displayed. For the delay optimization strategy analysis (Faux InSync), users must enter minimum and maximum green tunnel lengths as seen in Figure 8.10: System Level Parameters – Faux InSync. The fast occupancy logic (Faux SCATS), needs to have intersection groups defined in order to set up coordinated signal groups. It also requires volume thresholds to determine when to coordinate between groups of intersections. Finally, the fast occupancy signal control strategy determines which direction to enable progression based on the ratio of traffic in the increasing and decreasing directions. When the traffic ratio is less than the input ratio, the system will use balanced progression parameters collected in the next step. When the traffic flow ratio exceeds the input value, the system will prioritize progression in the major traffic flow direction if it exceeds the ratio provided.

Conventional signal logic has system level parameters based on plan selection methodology. Time of day plan selection requires the entry of times when each plan should be active as seen in Figure 8.11: System Level Parameters – Time of Day plan selection. Traffic responsive operation requires a reference intersection and then a set of volume thresholds for phases 2 and 6 to determine whether that traffic is “high”, “medium” or “low” as seen in Figure 8.12: System Level

Parameters – Traffic Responsive. Then, depending on what the combination of state pairs are for phases 2 and 6 at the reference intersection, the selection system picks a user entered plan number that corresponds to that specific pair of states (for example, High:High). Note that for time of day and traffic responsive systems there is a maximum of five plans. Note that the slow occupancy implementation uses time of day plan selection for selection of its base plans.

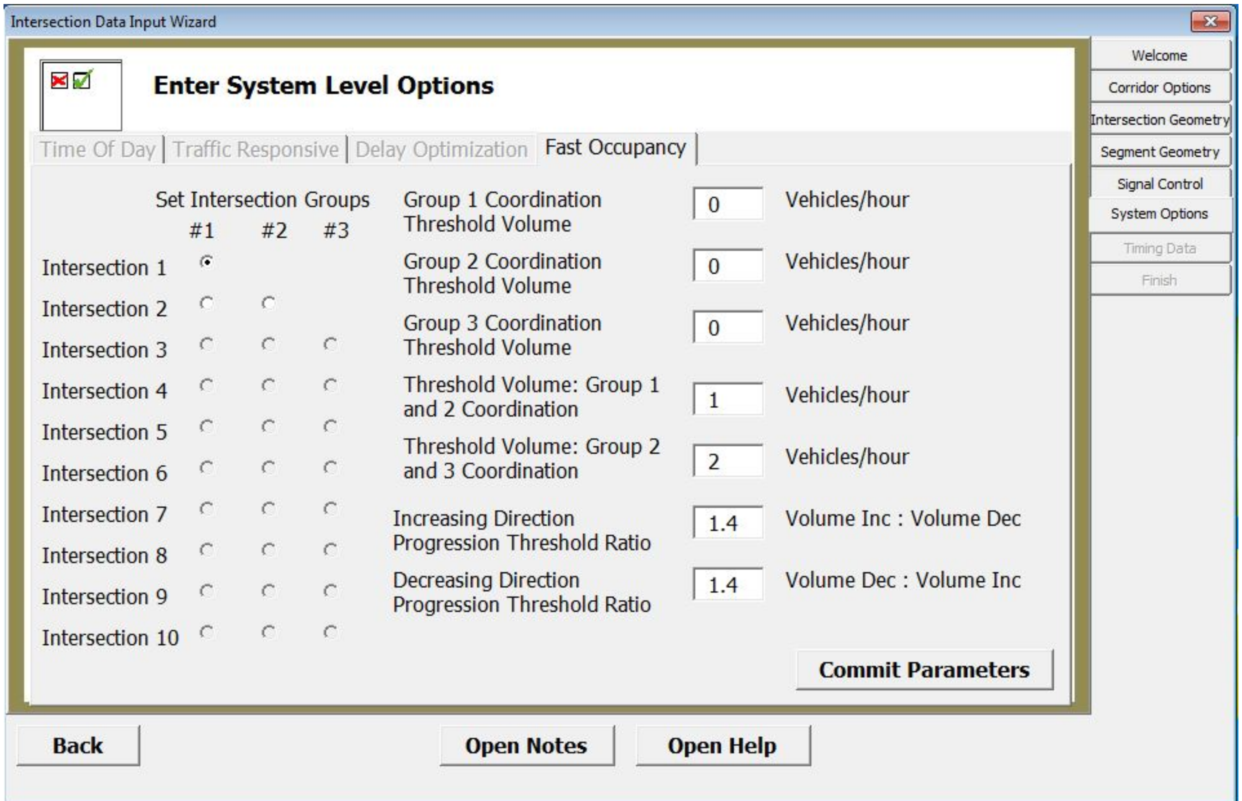

Figure 8.9: System Level Parameters – Faux SCATS

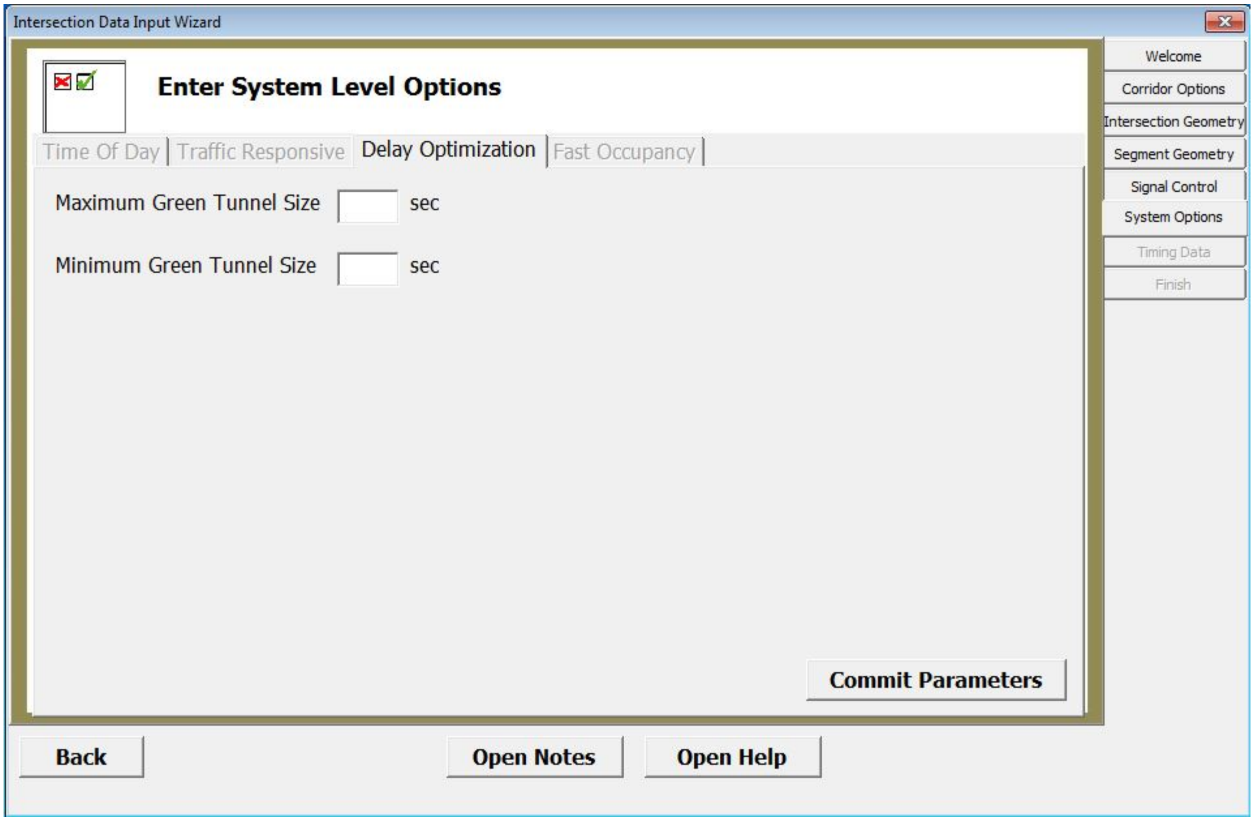

Figure 8.10: System Level Parameters – Faux InSync

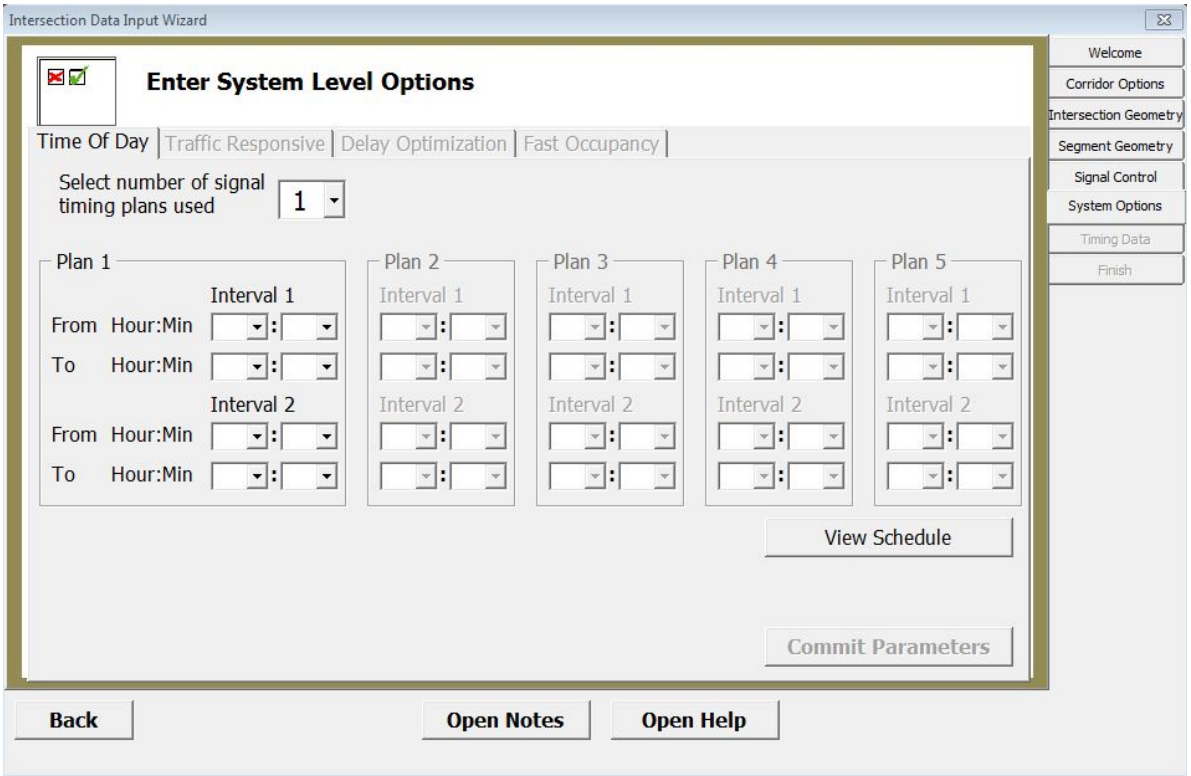

Figure 8.11: System Level Parameters – Time of Day plan selection

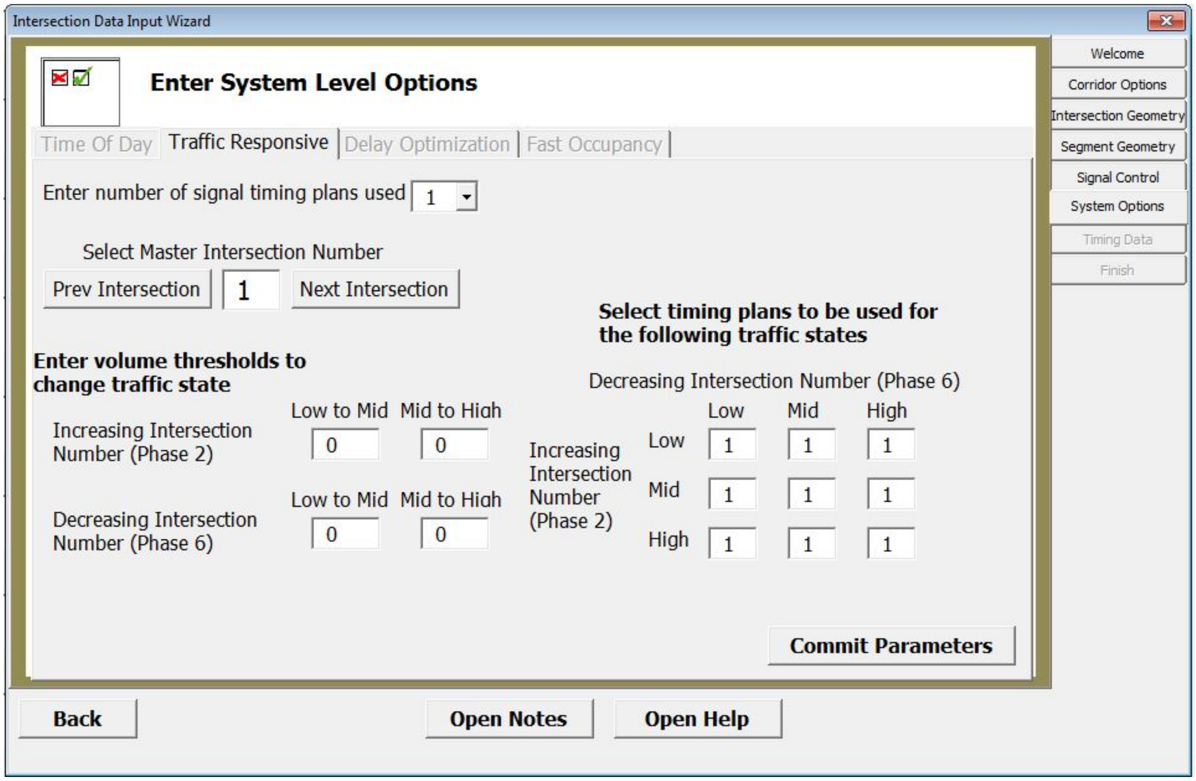

Figure 8.12: System Level Parameters – Traffic Responsive

8.2.6 Timing Parameters

After selecting a signal control system, users will advance to the screen seen in Figure 8.13. Each system requires different input data for timing purposes. Note that according to the phasing selected in the intersection geometry window, phases may be missing from this screen. For example, under four phase control, all of the odd numbered phases would be missing. Six phase control would make phases 3 and 7 disappear. Six phase split phasing would result in phases 7 and 8 being missing.

In this case the delay optimization strategy (Faux InSync) is the simplest, asking for minimum and maximum splits (Figure 8.13). Fast occupancy (Faux SCATS) adds voting biases for green time allocation to be biased by a multiplier (A multiplier greater than one gets more than proportional green time and a multiplier less than one gets less than proportional green time.) and asks for a minimum cycle length for use during low traffic free operation. Fast occupancy also requires input for minimum and maximum coordinated cycle length as seen in Figure 8.14. The Faux SCATS progression system is based upon three progression patterns, a balanced progression, and progression patterns biased toward the increasing intersection number and decreasing intersection number directions. The user enters an offset appropriate for the minimum coordinated cycle length for each of the three scenarios and does likewise for the maximum coordinated cycle length. During operation, the system selects one of the three progression patterns based upon whether the ratio of increasing intersection number to decreasing intersection number direction traffic meets or exceeds the progression ratios provided in the previous step. Both Faux InSync and Faux SCATS will supply pedestrian time during their appropriate phases and adjust other phases' timing as possible given the fixed pedestrian interval.

For other systems, the conventional systems and slow occupancy adaptive strategy (Faux ACS Lite) use timing plans that change either according to the time of day or in a traffic responsive manner. These systems may use up to five plans. Timing information must be entered for each active plan. Note that one plan number is selected for all intersections simultaneously in the model, so each intersection needs timing data for each active plan, even if multiple or all plans are the same for a given intersection.

Figure 8.15 shows the data input sheet for fixed time control, which only requires green splits for each active phase. In cases where the phase maximum time is less than the pedestrian walk plus flashing don't walk time, the control logic will change to the pedestrian alternate cycle to serve the pedestrian movement (on the next cycle). The pedestrian alternate cycle is unnecessary (and can be left blank) if the normal plan can cover all of the pedestrian crossing times. Note that it is usually the phase 4 and phase 8 crossings and timings that cause issues. Typically, phases 4 and 8 are serving relatively lower vehicle volumes and the phase 4 and 8 crosswalks have to cross a wider road, the main corridor. This means that the longer required crossing time is trying to operate at the same time as the shorter required phase split. Often this means that the phase 4 and 8 pedestrian movements need more time than is normally allocated for vehicle service. This necessitates handling pedestrians explicitly in the signal timing (This also applies to actuated control and Faux ACS Lite.).

Figure 8.16 shows the slow occupancy (Faux ACS Lite) system data entry sheet. Faux ACS Lite is based on an actuated control system, and so has minimum and maximum splits for each phase and, like Fixed time control, above, and actuated control, below it has a separate pedestrian plan for when the normal plan cannot cover the pedestrian interval. Slow occupancy also has positive and negative adjustments that allow the adaptive logic to grow or shrink specific splits as needed. Note that currently, the pedestrian splits are not adaptive.

Figure 8.17 shows an example of the timing data that is collected for actuated signal control system. Note that the advanced options tool box only appears when advanced actuated control is selected as the control type. The data collected in Figure 8.17 includes the normal operation minimum and maximum phase splits in seconds for each phase. For all of the non-coordinated phases (any phase but 2 or 6), there is a checkbox that allows the signal control logic to skip that phase if there are no vehicles waiting for that phase to be given a green light. Phases 2 and 6 have the option to allow the signal control system to rest in those phases. Resting in a phase allows the phase to continue to be served past its normal maximum time as long as there are no competing phase demands. Understandably, resting is generally only meaningful in light traffic time periods or on very low demand cross streets.

There a few other pieces of information that need to be entered into the control parameters screen. The user needs to select a set of starting phases, effectively selecting phase order. The user also needs to enter an offset so the system can coordinate multiple intersections. The final box, cycle length, is not a user input, but instead displays the current cycle length based on the entered splits and previously chosen phasing. This is provided to assist the engineer in identifying timing plan data entry errors.

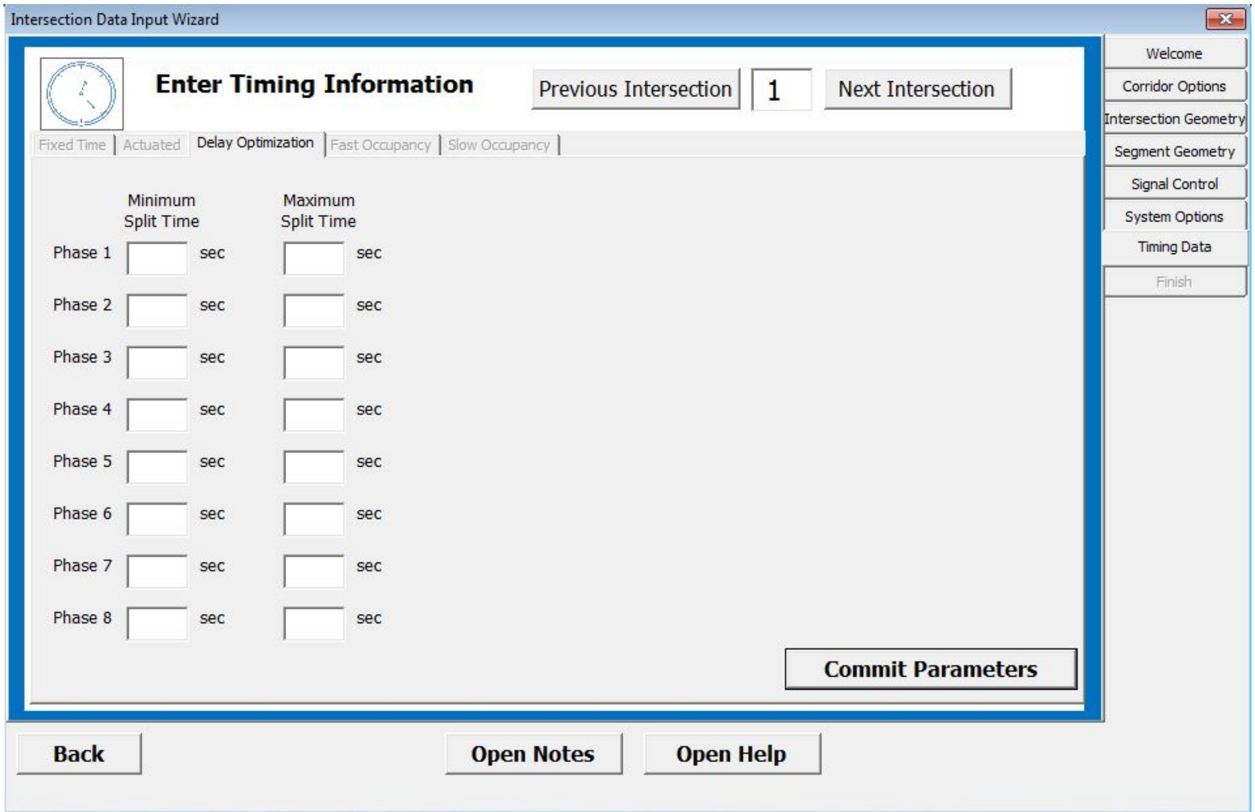

Figure 8.13: Signal Timing Information Entry – Faux InSync

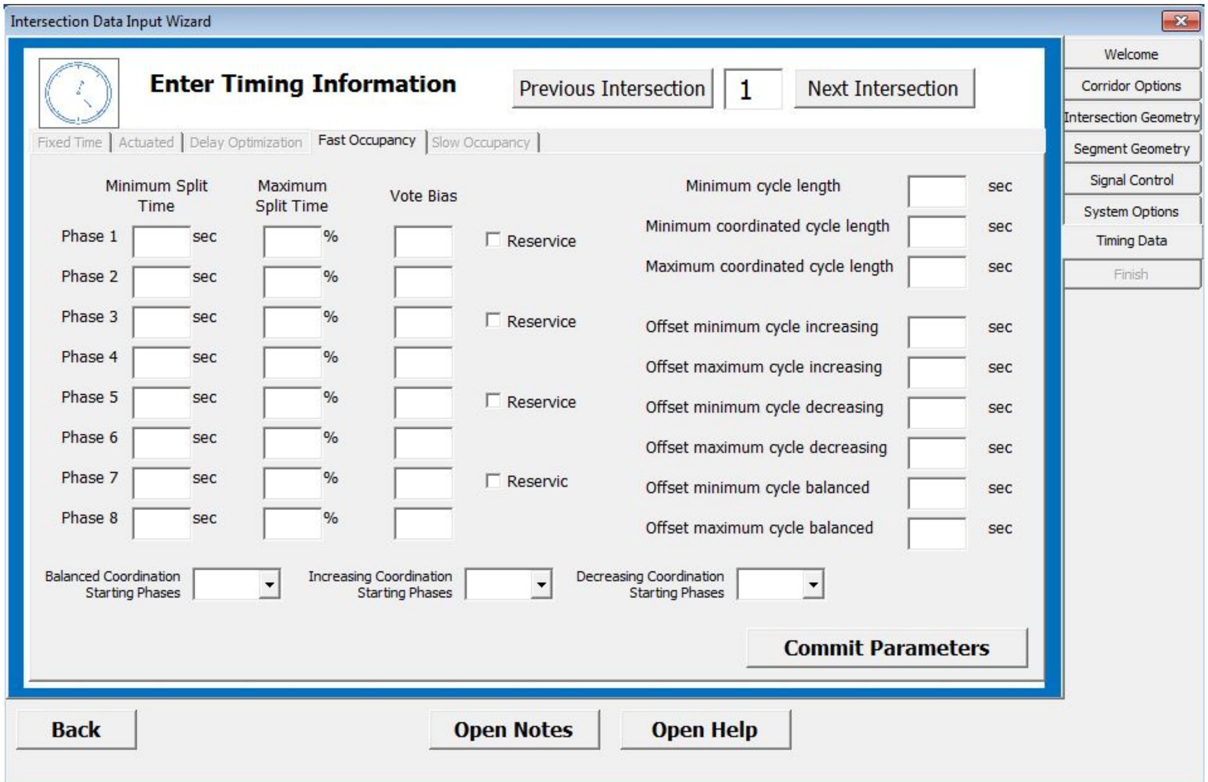

Figure 8.14: Signal Timing Information Entry – Faux SCATS

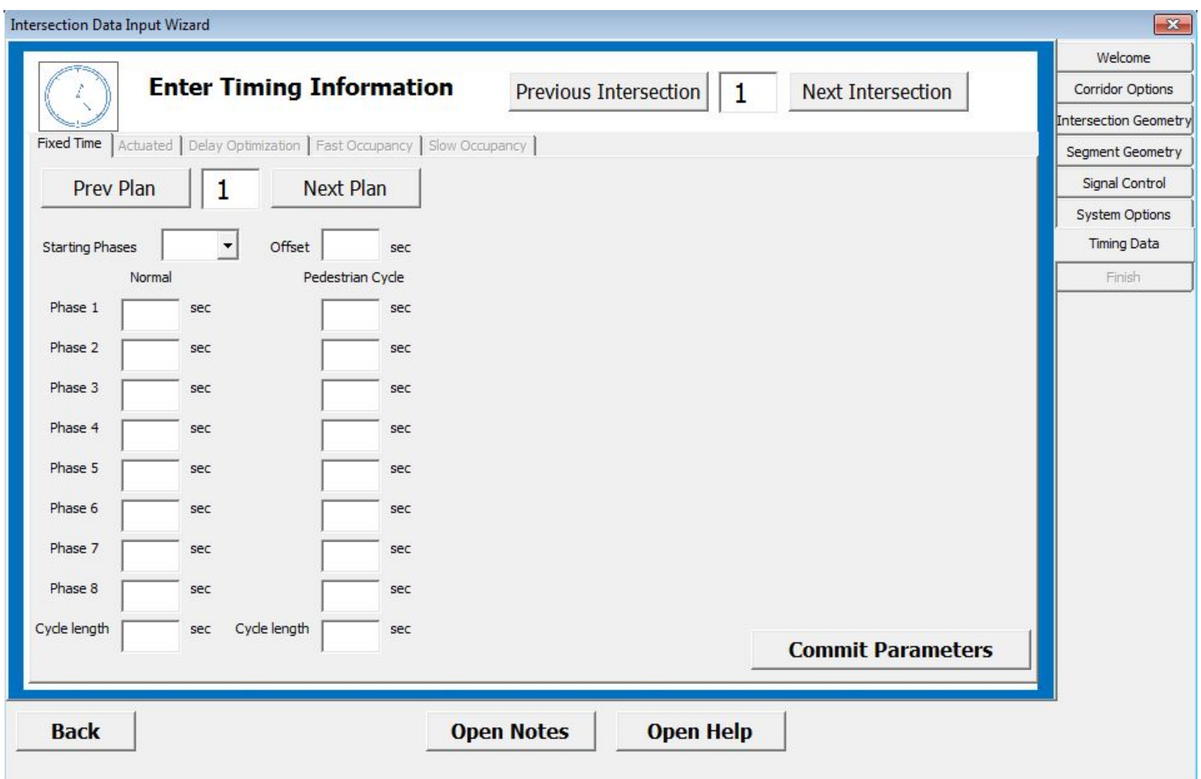

Figure 8.15: Signal Timing Information Entry – Fixed Time Control

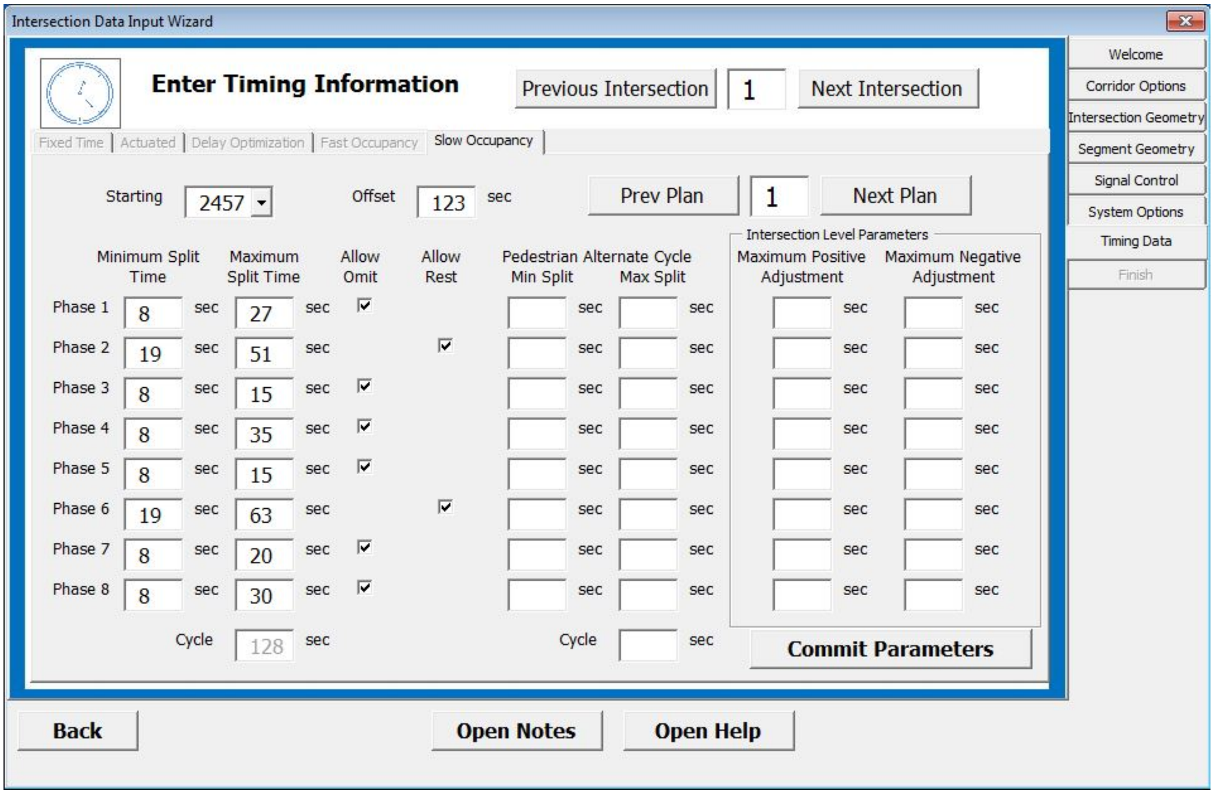

Figure 8.16: Signal Timing Information Entry – Faux ACS Lite

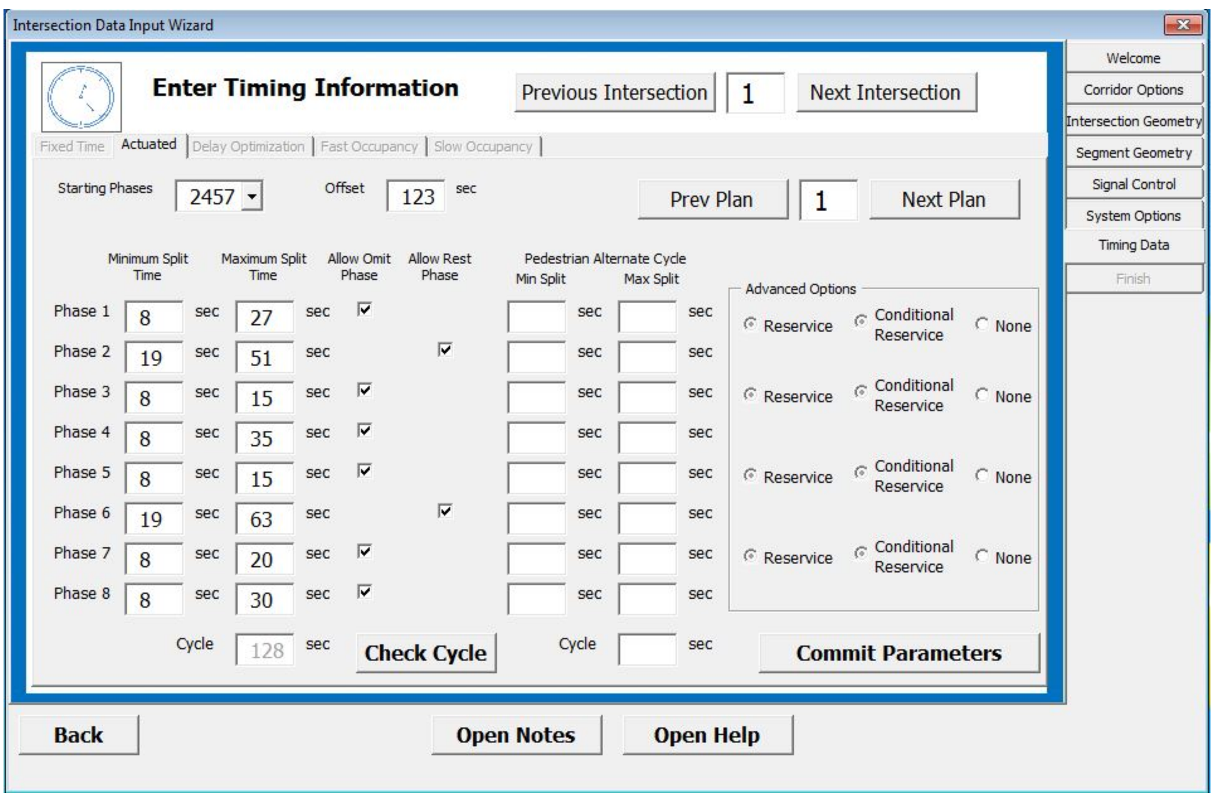

Figure 8.17: Signal Timing Information Entry – Actuated Control

8.2.7 Field Data Entry

The final task for the data input file is to input the volume data measured from the field. Specifically, for each intersection approach the model requires the volume of through vehicles, right turning vehicles and left turning vehicles for each 15 minute interval during the study time period. Pedestrians are not counted individually, but by pedestrian push button activation per 15 minutes. The data input file lists times at the left of the data entry table, for a 24 hour analysis, these times would represent the time of day. For shorter analyses these times represent time during the analysis interval. Data should always be allocated from input file time 0:00:00 for the model to correctly interpret the input data.

8.3 MODEL FILE

The model file user interface is very simple, as may be seen in Figure 8.18, below. When the file is opened a window opens automatically that has four buttons. The first button opens a file dialog to select and input file and import the relevant input data into the model file. The second button runs the modeling process, which ends in a file save dialog that saves the model file results with a different name to prevent confusion and overwriting of the model file itself. The third and fourth buttons are for packing and unpacking the model file. The model file itself is internally very repetitious. It is unnecessary to save the repeated formulae when sending the file via email or web service. The third button deletes the redundant lines of cells from the template sheets, the intersection sheets and the segment sheets. The fourth button copies the repetitive lines out again in the template sheet. Note that this process destroys any simulation results in the model file, but results should have been saved to a separate file after running the model.

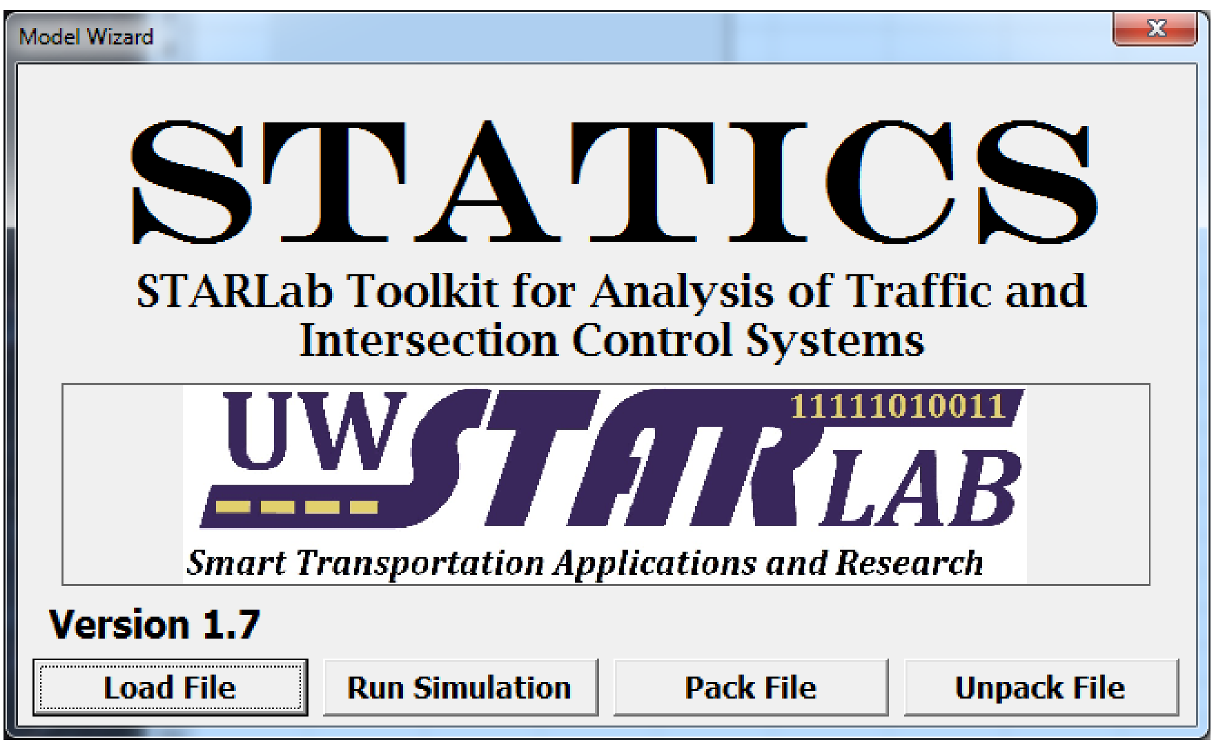

Figure 8.18: Model File User Interface

8.4 COST TO BENEFIT FILE

In order to aid decision makers in determining which systems to pursue for more in depth analysis, the research team chose cost to benefit ratio analysis as the means to select the control strategies that will probably perform the best for ODOT. The cost to benefit analysis will be conducted based on the outputs of the model file. After the model file has been run, a set of performance outputs will be saved to separate file that is imported into the cost to benefit ratio calculator file. These outputs include a number of factors such as delay, number of stops and the volumes of vehicles served on the corridor. The opening screen of the cost to benefit calculator file are shown in Figure 8.19.

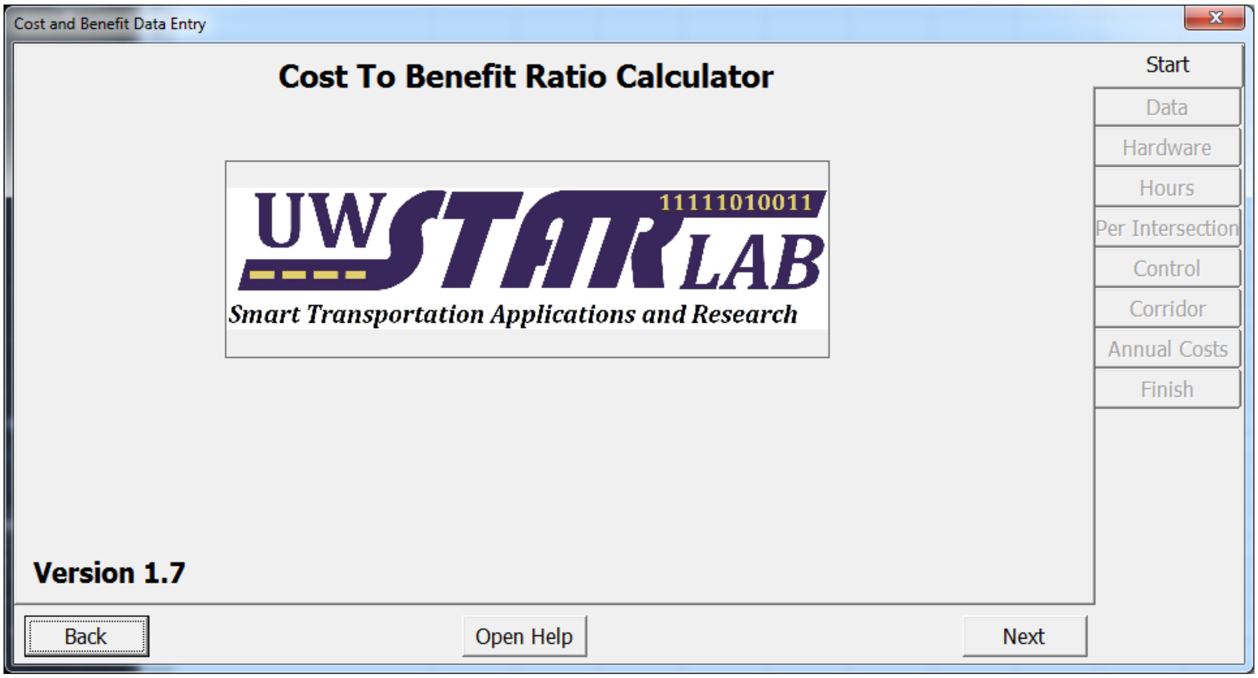

Figure 8.19: Cost to Benefit Calculation File

8.4.1 Data Input

As was stated previously, the cost to benefit calculator file relies on input data from the model file to perform its analysis. The calculator file actually needs two different model file results, one for the reference system (most likely to be the existing control system) and one for the candidate system. Figure 8.20 shows the data input screen. There is one other control on this screen; the comparison percentile button is used when both input data files contain the results of multiple model runs. It allows the user to determine whether to compare systems by their 50th percentile (median), 75th percentile or 90th percentile values.

By clicking the Select Comparison Data button users can choose which data to base their cost to benefit analysis upon. This makes the Select Comparison Data frame visible as seen in Figure 8.20. Users should note that selecting both phase 2 delay and travel time in the increasing direction will effectively double count phase 2 delay in the cost to benefit analysis. This is because the delay experienced by vehicles in phase 2 will also be reflected in their travel time. Phase 6 delay and travel time in the decreasing direction share this phenomenon. The two options are available for convenience, but should be used with caution and an understanding of the background calculations.

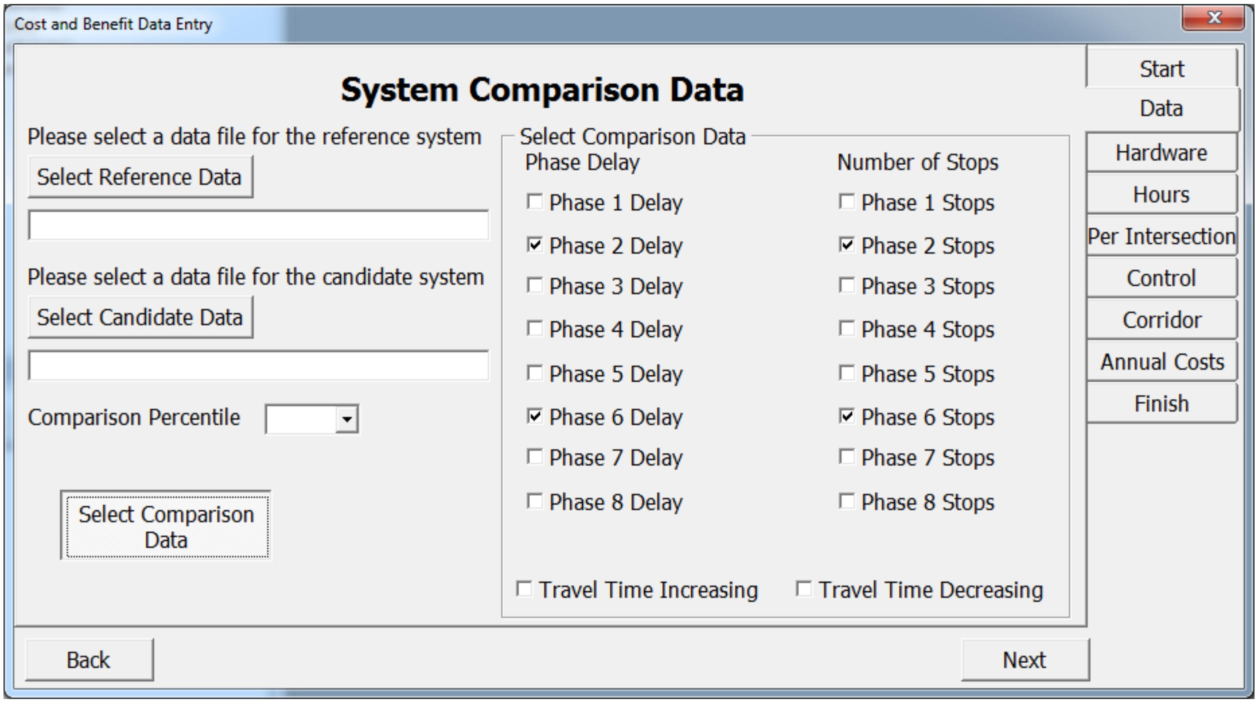

Figure 8.20: System Data Selection

8.4.2 Hardware Costs

Changing traffic signal systems can require a sizable investment in replacement hardware. There are numerous classes of hardware to be replaced, such as controllers, field detection equipment, detector cards in cabinets, and communications equipment such as modems. These commonly replaced pieces of equipment can change price based on volumes purchased, contract rates and many other factors. As such, it is important that users provide current costs for these pieces of equipment as in Figure 8.21. Note that other costs, such as cabinet replacement can be accounted for by the miscellaneous costs entry included in the intersection window as seen in Figure 8.23.

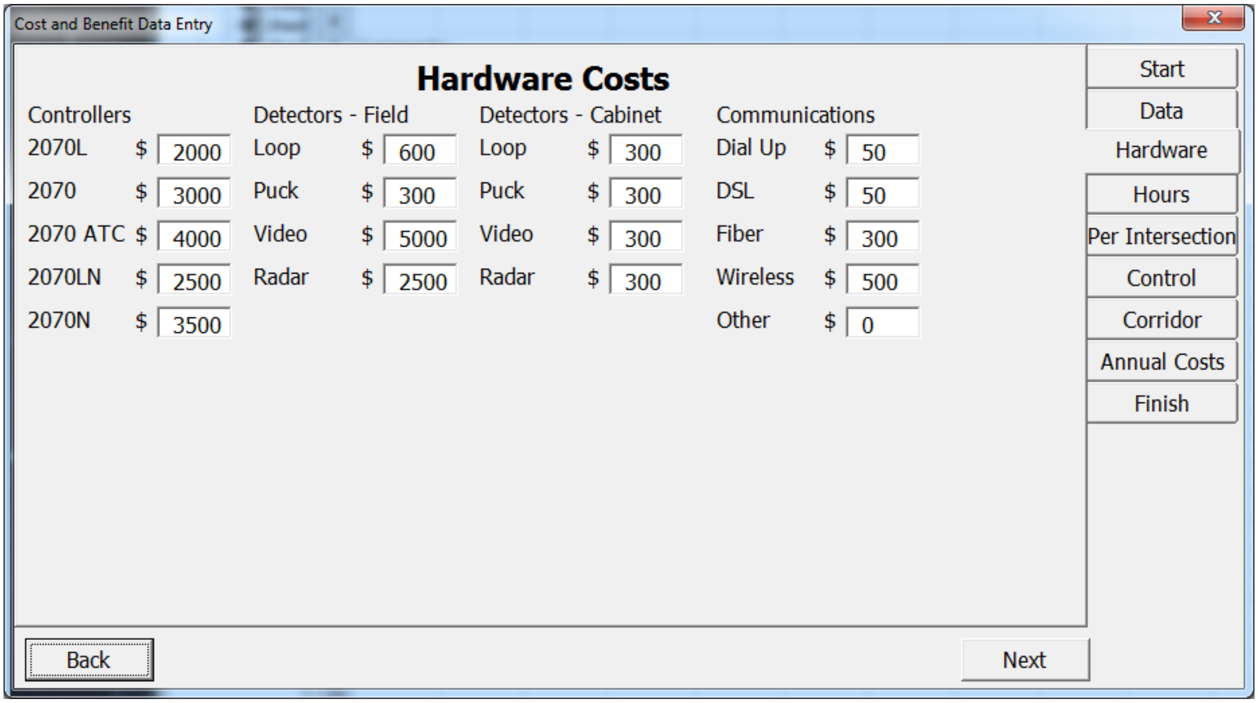

Figure 8.21: Hardware Costs Data Entry

8.4.3 Task Hours

Traffic signal system costs are not solely matters of hardware. There are personnel costs to consider. Personnel costs can be measured in labor hours or required personnel or a number of other metrics. The interest here is engineer task duration as shown in Figure 8.22. Hourly costs are addressed at the corridor level later. The calculation associates engineering time with intersection phasing, left turn treatments, right turn treatments and an estimate of the overall corridor complexity. Note that this time is not intended to be just the time invested in selecting settings and inputting control configurations, but also the time invested in tuning an intersection and any preliminary work associated with the engineering judgment to implement a given treatment.

Each system may find different circumstances to be challenging. Fixed time control, for example, may not perform as well under variable traffic flows as actuated control and may require more tuning to achieve the same results as an actuated system. Tuning systems for complex corridors requires more time than for simple corridors. It can be difficult to directly estimate the hours required to tune a system to a given corridor, but it should be practical to determine whether a given corridor broadly falls into a categorical description of low, medium or high complexity. The specific circumstances that cause a given system to treat a corridor as highly complex can change by system.

Particular care should be taken at this point to ensure that an intellectually honest appraisal is made of complexity and the difficulties of implementing various treatments. Because these numbers will have direct effect on the cost to benefit ratio, undervaluing one system's required hours or overvaluing another's can significantly impact the cost to benefit ratio calculation. It is the research team's recommendation that ODOT carefully examine its current practice to determine what values and ranges of values are appropriate to use in these calculations.

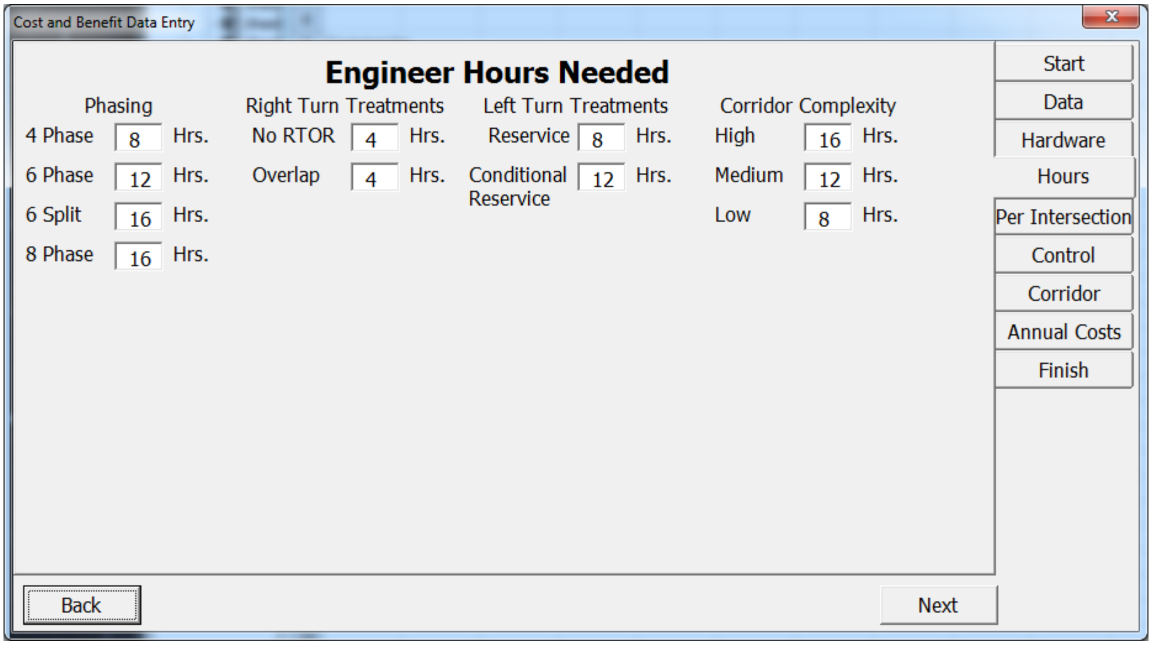

Figure 8.22: Engineer Hours Input

8.4.4 Per Intersection Hardware

Changing traffic signal systems often requires changing detection and communications equipment at an intersection. These changes are important to consider from both the hardware and installation cost perspective. Each piece of hardware needs to be purchased and then installed by a technician and the technician does not work for free. In the calculator, as seen in Figure 8.23, hardware costs such as replacement controllers, field sensors, cabinet detector cards and communications equipment are considered. Likewise, the technician time needed to install and calibrate equipment needs to be input.

It should be noted that there are costs which are specifically excluded. It is common to see corridor projects that include realignments, new signal poles, lighting, etc. Many of these improvements are pursued separately from the traffic signal control system used. Because these improvements are independent of traffic signal control strategy used, they should not be considered in the signal control system evaluation. Engineering judgment should be made as whether specific costs should be included in a given system analysis. For example, engineering judgment should be used to determine whether the hardware changes involved with a conversion from green ball permitted left turns or protected only left turns to flashing yellow arrow permitted left turns should be included in the analysis.

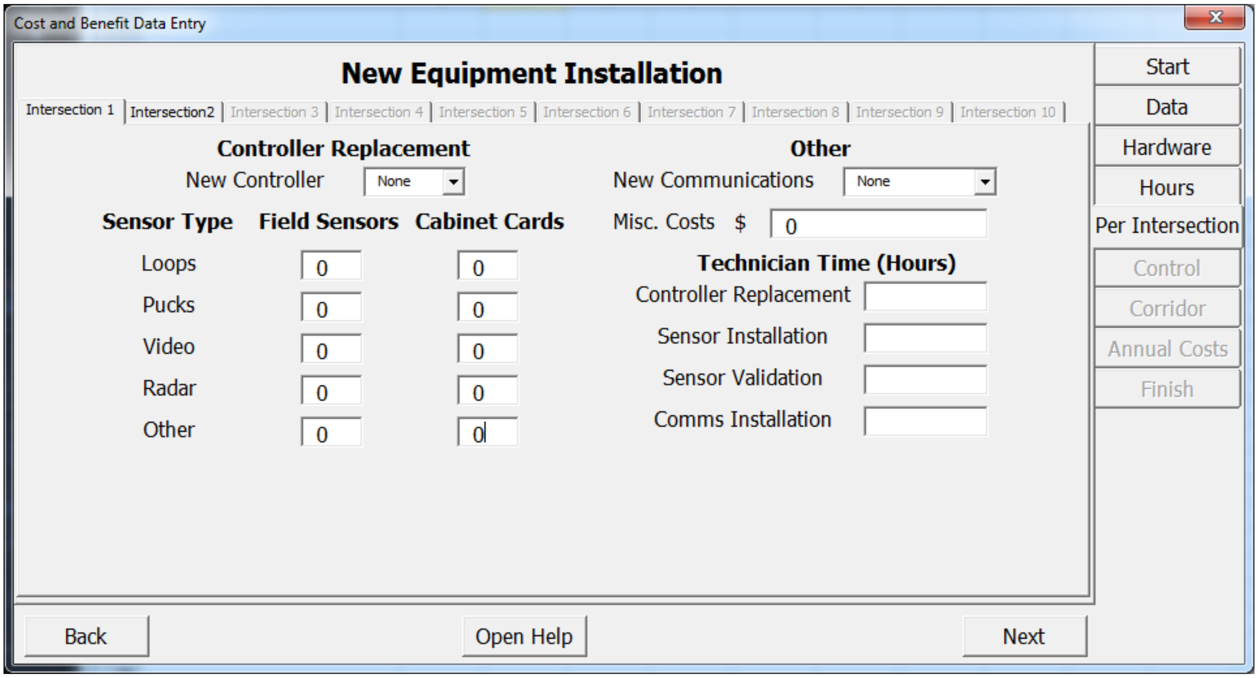

Figure 8.23: Intersection Hardware Installation

8.4.5 Intersection Control

After hardware costs and installations are considered, the engineering costs need to be considered. Setting up intersection signal control requires engineer and technician time. The hours associated with the various phasing, left turn treatments and right turn treatments were input by the user previously. Now, in Figure 8.24, the user selects which phasing and treatments are going to be used at each intersection. Each intersection also includes the option to include other engineer and technician hours associated with the signal control system. These other hours allow the user to incorporate costs associated with other features or complicating factors not explicitly considered in the analysis. Some factors that have not been explicitly considered include emergency vehicle preemption, rail roads, transit signal priority, etc.

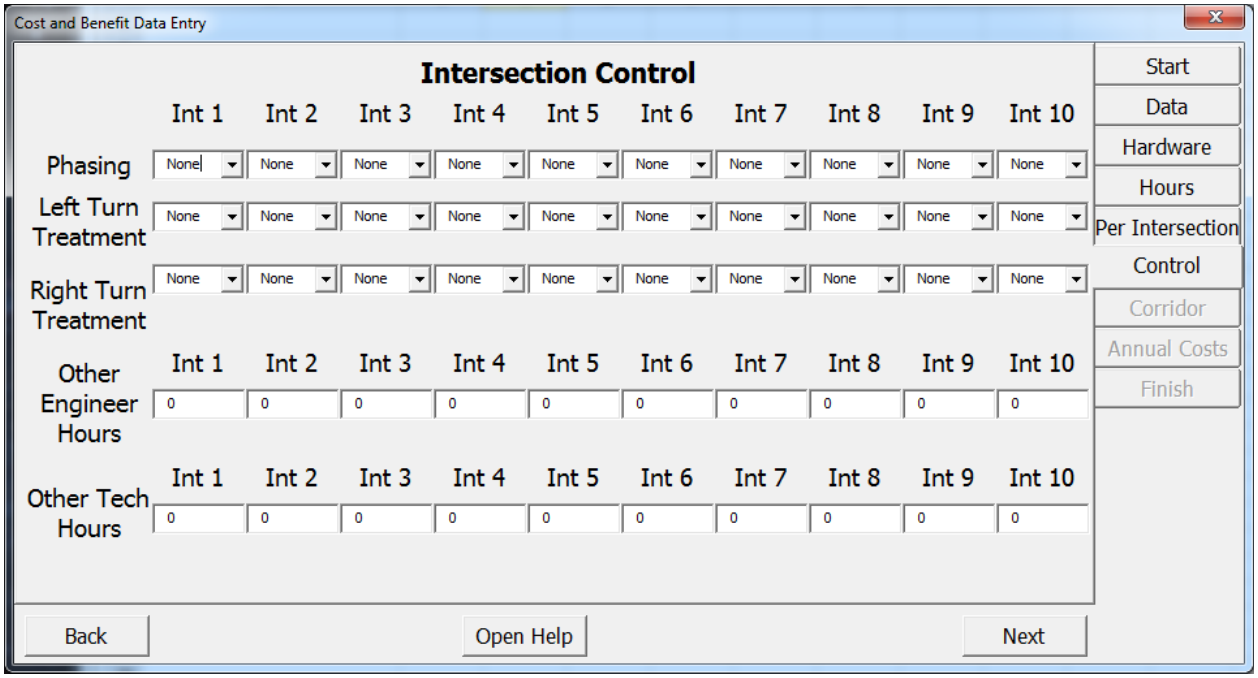

Figure 8.24: Intersection Control

8.4.6 Corridor Costs

There are some costs and cost factors that are naturally associated with the corridor or system level rather than a specific intersection. These include the in house engineering, outside engineering and technician hourly rates. Also of import is the percentage of design and implementation work being done in house by agency staff. Other engineering staff that may be involved in the process include system vendor and consultant engineers. Presumably these outside engineers are not made available at the same hourly rate as in house engineers. Costs such as additional corridor level hardware, system licensing for the system as a whole and any additional licensing costs per intersection (or system specific hardware), trenching and corridor communications are also entered in Figure 8.25.

Another important cost to consider is training. Depending on the terms of the system procurement contract there may or may not be a number of training sessions included with the purchase of the system. If training sessions are not included in the contract, than there will be a cost for the training session itself. Either way there are personnel costs associated with training. The engineers and technicians attending training sessions are not performing other work and their time has value that should be accounted for. Training costs associated with system design and startup should be included here. Ongoing training should be included in the annual costs in the next step.

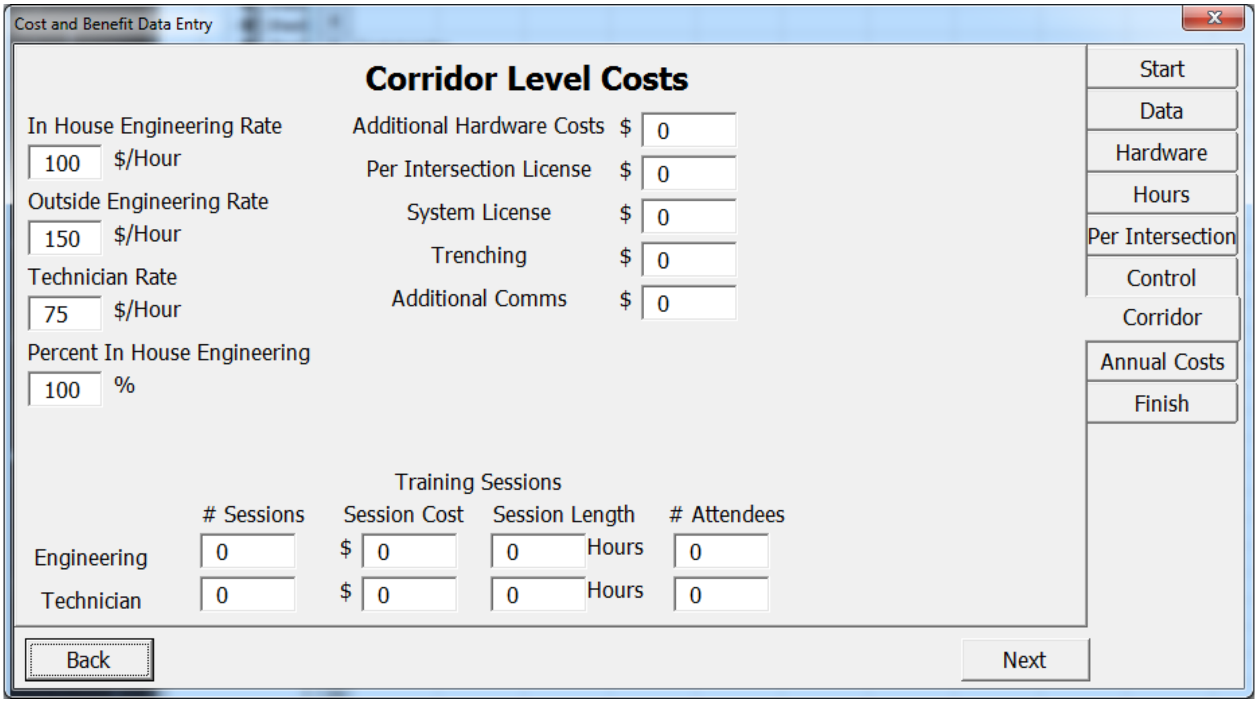

Figure 8.25: Corridor Level Costs

8.4.7 Annual Costs

The second to last input screen for the cost benefit ratio calculation is shown in Figure 8.26. This input screen captures ongoing annual costs for comparison to the annual benefits. For annual costs and benefits valuation it is important to know how many years of benefits and costs are being considered. The software uses this analysis period to determine how many annual costs and benefits should be included in the cost to benefit ratio calculation. Note, that this is a very simple algorithm as implemented. It does not include any factors for traffic growth or valuation changes. Care should be taken to choose appropriate evaluation intervals. In general, the research team recommends no more than ten year analysis intervals. Also, care should be taken in analizing multiple systems that the analysis periods be consistent.

Some users may not be familiar with net present value calculations. When computing the net present value a discount interest rate is used to decrease the value of money in the future relative to the present. Thus higher interest rates will decrease the value of costs and benefits over the analysis period. Specifically, a given year's annual benefits and costs are divided by one plus the interest rate raised to the power of the number of years in the future that value is realized. So money five years in the future would be worth its value divided by one plus the interest rate to the fifth power. As interest rates get larger, the impact of future money's value diminishes sharply. A rule of thumb for net present value is that the interest rate should be at least equal to the average rate of inflation.

Other annual costs considered include annual licensing and maintenance agreement costs, communications service costs, training costs and costs associated with changes in maintenance and personnel needs. Annual costs for licensing and maintenance agreements are some of the easiest factors to determine for existing systems, since they will be explicitly defined in the procurement contract. For new system purchases, these may be more difficult to determine. Depending on the current progress in the project there may not be a contract to examine, which could make it difficult to select a representative value.

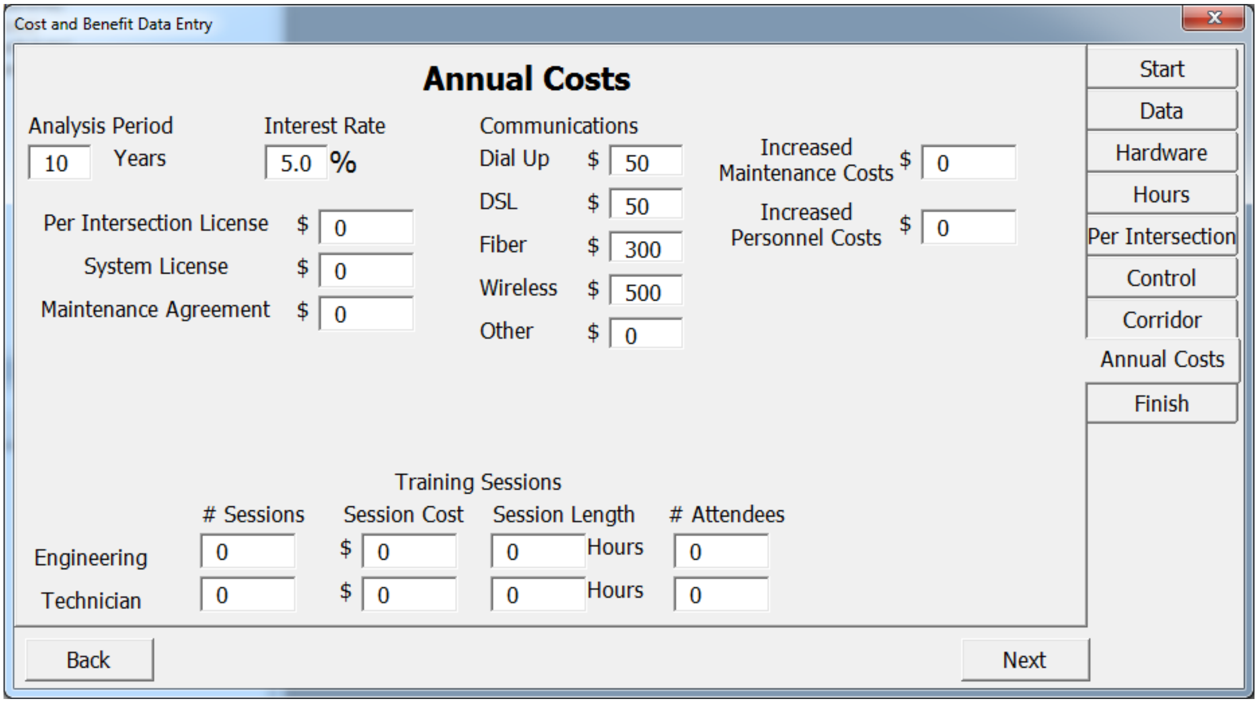

Figure 8.26: Annual Costs

8.4.8 Benefit Values

The final data entry task is to enter the values used to convert system benefits to dollar values as seen in Figure 8.27. The performance measures used in the system analysis are largely measures of time, such as delay, travel time savings, etc. The other benefit value of interest is the value of a stop. The calculator computes an annual savings in travel time, delay, stops, etc. based on the performance output of the model file and then applies the value of time and number of stops to find the annual benefit value. Once again, this is a simple calculation with no adjustments for growth in traffic.

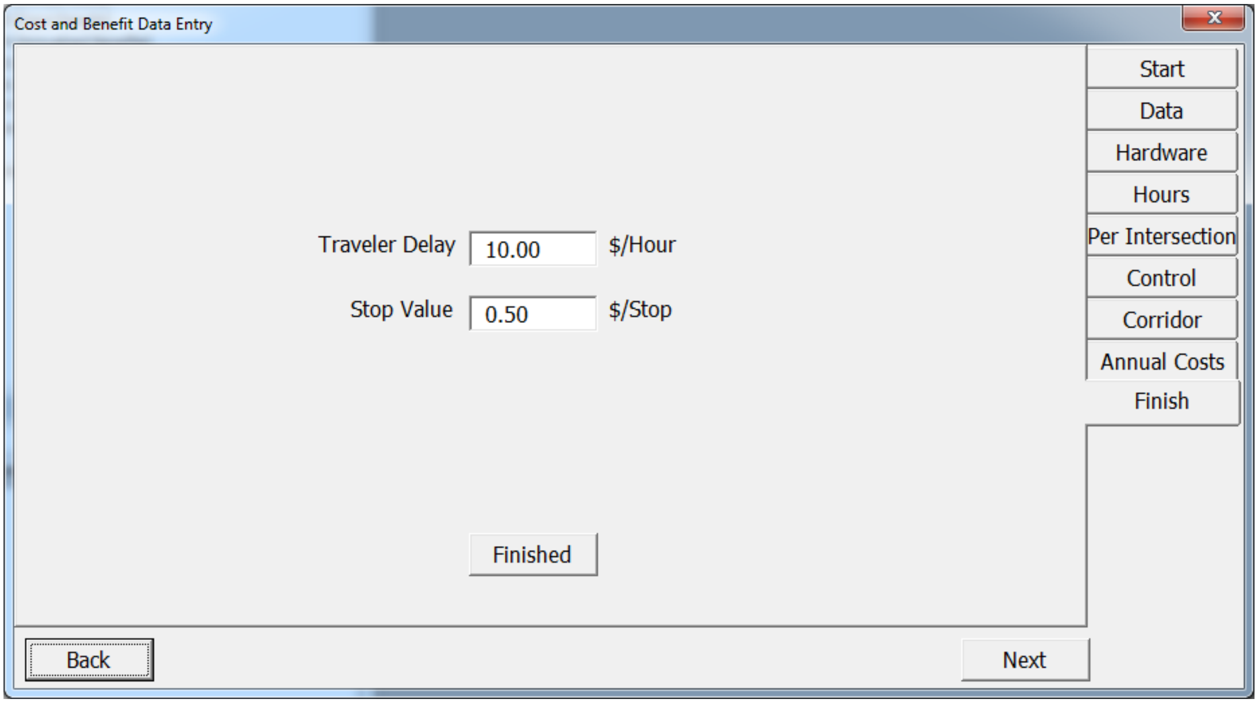

Figure 8.27: Benefit Valuation

8.4.9 Output

The final output of the modeling process from data input to cost to benefit ratio calculator is a single number indicating the ratio of the dollar value of the benefits to the dollar value of the costs. This number can then be used in the decision making process to identify which signal control systems are worth further examination.

8.5 HELP SCREENS

The STATICS Date Entry and Cost Benefit files have extensive help screens embedded within the files to supplement external documentation, such as this report. These help screens include details of the data entry options available on a given page and descriptions of some of the dependencies between data input in previous pages and options available on the current page. An example help screen is shown in Figure 8.28.

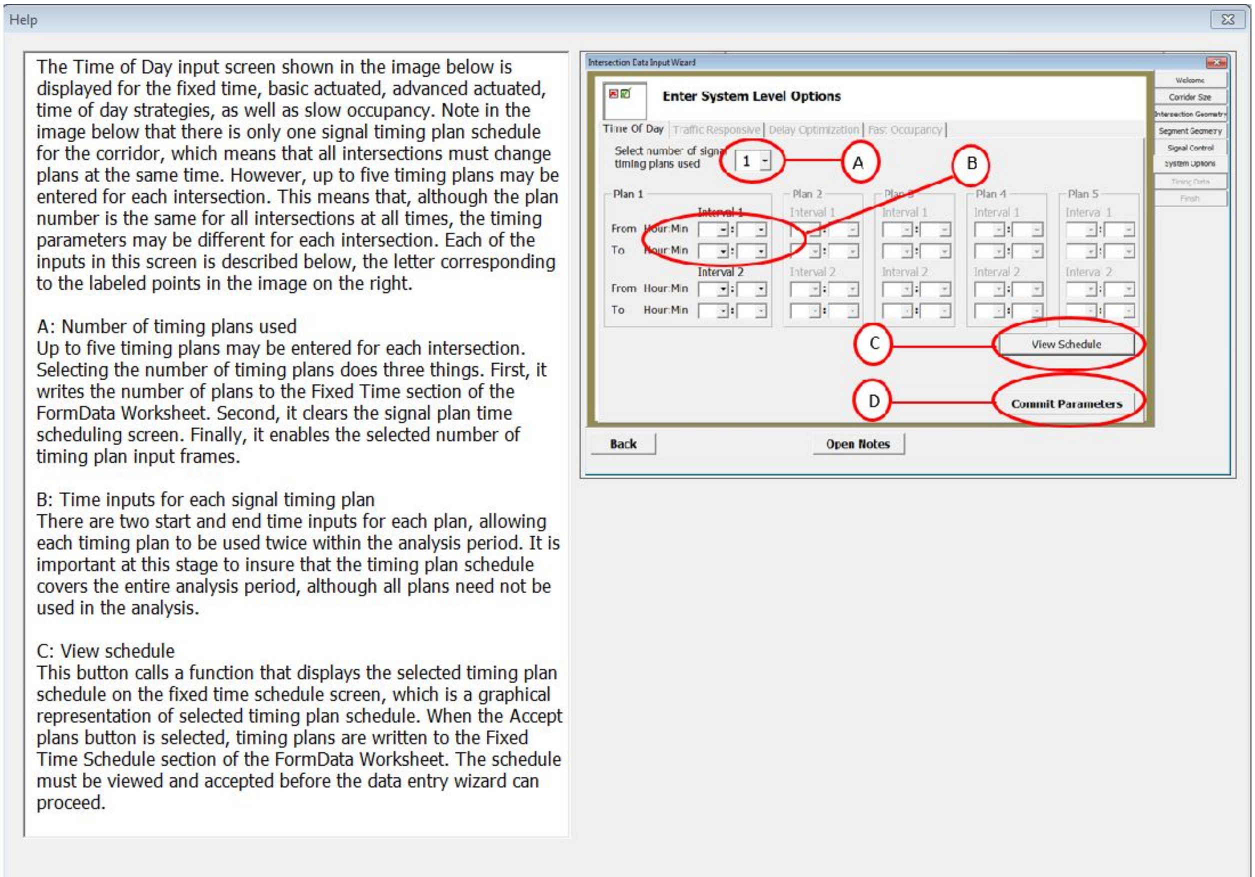

Figure 8.28: Example Help Screen

9.0 OTHER CONSIDERATIONS

There are considerations to signal system performance that extend beyond obvious input values and control logic implementations. These other aspects of corridor management may have little to no direct impact on performance, such as who owns a given traffic signal, or they may have substantial performance impacts, such as frequency of emergency vehicle preemption and recovery methods. It was not practical to include every possible factor in the performance or cost to benefit analyses, but these factors should still be considered in system evaluation.

9.1 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.

There may also be political, jurisdictional or operational hurdles where signal ownership varies. Two municipalities with a shared corridor may have different operational goals that can conflict. Many of the systems considered in this analysis use centralized control systems and that may be another conflict point with one agency not wanting to give up control of its signals to another agency.

9.2 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.

9.3 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.

9.4 TRANSITION

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.

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 or time of day system. It also limits traffic responsive systems' suitability to variable traffic demands because transition may cause more delay than a more appropriate plan saves.

9.5 EMERGENCY PREEMPTION

Fire, police and medical emergency vehicles can make use of emergency preemption systems to get green lights in time to go through intersections with a minimum of delay. These systems often disrupt the current phase order and effectively require a transition method to restore normal operations. As with transition, this process can list more than one cycle and cause considerable delay during recovery.

9.6 APPLICATION IMPLEMENTATION LIMITATIONS

Implementing such a complex modeling process in Excel was an ambitious and difficult undertaking. There were several points where simplifications and assumptions had to be made. Some of these assumptions have more potential impact than others and may be more or less applicable to a given intersection. Assumptions such as a single saturated through movement departure rate is applicable to every through movement at every intersection in the corridor are probably not as good as allowing each movement to have its own saturated flow value. Many of these assumptions represent tradeoffs between usability and accuracy. Entering different saturation flow rates for each movement on each approach would rapidly become unwieldly.

Other simplifications and limitations have been introduced into the system as well, particularly where practical data is hard to find or the data entry tasks may become burdensome. For example, pedestrian handling is very simple in the model because signal engineers rarely have data beyond whether a pedestrian push button was pressed in a given interval. The research team has done its best to make these assumptions and simplifications best match the practice and environment where decisions will be made, but it is impossible to cover every situation. Therefore it is important to remember that this application is the first step in the process, has room for improvement and is not intended to supplant engineering judgment.

10.0 CONCLUSIONS

The project began with a thorough literature review. A review of the available literature found that most evaluation criteria and methodologies for signal control systems 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 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 simulation observations with queuing model theory to enable quantitative evaluations on identified control features.

With the support of field and microsimulation observations 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 for varied signal control systems.

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.

The development of the performance measurement system has progressed from simple queuing models to an Excel spreadsheet implementation capable of measuring the impact of the various control strategies. This spreadsheet will allow engineers to input their corridor geometric data, volume data and a minimum of signal control parameters; which will then be used to estimate performance metrics such as queuing, travel time, etc. Additionally, the application of the MCM will enable collection of additional data related to reliability and consistency of the calculated performance.

These operational benefits will then be compared to the total cost of installing the candidate system. These costs include engineer time needed to perform the engineering work related to designing and installing the system, such as data collection, calibration of parameters, changeover details, etc. There are also costs associated with technician time needed to install equipment and ensure functionality. Engineers and technicians will both spend time on training and there may be additional costs for training sessions. Finally, there are costs associated with hardware procurement and software licensing.

Ultimately, this version 1.0 of the Excel application is a starting point for adaptive signal control systems analysis. ODOT will benefit from having a codified evaluation methodology and an Excel based toolset to assist engineers in performing planning level evaluations with high level and justifiable analyses of the performance, benefits and costs associated with a given signal control system. Because the application has been developed in Excel, it is within ODOT’s power and the skill sets of its engineers to continue to improve the methodology framework and its Excel implementation to best meet ODOT’s practical needs as signal control technology evolves.

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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
_____ Wapiti
_____ Insync
________ Voyage
________ ACSLite
________ Other ________________________

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

______ 170
______ 170E
______ 2070
______ ATC 2070
______ TS 1
______ TS 2
______ ATC as TS 2 or TS 1
______ 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
☐ Emergency vehicle activity
☐ Work zones
☐ School traffic
☐ Signal coordination
☐ Pedestrian traffic
☐ Weather
☐ Special events
☐ Traffic saturation
☐ Large vehicle effects
☐ Detector malfunction
☐ Field communications failure
☐ Controller programming
☐ 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.