AN EXTERNAL LOGIC ARCHITECTURE FOR IMPLEMENTING TRAFFIC SIGNAL SYSTEM CONTROL STRATEGIES

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16. Abstract

The built-in logic functions in traffic controllers have very limited capability to store information, to analyze input data, to estimate performance measures, and to adopt control strategy decisions. These capabilities are imperative to support traffic signal control research. In this research, a microcontroller was proven to be capable of filling this need in the form of an external logic processor for a network of traffic signal controllers. This research demonstrates this capability by addressing queue spillback congestion on a network of signalized intersections. In this study, the Rabbit 3000 microcontroller takes on the role of an external logic processor and is networked with multiple ASC/3 traffic controllers to prove the concept. Both the Rabbit and the traffic controllers support Ethernet connectivity and data exchange using the NTCIP standard. The findings show that the proposed architecture is capable of collecting data from multiple traffic controllers, calculating performance measures, and implementing control strategies in one or more traffic controller(s) that improves performance.

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Chapter 1: Introduction

This study investigates the possibility of implementing an external logic processor for real-time signalized intersection performance measurement and control feedback of multiple intersections in a traffic network. Using an external processor facilitates traffic control strategy research addressing special operational circumstances such as queue spillback. Typically, newer model traffic controllers have Ethernet connectivity and support data exchange using the National Transportation Communications for ITS Protocol (NTCIP) 1202 communication protocol to form an Ethernet based communication network of multiple traffic controllers. The architecture can be implemented to resolve various operational problems; however, in this research, the focus was to apply it in addressing the queue spillback problem. In this chapter, Section 1.1 provides a brief overview that explains the rationale of the proposed research direction. Examples of relevant research concepts are provided in Section 1.2, the state of current queue spillback methods are explained in Section 1.3, and a summary of the problem statement is provided in Section 1.4. The chapter concludes by summarizing the research objectives in Section 1.5.

1.1 Research Overview

Growing travel demand and limited capacity make efficient intersection operations difficult to maintain. Traffic control devices are used to ensure efficient operations by allocating “green time” (the duration of time when vehicles are allowed to move through the signalized intersection) among different traffic movements based on their demands. However, the demand scenario changes during the day and also during different times of the year. Therefore, an effective traffic control system needs to be demand responsive. An actuated traffic control system detects the traffic and responds by allocating the green accordingly so that the green times are used effectively rather than being “unused and wasted” (the portion of green time when there is no vehicle served). The controller, in an actuated system, serves a certain phase if it receives a call from any of the detectors associated with that phase and terminates the service once demand goes down, or there is a call for service at another conflicting phase. This demand responsiveness of modern traffic controllers makes the operation more efficient. Furthermore, in addition to the most frequently used traffic controller functions, some controllers have special functions to add more options and flexibility in programming simple control logic, e.g., the Econolite ASC/3 Controller has a built-in “Logic Processor.” However, this logic processor can only be programmed with very simple instructions. At this point, complex logic and program instructions required to address special traffic scenarios, such as queue spillback, introduces the need for using an external logic processor. While the traffic controller regulates the intersection operation, this external processor can monitor the performance and look for operational issues by collecting and processing data from the controller.

Additionally, for a traffic network of multiple intersections, the signal state and detector state data from other intersections downstream or upstream to the subject intersection are necessary to make a control algorithm for queue spillback scenarios. This data cannot be processed by the traffic controller itself. The implementation of an external logic processor can make the data processing and performance monitoring possible for multiple traffic controllers if these are connected to a common network. For this research, the collected data were analyzed to make decisions for queue spillback situations. A previously developed research methodology by Ahmed (2009) attempted to address this problem by communicating with a controller at a single intersection. The focus of this research is to employ a single external microcontroller to manage operations of multiple intersections.

1.2 Relevant Research

Numerous research endeavors focused on improving the process of data collection, performance monitoring, and control of signalized intersections. Technological advancements in this field produced new techniques, including the application of external devices in the form of microcontrollers. For example, Texas Transportation Institute developed a system to automatically collect data that required additional data processing hardware to be in the cabinet as well as count detectors placed in front of the stop bar. Smaglik (2007) developed an event-based data collection system for generating actuated controller performance measures. They developed an integrated general purpose data collection module that time-stamps detector and phase state changes within a National Electrical Manufacturers Association (NEMA) traffic controller. To facilitate this, the ASC/3 controller software was enhanced to include a data logger to collect time-stamped controller and detector status and an ftp server to send data files hourly.

Liu (2008) built a system for high resolution traffic signal data collection and performance measurement with support from the Minnesota Department of Transportation. The system, called

SMART-SIGNAL (Systematic Monitoring of Arterial Road Traffic and Signals), was able to simultaneously collect and archive event-based traffic signal data at multiple intersections and automatically generates real-time performance measures including queue length, travel time, and number of stops.

Ahmed et al. used a Rabbit microcontroller for data collection from ASC/3 traffic controllers, performance monitoring, and control strategy implementation. Two microcontrollers on separate networks were used to collect data from their respective traffic controllers connected to a Hardware-in-the-Loop Simulation (HILS) network. In this research, a similar approach was adopted, except that a single microcontroller was used to collect data from multiple traffic controllers instead of using one for each of the traffic controllers (Ahmed, 2009).

1.3 State of Queue Spillback Methods

Addressing Queue Spillback

Previous research documents and addresses various causes of queue spillback congestion. Some researchers addressed this at a local intersection level. Wu (2007) developed a method that considers a queue spillback scenario stemming from having insufficient turning lane lengths. Smaglik and Beaird worked with a method for modifying signal operations in response to downstream intersection queue spillback (Smaglik, 2006; Beaird, 2006). Beaird mentioned several reasons for flow restriction, including queue spillback from a downstream intersection, a disabled or stalled vehicle in the flow, or a railroad blockage resulting from a slow moving freight train (Beaird, 2006). Some other researchers focused on addressing queue spillback and associated problems from a network-wide perspective. Tian developed a framework for employing real-time adaptive diamond interchange control strategies based on two common diamond interchange phase plans and addressed freeway on-ramp queue spillback (Tian, 2006).

Queue Spillback Detection Methods

Current queue spillback detection methods utilize two kinds of detection information: presence and count. It is fairly common to place detectors at a distance from the stop bar to detect the presence of a queue. Detector counts exist in research and in software proposing control strategies to address queue spillback. A queue spillback detection method can be classified into two groups: i) responsive and ii) predictive. The first approach detects queue spillback when it occurs, and the second approach predicts queue spillback before it occurs.

Some researchers worked on developing a responsive queue spillback detection method. Smaglik developed an algorithm that integrates real-time stop bar presence detection with real time flow rate information to identify a downstream flow restriction (Smaglik, 2006). The algorithm measured headways using the detector status for the last 10 seconds of the green time. The flow was considered to be restricted if the phase was green and the average headway for the previous 10 seconds was greater than a specified threshold value determined from historic data. Beaird (2006) also developed an algorithm using the stop bar detection to detect queue spillback for a phase. Conditions used to detect queue spillback were: (a) the phase is green and (b) the detection zone is occupied for 10 seconds, and (c) the flow is zero or minimal (Beaird, 2006).

A predictive queue spillback detection method can define the position of the back of queue. The queue length may increase even while it is being discharged until the discharge shock wave reaches the last queued vehicle. Liu (2008) proposed a method of real time queue length estimation to determine the position of the back of queue.

1.4 Problem Statement

Previous traffic control research has defined causes of queue spillback and its effect on approach capacity. Some of this research goes as far as suggesting methodologies to determine control strategies that prevent queue spillback or reduce the symptoms. However, these control strategies were not implemented in an NTCIP compliant system. In addition, these strategies have not been tested in real-time without requiring human intervention. Therefore, an architecture needs to be developed that integrates NTCIP compliant traffic controllers and supports the implementation of an automated real-time response for multiple intersection traffic control.

Previously, a system of queue spillback detection and control feedback was developed at the National Institute of Advanced Transportation Technology (NIATT) (Ahmed, 2009). In that system, the microcontroller used the NTCIP 1202 protocol for real-time data collection from the ASC/3-2100 NTCIP 1202 compliant traffic controllers. Using NTCIP compliant controllers allowed an external device to change traffic signal control parameters (such as maximum green) while operating. This opened the door for accelerated development and testing of control strategies using HILS and a microcontroller. This capability allowed the application of a wide range of control strategies. However, in the case of this previous work, the collection of data and changing controller parameters was limited to the local intersection as the microcontroller could only communicate with one traffic controller within the developed architecture. The need still exists for improving the system architecture to enable the application of the control strategy simultaneously and automatically over more than one intersection.

Previously developed control strategies by Ahmed (2009) were tested by a simulated real-world network of two intersections and with actual traffic data collected from the field. The code developed for this research was hard coded to work with the tested intersections. In order to apply the program in other similar traffic networks, it needs to be flexible to readily accommodate different controller settings and network configurations.

1.5 Research Objectives

In an effort to develop an improved architecture and to address queue spillback conditions, this research achieved the following objectives:

> Objective 1: Extending the current architecture developed at NIATT for the Smart Signal System to implement proposed performance monitoring and control strategy decisions automatically for a system of traffic controllers.
>
> Objective 2: Incorporating performance measures, e.g., green time utilization (GTU), into the queue spillback control decision making process.
>
> Objective 3: Identifying potential opportunities for applying systems resembling the proposed architecture, and transferring knowledge for future research.

Chapter 2: The Architecture Description

This chapter describes the proposed architecture that was developed as part of the research with an objective of extending a current architecture to support the application traffic control strategies to more than one intersection. This chapter is organized into six sections. The first section describes the specification and constraints of the hardware upon which the architecture relies. The second section introduces the testing environment. The third section outlines the program structure of the code used in the microcontroller. The fourth section gives an overview of how a user would implement the architecture. The fifth section qualitatively assesses the capabilities of the architecture. Finally, the sixth section briefly describes potential applications of the proposed architecture.

2.1 Specifications and Constraints

The communication between the traffic controllers and the microcontroller was established in research conducted by NIATT (Dixon, 2011). The NTCIP 1202 standard communication protocol was used in the research to establish the communication. In this research, the same platform was applied to establish the communication. This section describes the following: i) the microcontroller and development environment, ii) the traffic controller communication and data logging features, and iii) the relevant communication protocols. These three discussions describe the hardware characteristics needed for the research and are necessary to understand the test environment.

Microcontroller and the Development Environment

In a similar previous research endeavor of implementing external control logic by (Ahmed, 2009), the Rabbit 3000® microcontroller (Rabbit 3000A LQFP Microprocessor, manufactured by Digi International) was chosen for the convenience of Ethernet connectivity support and processing speed. For the same reason, this processor is used for this research. The clock speed is 55 MHz, which supports real-time data collection and control logic application. Faster products are available, but the existing system was adopted to build on previous work.

The Rabbit 3000 processor is programmed using the Dynamic C software development system- an integrated C compiler, editor, loader, and debugger created specifically for Rabbit-based systems. Developing software with Dynamic C enables the users to write, compile, and test both C and assembly code without leaving the Dynamic C development environment, and no costly in-circuit emulators are required. Full TCP/IP stack with source code is provided in Dynamic C. In the previous research, the Dynamic Object-SMTP-UDP/IP-Ethernet protocol stack was used to develop the libraries that facilitate the communication between the microcontroller and the traffic controller. Selection of the same microcontroller and software development environment provided the advantage of using the library files developed and tested in previous research (Digi International, 2007).

The communication and data processing capability of the Rabbit microcontroller is limited by the processing capacity of the controller, size of the dynamic data packets, number of traffic controllers, and the physical network configuration. Chapter 4 quantifies the effects of these limitations on the overall performance of the architecture.

Traffic Controllers

The ASC/3-2100 traffic controller was developed to comply with the NTCIP communication protocol to achieve interoperability and interchangeability with computer and other electronic traffic control equipments from different manufacturers. The ASC/3 traffic controller adopted the NTCIP sub network level communication protocol, which includes all mandatory and optional Dynamic Objects. This controller has optional Ethernet support for 10/100 Base T networks, which enabled building the proposed network. It also allows the data exchange through the Synchronous Data Link Control (SDLC) communication ports, which was not used in this research.

Another very important feature of the ASC/3-2100 controller is its support for logging detector volume and/or occupancy data. This feature is assignable by detector. Each of the detectors can be configured for the controller to store the volume and/or occupancy data for a certain time period, defined as “volumeOccupancyPeriod” in the NTCIP 1202 v01.07 definitions and it is displayed as “NTCIP LOG PERIOD” in the ASC/3-2100 controller front panel.

Communications Protocol and Dynamic Objects

The NTCIP sets the rules that allow user specified data to be organized into messages that can be understood by other NTCIP compliant devices. The Simple Network Management Protocol (SNMP) is included in the NTCIP as a communication standard to manage network devices. Traffic controller software manages objects, or variables, that store parameters relevant to the current operation of the intersection. Each of these objects that are accessible via SNMP is called an “object” and they reside in a virtual database in the controller. When requested, traffic controllers can use SNMP to communicate portions of their database to requesting devices. Objects are given numerical names, which are organized hierarchically to facilitate logical access. Each managed object is described by its name, syntax, and an encoding. The unique name, known as the object identifier (OID), identifies the object. The syntax defines the data type in terms of integer or a string of octets. Finally, the encoding describes how the managed object information is serialized for transmission between machines” (DeVoe, 2009).

All definitions of standardized objects used in this research are contained in the document “NTCIP standard 1202, Object Definitions for Actuated Traffic Signal Controller Units” (AASHTO / ITE / NEMA, 2005). Appendix E contains a list of commonly used objects. Each OID is written as a sequence of decimal digits separated by periods and is generally around 17 bytes long when encoded.

For application layer bandwidth reduction, the NTCIP technical working group developed the Simple Transportation Management Protocol (STMP) that uses a similar GET/SET paradigm to that of SNMP without the protocol data unit (PDU) overhead of object identifiers and error codes. The content of every data packet requires each protocol entity to have prior knowledge of the configuration of that message. Every message is built from a user defined structured collection of variables known as a “dynamic object.” The process of building a dynamic object is a runtime operation that requires communication using SNMP and a list of object identifiers to include in the dynamic object. NTCIP dictates that up to 13 dynamic objects can be defined within the traffic controlling device (AASHTO / ITE / NEMA, 2006). In the proposed architecture, data were requested from the controller for a dynamic object containing 75 objects. The size of a dynamic object limits the microcontroller data collection resolution to 4 time steps per second, i.e., the microcontroller can send and receive data at approximately every quarter of a second.

2.2 Hardware Testing Environment

The testing environment was comprised of a traffic network developed using the VISSIM 5.30 simulation software, HILS using a NIATT controller interface device, Econolite ASC/3-2100 traffic controllers, and a microcontroller acting as an external data collection and control device. Figure 1 shows the basic hardware elements and the connection types in the system. The proposed architecture implements this environment in an extended form of a distributed traffic control network with multiple traffic controllers. Chapter 3 provides a more detailed description of the entire network and lab test-setup.

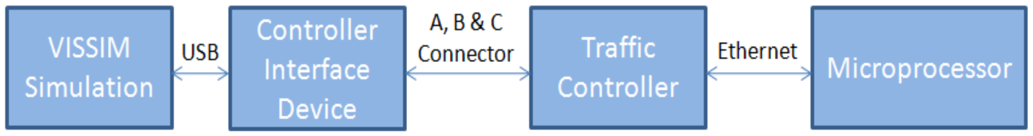


Figure 1: Hardware testing environment: HILS and microcontroller.

2.3 Program Structure

The main program and the associated libraries were developed in the Dynamic C 9.52 development environment. There are three principal libraries developed for this research that take advantage of libraries provided by the Dynamic C software package. The first two libraries contain the global definitions of data types for the variables used in the main program and other libraries, and the traffic system definition inputs respectively. The third and the most important library, which was previously developed and named as “Dynamic Signal Control Library,” contains two basic sections: the first section establishes the communication with the controller by sending data requests to the controller and receiving the data, while the second part processes the data, measures performance (e.g., detects queue spillback), determines control decisions, and sends data streams to the controller as feedback. This library was modified as part of this research to accommodate the process of communicating with multiple traffic controllers. The function-partitioning model and the data flow process that is required for this communication is described in the following collaboration diagram:

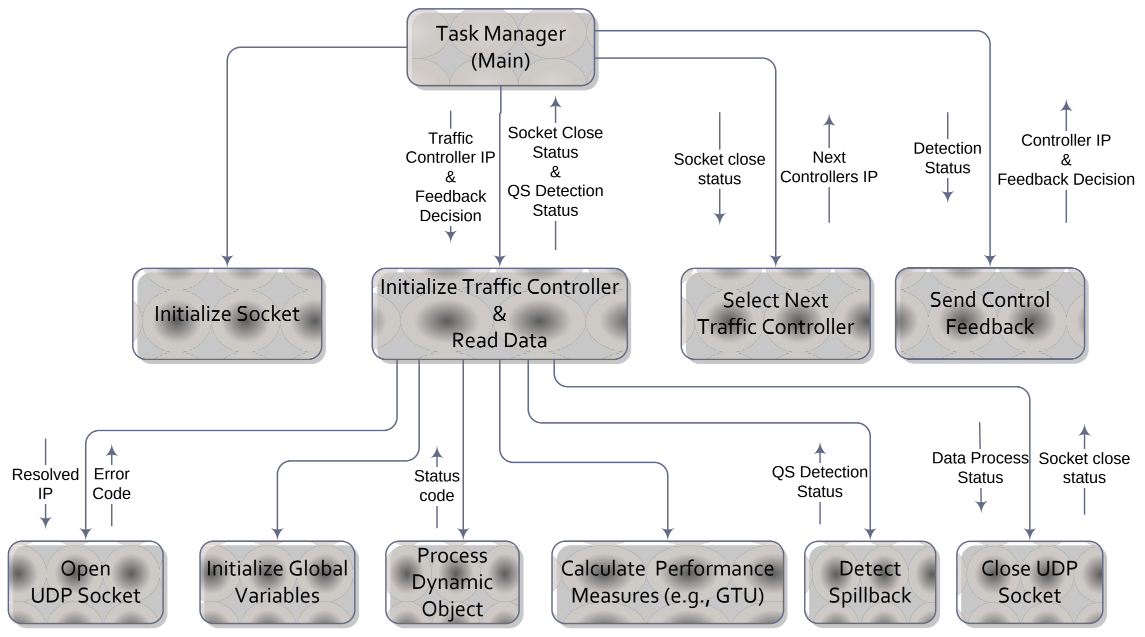


Figure 2: Program collaboration diagram.

The above collaboration diagram explains the basic tasks conducted by the proposed architecture. These tasks include communication with multiple traffic controllers, data collection and processing, performance measure calculations, queue spillback detection, and control feedback implementation. After initializing the socket, the task manager (main) starts the communication with the first traffic controller. Each traffic controller is identified by its Internet Protocol (IP) address. Once the communication is established, the global variables are initialized and the requested dynamic object is processed. Data contained in the dynamic object are extracted and stored in the global variables. Collected data are used to calculate the performance measures and detect queue spillback. The program keeps waiting for the traffic controller to complete the data processing. When the data processing completes, the socket is closed and the process is repeated to communicate and collect data from other traffic controllers in the network. If queue spillback is detected, the feedback algorithm task (described later in this section) sends the control decision and the traffic controllers IP address (where the decision needs to be implemented) to the task manager. The microcontroller then communicates with that specific traffic controller and implements the change. The task also contains the instruction about when to go back to the previous controller settings.

Request Data Task: Building Dynamic Object

The process of requesting data from a traffic controller using a dynamic object was explained in section 2.1 of this chapter. However, it is necessary to explain how a dynamic object is built. According to the definition given in this chapter, a dynamic object is a user defined structured collection of variables, or objects, where each variable contains the data being requested. The definition itself contains valuable information of the dynamic object building process. The first part of this definition, "user defined collection of variables," means that the content of the dynamic object can vary and the user has freedom to choose different variables and to define the size of the dynamic object for their purpose. Second, the variables have to be "structured," which indicates that the order of these variables inside the dynamic object must be known and given.

Therefore, the first step towards building a dynamic object is to identify which data are needed from the traffic controller. Each of the traffic controller parameters has a unique NTCIP object ID (OID) defined in SNMPv1202v107. The OIDs of the selected variables are collected and ordered in proper sequence. It should be noted that the order of the OIDs is important, because the traffic controller's response message packages the requested data in the same order. Table 1 shows the list of 12 objects that were used in this research to construct the dynamic object and their data accessibility determined by the controller manufacturer. The first seven objects are phase parameters and the following five are detector parameters.

Table 1: Data Contained and Accessibility Status of the Objects

Name of the Object	Data Stored	Accessibility
phaseStatusGroupVehCalls	Current call status of phase vehicle	Read-only
phaseStatusGroupGreens	Phase group green status	Read-only
phaseStatusGroupYellows	Phase group yellow status	Read-only
phaseStatusGroupReds	Phase group red status	Read-only
phaseMinimumGreen	Minimum green time of a phase	Read-write
phaseMaximum	Passage time of phase	Read-write
phaseStatusGroupPhaseNexts	Maximum green time of a phase	Read-write
vehicleDetectorStatusGroupActive	Detector status	Read-only
detectorOccupancy	Occupancy for a occupancy period	Read-only
detectorVolume	Vehicle counts for a occupancy period	Read-only
volumeOccupancySequence	Sequence number of occupancy period	Read-only
volumeOccupancyPeriod	Current occupancy period	Read-write

Traffic System Definition Input

The advanced programming features of ASC3 traffic controllers allow traffic engineers to work with various numbers of phases, different action plans, and flexible detector phase assignments. However, it does not provide some very valuable information regarding the traffic network. As a result, it is necessary to provide this information to the external logic processor, the Rabbit 3000. For example, the researcher can define the network to the microcontroller in terms of how many lanes a particular phase serves, which lane a particular detector monitors, or which upstream phases contribute to traffic served by a downstream phase in the network. One objective of this research is to develop the ability for researchers to define these network characteristic in order to analyze various traffic scenarios with greater detail. A library file was developed as a first step towards meeting this objective. The list of inputs and the added functionality of this library are described in Section 2.4 of this chapter. A list of functions used in this library is also provided in Appendix A.

Performance Measure Tasks

While the traffic simulation is running in the HILS environment, the microcontroller communicates with all the traffic controllers in sequence. During this time, the microcontroller retrieves the detector occupancy and controller state information from all the traffic controllers. Using the collected data, it calculates the performance measures for each intersection. In this research, green time utilization was selected as the performance measure to derive a feedback control decision. A new function was added in the "Dynamic Signal Control" library file for the calculation of GTUs. Different sets of variables were defined to store the detector occupancy information of different intersections. These data were used later to calculate the phase GTUs for each intersection.

Feedback Algorithm Tasks

At times during queue spillback, the microcontroller executes decision logic to choose the appropriate control strategy and communicate the control strategy settings to the traffic controllers. The traffic controllers receive the decision and implement them during the simulation in real-time. The task can be subdivided into three steps: i) detection of the queue spillback by implementing the selected detection method, ii) derive a control decision from the calculated performance measures, and iii) implement the control decision in one or more traffic controller(s) by changing the desired controller parameter (e.g., phase split).

In the first step of the feedback algorithm task, queue spillback characterization logic was programmed in the microcontroller to detect queue spillback. In this research, the detection logic was developed based on the method proposed by Smaglik (2006). To program the logic in the microcontroller, detector occupancy and signal status of the impeded upstream phase were collected from the upstream intersection signal controller. When the logic detected a queue spillback, the program moved to the second step to derive a control decision. In this step, the performance measure task was recalled to calculate the phase GTUs at the downstream intersection. From these calculations, some phases were identified for reducing the green splits to give more green time to the bottleneck phase at the downstream intersection. In the final step, new phase splits were written to the specific traffic controller for the phases identified in the second stage.

2.4 User Implementation

Implementation of the proposed architecture was facilitated in terms of inputting data and outputting the network performance. The following sections entitled “data input” and “data output” describe how this was accomplished.

Data Input

It is necessary for the program to support various traffic scenarios and intersection geometries rather than being hard-coded for some specific cases. To ensure this program functionality, a computer program was developed where the user was able to make inputs for the variables that define the traffic network, including intersection geometry. All library functions were thoroughly tested for desired outputs and properly documented for future application and modification. This library, named “Network Topography.lib,” adds several functions to the program by allowing the following network description information to be entered:

- Distance between intersections
- Intersection upstream/downstream relative to the traffic stream served by a phase
- Upstream phases that contribute to a given phase
- Traffic movements served by a phase
- Lanes served by a phase
- Phase served by a detector
- Detector location in terms of lane and setback
- Phase parameters (e.g., min green, max green, passage time, etc.)

To ensure the above mentioned functionality, user inputs were made through the “constants” defined at the beginning of the library. These are actually variable information related to a specific traffic network, however, in the library they were defined as constants so that they can be modified easily. For user convenience and elimination of input errors, these constants were listed in a text editor. After editing all the input values required to define a certain traffic network, the section of the file that lists the constants and user defined values is copied to the library before compiling and then executing the main program. The main input variables are listed in Table 2. The first five variables establish the bounds to define arrays for the network.

For example, “Max_nodes” defines the maximum number of intersections in a specific traffic network that this program can handle.

Table 2: Input Variables to Define Network Topography

Name of the Variable	Description
Max_nodes	Maximum number of nodes allowable
Max_link	Maximum number of links
Max_phase	Maximum number of phases
Max_mvmnt_phase	Maximum number of movements served by a phase
Max_lane_approach	Maximum number of lanes in an approach
Distance[Nodes]	Distance between the intersections
Number_lane[phase]	Number of lanes serving a particular phase or movement
Mvmnt[phase]	Movement associated with a given phase
Intx_number[Nodes]	Intersection number for a network of multiple intersections
Det_number[lane]	Detector numbers serving a certain lane
Det_position[lane]	Detector position, i.e., distance from the stop bar

Data Output

This section describes two methods developed to monitor the traffic signal timing performance in real-time while implementing the external microcontroller. The first method uses the software output window, named “stdio” window for Dynamic C. Desired outputs were printed on the “stdio” window in real-time. However, this is very problematic as the program updates and prints the data several times in a second. To be able to monitor the performance with great ease, a web based user interface was developed. Initially, the signal state of two intersections were displayed and tested. However, other information that is of interest to the researchers like detector status, performance measures data, or an error massage can be displayed as well. To accommodate this additional information, further program instructions similar to that used for signal state display, will be needed. The webpage can also be used to give input to the server (the Rabbit) by applying HTML forms. To illustrate this functionality, a button (named “feedback” on the webpage with a status display light) was provided on the webpage that can push a command (i.e., a control decision, like changing phase passage time) to the server, if pressed.

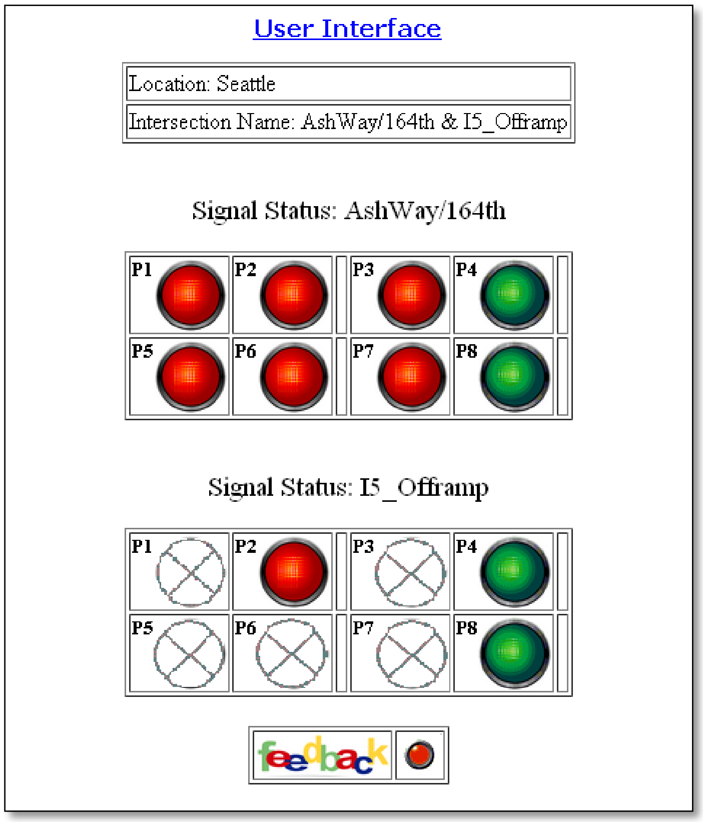

User Interface
Location: Seattle
Intersection Name: AshWay/164th & I5_Offramp
Signal Status: AshWay/164th
P1
P2
P3
P4
P5
P6
P7
P8
Signal Status: I5_Offramp
P1
P2
P3
P4
P5
P6
P7
P8
feedback

Figure 3: Web-based user interface.

The webpage was given self updating capability that ensures the displayed information is current. However, real-time display of the information is limited by the network speed, webpage refresh rate, and Rabbit's capability to perform as a web server. It is important to remember that the Rabbit can perform multiple tasks, but only one at a time. For example, it collects information from multiple traffic controllers, processes those to estimate the performance measures, and sends feedback to the controllers in sequence. Therefore, serving a webpage with too much functionality can increase the processing burden to an extent where it might stop running the program.

2.5 Architecture Assessment

The architecture offers an efficient method for collecting information from the traffic controllers. The overall signal control system effectiveness was improved by implementing an Ethernet based infrastructure and connecting multiple information sources, i.e., traffic controllers. The system described has the capability for improved communications that can result in more reliable operations and a higher degree of functionality. The purpose of this section is to qualitatively assess the proposed architecture in terms of performance and possible applications.

Quick Experiment Implementation

Devices like the Rabbit microcontroller and traffic controllers are readily able to communicate using NTCIP protocols. The testing environment resembles the field conditions, which offers increased testing accuracy and consistency. Furthermore, for small traffic networks, the test setup and data collection process can be done in a short amount of time which makes the system applicable for testing a wide range of traffic conditions and working out possible solutions fairly quickly.

Low Cost Entry to Traffic Control Strategy Development

The architecture described in this research can be implemented to develop new methods for data collection and performance evaluation. The communication with the controllers is direct and the implementation method in the field will be simple and cost effective, given reliable Ethernet communications and consistent NTCIP 1202 implementation. The only cost involvement for the system is an external microcontroller (e.g., the Rabbit, that comes with its own C based software development environment), and the hardware required for networking, e.g., switch/hub. Therefore, the system has the potential to create research or beta product (i.e., microcontroller and the program) that can act as a precursor for formal inclusion in traffic controllers.

Supports a Multiple-Controller System

The biggest advantage of the proposed method is that it is capable of connecting multiple traffic controllers in a single Ethernet based distributed network. This offers the collection of traffic state information from multiple intersections. This is a substantial improvement over the previously developed system where a microcontroller could only communicate with one traffic controller. In contrast, the proposed architecture connects multiple traffic controllers with a single microcontroller. This significantly reduces the number of logic processors, making it more cost effective and improves coordination of the monitoring and control activities.

Limited Network Size

Although the proposed system has advantages for developing traffic control strategies, it has limitations. The limitations are mainly posed by the microcontroller's data processing ability and the data transferring speed through the network. These limitations become important for time dependent data (e.g., signal and detector state information), because they need to be communicated with very short lag time for real-time control.

For information that does not vary with time (e.g., phase minimum green, phase passage, cycle length, or the offset settings in the controller) the time gap will not be problematic. However, the signal and detector state data might become too old for use. Fortunately, the ASC/3 traffic controller has an advanced feature of detector occupancy and volume data logging. This logging feature was used in this research instead of requesting detector state in real-time. Signal state is less sensitive to the lag time and should not be too old for situations with lags less than 1 or 2 seconds.

2.6 Suggested Work

The proposed system can be used to apply various control decisions related to a specific traffic network. However, there is still scope for development before full scale implementation. This section is focused on suggesting future work needed to improve the performance of the architecture.

Alternate Traffic Controllers

Although this experiment works well with the Econolite ASC/3, in order to achieve industry adaptation, the system should be tested on other (Ethernet enabled) traffic controllers that conform to NTCIP 1202 standards.

Substitute with Complete Controller State Log

Recently, the ASC/3 controller software was enhanced to include a data logger to collect time-stamped phase and detector state changes. Controller storage allows for more than 24 hours of raw data. These raw data are stored in a binary file on the controller in the format of 100 millisecond time-stamped phase and detector state changes. Data can be retrieved from the controller by using a transmission control protocol/Internet protocol network connection, where the controller serves as a file transfer protocol (FTP) server (Smaglik, 2007).

Once downloaded from the controller, a Windows-based wizard can be used to convert the binary data files into comma-separated-value (CSV) files for use in producing the appropriate reports. The maximum size of the compressed data logs for one hour is less than 100 kb, which can be downloaded and converted into CSV files to produce performance measures such as arrival type, delay, volume-to-capacity (v/c) ratios, or served volumes. These data files could provide a more efficient means of gathering the detailed complete controller state data necessary for developing and running control strategies.

Expand User I/O Interface

The web based user interface developed as part of this research has limited functionality in terms of user data input capability and displaying performance measure data. The interface has been introduced in a basic form to demonstrate the convenience it avails to future users. The signal status of two intersections was displayed, although any other data, e.g., detector state, detector count, detector occupancy, and performance measure data could be displayed as well. Expansion of the user interface could allow the user to input the traffic network description data from a visually appealing webpage to the microcontroller program. Thus eliminating the need to directly edit the library file developed for this research.

Wireless Connection to Enable Vehicle-Infrastructure Prototype Work

Connected Vehicle (CV) represents a new paradigm for surface transportation (AASHTO, 2006). It is a cooperative effort between federal and state departments of transportation (DOT's) and automobile manufacturers. Together they are evaluating the technical, economic, and social feasibility of deploying a communications system that will be used primarily for improving the safety and efficiency of the nation’s road transportation system. CV presents opportunities to advance surface transportation safety, mobility, and productivity through cost effective wireless communications between vehicles and the infrastructure. CV will support vehicle-to-infrastructure communications for a variety of vehicle safety applications and transportation operations. CV also enables the deployment of a variety of applications that support private commercial interests, such as vehicle manufacturers. On-board and roadside equipment will provide data to the applications that will process it for different uses and then send information back to the users.

The communication standard being used in this research, i.e., NTCIP, establishes protocols to communicate with roadside and other traffic management devices. If a microcontroller with wireless communication ability, e.g., Rabbit 5000 is implemented in the proposed system of networked traffic controllers, then it might be possible to integrate the system with CV. This will directly collect the data from the vehicles and other roadside devices and inform the drivers of system performance updates.

Adopt a Faster Microcontroller

For this research, a Rabbit 3000 microcontroller was used with Dynamic C 9.52 development software. However, this processor and the development environment is not the latest from Rabbit. Moving to a faster processor (e.g., Rabbit 5000, PSoC 5, etc.), could yield better performance in terms of code execution and data processing time in the microcontroller. This would allow processing more complex instructions and control a larger system of traffic controllers.

Application of the Rabbit 5000 microcontroller in the proposed network is expected to bring significant improvement in the system performance for its faster data processing speed and better network connectivity features. PSoC 5 might also be a viable replacement for Rabbit 3000. PSoC 5 is a powerful low cost device powered by the “PSoC Creator” Integrated Development Environment that supports C based program instructions. PSoC Creator has a user friendly graphical design editor to form a hardware/software co-design environment. Programming in PSoC is also facilitated by the integrated source editors, and built-in debugger of the PSoC Creator.

Transferring Knowledge

This research is an effort to improve the techniques previously developed to implement external logic processors as performance monitoring and decision making devices. The previously developed architecture was enhanced by making it possible for one microcontroller to communicate with multiple traffic controllers, instead of a single controller. This enhanced system will offer greater flexibility to traffic engineering researchers by extending their test ground to a network of multiple intersections. With this extension, researchers will be able to test more comprehensive control strategies. However, any future development with the enhanced system will require researchers to have knowledge in the following areas, in addition to traffic signal systems operations:

- Software development environment, e.g., Dynamic C development environment.
- NTCIP dynamic object management (objective definition, requesting/sending, and reading/writing).

In an effort to educate future researchers and traffic engineering students, a brief description of the Dynamic C development environment, the NTCIP communication standard, dynamic objects, and the data requesting tasks are presented in Chapter 6.

Chapter 3: Test Setup and Data Collection

This chapter describes the detailed test setup established in the NIATT lab to test and validate the quality of communications between the Rabbit 3000 microcontroller and a system of multiple traffic controllers. The data collection process from multiple traffic controllers is also presented in this chapter.

3.1 Lab Test Setup

The architecture supports an NTCIP compliant automated environment, where the basic elements were described in Chapter 2. To the extent possible, the equipment used in this test environment is based upon standard industry products. Figure 4 describes the actual arrangement of the hardware devices used for the lab test.

Hardware Devices

The architecture is based on a 10 Mbps Ethernet backbone. The list of hardware, as shown in Figure 4, includes the following elements:

Element 1: Rabbit Semiconductor RCM 3000 series microcontroller.

Element 2: Eight network accessible Econolite model ASC/3-2100 NEMA TS2 Type 2 traffic controllers.

Element 3: Eight Controller Interface Devices (CID), one for each of the traffic controllers for HILS implementation.

Element 4: Four computers to run VISSIM simulation software.

Element 5: Two network switches/hubs to communicate Ethernet messages between the traffic controllers and the microcontroller for data retrieval and management.

Element 6: NIATT local area network infrastructure was used for displaying information on the webpage, where the Rabbit microcontroller functioned as the server.

To load the program on the microcontroller, a computer (one of the four, shown in Figure 4) was used. It was connected with the Rabbit through a serial connection. Once the program was loaded to the microcontroller, the computer was no longer required to be connected.

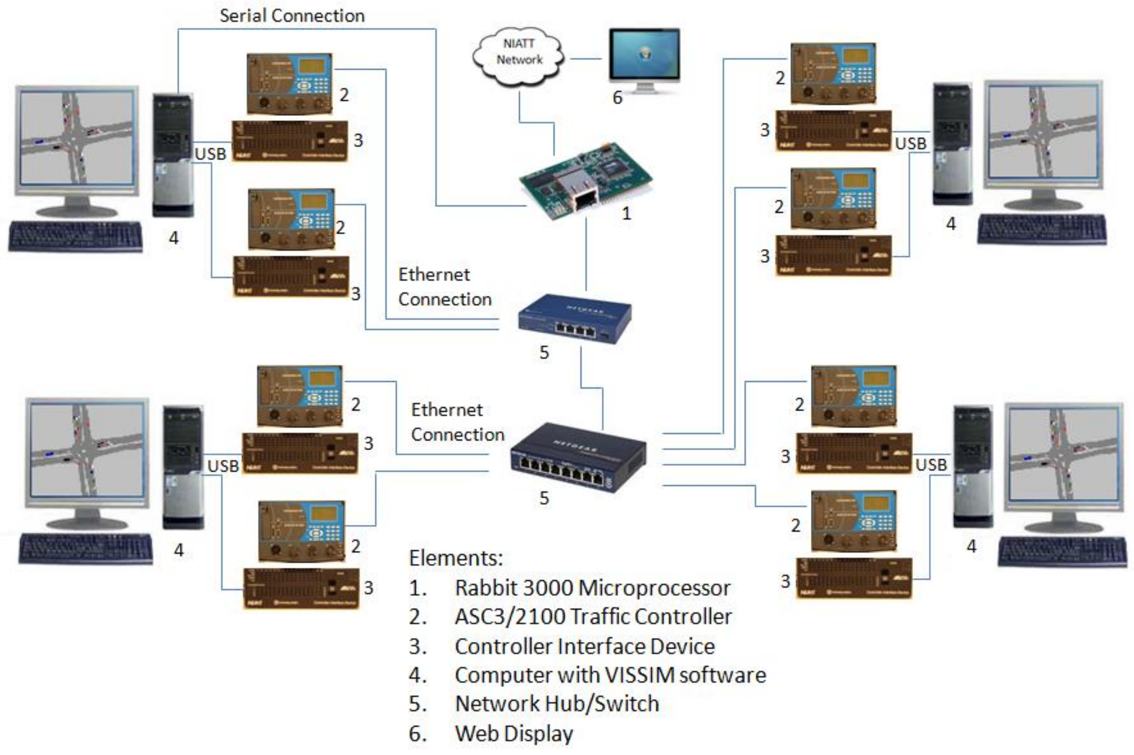

Serial Connection
NIATT Network
USB
Ethernet Connection
Ethernet Connection
Elements:
1. Rabbit 3000 Microprocessor
2. ASC3/2100 Traffic Controller
3. Controller Interface Device
4. Computer with VISSIM software
5. Network Hub/Switch
6. Web Display

Figure 4: Communication architecture of the proposed system.

Software

VISSIM 5.30 simulation software was used to implement HILS and the Dynamic C 9.52 development environment was used to load the C based program developed for this research into the Rabbit. Out of eight traffic controllers, five were running on operating system version V2.46.00, and the remaining three were running on version V2.40.00. However, no permanent substitution for changing controller firmware and system software was needed as the Rabbit was able to communicate with traffic controllers with different operating system and firmware versions.

Simulation Network

The simulation used for this research emulated a real-world network of two intersections along a coordinated corridor in Lynnwood, WA. The two intersections were the I-5 south bound off-ramp intersection and the Ash Way intersection at 164th St SW, shown in Figure . The two intersections were 400 ft apart from each other. The major street is 164th Street with the eastbound and westbound movements coordinated. The intersection on Ash Way experiences queue spillback because of heavy westbound traffic, heavy traffic coming from the I-5-off ramp, and a short queue storage between the two intersections. This queue spillback occasionally blocks the I-5 off ramp intersection and breaks down the normal performance, which makes it an ideal case for applying the queue spillback control logic.

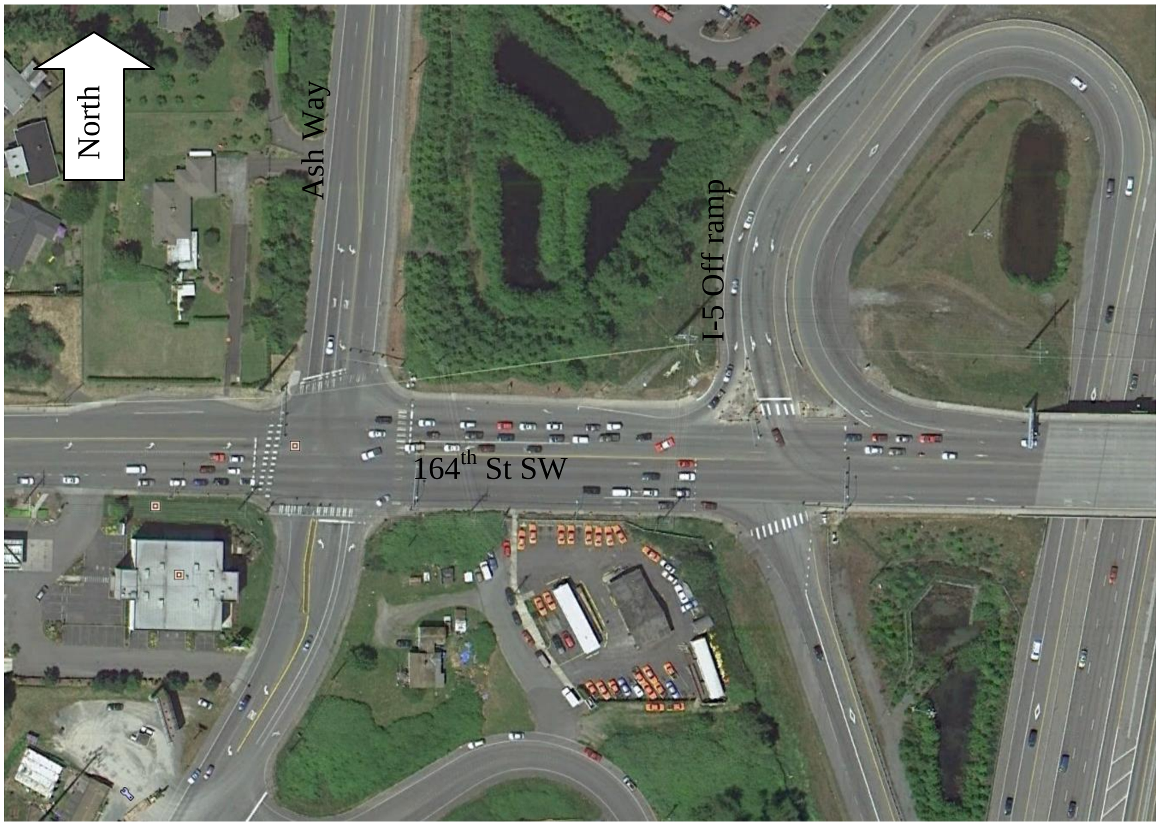


Figure 5: Traffic network applied in the simulation.

Communications

The communication and data transfer occurring in the architecture can be classified into two main categories: i) communication between the simulation and the traffic controller that happens in HILS and ii) communication between Rabbit and the traffic controllers. All the traffic controllers and the Rabbit were assigned a unique IP address through which each of the devices is identified in the network during the data transfer process. Network switches facilitated this communication by guiding each data packet to its correct destination.

The Rabbit, given the IP address 192.168.1.10, initiates the dynamic object request to one of the traffic controllers in the network. The first traffic controller was given an IP address of 192.168.1.4, and for remaining controllers only the last digit was changed to form a new unique IP address. Once the Rabbit receives a response from the traffic controller, the main program determines the next controller from which to request data and sends a request to its address. Any number of traffic controllers can be included in this communication sequence. However, it will take longer to complete the sequence and update data for a given controller as the number of controllers increases.

3.2 Data Collection

To validate the proposed architecture, the data were collected from two sources. First, the signal and detector state data and the performance measure data were collected from the text file generated by Dynamic C for the outputs printed on the "stdio" window after each data read cycle (about every third of a second). Second, the signal and detector state data were collected from the simulation output (*.LDP file) printed every tenth of a second by VISSIM.

The VISSIM simulation file was run on four different computers, as shown in Figure 5. Four computers were used to minimize communication latency problems. Ideally, for a full scale test with eight networked traffic controllers, eight CID/controller pairs should be connected with the computer that runs the simulation and the simulation should contain eight intersections (one for each CID/controller pair). However, previous research found that HILS latency increases with the number of CIDs. This is because increasing quantities of CIDs trying to communicate with the simulation at the same time can slow down the simulation. This is undesirable for this test, because the traffic controller processes information in real-time, so the data collected from the two sources will become unsynchronized due to this latency. As a result, each of the four computers was connected with two traffic controllers for the HILS network, where one traffic controller controlled the intersection on Ash Way and the other controlled the I-5-off ramp intersection.

Data were collected in three stages:

1. To test the data exchange capability for static data (e.g., phase parameters), phase minimum green, phase passage, and phase max green data were requested from all eight traffic controllers. To ensure that the collected data resembled exactly what was stored in the controllers, each controller was programmed with different parameter values.
2. To validate the proposed architecture, data were collected for phase status, detector actuation and occupancy status and detector volume from two sources, the Rabbit and the VISSIM output file. Information from the two files was compared to observe the difference, if any. Data were collected from two controllers (one for Ash Way and another for the I-5-off ramp intersection) for a 15 minute period.
3. The Response time (time required to collect data from one traffic controller) data were collected for varying numbers of traffic controllers, e.g., 1, 2, 3…, 8 controllers. Varying the number of traffic controllers changed the number of requests for controller data. A 15 minute period was used to collect data for each condition.

Chapter 4: Method Validation and System Size Limitation

The main contribution of the proposed architecture is to demonstrate the ability of a microcontroller external to the traffic controller to accumulate data from multiple traffic controllers and use the data to derive control decisions. The architecture was validated by presenting the data collected by the microcontroller and comparing it to the ground truth data recorded by VISSIM. This comparison is the primary objective of this chapter. This chapter contains four sections that discuss the results of different tests. The purposes of these sections are summarized in the list below:

Section 4.1 Data Exchange Capability Test: summarizes the proposed architecture's capability to read and write controller settings with a network of eight controllers.

Section 4.2 Data Validation: summarizes the proposed architecture's ability to acquire different data types (phase status, detector status, five second detector occupancy logs, and five second detector volume logs).

Section 4.3 System Size: quantifies the incremental effect of adding a controller to the architecture in terms of controller response time and data read cycle. Response time is the time from when the microcontroller initiates the request data task to the time it receives the data. The data read cycle is the time transpired between two consecutive times the microcontroller receives data from a given traffic controller.

Section 4.4 Summary: summarizes the findings of the previous three sections.

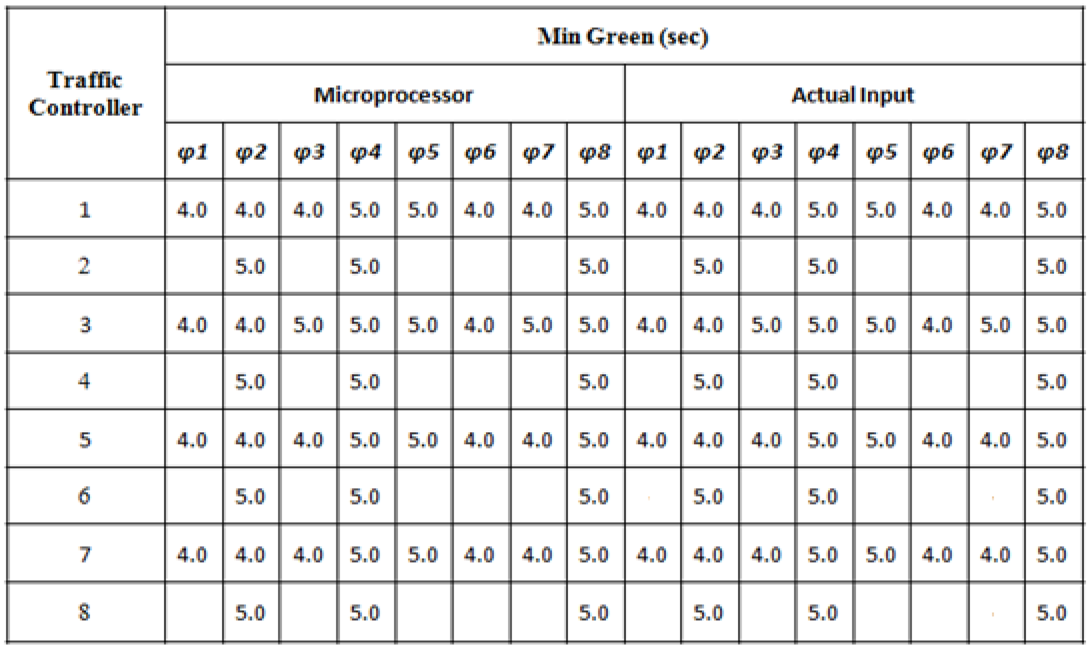
4.1 Data Exchange Capability Test

The data exchange capability of the microcontroller with a single traffic controller has already been tested in previous research conducted by Ahmed (2009). However, a multi-controller environment targeted by this research needs to be tested. The first step is to test the data read and write capability of the Rabbit. It should be capable of reading any data readable through the NTCIP from any traffic controller connected in the network. It should also be capable of modifying a read-write accessible controller parameter of any traffic controller. The test was conducted to prove the Rabbit possess both of these capabilities. The test was done in two phases, first with data that do not vary with time, e.g., phase parameters and then, later with the data that vary frequently with time, e.g., signal status.

Reading Phase Parameters

To test the Rabbit's data reading ability, three phase parameters, namely minimum green, maximum green, and phase passage parameters, were selected to read from all eight traffic controllers and these values were compared to what was manually programmed in each of them. A comparison of the actual input values to what was read by the microcontroller is shown in Table 3. The values are listed for all eight phases and for all eight traffic controllers. From this table it can be seen that all of the parameter values match. This shows that the Rabbit is capable of extracting information correctly from traffic control devices connected through an Ethernet network. A similar comparison of phase maximum green and phase passage resulted in the same level of accuracy which is shown in Appendix B.

Table 3: Minimum Green Time Comparison for Data Reading Capability Test

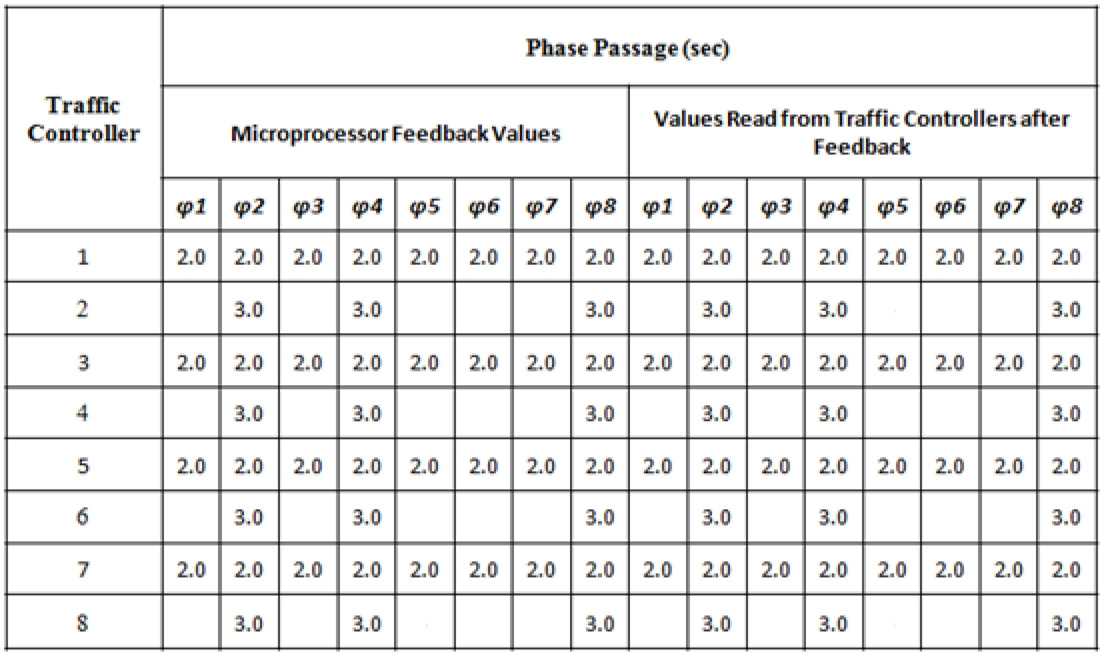


Traffic Controller	Min Green (sec)															
	Microprocessor								Actual Input							
	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8
1	4.0	4.0	4.0	5.0	5.0	4.0	4.0	5.0	4.0	4.0	4.0	5.0	5.0	4.0	4.0	5.0
2		5.0		5.0				5.0		5.0		5.0				5.0
3	4.0	4.0	5.0	5.0	5.0	4.0	5.0	5.0	4.0	4.0	5.0	5.0	5.0	4.0	5.0	5.0
4		5.0		5.0				5.0		5.0		5.0				5.0
5	4.0	4.0	4.0	5.0	5.0	4.0	4.0	5.0	4.0	4.0	4.0	5.0	5.0	4.0	4.0	5.0
6		5.0		5.0				5.0		5.0		5.0				5.0
7	4.0	4.0	4.0	5.0	5.0	4.0	4.0	5.0	4.0	4.0	4.0	5.0	5.0	4.0	4.0	5.0
8		5.0		5.0				5.0		5.0		5.0				5.0

Writing to Traffic Controllers

The microcontroller needs to be able to change some parameters in traffic controllers when it changes control strategies. The microcontroller's feedback decisions to the traffic controllers is usually implemented by changing values of some parameters that have write access like phase splits, phase minimum or maximum green, phase passage time, offset, and cycle length. To test the data writing capability, the Rabbit was instructed to change the phase passage time, offset and cycle length to some specific values. Table 4 shows the comparison between the phase passage time values that the Rabbit wrote to the traffic controllers and the values manually read from the traffic controllers. Similar to the previous test, the values match. This demonstrates that the microcontroller can modify traffic control parameters in multiple traffic controllers with a single program instruction.

Table 4: Phase Passage Comparison for Data Writing Capability Test



Traffic Controller	Phase Passage (sec)															
	Microprocessor Feedback Values								Values Read from Traffic Controllers after Feedback							
	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8
1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
2		3.0		3.0				3.0		3.0		3.0				3.0
3	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
4		3.0		3.0				3.0		3.0		3.0				3.0
5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
6		3.0		3.0				3.0		3.0		3.0				3.0
7	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
8		3.0		3.0				3.0		3.0		3.0				3.0

4.2 Data Validation

As shown earlier, the microcontroller can exchange data to and from at least eight traffic controllers using the proposed architecture. The data exchange capability presented was only for data that do not vary in time unless a traffic controller's action plan changes. However, precision in real-time reading of time-varying data, such as signal status and detector status, is another matter. For signal and detector status, a long time elapse between two successive data reads is a big concern, because it inaccurately represents intersection operations. To accurately and efficiently test the effects of network size, factors affecting the response time must be isolated from factors affecting the data read cycle. This section quantifies the effect of the response time on data validity for a network containing two traffic controllers. Network size effects on response time and data read cycles will be quantified later in section 4.3.

For a single controller, the response time is between 250 milliseconds to 300 milliseconds. Unfortunately, this response time increases when cycling through communications with more than one traffic controller. Therefore, to validate the performance of the architecture, the microcontroller needs to cycle through data requests with more than one traffic controller and then compare this with the simulation data. To validate the performance of the proposed architecture with time dependent data, a network of two traffic controllers was used for data collection and analysis. The collected data were analyzed to extract the phase status, detector status, logged detector occupancy, and logged detector volume. Comparisons of the data were made to analyze any inconsistencies.

Phase Signal Status Comparison

The phase status information was extracted from both the Rabbit microcontroller and the VISSIM output files, as described in section 3.2 of the previous chapter. For both intersections, the status of phases 2 and 4 was reported by the microcontroller and the simulation. The phase status data are presented side by side in Figure 6 to illustrate any mismatches. In the figure, “Intersection 1” refers to the intersection on Ash Way. Phase 2 and 4 were chosen to cover possible variations in traffic scenarios. Phase 4 is the coordinated phase for both intersections and it has the highest split demand. Phase 2 is the minor street phase conflicting with phase 4, and this is the case for both intersections. The phase status was reported for a 15 minute period, starting from 300 seconds of simulation time and ending at 1200 seconds. As shown in Figure 6, the two data sets are in close agreement with a slight variation of the microcontroller data lagging the simulation data. This variation is explained in more detail later in this chapter. The signal status comparison for the I-5 Off-ramp intersection gave similar results and is given in Appendix C.

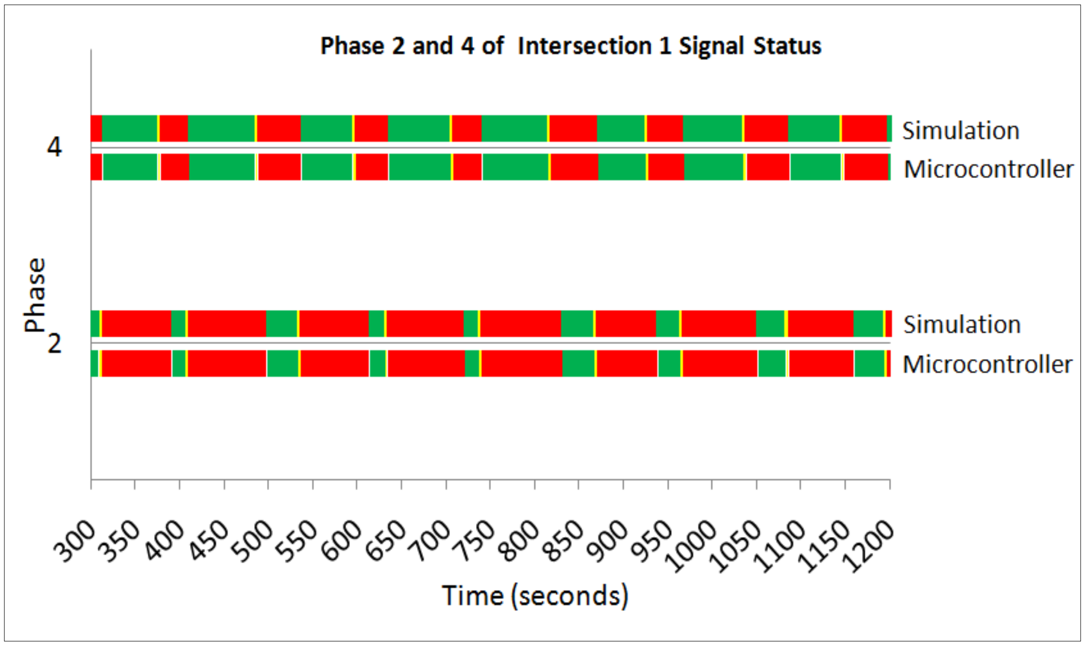


Figure 6: Comparison of signal status data for intersection 1 (Ash Way).

Detector Status Comparison

Like the signal status, detector status is also subject to change in small time steps. In fact, detector status changes much more frequently on a sub-second scale. Furthermore, detector status represents the vehicle at an intersection, and as such, it plays an important role in signalized intersection operations.

To compare the detector status data, two detectors were selected from both intersections. Similar to the phase status test, one detector serves a coordinated phase and the other serves a minor street phase. Detectors 5 and 7 were selected for the Ash Way intersection, and detectors 3 and 1 were selected for the I-5-off ramp intersection. Detector status data were collected for a 15 minute period from both sources. This increases the sample size and the range of observed conditions. Figure 7 shows representative results comparing detector status between microcontroller and simulation data for detector number 1 of the I-5-off ramp intersection. The other three detectors' status comparison graphs are similar and are included in Appendix D.

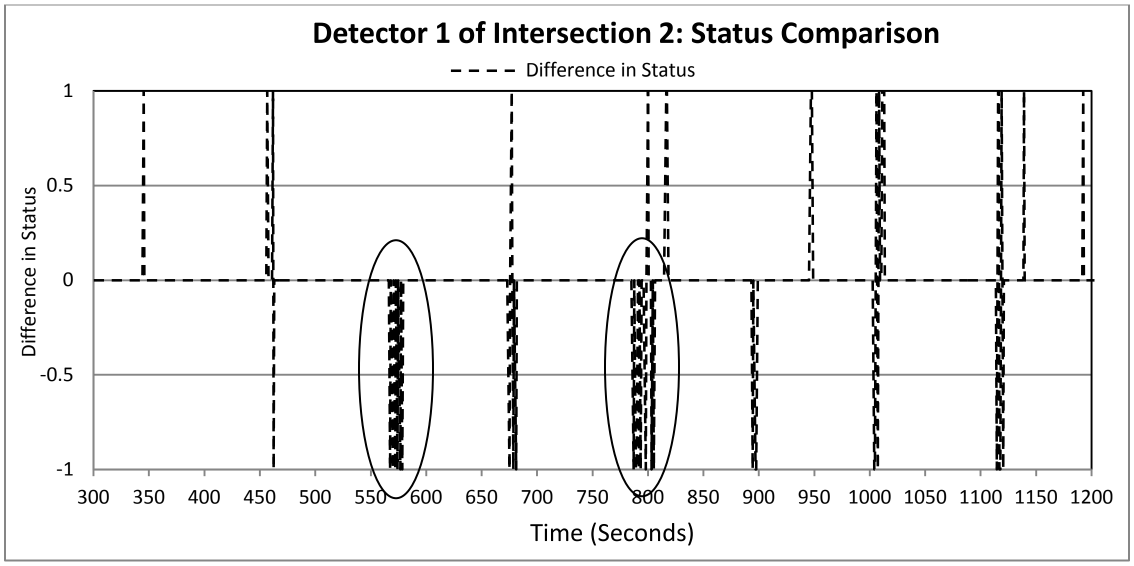


Figure 7: Comparison of detector status.

In Figure 7, the Y-axis contains the difference in detector status. The line represents the difference in detector status, where a positive reading indicates a portion of time in which the simulation detector status is on, but the microcontroller detector status was off. A negative reading represents the opposite scenario. For example, at 345 seconds, the line is positive showing that the simulation detector was on, but it was off according to microcontroller data.

The mismatch in the data mainly happens due to the difference in resolution of the two environments. The controller response time is about 250 - 300 ms, whereas the simulation collects data at every 100 ms. In addition, the variation of the controller response times results in some inconsistencies. In Figure 7, there are two noticeable areas of mismatch marked by circles, one between 550 to 600 seconds and the other at 800 seconds. In these two areas, there are several closely spaced mismatches, which indicate that the Rabbit is receiving calls from the detector, whereas in truth there is no incoming call according to the simulation.

Even though the total amount of mismatched cases are significantly higher than that of a single-traffic-controller network, all of these cannot be interpreted as losing detector calls or losing the detection of vehicles, which is demonstrated later in this section. As explained above, most of the mismatches happened due to the difference in reporting times of the two sources. These small detector status time differences should not pose a problem for performance measurement purposes. However, increasing the number of controllers will further decrease the accuracy, because the controller response time will accumulate to further increase the lag between the simulation data and the microcontroller data.

Detector Occupancy Comparison Using Five Second Detector Logs

This test was conducted to demonstrate that in the proposed architecture the microcontroller is capable of detecting vehicles using a detector occupancy log accumulated by, and received from, eight controllers. Detector occupancy data were used in the green time utilization calculation and in the queue spillback detection method. The microcontroller needed to collect this data fairly accurately for the correct estimation of green time utilization and accurate detection of queue spillback. To conduct this test, detector occupancy data for five second intervals were collected from the traffic controllers. Then the detector state data were collected from the simulation and the occupancies were accumulated for 5 seconds to compare with the microcontroller data. Figure 8 shows the comparison of the occupancy data collected from the two sources for a 15 minute period. From the comparison, it can be seen that there is no significant discrepancy that would pose a problem for performance measurements and queue spillback detections. This is interesting to note, given the variations in the detector status data, indicating that the detector status differences are insignificant for 5 second aggregation.

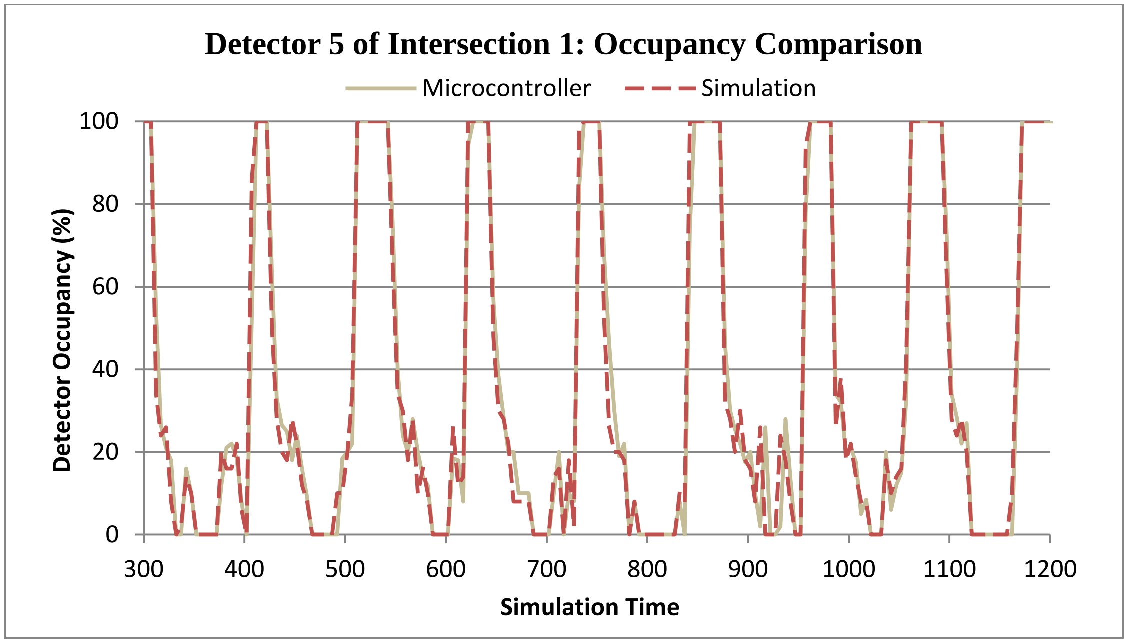


Figure 8: Comparison of detector occupancy from 5-second logs.

Detector Volume Comparison Using Five Second Detector Logs

This test was conducted to demonstrate that in the proposed architecture the microcontroller is capable of detecting vehicles using a detector volume log accumulated by, and received from, controllers. As seen earlier from the detector status test, detector status logged by the Rabbit microcontroller was frequently mismatched, which justifies using the detector volume log. An explanation is necessary to further support this decision.

The response time of a traffic controller is about 300 ms, which means that for a system of two controllers, the microcontroller will take about 600 ms between two successive data packets from a particular traffic controller. If the intersection is on a road with a design speed equal to 30 mph, a 20 ft vehicle will take about 590 ms to traverse a 6 ft detector. Therefore, it is likely that the microcontroller will miss this vehicle's detection.

As a result of these findings, traffic controller detector volume logs were used in the remainder of this research to improve detector reporting accuracy. Specifically, the ASC/3 detector logging setting "volumeOccupancyPeriod" was set to 5 seconds.

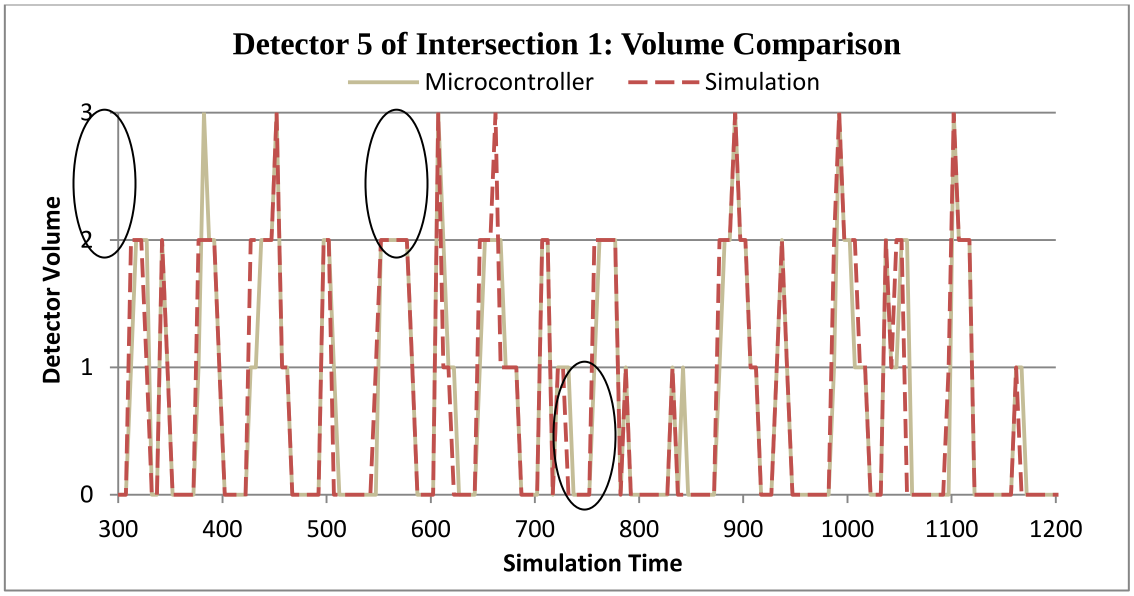


Figure 9: Comparison of detector volume.

Vehicle counts for detector 5 of the Ash Way intersection are shown in Figure 9. The X-axis represents the time interval and the Y-axis represents detector volume. Data presented in the figure constitute a 15 minute period of simulation. Only in a few cases do the detector volumes differ. Illustrative cases are circled in the graph. It was observed from the data that occasionally the controller detector volume log did not count a vehicle in a given 5 second period, when the simulation did count it. However, in almost all such occasions, the log does count the vehicle in the following period. In order to quantify the vehicles that were left uncounted, the total number of vehicles was counted for the whole duration of the data collection. For instance, the total number of vehicles counted on detector 5 logged by the controller was 136, while the simulation count was 138. This difference is smaller than typical detection error that could be seen in the field (Bullock, 2004; Haoui, 2008). In addition, the detector data will only be used to estimate aggregated performance measures, not for phase service calls or green extension. Given these two points, the accuracy of the Rabbit's counts is adequate.

4.3 System Size

Although any number of traffic controllers can be connected in the proposed network, the data validation was only completed using eight controllers for the controller setting data. Detector and phase status data validation was performed with two controllers. However, it was an objective of this research to identify the problems associated with the increase in network size, i.e., the number of traffic controllers. This section will relate the findings in the previous two sections to variations in network size.

The size of the network is mainly restricted by two facts: i) the response time of the controllers increases with the increase in network size, and ii) for a large network the time required for the microcontroller to complete one data read cycle will exceed the specified detector logging period and be too long for a reliable sampling rate. As presented earlier in this chapter, the microcontroller can communicate with eight traffic controllers to retrieve data. However, the test was conducted with controller setting information, which is not time sensitive. If the data changes frequently, some data will be lost, and this data loss is a function of the network size and controller response time. This section describes the issues regarding the system size in light of controller response time and the duration of data read cycle.

Response Time

In this research, response time was defined as the time elapsed to complete a data read sequence for a traffic controller that is on a network containing other traffic controllers. It can be subdivided into three components: i) time taken by the microcontroller to process and send a request to a specific traffic controller in the network, ii) time taken by the controller to process the requested data and to send it back to the microcontroller, and iii) time taken by the microcontroller to process the requested data and end the communication before starting another data read sequence with the next traffic controller in the network. The process also includes the latency, which is the delay incurred in communicating a message (the time the message spends on the wire). Changes in latency are typically unavoidable through changes to the code, because it is a resource issue, which is affected by hardware adequacy and utilization. It is also important to notice that the microcontroller takes time to process other instructions in the program source code to perform other tasks, like processing the control logic. For example, when the microcontroller was asked to output the signal status data for eight phases, the response time was about 285 ms. On the other hand, the time increased to about 295 ms to output the detector volumes for all 20 detectors. For the first case, the microcontroller went through a task only eight times, compared to twenty times in the second case. Therefore, the response time also varies with the amount of C instructions used by the control logic.

The response time for individual traffic controllers was observed for different network sizes, starting from one traffic controller and ending at eight. For each case, data were collected for a 15 minute period, and the same program instructions were used. The results are shown in Table 5 from which it can be seen that the mean response times can be classified in three groups based on the number of traffic controllers in the system, i) one controller, ii) two ~ five controllers, and iii) six ~ eight controllers.

Table 5: Descriptive Statistics of Controller Response Time Data

Number of Traffic Controllers	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
Mean (millisecond)	250	282	281	281	280	507	509	510
Standard Error (millisecond)	0.05	0.27	0.30	0.26	0.24	0.27	0.52	0.21
Standard Deviation (millisecond)	0.47	2.68	2.96	2.55	2.36	2.69	5.03	2.09
Minimum (millisecond)	248	277	277	278	278	504	503	503
Maximum (millisecond)	251	288	292	294	295	516	525	516

The mean response time increased as the number of traffic controllers increased from one to two. This is understandable because for a system of more than one traffic controllers, the microcontroller needs to establish the communication with a traffic controller and end the communication after reading the data. Whereas for just one traffic controller in the system once the communication is established, the microcontroller does not need to spend time opening or closing the sockets. Response time experienced a significant jump when the network size increased from five to six traffic controllers. This increase in response time may be due to the addition of another network device; a hub that was used to connect additional traffic controllers. For network hubs, performance decreases with the increase in the number of nodes connected through it.

The processing power of the Rabbit 3000 might have created a delay in data reading as well. Therefore, it was of some interest to see whether replacing it with a faster microcontroller can reduce the response time. To test this, a 5000 series Rabbit microcontroller was implemented to estimate the response times. The program was run with compatible Dynamic C version 10.50 as Rabbit 5000 is not able to execute a program using Dynamic C version 9.52 or other older versions of the software. Although, a faster processor was expected to increase the performance by reducing the response time, the results were quite opposite. The average response time was about 450 ms for 5 or less traffic controllers and about 700 ms for six or more. The reason was that the Rabbit 5000 ran the program on Dynamic C 10.50, while the program was written with an older version of the software, Dynamic C 9.52. In order to run on the Rabbit 5000, the program had to emulate the libraries written with the older version of Dynamic C, which eventually took longer execution time. Therefore, to benefit from using a faster microcontroller, the program should be written on the software development environment that comes with the microcontroller.

The effect of response delay in real-time control is further explained in Figure 10, where the signal status of phase 2 and 4 of the Ash Way intersection is displayed in greater resolution. The difference in reporting time of an event between the simulation and the microcontroller can be observed from Figure 10. In Figure 10, a gap on the signal status bar represents the time taken by the simulation or the microcontrollers to report a change in the signal indication. The graph shows that the gaps are wider for the microcontroller than for the simulation. For the microcontroller, this time gap varied and can be as high 0.7 seconds, whereas it was consistently 0.1 seconds for the simulation. The graph also shows the difference between true occurrence times (simulation time) of an event and the time when it was reported by the microcontroller. For example, in phase 2 the start of red was reported 1.2 seconds later by the microcontroller. It should be noted that this variation in the reporting time was observed when there were only two controllers. Table 5 shows that this variation in reporting time would gradually worsen with an increase in the number of controllers. This gives us an indication of how the systems' performance will be affected if the network size increased.

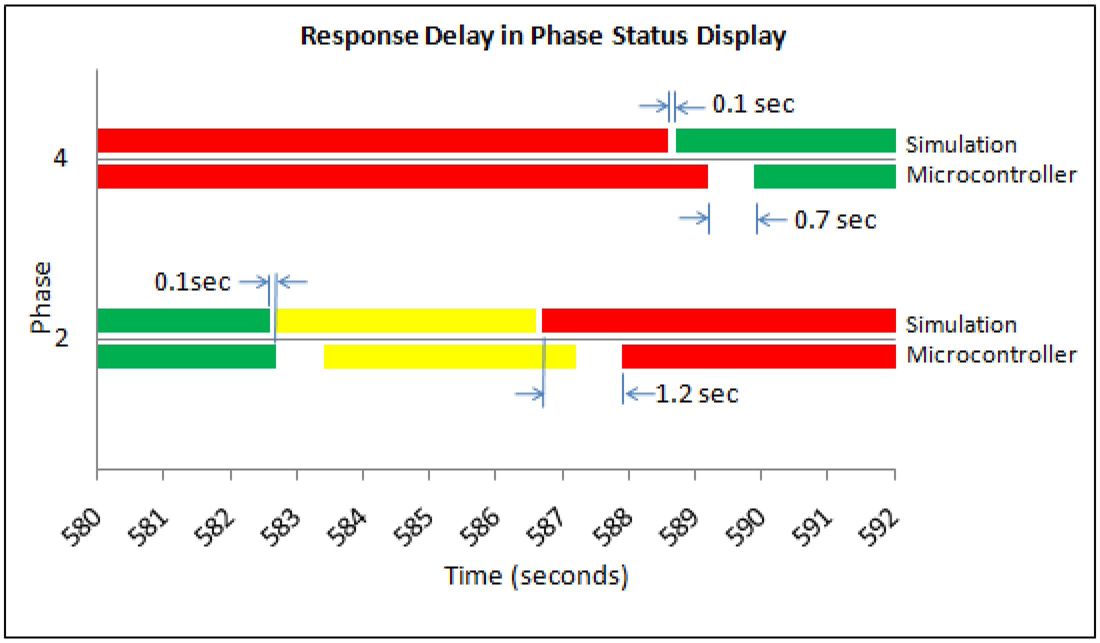


Figure 10: Response delay in signal status display.

Duration of Data Read Cycle

As described in the previous section, response time increases with the increase in network size. However, the most significant issue to consider while increasing the network size is the duration of a data read cycle. That is, the time taken by the microcontroller to complete a data reading sequence for all the traffic controllers. If four traffic controllers were in the network, the duration of the cycle would be four times the response time (values reported in Table 5), that is, there would be a time elapse (4 controllers × 0.281 seconds/controller = 1.124 seconds) between two successive data packets from a particular traffic controller. The data read cycle will be even longer for a system of six or eight traffic controllers. This data read cycle limits the frequency of data coming from an intersection. Moreover, this frequency is critical for accurate estimation of performance measures. In essence, a lower sampling rate leads to less accurate performance measure estimates, which may lead to inaccurate control decisions. Therefore, this data read cycle is a serious limiting factor for the system size within the proposed architecture.

4.4 Summary

The system architecture was validated with both time independent and time varying data. The system was accurate for the time independent data, and the accuracy was unaffected by system size. For the time varying data, such as detector and signal status, the accuracy was found to be a function of the system size. The data read cycle between successive samplings observed during the data collection was the main limiting factor for data accuracy and system size. Due to frequent changes in detector status, detector logs of occupancy and volume data can be used to avoid losing vehicle detections. However, the signal status data during this data cycle read would be increasingly obsolete. This obsolescence would eventually undermine the performance measure and control decision accuracy, as the number of traffic controllers in the architecture increases.

Chapter 5: Performance Measure and Feedback Process Evaluation

In the previous chapter, the method was validated with raw data collected from multiple traffic controllers. The objective of this chapter is to demonstrate that the architecture can not only collect the data, but use it to estimate performance measures and determine control feedback. In this chapter, the architecture performance is evaluated in terms of detecting queue spillback, estimating GTU as a performance measure, and the quality of its feedback decision process for a specific queue spillback scenario.

5.1 Context: Insufficient Downstream Storage

Queue spillback is a common characteristic of arterial congestion that can occur for several reasons. One of the more common queue spillback problems occurs in a corridor of closely spaced intersections with heavy traffic demand combined with insufficient downstream queue storage. Queue spillback can also occur due to the insufficient left turn bay length, which can interfere with the through phase traffic. In this research, the former type of queue spillback was addressed. The problem is described in Figure 11, where the westbound traffic at the upstream intersection is not able to move due to the downstream intersections queue storage overflow.

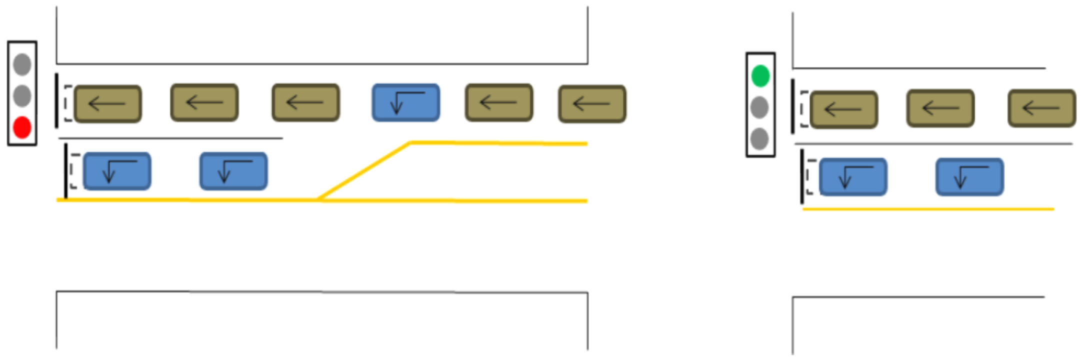


Figure 11: Downstream storage queue spillback illustration.

5.2 Queue Spillback Detection: Smaglik/Beaird Approach

Queue spillback can be detected by using information collected from detectors and controller status. For the case illustrated in Figure 12, the stop bar detector for the upstream through phase would have a high occupancy while the corresponding phase is green. Simple logic could characterize the traffic condition as one where queue spillback occurred and conclude that the downstream queue is interfering with the upstream intersections traffic flow.

The queue spillback detection method used in this research to test the performance of the proposed architecture was developed by Smaglik and Beaird (Smaglik, 2006; Beaird, 2006). The method can be referred to as responsive queue spillback detection as it only detects a queue spillback when it occurs, and it cannot be applied to predict an upcoming queue spillback.

According to this method, a queue spillback will be detected when a vehicle at any approach suffers delay during the green indication due to a downstream queue. In this method, a 10 second aggregation interval was used to determine the occupancy. The algorithm measured and averaged the headways using detector status for the latest 10 seconds of green time. From historic data, a threshold value of headway was determined and compared with the current cycle’s headway. Flow was considered to be restricted if the current headway was greater than the threshold value and the vehicle presence was detected. For this research, the method was modified to accommodate smaller intervals, because 10 second intervals seemed too long for a 6 ft detector. For a 6 ft stop bar detector, it is very likely that there will be a un-occupancy period between two vehicles, even during queue discharge. For normal flow during the green interval, the occupancy during green should be less than 100 percent, unless there is a flow restriction. Therefore, the threshold value of the occupancy used for the detection algorithm was 100 percent. The advantage of using a shorter interval over a longer one is that the queue spillback can be detected earlier. However, the interval should not be so short that it detects a queue spillback which does not exist. This can occur especially at the beginning of the green when a vehicle waiting at the stop bar usually takes longer to move away from the detector.

Detection Logic

The detection logic proposed by the method was fairly simple to program in the microcontroller. In words, if the phase is green and the detection zone is occupied for 5 seconds there is a queue spillback from the downstream intersection, as stated below:

```
If (Phase state = Green & Detector occupancy for 5 seconds = 100%)
    Queue Spillback Occurrence = True;
    Else
            Queue Spillback Occurrence = False;
```

Simulation Model

To test whether the proposed architecture can successfully run the detection logic to detect the queue spillback, a simulation model of the two intersections, described in Chapter 3, was used. Two ASC/3 traffic controllers controlled the traffic at the two intersections. The model is shown in Figure 12, where both the intersections are labeled.

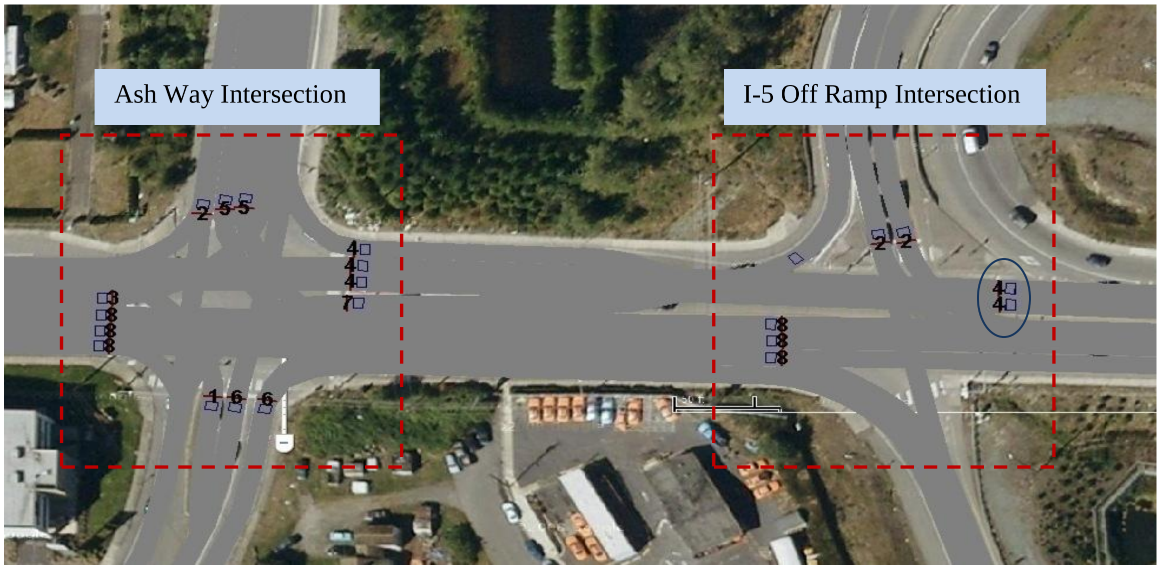


Figure 12: VISSIM simulation model.

The small blue rectangles represent 6 ft detectors placed at the stop bars. The numbers shown near the detectors are the phases that those detectors serve. The two stop bar detectors at the I-5 off ramp intersection, shown in the circle, were used to detect the queue that backed up from the Ash Way intersection to block the intersection. Also, the signal status of phase 4 at the I-5 intersection, one that the two detectors serve, was used to implement the detection logic stated above. There were two upstream traffic movements that contributed to the queue on westbound approach of the Ash Way intersection, and the input volumes for these two movements in the simulation were such that the queue spillback would occur with sufficient frequency to provide informative test results.

Queue Spillback Detection Test

For the test, the simulation was run for a one hour period and signal status, detector status, and queue length data were collected from the VISSIM output files. Ground truth queue spillback detection data were acquired using the detector status and signal status acquired from simulation output files. The queue spillback detection logic explained earlier in this section, was used to find the queue spillback occurrences. On the other hand, the detection logic was implemented in the microcontroller, where it detected queue spillback using information it acquired from the controller. For both cases, the time of detection was recorded to make a comparison, which is shown in Figure 13. Observations of when queue spillback actually occurred in the simulation were not used as the ground truth. The reason is that the object of this test is to observe the microcontroller's ability to detect an event using data it collects from the traffic controllers and compare this to the ability to detect this same event using the ideal simulation data.

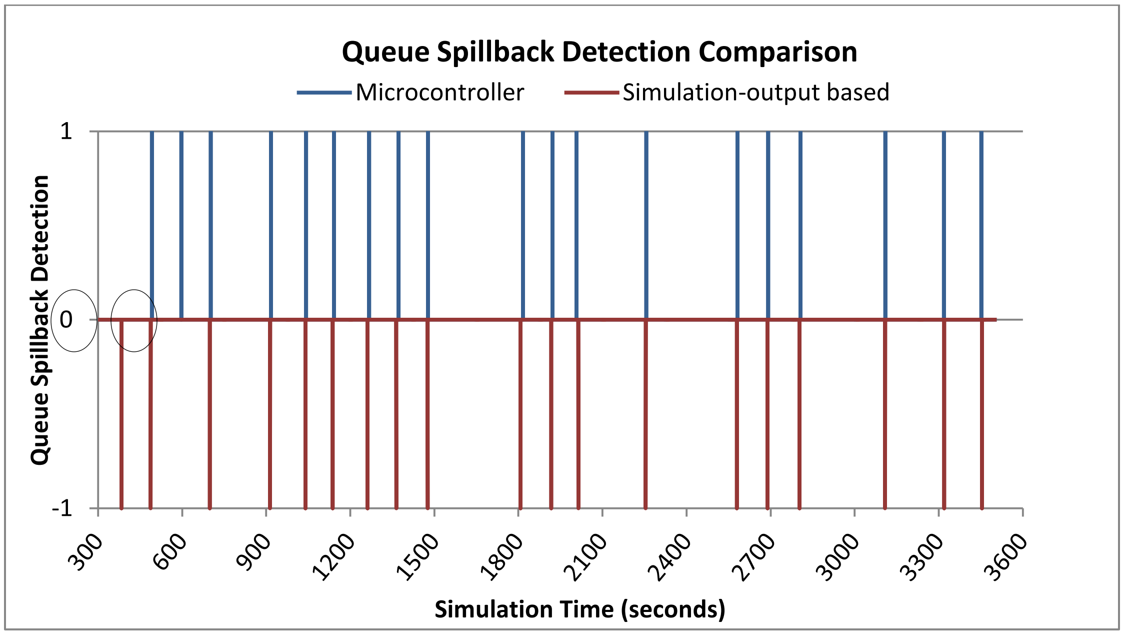


Figure 13: Queue spillback detection comparison.

From the above figure, it can be seen that the microcontroller was able to correctly detect the queue spillback, except for two occasions. The microcontroller omitted detection at about 380 seconds. However, it detected queue spillback at 597 seconds that was not detected when using the simulation-output. For the first case, the duration of the queue spillback was smaller than 5 seconds; therefore it should not be a problem. For the second case, the microcontroller falsely detected a queue spillback, which was actually during the beginning of green where the first vehicle waited for a little longer before starting to move. Furthermore, there tended to be small time gaps between the detection times resulting from the two queue spillback detection processes (one processing using the controller data and the other using the simulation data). This time gap was not significant in terms of the responsiveness of the feedback decision process. However, this time gap is subject to the individual controller response times and has the potential to increase with an increasing number of controllers in the system.

5.4 Performance Measure

Green Time Utilization (GTU)

Green time utilization is an informative measure of performance for signalized intersections. It can be defined as the percent phase green time that serves the traffic. It measures the degree to which intersection capacity is utilized overall and can do this by individual phases. For example, a phase may have 30 seconds of green time but, on average, its corresponding detectors are occupied for a total of 10 seconds. For such a case, 20 seconds of green time would be better spent serving another conflicting phase with higher green utilization.

In this research, a simple ratio of occupancy time verses total green was used. There were other performance measures that could be considered, for example, delay, cycle failure, queue length etc. However, green time utilization seemed to be the most relevant performance measure for addressing the queue spillback scenario. Green time redistribution on the downstream intersection, where the bottleneck and queue occur, was chosen as the control feedback measure, in addition to queue spillback detection. This is because the GTU of the phases give a clear indication of the quality of green distribution indicating which phases to cut short and which to extend. Furthermore, Lowri (1990) showed that GTU is closely related to the v/c ratio. As such, it can be used as an index of the unused capacity of the intersection. The relation is such that the higher the GTU value the less spare capacity exists.

Calculation of GTU

There are two basic ways to calculate the GTU: simple aggregation, and detector occupancy trends. In the first method, detector occupancy times are aggregated for the duration of the green.

In the second method, total green duration is subdivided into smaller time intervals and GTU is calculated at each subinterval. For the simplicity of calculation, the first method was applied in this research. However, the latter method is more informative, because of higher resolution in calculations, and is worth considering in future efforts.

Tuly applied Equation 5-1 for calculating GTU. "It describes how the simple aggregation of green time utilization should be calculated using detector data for phase ϕ. The numerator of this equation is the sum of times that the active phase detector is occupied, which is assumed to be the time that the phase is serving vehicles. The variable d_{ϕ}^{i} is '1' if the active phase detector is occupied and zero otherwise. The denominator is the sum of detector intervals, and should be equivalent to the phase green time" (Tuly, 2010).

$$GU_{\phi} = \frac{\sum_{i \in T} \left(d_{\phi}^{i} \cdot t_{\phi}^{i} \right)}{\sum_{i \in T} t_{\phi}^{i}} \qquad 5\text{-}1$$

Where

ϕ = Active phase,

GU_{ϕ} = Green time utilization for ϕ,

i = Interval of time during which the detector status does not change for ϕ,

T = Contiguous set of detector status time intervals for the G interval of ϕ,

d_{ϕ}^{i} = Detector status for the ϕ during detector interval *i* (d_{ϕ}^{i} = 1 if detector is on, zero otherwise), and

t_{ϕ}^{i} = Time length of detector interval *i* during ϕ (seconds)

The GTU is most informative when each detector for a given phase has a separate input channel to the controller. In this case, the summation can be rearranged to sum occupancy times one for each lane controlled by the corresponding phase. By doing this, each vehicle's occupancy time is much more likely to be included and it would only be included once.

To estimate the GTU, data were collected from both microcontroller and the simulation for 30 cycles. The calculation process was different for the two sources. In both cases, the calculations can be described by Equation 5-1. However, the microcontroller calculated GTU based on detector occupancy data collected from the controller using its detector logging function. In this case, detector occupancy was logged in 5 second intervals, so t_{ϕ}^{i} = 5 seconds. Whereas, detector occupancy data collected from the simulation output files were available in 0.1 second intervals, so t_{ϕ}^{i} = 0.1 seconds. The comparison of the phase 4 calculated values from the two sources (the bottleneck phase) and phase 5 (conflicting with phase 4) of the Ash Way intersection is shown in Figure 14.

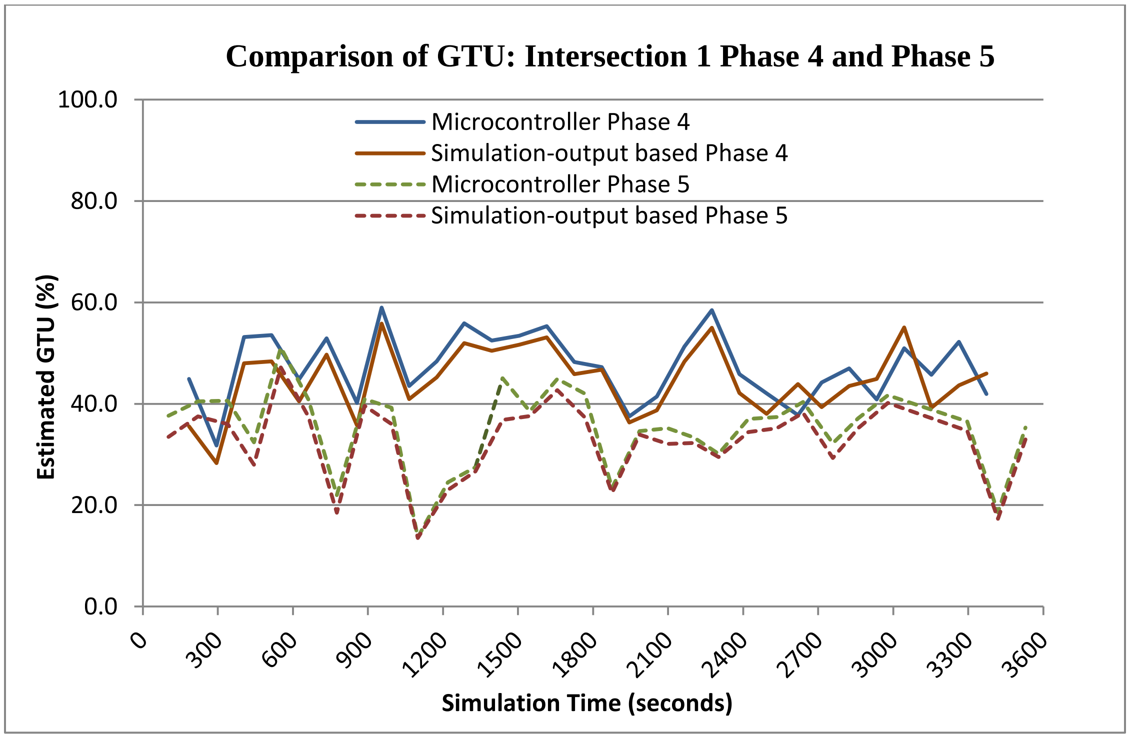


Figure 14: Comparison of estimated GTU for 5 seconds occupancy period.

In the above figure, two lines represent the GTU of the phase calculated by the microcontroller and from the simulation-output based data. A vertex in a line represents the end of a 110 second cycle. It can be visually observed from the graph that the two lines are closely spaced indicating a small difference between the two estimates. However, there is clear bias where the microcontroller GTUs are almost always higher than the simulation-output GTU. This is because the traffic controller logs the occupancy data in 0.5percent increments, which are always reported to the nearest integer value. However, there are some larger variations near 450 and 1500 seconds, which could have resulted from a detector log at the end of a given cycle being received at the microcontroller at the beginning of the following cycle for one or more intervals.

Two-tailed paired t-tests were conducted for both phase 4 and 5 to see whether the differences between the values from two sources were significant or not. The detailed test results were given in Appendix E. For both phases, p-values were less than the critical p level (0.05), which implies that the differences were statistically significant. However, these differences are likely insignificant in terms of engineering judgment. For example, assume the decision was to either reduce the green time of phase X or phase Y. Then the magnitude of a wrong decision is directly related to the GTU measurement error. In this test, the GTU measurements for phases 4 and 5 had an average error of 2.6 percent. Assuming this error is generally applicable than an incorrect phase selection for reducing the green time would not be far off the mark. Even so, it is clear that the architecture would incrementally benefit from a more consistent source for detector occupancy data and the phase and detector state event log recommended in previous research would fill this role well (Smaglik, 2007).

5.5 Feedback Decision Process

The total green time in a cycle is divided among all the phases at an intersection, and thus, each phase competes for time to serve the corresponding traffic movements. If an adjustment is made to one of the phases, operations of the other phases will be affected. Therefore, a feedback decision made to solve a queue spillback problem should consider the impacts that adjustments to one phase will have on the other phases. Incorporating green time utilization will enable an engineer to monitor the impacts and to determine how well a phase is operating. While some phases may not experience problems, they may be operating close to the point where problems will result. GTU measurement for each phase will make it possible to foresee the impacts of phase plan and timing adjustments that comprise a control strategy.

Redistribution of Green Time

In this research, the redistribution of the green times among the phases of the problem intersection was used as a technique to mitigate queue spillback problem. The focus of this method is to add more green time to the bottleneck-phase of the downstream intersection by taking green time away from other conflicting phases. Smaglik and Beaird's approach toward solving the queue spillback issue was to truncate the upstream phase that is facing the queue spillback problem by immediately gapping it out. This approach does not really solve the problem; rather it is an attempt to stop the queue from building up and blocking the intersection so that other conflicting phases can utilize the time. Therefore, in this research phase truncation was not adopted as a feedback measure to test.

The technique applied in this research was to terminate the downstream phases conflicting the bottleneck-phase and increase the maximum green settings for the bottleneck-phase when a queue spillback was detected. In this way, the bottleneck-phase started earlier and lasted longer. Terminating a phase can be done in two ways: Max-out (maximum green timer expires), or Gap-out (phase passage timer expires). To terminate a conflicting phase, the max-out technique was implemented. However, there is a benefit of using gap-out over max-out termination. Gap-out terminates the phase immediately, whereas max-out takes more time, because it involves changing a setting and waiting until a longer maximum green time expires. Typically, the benefit of max-out starts with the next cycle. To add more green time to the bottleneck-phase (phase 4 of the downstream intersection), other active conflicting phases were set to max-out earlier by resetting their respective maximum green settings. To resolve the problem in the earliest possible time, the microcontroller changed the maximum green times to the corresponding minimum green times. After the queue was cleared (typically in the next cycle), the microcontroller returned the maximum green to its normal setting. The benefit of maintaining the plans maximum green setting is that this can be implemented as a short-term control measure and the normal settings can be restored when the operations become normal.

From the previous discussion, the feedback decision process can be clearly divided into several steps.

1. The microcontroller detects queue spillback by the method explained in Section 5.2 of this chapter.
2. Microcontroller calculates GTU values to determine the uncoordinated phases with the most unused green that could be reallocated to the bottleneck-phase.

3. Microcontroller determines the uncoordinated phase from which to reallocate unused green. To determine the phases to terminate earlier, a threshold value of GTU was used. A phase was considered to have unused green time if its estimated GTU was below the specified threshold value. Tuly (2010) suggested a simple GTU threshold of 45 percent, which was used in this research.
4. Microcontroller changes the maximum green times of the uncoordinated phases with GTU below the threshold value to have equal values with their respective minimum green times (for Ash Way intersection it was 5 seconds). This change goes into effect in the next cycle. This feedback measure does not affect the cycle start time or the coordination, and the implementation is a direct approach, because the NTCIP object phaseMaximum1 has both read and write data accessibility.

To assess the feedback process, a simulation was run for 1 hour, and queue length data were collected for both a base condition and after implementing the feedback. The average queue length of the WB through movement at the Ash Way intersection reduced to 135 ft from 189 ft. This indicates that the feedback decision employed by the microcontroller was able to improve the situation for the WB through movement. For the conflicting movements, the queue lengths were increased, especially for the SB left turn movement the change was noticeable. The average queue length increased from 43 ft to 67 ft. For future research, a more balanced approach to setting max green times should be taken to lessen the adverse effects on the uncoordinated phases.

Chapter 6: Technology Transfer

This chapter provides a brief description of the Dynamic C code setup and the NTCIP communication implementation in terms of dynamic objects and data communications. In addition to the broad description given in Chapter 2, this chapter accomplishes two objectives: i) describes how these elements were implemented in the proposed architecture to increase researcher awareness of issues associated with external logic traffic control systems monitoring and ii) facilitates future implementation of the proposed architecture as it stands with the Rabbit 3000 microcontroller.

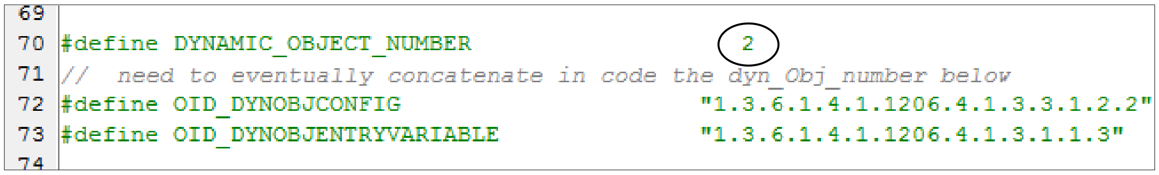
6.1 Requesting Data and Using NTCIP 1202

Requesting data and sending data to and from the traffic controller are a foundation for this research and are accomplished through "dynamic objects" and the NTCIP 1202 communication protocol. This report only describes the process followed for requesting data. Sending data uses similar resources, but also requires a description of how to interpret the dynamic object sent from the controller. The process followed for sending data is described elsewhere (DeVoe, 2009).

The definitions and the process of building a dynamic object, and the communication protocols were described in Chapter 2. In this section, the data requesting process is documented by referring to specific lines in the microcontroller code. In addition to the signal and detector state information, detector volume and occupancy data logs were requested from the traffic controller for this research. The data requesting task requires the following steps:

Step 1: Define a new dynamic object, by establishing a dynamic object number and then selecting the objects corresponding to the desired controller parameters by listing their corresponding OIDs,

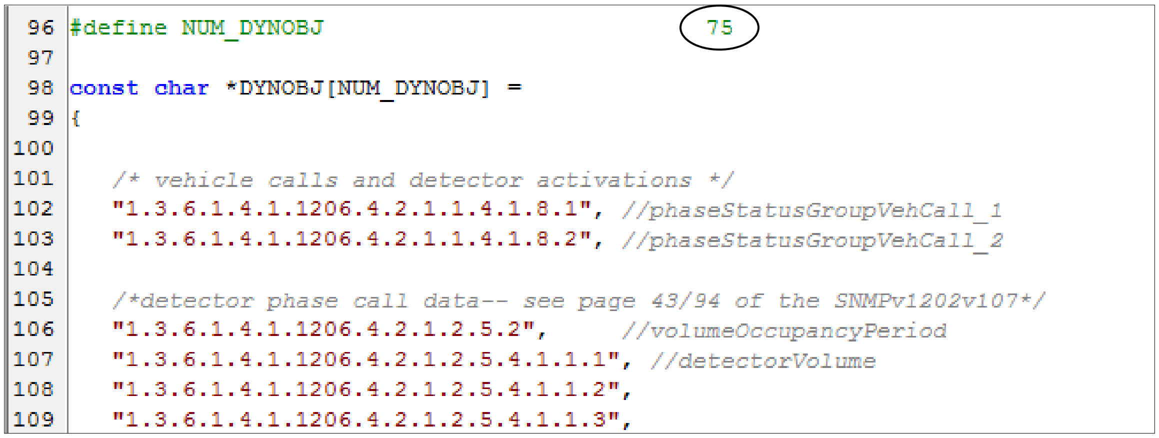
Step 2: Request data by referring to the desired dynamic object's "Dynamic Object Number." The number is circled in Figure 15 (line 70), set as a constant in the dynamic object setup file, a Dynamic C executable file.



```
#define DYNAMIC_OBJECT_NUMBER                        2
//  need to eventually concatenate in code the dyn_Obj_number below
#define OID_DYNOBJCONFIG                            "1.3.6.1.4.1.1206.4.1.3.3.1.2.2"
#define OID_DYNOBJENTRYVARIABLE                     "1.3.6.1.4.1.1206.4.1.3.1.1.3"
```

Figure 15: Locating Dynamic Object Number in Dynamic Object setup file.

Step 3: In this step, the total number of parameters or objects in the dynamic object is set. This is the number of controller parameters that the user decides to include in the dynamic object (circled in Figure 16).

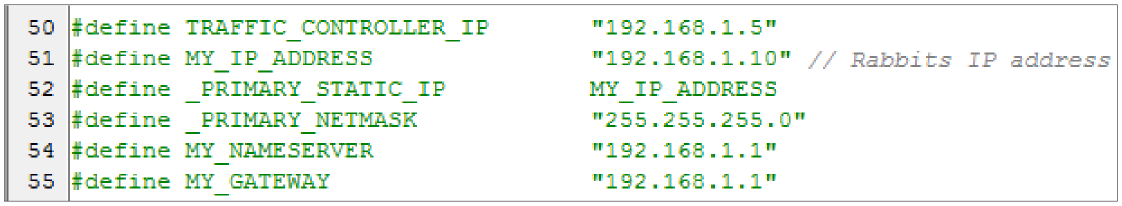


```
 96 #define NUM_DYNOBJ                          75
 97
 98 const char *DYNOBJ[NUM_DYNOBJ] =
 99 {
100
101    /* vehicle calls and detector activations */
102    "1.3.6.1.4.1.1206.4.2.1.1.4.1.8.1", //phaseStatusGroupVehCall_1
103    "1.3.6.1.4.1.1206.4.2.1.1.4.1.8.2", //phaseStatusGroupVehCall_2
104
105    /*detector phase call data-- see page 43/94 of the SNMPv1202v107*/
106    "1.3.6.1.4.1.1206.4.2.1.2.5.2",      //volumeOccupancyPeriod
107    "1.3.6.1.4.1.1206.4.2.1.2.5.4.1.1.1", //detectorVolume
108    "1.3.6.1.4.1.1206.4.2.1.2.5.4.1.1.2",
109    "1.3.6.1.4.1.1206.4.2.1.2.5.4.1.1.3",
```

Figure 16: Defining total number of objects and listing the OIDs.

Step 4: List each of the OIDs corresponding to the traffic controller parameters as defined in SNMPv1202v107 (Case, 1996). The most commonly used OIDs are listed in the text file named (see Appendix F). The process is very simple, finding the appropriate OID from the OID list and copying it to the list, the top of which is shown in Figure 16. To add detector volume to the existing list of objects, add the OID for detector volume (1.3.6.1.4.1.1206.4.2.1.2.5.4.1.1) to the list (line 107 in Figure 16). The last digit represents the detector number. As a result, this OID will be used to retrieve the volume data of detector number 1. The sequence of the OIDs in the list is very important, because this order defines the structure of the data received from the traffic controllers. In the case of this research, the packet size was specified by the number of objects or parameters required to be collected from the traffic controllers.

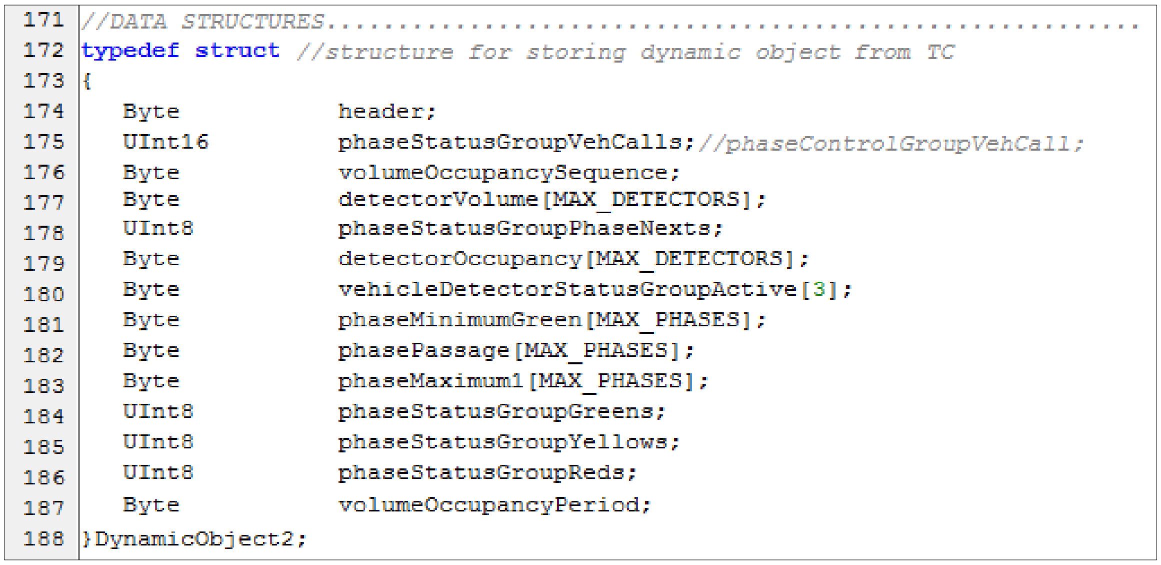
Step 5: Create the dynamic object. The dynamic object setup file is compiled and executed in the Rabbit after specifying the desired traffic controller in the program, as shown on line 50 of Figure 17. Both the traffic controller and the Rabbit should be connected to the same Ethernet network while the program executes. The program must run one time for each traffic controller. Once a dynamic object is setup, it can be used throughout the runtime of the microcontroller.



```
50 #define TRAFFIC_CONTROLLER_IP       "192.168.1.5"
51 #define MY_IP_ADDRESS               "192.168.1.10" // Rabbits IP address
52 #define _PRIMARY_STATIC_IP          MY_IP_ADDRESS
53 #define _PRIMARY_NETMASK            "255.255.255.0"
54 #define MY_NAMESERVER               "192.168.1.1"
55 #define MY_GATEWAY                  "192.168.1.1"
```

Figure 17: Changing the IP address before executing the setup file.

Step 6: Store the dynamic object data. The dynamic object data structure in the “DYNAMIC_SIGNAL_CONTROL" library file is modified by adding a variable to store the value of the newly added object. For example, Figure 18 shows the variable array “detectorVolume[MAX_DETECTOR]” (line 177), which was defined to store the detector volume data. It is also important to note that this structure must list the variables in the same order as the corresponding OIDs given in the dynamic object (shown in Figure 16).



```
171 //DATA STRUCTURES..............................................
172 typedef struct //structure for storing dynamic object from TC
173 {
174    Byte           header;
175    UInt16         phaseStatusGroupVehCalls;//phaseControlGroupVehCall;
176    Byte           volumeOccupancySequence;
177    Byte           detectorVolume[MAX_DETECTORS];
178    UInt8          phaseStatusGroupPhaseNexts;
179    Byte           detectorOccupancy[MAX_DETECTORS];
180    Byte           vehicleDetectorStatusGroupActive[3];
181    Byte           phaseMinimumGreen[MAX_PHASES];
182    Byte           phasePassage[MAX_PHASES];
183    Byte           phaseMaximum1[MAX_PHASES];
184    UInt8          phaseStatusGroupGreens;
185    UInt8          phaseStatusGroupYellows;
186    UInt8          phaseStatusGroupReds;
187    Byte           volumeOccupancyPeriod;
188 }DynamicObject2;
```

Figure 18: Dynamic object data structure (“DYNAMIC_SIGNAL_CONTROL.Lib").

6.2 Interfacing with Relevant Tasks

The microcontroller executes many tasks and all of them share the same resources. To ensure accurate flow of the data in the program, proper correlation of resource use between the tasks is important. In this section, the term “task” refers to a single or a set of functions to perform an action. The interfacing between tasks was done by using global variables. To explain this, the queue spillback detection and control feedback tasks are used as illustrations (see Figure 19).

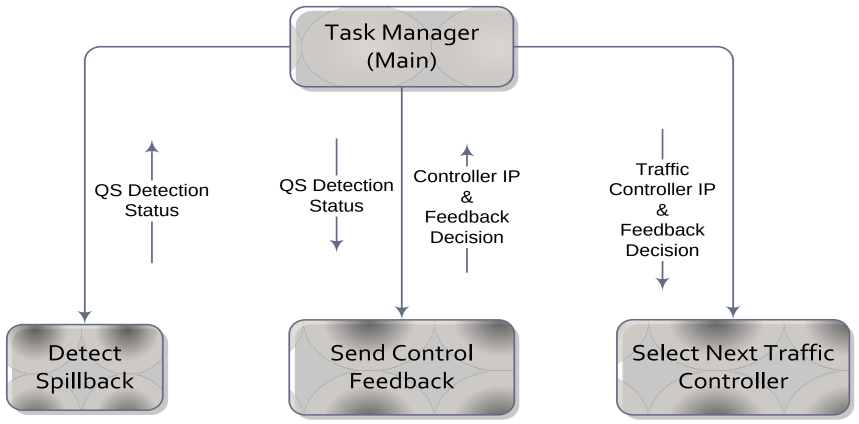
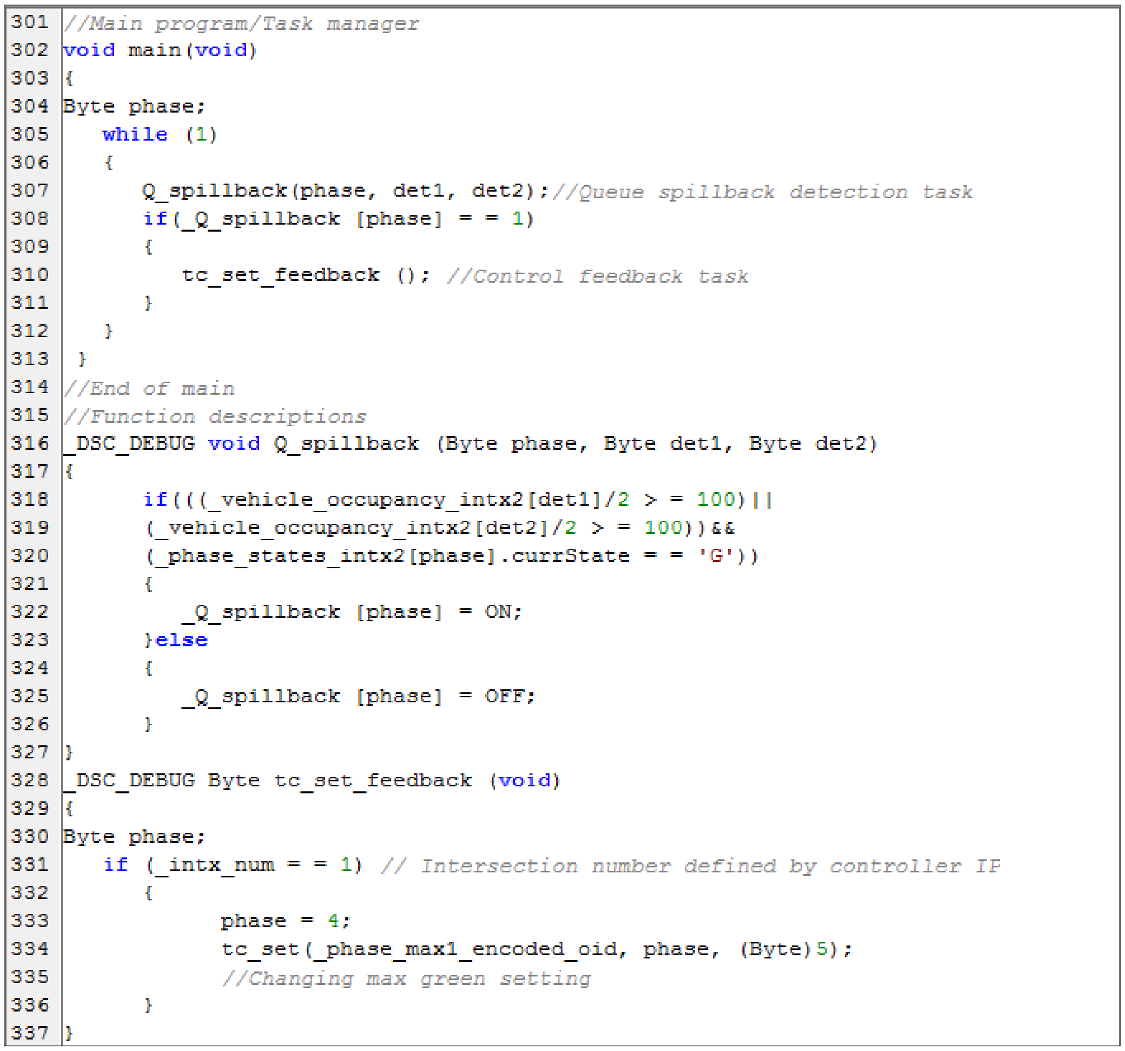

Task Manager (Main)
QS Detection Status
QS Detection Status
Controller IP & Feedback Decision
Traffic Controller IP & Feedback Decision
Detect Spillback
Send Control Feedback
Select Next Traffic Controller

Figure 19: Collaboration diagram for queue spillback detection and feedback.

The above figure shows the flow of data that regulates the order of execution of relevant tasks. The above figure illustrates tasks executed beginning with queue spillback detection and ending with sending the feedback decision to the relevant controller. The tasks are described in order as follows:

1. Queue spillback was detected; a “QS Detection” message passes from the detect spillback task to the task manager.
2. The task manager calls the send control feedback task with this message.
3. The send control feedback task formulates a control decision and sends it back to the task manager in the form of a “Controller IP and Feedback Decision” message. The IP address contained in this message is that of the traffic controller(s) where the plan changes are needed.
4. The task manager sends the feedback decision to the controller with the corresponding IP address.

The above process is further illustrated in the example code given in Figure 20.



```
301 //Main program/Task manager
302 void main(void)
303 {
304 Byte phase;
305    while (1)
306    {
307       Q_spillback(phase, det1, det2);//Queue spillback detection task
308       if(_Q_spillback [phase] = = 1)
309       {
310          tc_set_feedback (); //Control feedback task
311       }
312    }
313  }
314 //End of main
315 //Function descriptions
316 _DSC_DEBUG void Q_spillback (Byte phase, Byte det1, Byte det2)
317 {
318       if(((_vehicle_occupancy_intx2[det1]/2 > = 100)||
319       (_vehicle_occupancy_intx2[det2]/2 > = 100))&&
320       (_phase_states_intx2[phase].currState = = 'G'))
321       {
322          _Q_spillback [phase] = ON;
323       }else
324       {
325          _Q_spillback [phase] = OFF;
326       }
327 }
328 _DSC_DEBUG Byte tc_set_feedback (void)
329 {
330 Byte phase;
331    if (_intx_num = = 1) // Intersection number defined by controller IP
332       {
333             phase = 4;
334             tc_set(_phase_max1_encoded_oid, phase, (Byte)5);
335             //Changing max green setting
336       }
337 }
```

Note: All comments are prefixed with the '// (double slash)' symbol in the code.

Figure 20: Example source code illustrating interactions between tasks.

In the above figure, there is the relevant portion of the task manager code (line 302 to 313) and two functions: Q_spillback (line 316 to 327) and tc_set_feedback (line 328 to 337). The Q_spillback function represents the detect spillback task shown in Figure19. The tc_set_feedback function represents the send control feedback task, also shown in Figure 19. Beginning at line 307, the task manager calls the Q_spillback function, which checks for queue spillback conditions (line 318 to 320). "_Q_spillback [phase]" (line 322) is a global variable array declared to contain the queue spillback detection state for each phase. Based on the check, "_Q_spillback [phase]" is changed to "ON" or "OFF" (lines 322 to 326). Back on line 308, if

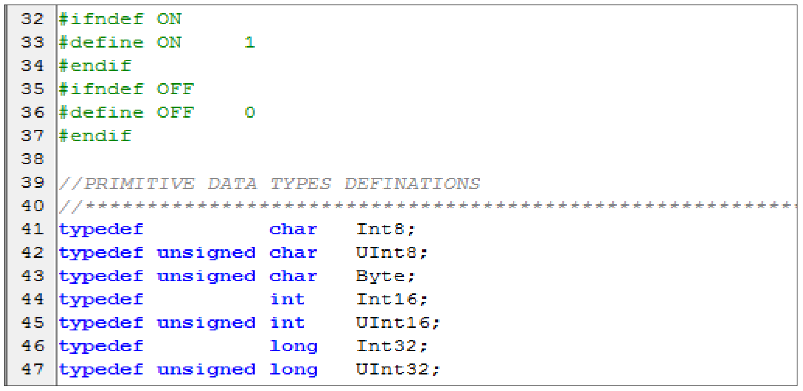
"_Q_spillback [phase]" is true then the control decision is implemented by calling the tc_set_feedback function (line 310) and changes the max green setting of phase 4 to 5 seconds (line 334).

6.3 Using Relevant Libraries and Variables

The main program (referred to as "main") is referred to in Figure 19 as the task manager and contains the instructions to initialize the communication and control the relevant tasks. It uses the following library files by using the compiler directive "#use" {library name}:

- "DTC_GLOBAL_DEFS.LIB": includes global definitions of the variable types
- "DYNAMIC_SIGNAL_CONTROL.LIB": includes tasks for communication and traffic operation monitoring
- "NETWORK_TOPOGRAPHY.LIB": contains user defined variables and tasks for defining the traffic network
- "dcrtcp.lib": includes functions for networking (communication protocols)
- "http.lib": includes primary HTTP functionality, providing a website that shows the traffic network performance

All of the library files should be located to the directory named "Lib" inside the Dynamic C installation directory. The first three library files were developed and/or modified by this project for research with traffic signal systems and the last two were built-in libraries that came with the Dynamic C software. The libraries were developed to serve specific objectives. As shown in Figure 21, the first library contains the global definitions of all data types used in other libraries. For example, a "Byte" data type was defined as an unsigned character (line 43). All seven types that were defined in the library are shown in the figure (line 41 to 47). To define a type, the Dynamic C keyword "typedef" is used. It basically renames a variable type.



```
#ifndef ON
#define ON      1
#endif
#ifndef OFF
#define OFF     0
#endif

//PRIMITIVE DATA TYPES DEFINATIONS
//***********************************************************
typedef          char   Int8;
typedef unsigned char   UInt8;
typedef unsigned char   Byte;
typedef          int    Int16;
typedef unsigned int    UInt16;
typedef          long   Int32;
typedef unsigned long   UInt32;
```

Figure 21: Variable type definitions in "DTC_GLOBAL_DEFS.LIB."

The second library contains the instructions for communication and traffic operations monitoring, and the third file contains the user defined variables for a traffic network. These user defined variable act as constants and some quantify restrictions regarding array sizes and loops in terms of the maximum number of intersections, phases, detectors, lanes, and controllers. As with the other libraries, these libraries contain documentation in the form of "comments." However, in the case of the third library, the comments direct the user to make necessary modifications to change these restrictions. For example, the maximum number of phases were defined as a constant named "MAX_PHASE" and the value given to it was eight. If the user wants to work with sixteen phases, then this value should be changed to sixteen, and a program instruction checking for some conditions for all eight phases would run sixteen times instead of eight. The last two libraries are built-in libraries and contain the functions required for displaying information in the webpage accompanying the microcontroller.

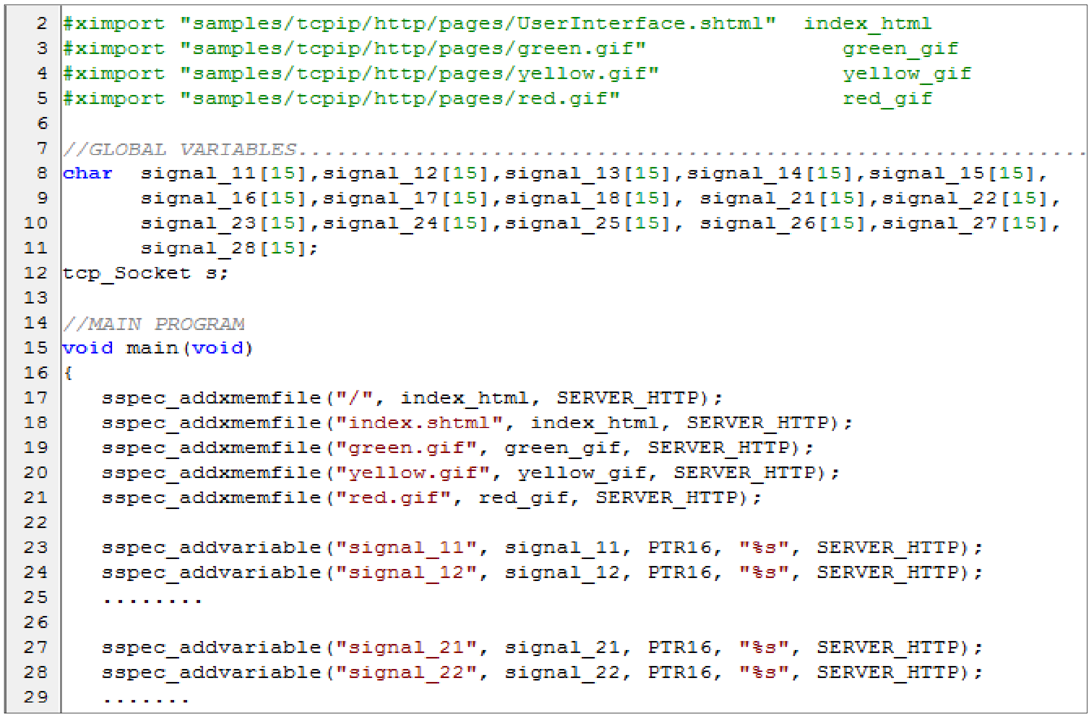
All of the functions in the library files are available for use from the main program. Also, the variables can be used from anywhere within the main program or inside the libraries if they are defined as global variables. This feature of global variables simplifies the code. However, using global variables should be avoided when unnecessary, because the code is easier to understand when the scope of its individual elements are limited. Also, a global variable can be changed by any part of the program, and any rules regarding its use can be easily broken or forgotten.

6.4 Using the User Interface (The Webpage)

For the convenience of monitoring the network performance, a webpage was developed as part of this research. The functionalities were scoped to demonstrate webpage applications, leaving more detailed and rigorous development for future consideration. For only outputting information, the signal status of two intersections was displayed. For inputting information to the server from the webpage a link was provided to implement a control feedback decision. The task can be subdivided into two principal steps: building the webpage by using HTML language and linking the variables declared for displaying signal status with the microcontroller program.

For the signal status display, one variable was declared for each phase. For example, in Figure 22 “signal_11[15]” was used to display the phase one state for intersection one (see line 8). The number “15” in the square brackets means that the variable contains 15 elements, i.e., the variable basically represents a “string” (a Dynamic C data type) of 15 characters. The webpage updates the values of the variables at a certain rate and displays images that represent the appropriate signal status. The HTML and other image files were added in the main program (line 17 to 21) by using “sspec_addxmemfile()” functions, which are defined in the “http.lib” library file. To add a signal status display of another intersection, similar variables should be added both in the global variable section (line 8 to 12) and in the main. The compiler directive “#ximport” (line 2 to 5) imports the HTML and other image files from the specific location on the computer hard drive to the server while the program executes.

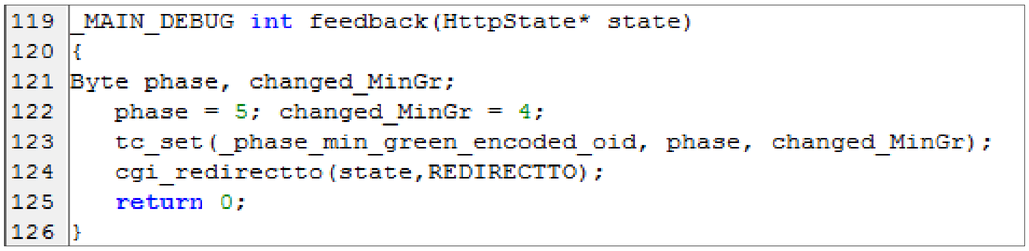
To learn more about exchanging information to a webpage, the user should refer to the example problems provided with the Dynamic C software. “Post.C” is such an example that can be found in the installation directory of the software. There are other examples in the directory that contain source codes with documentation, and these are executable programs.



```
#ximport "samples/tcpip/http/pages/UserInterface.shtml"  index_html
#ximport "samples/tcpip/http/pages/green.gif"               green_gif
#ximport "samples/tcpip/http/pages/yellow.gif"              yellow_gif
#ximport "samples/tcpip/http/pages/red.gif"                 red_gif

//GLOBAL VARIABLES...............................................................
char   signal_11[15],signal_12[15],signal_13[15],signal_14[15],signal_15[15],
       signal_16[15],signal_17[15],signal_18[15], signal_21[15],signal_22[15],
       signal_23[15],signal_24[15],signal_25[15], signal_26[15],signal_27[15],
       signal_28[15];
tcp_Socket s;

//MAIN PROGRAM
void main(void)
{
   sspec_addxmemfile("/", index_html, SERVER_HTTP);
   sspec_addxmemfile("index.shtml", index_html, SERVER_HTTP);
   sspec_addxmemfile("green.gif", green_gif, SERVER_HTTP);
   sspec_addxmemfile("yellow.gif", yellow_gif, SERVER_HTTP);
   sspec_addxmemfile("red.gif", red_gif, SERVER_HTTP);

   sspec_addvariable("signal_11", signal_11, PTR16, "%s", SERVER_HTTP);
   sspec_addvariable("signal_12", signal_12, PTR16, "%s", SERVER_HTTP);
   ........

   sspec_addvariable("signal_21", signal_21, PTR16, "%s", SERVER_HTTP);
   sspec_addvariable("signal_22", signal_22, PTR16, "%s", SERVER_HTTP);
   .......
```

Figure 22: Codes for displaying signal state on the webpage (main program).

An HTML reference (or a "link") named "feedback," is also given on the webpage. This link works like a push button, and if pressed, it sends a command to the Rabbit to call the "feedback" function shown in Figure 23.



```
119 _MAIN_DEBUG int feedback(HttpState* state)
120 {
121 Byte phase, changed_MinGr;
122    phase = 5; changed_MinGr = 4;
123    tc_set(_phase_min_green_encoded_oid, phase, changed_MinGr);
124    cgi_redirectto(state,REDIRECTTO);
125    return 0;
126 }
```

Figure 23: Codes for inputting data to the Rabbit server from the webpage (main program).

Simply as a demonstration, the function sets the phase 5 minimum green to 4 seconds from its initial value of 5 seconds (line 123). Similar control decisions can be implemented by changing the instruction on line 123. Although, the program was made self-sufficient to detect an operational problem and implement a control decision, this webpage functionality actually facilitates human intervention, in the form of monitoring the traffic and controller operations and changing traffic signal control plans.

Chapter 7: Conclusion and Recommendations

The main purpose of this research was to develop an improved and cost effective system for collecting data in real-time, monitoring signalized intersection performance, and facilitating the implementation of improved control logic external to the traffic controllers. This chapter summarizes the important achievements of this research related to the above mentioned objective.

7.1 Synthesis of the Findings

Based on the analysis conducted in this research, the following were concluded:

- The proposed architecture is capable of extracting accurate data from one or more NTCIP compliant traffic controllers via a common Ethernet network.
- The time taken by the microcontroller to read and process the information collected from a certain traffic controller, defined as the response time, depends on the number of traffic controllers in the system. For a system of one traffic controller, the response time is 250 ms. For a system of two or more controllers, the controller response time varies between 275-285 ms per controller.
- A Dynamic C library file can help establish system definitions and network topography information. This information formalizes some relations between control decisions considered at different locations.
- It is clear that the microcontroller’s performance will degrade with each additional controller and this deterioration was quantified in terms of the data read cycle, which is the time transpired between two consecutive times the microcontroller receives data from a given traffic controller.
- Traffic performance measures can be calculated by the microcontroller with acceptable accuracy using controller detector occupancy and volume logs. For a 5 second occupancy interval, the GTU calculated by the microcontroller varied about 1.5 percent from the actual measurements. Although this error can be positive or negative, the data that the microcontrollers estimate are biased high.
- The architecture implements performance measurement and control strategy decisions effectively with multiple controllers. This was shown using a queue spillback scenario.

- A variety of control feedback strategies can be applied within the proposed architecture to improve the queue spillback condition. The green redistribution, as a feedback, improves the queue spillback scenario significantly by making acceptable performance sacrifice for some traffic movements in order to achieve acceptable performance at other traffic movements.

7.2 Opportunities for Microcontroller Application

Data collection and performance measurement for signalized intersections are receiving more attention day by day with the technological advancement in the field. The application of a microcontroller for this purpose was demonstrated in this research through the proposed architecture. However, there are many opportunities for an application of a microcontroller in this setting.

Dual Resolution Performance Monitoring

Typically, traffic operations and maintenance agencies do not have the resources to monitor traffic system performance of signalized arterials in the detail consistent with what a microcontroller can achieve. Therefore, there are very limited means to improve their operations. In addition, the proposed architecture would still be limited by communication bandwidth. It may be more practical to conduct performance monitoring of a signalized arterial with high resolution monitoring surrounding the problem area and low resolution elsewhere. Doing so would support key decisions at critical areas, while continuing basic monitoring at other locations to maintain the ability to change focus to these areas if conditions change.

Excessive Stops Applied in Coordinated System Feedback

In many instances, the purpose of traffic signal coordination is to improve the level of service of a road or a network of roads by minimizing overall delay or travel time and the number of stops. In some cases, this can be achieved by implementing an adaptive traffic control system. The principal benefit of an adaptive system is that it can be effectively used where variability and unpredictability in traffic demand results in excessive delay and stops that cannot be reasonably accommodated by updating coordinated signal timing parameters in a time-of-day fashion. Modifying and testing traffic control logic to be more adaptive requires many resources. To address this, prototyping through the application of microcontrollers can streamline the development effort. This research provides an example of adaptive control in the context of queue spillback. When a queue spillback scenario is detected, the microcontroller determines a control strategy and employs it to mitigate the problem. However, the number of stops was not taken into account while implementing this strategy. Depending on the detection system, the existing adaptive logic could be readily changed to address the number of stops and tested in the laboratory and subsequently in the field.

7.3 Next Steps in Research

It was believed that signalized intersection systems may benefit from applying the architecture and techniques developed in this research. However, some issues and limitations were recognized that might be encountered while implementing this in the field. In an effort to resolve those issues, the following topics were identified for further research:

- The proposed network of microcontroller and the traffic controllers was only tested in the lab. It needs to be tested in the field with the queue spillback detection logic and feedback strategies in order to develop a field ready instrument. Testing in the field might expose issues that were either overlooked or considered to have little impact in the lab. For example, the distance between intersections and field network connections might cause delays that could undermine the performance of the system.
- Future research could improve data resolution and at the same time reduce data read cycles. One direction to pursue for achieving this is the ftp server style communication of data packets employed by Econolite. This introduces some security concerns and additional questions. One question is the data packet request frequencies suitable for real-time performance monitoring and adaptive control. Another question is the potential of PCs to take the place of microcontrollers in the proposed architecture, at least in terms of performance monitoring. In this sense, they would act as a research grade central control computer.
- Response time can be improved by implementing a faster microcontroller and rewriting the program in its corresponding software development environment.

- There is room for refining the detection algorithm. For example, in the queue spillback detection algorithm a 5 second occupancy interval was used. This interval is too short for heavy vehicles, because of their large discharging detector occupancy time.
- Other performance measures (e.g., delay and number of stops) and additional control feedback should be considered (e.g., changing cycle length, or offset).
- Performance measurement and control feedback should more thoroughly consider the network topography to establish stronger and further reaching relationships and strengthen improvement strategies.

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APPENDIX A: List of Functions in Traffic System Definition Library

NETWORK_TOPOGRAPHY.LIB

Function Number: 1

Syntax: *Byte NT_intx_phase(Byte node)*

Description: Defines the number of phases associated with each intersection, a node with a non-zero phase is regarded as an intersection.

Parameter1: Node number

Return value: Number of phases in the given node/intersection

Function Number: 2

Syntax: *Byte NT_link_from_node(Byte link)*

Description: For a given link number, this function returns the node from where it originated.

Parameter1: Link number

Return value: Origin node

Function Number: 3

Syntax: *Byte NT_link_to_node(Byte link)*

Description: For a given link number, this function returns the destination node.

Parameter1: Link number

Return value: Destination node

Function Number: 4

Syntax: *Byte NT_phase_from_link(Byte phase, Byte intx)*

Description: For a given phase number of an intersection, this function returns the link number where it comes from.

Parameter1: Phase number

Return value: Intersection number

Function Number: 5

Syntax: *Byte NT_phase_to_link(char mvmnt, Byte phase, Byte intx)*

Description: For a given phase number of an intersection, this function returns the link number to which the phase goes.

Parameter1: Movement, 'L'= Left-turn, 'T'= Through, 'R'=Right-turn

Parameter2: Phase number

Return value: Intersection number

Function Number: 6

Syntax: *Byte NT_phase_Upstream_intx(Byte phase, Byte intx)*

Description: For a given phase number of an intersection, this function returns the link number where it comes from.

Parameter1: Phase number

Parameter2: Intersection to which the phase belongs

Return value: Origin Node

Function Number: 7

Syntax: *Byte NT_phase_Downstream_intx(char mvmnt, Byte phase, Byte intx)*

Description: For a given movement and phase number of an intersection, this function returns the link number where it goes.

Parameter1: Movement, 'L'= Left-turn, 'T'= Through, 'R'=Right-turn

Parameter2: Phase number

Parameter3: Intersection to which the phase belongs

Return value: Origin Node

Function Number: 8

Syntax: *Byte NT_offset_between_intx(Byte intx1, Byte intx2)*

Description: For a given phase number of an intersection, this function returns the link number where it comes from.

Parameter1: Upstream intersection from where the traffic comes

Parameter2: Downstream intersection to which the traffic moves

Return value: Offset in seconds from intersection 1 to 2

Function Number: 9

Syntax: *void NT_contributing_upstream_phases(Byte phase, Byte intx)*

Description: For a given phase of an intersection, this function computes the upstream contributing phases.

Parameter1: Phase number

Parameter2: Intersection to which the phase belongs

Return value: None (stores the number of u/s contributing phases in global variable "_contributing_us_phase[3]").

Function Number: 10

Syntax: *void NT_movements_served(Byte phase, Byte intx)*

Description: For a given phase number of an intersection, this function computes the movements it serves.

Parameter1: Phase number

Parameter2: Intersection to which the phase belongs

Return value: None

Function Number: 11

Syntax: *Byte NT_number_lanes_served(Byte phase, Byte intx)*

Description: For a given phase number of an intersection, this function returns the number of lanes it serves.

Parameter1: Phase number

Parameter2: Intersection to which the phase belongs

Return value: None

Function Number: 12

Syntax: *void NT_lanes_served_phase(Byte phase, Byte intx)*

Description: For a given phase number of an intersection, this function computes the lanes being served by it.

Parameter1: Phase number

Parameter2: Intersection to which the phase belongs

Return value: None

Function Number: 13

Syntax: *Byte NT_lane_mvmnt(Byte lane, Byte phase, Byte intx)*

Description: For a given lane number and phase of an intersection, this function returns a number that represents the movements being served by the lane.

Parameter1: Lane number (starts from inside, inside most lane is number 1)

Parameter2: Phase that serves the lane, it defines the approach of intersection

Parameter3: Intersection to which the phase belongs

Return value: Number representing the movement being served according to the Lane-Movement Assignment Table described inside the function.

Function Number: 14

Syntax: *void print_lane_mvmnts(Byte intx)*

Description: For a given intersection, this function prints the movements each lane serves.

Parameter1: Intersection to which the phase belongs

Return value: None.

Function Number: 15

Syntax: *int NT_det_position(Byte det, Byte intx)*

Description: For a given detector number at a given intersection, this function returns the position of the detector, i.e., distance from the stop bar.

Parameter1: Detector number

Parameter2: Intersection to which the detector belongs

Return value: None.

APPENDIX B: Comparison of Phase Maximum Green and Phase Passage Values

Table 6: Phase Max Green Comparison for Data Reading Capability Test

Traffic Controller	Max Green (sec)															
	Microprocessor								Actual Input							
	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8
1	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0
2	-	20.0	-	30.0	-	-	-	30.0	-	20.0	-	30.0	-	-	-	30.0
3	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0
4	-	20.0	-	30.0	-	-	-	30.0	-	20.0	-	30.0	-	-	-	30.0
5	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0
6	-	20.0	-	30.0	-	-	-	30.0	-	20.0	-	30.0	-	-	-	30.0
7	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0	4.0	27.0	13.0	35.0	23.0	8.0	13.0	35.0
8	-	20.0	-	30.0	-	-	-	30.0	-	20.0	-	30.0	-	-	-	30.0

Table 7: Phase Passage Comparison for Data Reading Capability Test

Traffic Controller	Phase Passage (sec)															
	Microprocessor								Actual Input							
	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8	φ1	φ2	φ3	φ4	φ5	φ6	φ7	φ8
1	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0
2	-	3.0	-	2.0	-	-	-	2.0	-	3.0	-	2.0	-	-	-	2.0
3	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0
4	-	3.0	-	2.0	-	-	-	2.0	-	3.0	-	2.0	-	-	-	2.0
5	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0
6	-	3.0	-	2.0	-	-	-	2.0	-	3.0	-	2.0	-	-	-	2.0
7	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0	2.0	2.0	3.0	2.0	3.5	2.0	3.0	2.0
8	-	3.0	-	2.0	-	-	-	2.0	-	3.0	-	2.0	-	-	-	2.0

APPENDIX C: Signal State Comparison of I5-Off ramp Intersection

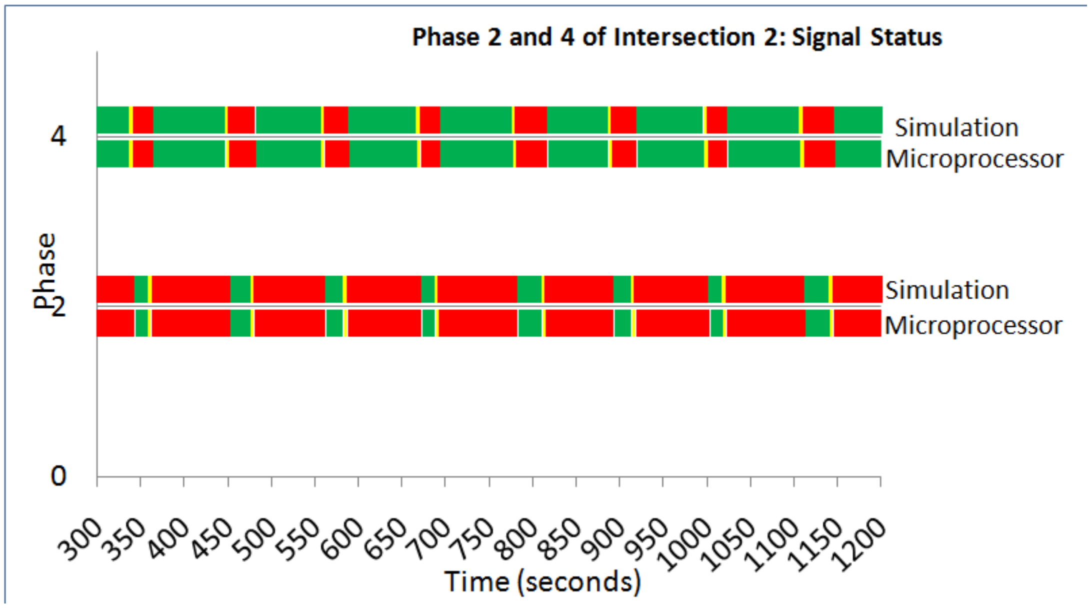

Figure 24: Comparison of signal status data (intersection 2).

APPENDIX D: Detector Status Comparisons

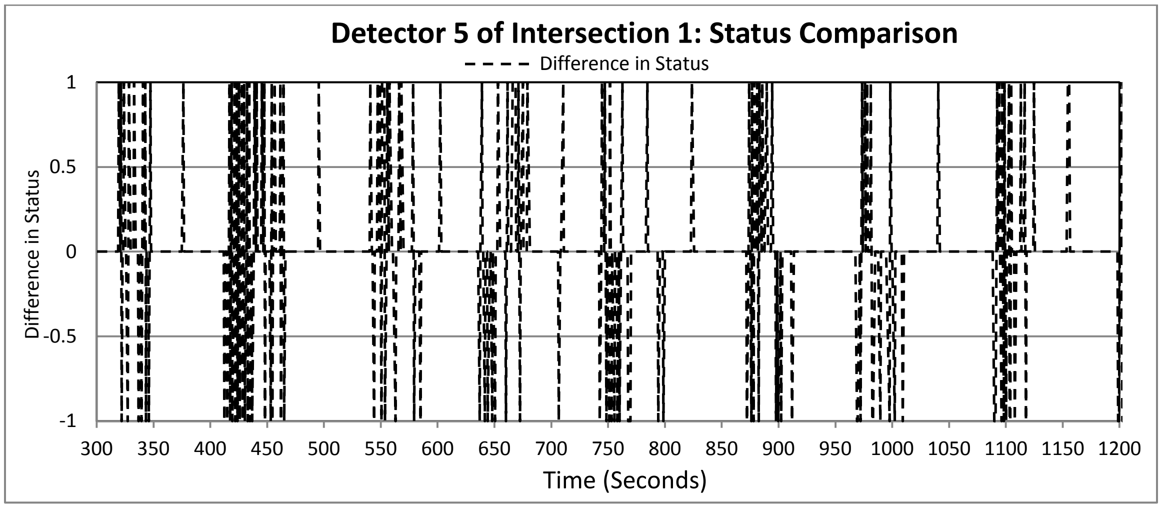

Figure 25: Comparison of detector status (detector 5 of intersection 1).

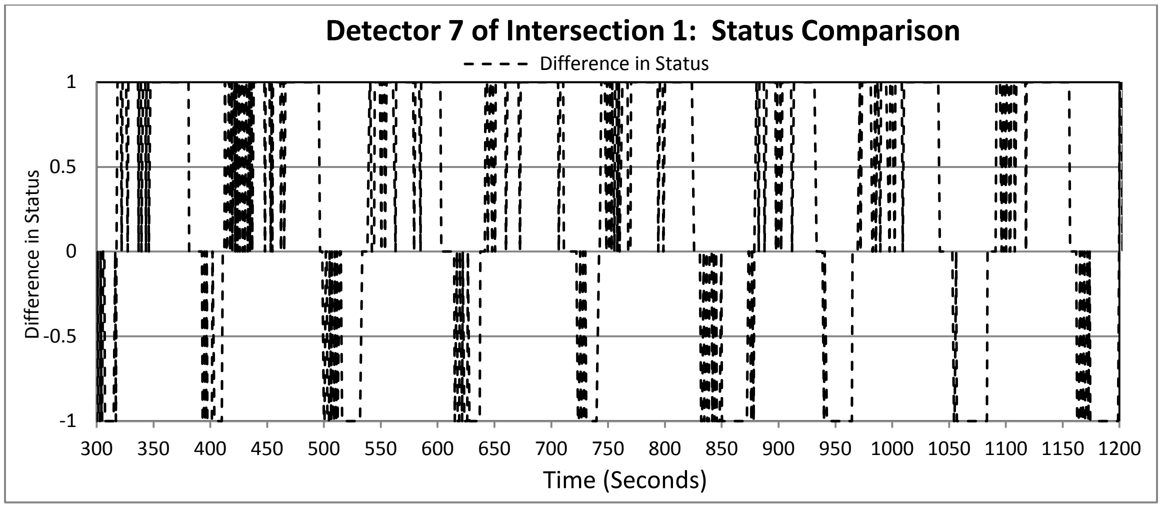

Figure 26: Comparison of detector status (detector 7 of intersection 1).

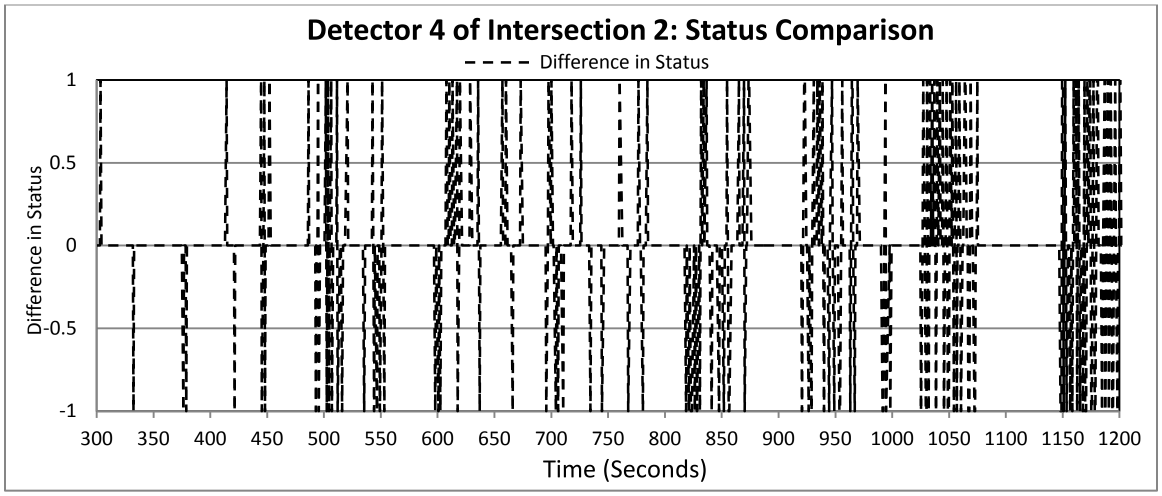

Figure 27: Comparison of detector status (detector 4 of intersection 2)

APPENDIX E: Paired t-Tests for GTU Comparison

Table 8: Intersection 1 Phase 4 GTU Comparison (Paired t-Test)

	Microcontroller	Simulation-based
Mean	*47.40*	*44.73*
Variance	*43.89*	*44.74*
Observations	*30*	*30*
Hypothesized Mean Difference	*0*	
df	*29*	
t Stat	*4.22*	
P(T<=t) two-tail	*0.0002*	
t Critical two-tail	*2.05*	

Table 9: Intersection 1 Phase 5 GTU Comparison (Paired t-Test)

	Microcontroller	Simulation-based
Mean	*35.14*	*32.63*
Variance	*68.98*	*58.03*
Observations	*30*	*30*
Hypothesized Mean Difference	*0*	
df	*29*	
t Stat	*8.19*	
P(T<=t) two-tail	*5.00E-09*	
t Critical two-tail	*2.05*	

Table 10: Intersection 1 Phase 4 GTU Comparison (Paired t-Test with Hypothesized Mean Difference)

	Microcontroller	Simulation-based
Mean	*47.65*	*45.04*
Variance	*43.53*	*43.35*
Observations	*30*	*30*
Hypothesized Mean Difference	*1.50*	
df	*29*	
t Stat	*1.71*	
P(T<=t) two-tail	*0.10*	
t Critical two-tail	*2.05*	

Table 11: Intersection 1 Phase 5 GTU Comparison (Paired t-Test with Hypothesized Mean Difference)

	Microcontroller	Simulation-based
Mean	*47.65*	*45.04*
Variance	*43.53*	*43.35*
Observations	*30*	*30*
Hypothesized Mean Difference	*1.50*	
df	*29*	
t Stat	*1.71*	
P(T<=t) two-tail	*0.10*	
t Critical two-tail	*2.05*	

APPENDIX F: List of the Most Commonly Used OIDs

1.3.6.1.4.1.1206.4.2.1.1	phase
1.3.6.1.4.1.1206.4.2.1.1.1	maxPhases
1.3.6.1.4.1.1206.4.2.1.1.2.1.1	phaseNumber
1.3.6.1.4.1.1206.4.2.1.1.2.1.2	phaseWalk
1.3.6.1.4.1.1206.4.2.1.1.2.1.3	phasePedestrianClear
1.3.6.1.4.1.1206.4.2.1.1.2.1.4	phaseMinimumGreen
1.3.6.1.4.1.1206.4.2.1.1.2.1.5	phasePassage
1.3.6.1.4.1.1206.4.2.1.1.2.1.6	phaseMaximum1
1.3.6.1.4.1.1206.4.2.1.1.2.1.7	phaseMaximum2
1.3.6.1.4.1.1206.4.2.1.1.2.1.8	phaseYellowChange
1.3.6.1.4.1.1206.4.2.1.1.2.1.9	phaseRedClear
1.3.6.1.4.1.1206.4.2.1.1.2.1.12	phaseMaximumInitial
1.3.6.1.4.1.1206.4.2.1.1.2.1.13	phaseTimeBeforeReduction
1.3.6.1.4.1.1206.4.2.1.1.2.1.15	phaseTimeToReduce
1.3.6.1.4.1.1206.4.2.1.1.2.1.17	phaseMinimumGap
1.3.6.1.4.1.1206.4.2.1.1.2.1.19	phaseDynamicMaxStep
1.3.6.1.4.1.1206.4.2.1.1.2.1.20	phaseStartup
1.3.6.1.4.1.1206.4.2.1.1.2.1.21	phaseOptions
1.3.6.1.4.1.1206.4.2.1.1.2.1.22	phaseRing
1.3.6.1.4.1.1206.4.2.1.1.3	maxPhaseGroups
1.3.6.1.4.1.1206.4.2.1.1.4	phaseStatusGroupTable
1.3.6.1.4.1.1206.4.2.1.1.4.1	phaseStatusGroupEntry
1.3.6.1.4.1.1206.4.2.1.1.4.1.1	phaseStatusGroupNumber
1.3.6.1.4.1.1206.4.2.1.1.4.1.2	phaseStatusGroupReds
1.3.6.1.4.1.1206.4.2.1.1.4.1.3	phaseStatusGroupYellows
1.3.6.1.4.1.1206.4.2.1.1.4.1.4	phaseStatusGroupGreens
1.3.6.1.4.1.1206.4.2.1.1.4.1.5	phaseStatusGroupDontWalks
1.3.6.1.4.1.1206.4.2.1.1.4.1.6	phaseStatusGroupPedClears
1.3.6.1.4.1.1206.4.2.1.1.4.1.7	phaseStatusGroupWalks
1.3.6.1.4.1.1206.4.2.1.1.4.1.8	phaseStatusGroupVehCalls
1.3.6.1.4.1.1206.4.2.1.1.4.1.9	phaseStatusGroupPedCalls
1.3.6.1.4.1.1206.4.2.1.1.4.1.10	phaseStatusGroupPhaseOns
1.3.6.1.4.1.1206.4.2.1.1.4.1.11	phaseStatusGroupPhaseNexts
1.3.6.1.4.1.1206.4.2.1.1.5	phaseControlGroupTable
1.3.6.1.4.1.1206.4.2.1.1.5.1	phaseControlGroupEntry
1.3.6.1.4.1.1206.4.2.1.1.5.1.1	phaseControlGroupNumber
1.3.6.1.4.1.1206.4.2.1.1.5.1.2	phaseControlGroupPhaseOmit
1.3.6.1.4.1.1206.4.2.1.1.5.1.3	phaseControlGroupPedOmit
1.3.6.1.4.1.1206.4.2.1.1.5.1.4	phaseControlGroupHold
1.3.6.1.4.1.1206.4.2.1.1.5.1.5	phaseControlGroupForceOff
1.3.6.1.4.1.1206.4.2.1.1.5.1.6	phaseControlGroupVehCall
1.3.6.1.4.1.1206.4.2.1.1.5.1.7	phaseControlGroupPedCall
1.3.6.1.4.1.1206.4.2.1.2	detector

1.3.6.1.4.1.1206.4.2.1.2.1	maxVehicleDetectors
1.3.6.1.4.1.1206.4.2.1.2.2	vehicleDetectorTable
1.3.6.1.4.1.1206.4.2.1.2.2.1	vehicleDetectorEntry
1.3.6.1.4.1.1206.4.2.1.2.2.1.1	vehicleDetectorNumber
1.3.6.1.4.1.1206.4.2.1.2.2.1.2	vehicleDetectorOptions
1.3.6.1.4.1.1206.4.2.1.2.2.1.4	vehicleDetectorCallPhase
1.3.6.1.4.1.1206.4.2.1.2.2.1.5	vehicleDetectorSwitchPhase
1.3.6.1.4.1.1206.4.2.1.2.2.1.6	vehicleDetectorDelay
1.3.6.1.4.1.1206.4.2.1.2.2.1.7	vehicleDetectorExtend
1.3.6.1.4.1.1206.4.2.1.2.2.1.8	vehicleDetectorQueueLimit
1.3.6.1.4.1.1206.4.2.1.2.2.1.9	vehicleDetectorNoActivity
1.3.6.1.4.1.1206.4.2.1.2.2.1.10	vehicleDetectorMaxPresence
1.3.6.1.4.1.1206.4.2.1.2.2.1.11	vehicleDetectorErraticCounts
1.3.6.1.4.1.1206.4.2.1.2.2.1.12	vehicleDetectorFailTime
1.3.6.1.4.1.1206.4.2.1.2.2.1.13	vehicleDetectorAlarms
1.3.6.1.4.1.1206.4.2.1.2.2.1.14	vehicleDetectorReportedAlarms
1.3.6.1.4.1.1206.4.2.1.2.2.1.15	vehicleDetectorReset
1.3.6.1.4.1.1206.4.2.1.2.3	maxVehicleDetectorStatusGroups
1.3.6.1.4.1.1206.4.2.1.2.4	vehicleDetectorStatusGroupTable
1.3.6.1.4.1.1206.4.2.1.2.4.1	vehicleDetectorStatusGroupEntry
1.3.6.1.4.1.1206.4.2.1.2.4.1.1	vehicleDetectorStatusGroupNumber
1.3.6.1.4.1.1206.4.2.1.2.4.1.2	vehicleDetectorStatusGroupActive
1.3.6.1.4.1.1206.4.2.1.2.4.1.3	vehicleDetectorStatusGroupAlarms
1.3.6.1.4.1.1206.4.2.1.2.5	volumeOccupancyReport
1.3.6.1.4.1.1206.4.2.1.2.5.1	volumeOccupancySequence
1.3.6.1.4.1.1206.4.2.1.2.5.2	volumeOccupancyPeriod
1.3.6.1.4.1.1206.4.2.1.2.5.3	activeVolumeOccupancyDetectors
1.3.6.1.4.1.1206.4.2.1.2.5.4	volumeOccupancyTable
1.3.6.1.4.1.1206.4.2.1.2.5.4.1	volumeOccupancyEntry
1.3.6.1.4.1.1206.4.2.1.2.5.4.1.1	detectorVolume
1.3.6.1.4.1.1206.4.2.1.2.5.4.1.2	detectorOccupancy
1.3.6.1.4.1.1206.4.2.1.2.6	maxPedestrianDetectors
1.3.6.1.4.1.1206.4.2.1.2.7	pedestrianDetectorTable
1.3.6.1.4.1.1206.4.2.1.2.7.1	pedestrianDetectorEntry
1.3.6.1.4.1.1206.4.2.1.2.7.1.1	pedestrianDetectorNumber
1.3.6.1.4.1.1206.4.2.1.2.7.1.2	pedestrianDetectorCallPhase
1.3.6.1.4.1.1206.4.2.1.2.7.1.3	pedestrianDetectorNoActivity
1.3.6.1.4.1.1206.4.2.1.2.7.1.4	pedestrianDetectorMaxPresence
1.3.6.1.4.1.1206.4.2.1.2.7.1.5	pedestrianDetectorErraticCounts
1.3.6.1.4.1.1206.4.2.1.2.7.1.6	pedestrianDetectorAlarms
1.3.6.1.4.1.1206.4.2.1.3.13	maxSpecialFunctionOutputs
1.3.6.1.4.1.1206.4.2.1.3.14	specialFunctionOutputTable
1.3.6.1.4.1.1206.4.2.1.3.14.1	specialFunctionOutputEntry
1.3.6.1.4.1.1206.4.2.1.3.14.1.1	specialFunctionOutputNumber
1.3.6.1.4.1.1206.4.2.1.3.14.1.3	specialFunctionOutputControl
1.3.6.1.4.1.1206.4.2.1.3.14.1.4	specialFunctionOutputStatus

1.3.6.1.4.1.1206.4.2.1.4	coord
1.3.6.1.4.1.1206.4.2.1.4.1	coordOperationalMode
1.3.6.1.4.1.1206.4.2.1.4.2	coordCorrectionMode
1.3.6.1.4.1.1206.4.2.1.4.3	coordMaximumMode
1.3.6.1.4.1.1206.4.2.1.4.4	coordForceMode
1.3.6.1.4.1.1206.4.2.1.4.5	maxPatterns
1.3.6.1.4.1.1206.4.2.1.4.6	patternTableType
1.3.6.1.4.1.1206.4.2.1.4.7	patternTable
1.3.6.1.4.1.1206.4.2.1.4.7.1	patternEntry
1.3.6.1.4.1.1206.4.2.1.4.7.1.1	patternNumber
1.3.6.1.4.1.1206.4.2.1.4.7.1.2	patternCycleTime
1.3.6.1.4.1.1206.4.2.1.4.7.1.3	patternOffsetTime
1.3.6.1.4.1.1206.4.2.1.4.7.1.4	patternSplitNumber
1.3.6.1.4.1.1206.4.2.1.4.7.1.5	patternSequenceNumber
1.3.6.1.4.1.1206.4.2.1.4.8	maxSplits
1.3.6.1.4.1.1206.4.2.1.4.9	splitTable
1.3.6.1.4.1.1206.4.2.1.4.9.1	splitEntry
1.3.6.1.4.1.1206.4.2.1.4.9.1.1	splitNumber
1.3.6.1.4.1.1206.4.2.1.4.9.1.2	splitPhase
1.3.6.1.4.1.1206.4.2.1.4.9.1.3	splitTime
1.3.6.1.4.1.1206.4.2.1.4.9.1.4	splitMode
1.3.6.1.4.1.1206.4.2.1.4.9.1.5	splitCoordPhase
1.3.6.1.4.1.1206.4.2.1.4.10	coordPatternStatus
1.3.6.1.4.1.1206.4.2.1.4.11	localFreeStatus
1.3.6.1.4.1.1206.4.2.1.4.12	coordCycleStatus
1.3.6.1.4.1.1206.4.2.1.4.13	coordSyncStatus
1.3.6.1.4.1.1206.4.2.1.4.14	systemPatternControl