A Bus Signal Priority System Using Automatic Vehicle Location / Global Position Systems and Wireless Communication Systems

Final Report

Prepared by:

Chen-Fu Liao
Gary A. Davis
Priya Iyer

Department of Civil Engineering
University of Minnesota

CTS 08-18

Technical Report Documentation Page

1. Report No. CTS 08-18	2.	3. Recipients Accession No.	
4. Title and Subtitle A Bus Signal Priority System Using Automatic Vehicle Location / Global Position Systems and Wireless Communication Systems		5. Report Date December 2008	
		6.	
7. Author(s) Chen-Fu Liao, Gary A. Davis, and Priya Iyer		8. Performing Organization Report No.	
9. Performing Organization Name and Address Department of Civil Engineering University of Minnesota 500 Pillsbury Drive S.E. Minneapolis, MN 55455-0116		10. Project/Task/Work Unit No. CTS project # 2007089	
		11. Contract (C) or Grant (G) No.	
12. Sponsoring Organization Name and Address Intelligent Transportation Systems Institute University of Minnesota 200 Transportation and Safety Building 511 Washington Ave. SE Minneapolis, Minnesota 55455		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes http://www.cts.umn.edu/Publications/ResearchReports/			

16. Abstract (Limit: 250 words)

Current signal priority strategies implemented in various US cities mostly utilize sensors to detect buses at a fixed or preset distance away from an intersection. Traditional presence detection systems, ideally designed for emergency vehicles, usually send signal priority request after a preprogrammed time offset as soon as transit vehicles were detected without the consideration of bus readiness. The objective of this study is to integrate the already equipped Global Positioning System/Automated Vehicle Location (GPS/AVL) system on the buses in Minneapolis and develop an adaptive signal priority system that could consider the bus schedule adherence, its number of passengers, location and speed. Buses can communicate with intersection signal controllers using wireless technology to request for signal priority. Similar setup can also be utilized for other transit-related Intelligent Transportation Systems (ITS) applications. The City of Minneapolis recently deployed wireless technology to provide residents, businesses and visitors with wireless broadband access anywhere in the city. Communication with the roadside unit (e.g., traffic controller) for signal priority may be established using the readily available 802.11x WLAN or the Dedicated Short Range Communication (DSRC) 802.11p protocol currently under development for wireless access in vehicular environment. This report documents the development, verification and validation of the embedded signal priority prototype systems, field testing results and limitations of using the City of Minneapolis Wi-Fi network for Transit Signal Priority (TSP).

17. Document Analysis/Descriptors Transit Signal Priority (TSP), Automated Vehicle Location (AVL), Wireless Communication, Dedicated Short Range Communication (DSRC)		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 111	22. Price

A Bus Signal Priority System Using Automatic Vehicle Location / Global Position Systems and Wireless Communication Systems

Final Report

Prepared by

Chen-Fu Liao
Gary A. Davis
Department of Civil Engineering
University of Minnesota

Priya Iyer
Department of Electrical and Computer Engineering
University of Minnesota

December 2008

Published by

Intelligent Transportation Systems Institute
Center for Transportation Studies
200 Transportation and Safety Building
511 Washington Avenue S.E.
Minneapolis, Minnesota 55455

ACKNOWLEDGEMENTS

We would like to thank the Intelligent Transportation Systems (ITS) Institute and Center for Transportation Studies (CTS), University of Minnesota, for supporting this project. The ITS Institute is a federally funded program administrated through the Research & Innovative Technology Administration (RITA). We also would like to recognize the following people and organizations for their invaluable assistance in making this research possible.

- Bryan Newstrom at Intelligent Vehicle Laboratory, Department of Mechanical Engineering, for providing support on embedded Linux operating system.
- Intelligent Vehicle Laboratory, Department of Mechanical Engineering, for using its Denso DSRC radio modems.
- Minnesota Traffic Observatory, Department of Civil Engineering, for using the lab facility.
- Scott Tacheny, Don Sobania and their electricians at the City of Minneapolis Department of Public Works for providing traffic data, signal timing plan and numerous discussions and responses to our questions.
- Gary Nyberg, Janet Hopper, and John Levin at Metro Transit, for providing bus GPS data, schedule and trip count data.
- WenTeng Ma, Sundeep Bhimireddy and Prof. Henry Liu at Department of Civil Engineering, for provide access to their SMART-SIGNAL traffic controller cabinet for TSP testing.
- Jim Welna, owner of Welna II Hardware on East Franklin Avenue, for providing AC power access for roadside unit testing with the Minneapolis Wi-Fi network.
- USI Wireless, for providing technical support on its wireless network in Minneapolis.
- Tony Juettner at Brown Traffic Products, Inc., for providing information on EPAC traffic controller.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Current signal priority strategies implemented in various US cities mostly utilize sensors to detect buses at a fixed or preset distance away from an intersection. Traditional presence detection systems, ideally designed for emergency vehicles, usually send a signal priority request after a preprogrammed time offset as soon as transit vehicles were detected without the consideration of bus readiness. Significant amount of research projects focusing on various intelligent transportation systems (ITS) applications under the Vehicle Infrastructure Integration (VII) framework have been investigated since the introduction of the VII initiative. Data collected through the VII network could potentially enable hundreds of possibilities including safety, mobility, and commercial uses, from intersection collision avoidance and dynamic route guidance to road-level weather advisories and electronic toll collection.

Wireless communications systems have made rapid progress in the past decade and are commercially available. Los Angeles County Metropolitan Transportation Authority (MTA) has implemented wireless technology in a transit signal priority system along a corridor using the IEEE 802.11b protocol. The wireless system on each bus sends an IP addressable message to an access point that covers three to four intersections. A wireless client installed in the signal cabinet communicates with a modified traffic controller to request signal priority. King County MTA in Washington is also planning to design wireless TSP system similar to the implementation in LA County. Pace, a suburban bus division of the Regional Transportation Authority, provides bus services throughout Chicago's six-county suburban region. Pace recently was awarded with several research projects to deploy bus rapid transit (Cermak, Golf Road, and south suburban) and transit signal priority (Cicero Avenue and Rand Road) through the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) bill. Pace is also working with a consulting company to identify wireless-based systems to provide bus signal priority and to report priority status and system performance back to its transit operation center.

The objective of this study is to develop a wireless-based Transit Signal Priority (TSP) system that will integrate the already installed Global Positioning System/Automated Vehicle Location (GPS/AVL) system on the buses in Twin Cities. An adaptive signal priority strategy developed from phase I study was incorporated to consider the bus schedule adherence, its number of passengers, location and speed. Buses can communicate with intersection signal controllers using wireless technology to request for signal priority. Similar setup can also be utilized for other transit-related ITS applications. The goals of the phase 2 study are to evaluate the performance of DSRC (Dedicated Short Range Communication) and Wi-Fi network, develop wireless communication prototype using commercial off-the-shelf (COTS) products, implement adaptive TSP algorithm and validate the signal priority strategy based on the AVL/GPS and wireless technology. The City of Minneapolis recently deployed wireless technology to provide residents, businesses and visitors with wireless broadband access anywhere in the city. Communication with the roadside equipment (e.g., traffic controller) for signal priority was tested using the available 802.11x Wireless Local Area Network (WLAN) or the DSRC modems in vehicular environment.

A set of PC/104 stand-alone Single Board Computer (SBC) was selected for the embedded system development. Additional I/O modules were integrated to the embedded system to perform data communication between traffic signal controller and roadside computer, and a transit vehicle and onboard computer. A pair of 5.9-GHz Wireless Access in Vehicular Environment (WAVE) radio modules was manufactured by DENSO Corporation (http://www.denso.co.jp/en/). The DSRC radio modems and 802.11x wireless adapters were utilized to establish wireless communications between the onboard equipment (OBE) and the roadside equipment (RSE).

Performance of wireless communication is highly affected by the changing environment in which transmission errors are unavoidable and quite common. Wireless signals suffer attenuations as they propagate through space and other obstacles cause absorptions and reflections. Communication coverage and latency were tested for both DSRC and 802.11x Wi-Fi modules at two different locations (East Franklin Avenue at 22nd Avenue and Como Avenue at 29th Avenue in Minneapolis). The latency of DSRC radio ranges from 3 to 6 milliseconds at both test sites. The latency of the University of Minnesota

(UMN) wireless network ranges from 10 to 30+ milliseconds depending on location. The DSRC modem has potentially excellent performace with a high data communication rate; however, the availability of DSRC is limited and we don't know whether there will be national "rollout". The Wi-Fi network has the advantage of using existing infrastructure in Minneapolis; however, data latency and bandwidth need to be considered. The wireless system evaluation helps us better understand the performance of each system and potential constraints while requesting for signal priority in real-time application. Data communication programs using User Datagram Protocol (UDP) were developed on a host machine and then later downloaded to both roadside and onboard embedded computers.

Signal priority request output from roadside equipment was connected to a pre-emption input channel on the signal controller inside the controller cabinet. Program in the traffic controller was also configured and activated to accept external pre-emption inputs. The traffic signal controller was programmed by the City of Minneapolis traffic engineer to specify corresponding delay, dwell, maximum call and extension time. Developed prototype systems were deployed and tested at an intersection at Como and 29th Avenue near the University of Minnesota campus to validate the bus signal priority algorithm using different wireless communication protocols. The mobile design of the wireless transit signal priority system allows us to test the prototype at different intersections and on different vehicles easily. The OBE was placed on a test minivan with GPS receiver and radio antenna mounted on top of the vehicle to represent a transit vehicle. The onboard embedded system interfaces with the GPS and wireless communication systems to transmit vehicle location and other information (for example, vehicle ID, route ID, passenger counts, door opening status and so on) to the roadside equipment. The RSE continuously monitors the vehicle location when it travels within the range of the wireless communication and then generates a signal priority request to traffic signal controller as needed.

Field testing results show that the test vehicle successfully submitted a signal priority request through the wireless communication as it is traveling toward the intersection instrumented with roadside equipment. The test vehicle was initially traveling from a location outside the communication range of the DSRC WAVE radios. As soon as the vehicle moved within the wireless communication range, the adaptive signal priority algorithm began to monitor the location and speed of the test vehicle and submited a request for priority through the roadside interface to the signal controller when the vehicle was ready to enter the intersection. The Eagle EPAC traffic signal controller is capable of providing green extension or red truncation (or early green) to the qualified or authenticated vehicle as it is approaching the intersection. The signal priority request is dropped when the test vehicle passes the intersection or when the duration of priority call exceeds the maximum call setting.

We also tested our signal priority systems using the Minneapolis Wi-Fi network. In 2006 the City of Minneapolis signed a 10-year contract with USI Wireless of Minnetonka (http://www.usiwireless.com/) to provide city-wide wireless broadband technology. According to the City of Minneapolis, the Minneapolis wireless network will cover all 59 square miles of Minneapolis providing residents, businesses and visitors with wireless broadband access anywhere in the city. The network will allow the city to deliver services more efficiently and effectively. However, the current settings and configuration of the Minneapolis Wi-Fi network would not allow direct TCP/UDP communications through their Wi-Fi network between the OBE and RSE. Both OBE and RSE can receive dynamic IP addresses assigned under the private network within the intranet connected to the wireless modems or adapters. The OBE or RSE can freely communicate to the Internet through the Minneapolis Wi-Fi network individually. However, the OBE cannot communicate with the RSE directly through the Wi-Fi network due to security settings on the servers of USI wireless network. We were advised by the USI wireless technical support to use third-party software to communicate between our onboard and roadside equipment through Minneapolis Wi-Fi network. If a device on a private network needs to communicate with other networks, a "mediating gateway" is needed to ensure that the outside network is presented with an address that is real or publicly reachable so that Internet routers allow the communication. The mediating gateway is typically a network address translation (NAT) device or a proxy server. Routers by default will forward packets with RFC 1918 (http://tools.ietf.org/html/rfc1918) addresses. Unlike public Internet routers that need additional configuration to discard these packets, internal routers do not need any additional configuration to forward these packets. Someone may argue that latency of data communication between the onboard system and the roadside system may increase significantly when introducing additional software or the NAT gateway. However, variation of the network latency plays a more critical role than the latency itself. Latency can be compensated for realtime application as long as the wireless network is reliable.

Using the Minneapolis Wi-Fi network for TSP application can certainly reduce cost by taking advantage of the existing infrastructure. However, availability of data bandwidth and quality of service, concern of network reliability and data security need to be addressed when choosing the Wi-Fi technology. The DSRC radio is potentially good with excellent performance (short range with fast data communication rate), but the availability of DSRC is currently limited. We certainly don't know whether there will be national "rollout". The UMN TSP system uses wireless technology to establish data communication between transit vehicles and roadside systems. It is not limited to any particular wireless technology.

This report documents the development, verification and validation of the embedded signal priority prototype systems, field testing results and limitations of using the Minneapolis Wi-Fi network for TSP. Detail documentations of the system design and integration are included in the appendices.

1. INTRODUCTION

Transit Signal Priority (TSP) for transit has been studied and proposed as an efficient way to improve transit travel & operation. Bus signal priority has been implemented in several US cities to improve schedule adherence, reduce transit operation costs, and improve customer ride quality. Signal priority strategies have helped reduce the transit travel time delay, as discussed in the literature (ITSA, 2002), but the transit travel time reduction varies considerably across studies (Collura et. al, 2003). Signal priority and preemption are often used synonymously; however, they are different processes. Signal preemption is traditionally used for emergency vehicles (EV) or at railroad crossing. Preemption interrupts normal intersection signal process to provide high priority for special events. Signal priority modifies the normal signal operation in order to accommodate better service for transit vehicles (ITSA, 2004).

1.1 Background

Current signal priority strategies implemented in various US cities mostly utilized sensors to detect buses at a fixed or at a preset distance away from the intersection. Signal priority is usually granted after a preprogrammed time offset, after detection. Engineers have to adjust the detector location, receiver line of sight and timing offset for each intersection in order to ensure its effectiveness. These TSP strategies do not consider the bus's speed and its distance from intersection when determining the appropriate time to request signal priority. The proposed study would like to incorporate the GPS/AVL system on the buses in Minneapolis and develop a signal priority strategy based on the bus's timeliness with respect to its schedule, number of passengers, location and speed of a bus.

Wireless communications systems have made rapid progress and are commercially available. Bus information (e.g. speed, location, number of passengers, bus ID) can be transmitted wirelessly to a traffic controller or to a regional Traffic Management Center (TMC) in making decisions for signal priority. There are several wireless communication systems installed on each bus under the current Metro Transit setup. An 800-MHz Motorola digital voice radio is used for communication between bus driver and Transit Control Center (TCC). Another 800-MHz analog data radio is used to poll bus location and passenger count data every minute. A Wireless Local Area Network (WLAN) 802.11x is also installed on the bus. This is used to upload/download files between the bus and the TCC central server, when the bus is within the proximity of the transit garage.

1.2 Research Objectives

We would like to provide effective signal priority to buses with minimal impact on other traffic using the already equipped GPS/AVL system on the bus. The GPS system offers better information regarding bus trajectory than the presence detection sensors previously used while requesting for traffic signal priority. Our objective is to investigate the performance of GPS/AVL and deploy a wireless-based adaptive signal priority strategy to provide reliable and efficient bus transit services with minimal impact on traffic flow. Metro Transit buses currently equip with 800MHz data and voice radio and 802.11b/g systems. We would like to utilize the existing systems with little or no additional hardware installation on the buses for signal priority or other transit-related ITS applications. Communication with the roadside unit (e.g., traffic controller) for signal priority can later be established using the DSRC (Dedicated Short Range Communication) 802.11p protocol for wireless access in vehicular environment after the implementation and deployment of the VII initiatives. The improved transit services will hopefully make the transit system more attractive to the public and increase ridership. Simulation studies and field data collection were conducted to estimate changes in bus travel time, delay, as well as potential impact on other traffic.

1.3 Literature Review

The vision of the Vehicle Infrastructure Integration (VII) is to deploy a nationwide communications network along the national roadways that enables communications between vehicles and roadside infrastructure to improve transportation and quality of life. The report from Federal Highway Administration (FHWA) documents the VII architecture and its design requirements (Farradyne, 2005). Significant amount of research projects focusing on various intelligent transportation systems (ITS) applications under the VII framework have been investigated since the introduction of the VII initiative. Data collected through the VII network could potentially enable hundreds of possibilities including safety, mobility, and commercial uses, from intersection collision avoidance and dynamic route guidance to road-level weather advisories and electronic toll collection. For example, Wischhof et al. (2003) and Zhang (2003) investigated the dissemination of vehicle-based traffic and travel information through the VII network. Wu et al. (2005) evaluated the efficiency of message propagation between vehicles through simulation. Xu et al. (2002) study the effect of vehicle vehicle/vehicle-roadside communication on the performance of adaptive cruise control (ACC) systems through simulations. Collision avoidance technologies that use the VII infrastructure are also being developed as part of the Cooperative Intersections Collision Avoidance Systems (CICAS, http://www.its.dot.gov/cicas/index.htm) initiative. Biswas et al. (2006) presented the concept of Cooperative Collision Avoidance (CCA) and its implementation requirements in the context of the vehicle-to-vehicle wireless network. Alexander et al. (2006) designed and deployed a transportable rural intersection surveillance system encompassing RADAR (Radio Detection and Ranging), LIDAR (Light Detection and Ranging), camera systems and wireless communications between infrastructure and vehicles to investigate the gap acceptance behavior of drivers at rural intersections.

Wireless communications systems have made rapid progress in the past decade and are commercially available. McNally et al. (2003) developed an in-vehicle, GPS-based system to provide real-time vehicle guidance information through wireless communication technologies. Fitzmaurice (2005) reviewed the recent technology advances and regulatory changes that have encouraged the mobile wireless applications in rail and urban transit environments. Torrent-Moreno et al. (2004) investigated a study on the probability of reception of a broadcast message by another car and how to provide priority access for important warnings in 802.11-based vehicular ad-hoc networks (VANET). One of the key usages of VANET is to support vehicle safety applications through the broadcast operations for informing the immediate neighboring vehicles. Stibor et al. (2007) evaluated the number of communication partners in communication range and maximum communication duration for a vehicular ad-hoc network using the IEEE 802.11p transceivers in a highway scenario. Marca (2006) performed testing and benchmarked possible throughput of 802.11b wireless communication technology for vehicle to roadside infrastructure communications. Böhm et al. (2008) evaluated different wireless communication technologies, including broadcast, cell based and dedicated short range technologies, and their effectiveness of transmitting road-safety relevant information from infrastructure to vehicle (I2V) as part of the Co-operative Systems for Intelligent Road Safety (COOPERS) program co-funded by the European Commission. Ahmed et al. (2008) developed a blue tooth and wireless mesh networks platform for traffic network monitoring. The platform uses traveling cars as data collecting sensors or probes and uses wireless municipal mesh networks to transmit collected traffic data.

Los Angeles County Metropolitan Transportation Authority (LACMTA) has implemented wireless technology in a transit signal priority system along several corridors using the IEEE 802.11b protocol (Kittleson & Associates, 2006). The wireless system on each bus sends an IP addressable message to an access point that covers three to four intersections. A wireless client installed in the signal cabinet communicates with a modified traffic controller firmware to request for signal priority. TSP request was sent wirelessly from bus onboard unit to an access point connected to traffic controller through a serial (RS-232) interface. Bus messages and TSP responses from controller were also collected and sent to central control via cellular communication. Iteris, Inc. (www.iteris.com) was recently selected by LACMTA for the design, acquisition, deployment, and ongoing operation and maintenance of bus traffic signal priority systems at 211 signalized intersections maintained by18 local agencies along Manchester Boulevard, Garvey Boulevard/Cesar Chavez Avenue, and Atlantic Boulevard. King County MTA in Washington is also planning to design wireless TSP system similar to the implementation in LA County.

Pace, the suburban bus division of the Regional Transportation Authority, provides bus services throughout Chicago's six-county suburban region. Pace recently awarded several research projects to deploy bus rapid transit (Cermak, Golf Road, and south suburban) and transit signal priority (Cicero Avenue and Rand Road) through the SAFETEA-LU bill (http://www.pacebus.com/sub/vision2020/federal_projects.asp). Pace is working with a consulting company to identify a wireless-based system to provide signal priority to buses and report status and performance back to the transit operation center.

Signal priority requests for transit or emergency vehicles can potentially be sent to the signal controller through the vehicle-to-infrastructure communication architecture as described in VII architecture (Farradyne, 2005). Signal priority for transit vehicles has been studied and proposed as an efficient way to improve transit travel time and schedule adherence, to reduce transit operation costs, and to improve customer riding quality. Signal priority strategies have helped reduce the transit travel time delay, as discussed in the literature (ITS America, 2002), but the transit travel time reduction varies considerably across studies (Collura et al., 2006). Unlike signal preemption, which interrupts the normal intersection signal process to provide high priority for special events (emergency vehicle or railroad crossing), transit signal priority (TSP) modifies the normal signal operation in order to accommodate better service for transit vehicles (ITS America, 2004).

Transit signal priority has been implemented in several US cities (Seattle, Portland, Los Angeles, and Chicago) as well as in Europe. Various technologies have been deployed for bus priority including Opticom™ (St. Cloud, 2000), inductance loop detectors (Los Angeles), and RF tag (Seattle, King County, 2002). Recently, Crout (2005) at Tri-County Metropolitan Transportation District of Oregon (TriMet) proposed two types of analyses (corridor and intersection level) to evaluate the effectiveness of the TSP effort on transit operations over 300 signals implemented with signal priority. Current signal priority strategies implemented in various US cities mostly utilize sensors to detect buses at a fixed or at a preset distance away from the intersection. Signal priority is usually granted after a preprogrammed time-offset, after detection. Engineers usually have to adjust the detector location, receiver line of sight and timing offset for each intersection in order to ensure its effectiveness. Liu et al. (2004) presented a theoretical model to quantitatively address the relation between bus detector location and effectiveness of transit signal priority systems. Li et al. (2007) proposed an active signal priority optimization model for Light-Rail Transit (LRT) in a simulation study by estimating the train travel and dwell time. Most TSP strategies do not consider the transit's speed and its distance from the intersection when determining the appropriate time to request signal priority.

Metro Transit in Twin Cities Metro area (http://www.metrotransit.org/) previously performed an evaluation to provide signal priority for buses on Lake Street in Minneapolis using 3M Opticom™ systems. A special software modification was made to provide transit priority using green extension and red truncation strategies. However, the Opticom™ system, ideally designed for emergency vehicle preemption (EVP), was not able to adjust the trigger timing for buses approaching nearside bus stops, and buses often missed the priority green period when they were ready to depart. Since several intersections along Lake Street were already operating at their capacity, the potential for providing transit priority without delaying vehicle traffic was somewhat constrained. There were also issues of buses traveling across different municipalities that were unwilling to provide signal priority for transit. Results from this previous evaluation study were not promising. With the installation of GPS system on its fleet, Metro Transit now constantly monitoring bus locations in relation to their schedules, in order to provide more reliable transit services and enhance transit operation and management. Bus location, travel time, delay and other traffic information can also be collected and integrated to assist traffic operation management and to inform the traveling public. Metro Transit would like to use the already installed GPS/AVL system as the basis of a transit-based intelligent transportation system (ITS).

Bus information (e.g. speed, location, number of passengers, bus ID) can be transmitted wirelessly to a traffic controller or to a regional Traffic Management Center (TMC) in making decisions to grant signal priority request. Several wireless communication systems were installed on Metro Transit buses as standard system configuration. An 800-MHz Motorola digital voice radio is used for communication between bus driver and Transit Control Center (TCC). Another 800-MHz analog data radio is used to poll bus location and passenger count data every minute. A Wireless Local Area Network (WLAN) 802.11x is also installed on the bus to automatically upload or download data files between the bus computer and the central server at TCC when the bus is within the proximity of the transit garage.

Researchers at California PATH (Partners for Advanced Transit and Highways) studied an "Adaptive Bus Signal Priority" (ABSP) to apply an active priority strategy for buses, by including bus GPS information, traffic detector data, and a travel-time predictor to an adaptive model (Liu et al., 2003). Wadjas and Furth (2003) developed a methodology by adapting advanced detection and cycle length to provide transit signal priority. The adaptive control includes traffic density and queue length estimation in a simulation study. Skabardonis and Geroliminis (2008) developed an analytical model for real-time estimation of arterial travel time. A signal priority algorithm, extends the active signal priority strategy initially proposed by Skabardonis (2000), was developed and incorporated into their base model to provide system wide adjustments to the signal timing plans and priority based on the real-time traffic information. Li et al (2005) proposed a heuristic TSP algorithm to provide signal priority to buses as well as limit negative impact on cross-street traffic. Traditional TSP strategies implemented in United States are mostly fixed-location detection systems and implemented with time-of-day signal control systems. TSP systems using fixed-location detection usually do not work well with nearside bus stops, due to the uncertainty in bus dwell time. Zheng et al. (2007) developed a theoretical model to estimate the corresponding delays at nearside bus stops. Kim and Rilett (2005) proposed a weighted least squares regression model in simulation to estimate bus dwell time in order to overcome nearside bus stop challenges. Ghanim et al. (2007) developed an artificial neural network modeling tool to predict intersection bus arrival time on approaches with nearside bus stops. Rakha et al. (2006) performed field and simulation evaluation along US Route 1 corridor. They recommended further consideration on existence of queues in transit signal priority strategy and suggested no near-side bus stop implementation. Furth and SanClemente (2006) investigated the impact of bus stop location on bus delay. They found far-side bus stops cause small reduction in delay or no effect. Nearside bus stops more often increase bus delay.

A bus priority algorithm could also be integrated into an adaptive intersection signal control model. Research based on the bus priority facilities available within the Split Cycle Offset Optimization Technique (SCOOT) traffic signal control system was conducted by Bretherton et al. (1996). Traffic signal priorities can be controlled by a central SCOOT computer or by a local traffic signal controller. A local controller can achieve faster TSP response to buses than a centralized control. Different strategy options for providing bus priority at signals are compared by McLeod & Hounsell (2003) using the simulation model called Selective Priority to Late buses Implemented at Traffic signals (SPLIT). McLeod suggested that differential (conditional) priority strategies (e.g. granting priority for lateness) give the best results, as these provide a good balance between travel time and passenger waiting time. Furth and Mueller (2000) conducted a field study with three priority conditions (no priority, absolute priority, and conditional priority) at a transit route in the Netherlands. The study found absolute priority caused large delays to other traffic while conditional priority caused little, if any additional delay. Dion and Rakha (2005) developed a simulation approach to integrate TSP within an adaptive traffic control system. They evaluate three different signal control scenarios and found adaptive signal control reduced negative impacts on general traffic while providing signal priority to buses. Recently, Mirchandani & Lucas (2004) developed a Categorized Arrival-based Phase Reoptimization at Intersection (CAPRI) strategy that integrates transit signal priority within a real-time traffic adaptive signal control system, called RHODES (Real-time Hierarchical Optimized Distributed Effective System, 2001). "Weighted bus" and "phase constrained" approaches were developed for providing transit priority through the RHODES-CAPRI framework. Mirchandani et al. (2001) proposed a hierarchical optimization approach where traffic signals are determined by considering delays of all vehicles on the network as well as bus passenger counts and schedule while providing transit priority (RHODES/BUSBAND).

2. WIRELESS TRANSIT SIGNAL PRIORITY (W-TSP) SYSTEMS

A set of PC/104 stand-alone Single Board Computer (SBC), as shown in Figure 2.1, was selected for the embedded system development. The Puma series (EPM-5) SBC, manufactured by VersaLogic (http://versalogic.com/) and additional I/O modules were integrated to perform data communication between traffic signal controller and a transit vehicle. A pair of 5.9GHz DSRC (Dedicated Short Range Communications) prototypes, WAVE (Wireless Access in Vehicular Environment) radio modules manufactured by DENSO Corporation (http://www.denso.co.jp/en/) and 802.11x wireless modems were used for wireless communications between the embedded computers.

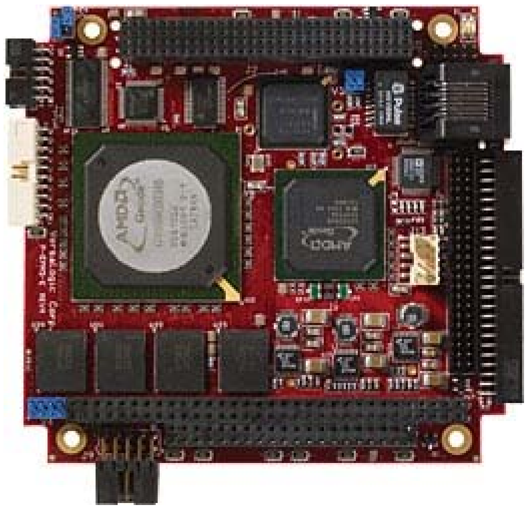


Figure 2.1 Puma PC/104 Plus Single Board Computer

2.1 Embedded Computers

The Puma SBC features the AMD GX 500 processor, which offers 500 MHz equivalent performance while drawing only one watt of power. This highly-integrated processor provides extremely fast on-board transfers (6 GB per second), high-speed memory access. The Puma can operate as a stand-alone SBC or can be combined with specialized PC/104 or PC/104-*Plus* I/O boards for additional functionality. Pass-through connectors for the PC/104 and PC/104-*Plus* interfaces provide support for many off-the-shelf I/O boards. Block diagram and start configuration of the Puma (EPM-5) SBC board is included in Appendix C.1. As shown in Figure 2.2, a digital I/O board R104-88, manufactured by Tri-M Systems (http://www.tri-m.com/) includes 8 isolated inputs and 8 relay outputs. It is added to the Puma SBC to interface with traffic controller cabinet for signal priority request. Detail board layout and jumper settings of the R104 I/O board are documented in Appendix C.2. A HC104 power supply module, as shown in Figure 2.3, is stacked under the single computer and IO module to provide 5 and 12VDC power through the pass-through connectors. The Puma SBC offers a CompactFlash (CF, http://www.compactflash.org/) socket to allow removable media storage and support bootable media. Linux (www.linux.org/) kernel for each embedded computer is built on a Linux host machine which compiles and creates a bootable Linux OS image on a CompactFlash disk of less than 1 Gigabyte. Detail instructions on building a Linux kernel on a CompactFlash disk are discussed in Appendix C.3.

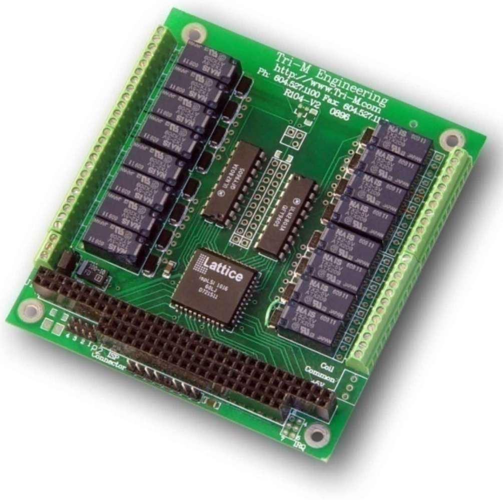


Figure 2.2 R104-88 Optoisolated Input and Relay Output Board

Figure 2.3 HE104 50 Watt High Efficiency PC/104 Power Supply

2.2 Wireless Communication Modules

Buses can communicate with intersection signal controllers using wireless technology to request for signal priority. Communication between the RSE and OBE can be tested using the 802.11x WLAN or the DSRC (Dedicated Short Range Communication) 802.11p protocol currently under development for wireless access to and from the vehicular environment.

2.2.1 Denso WAVE Radio Modems

A pair of Denso DSRC radio modems, as shown in Figure 2.4, was previously purchased by Intelligent Vehicles Laboratory (http://www.its.umn.edu/ProgramsLabs/IntelligentVehicles/) for research on vehicle to vehicle communications (for example, electronic braking). The Denso radio modems were early prototypes operating at 5.9GHz using the 802.11b protocol. Each onboard and roadside computer was connected to a Denso modem for wireless data communications. The data flow chart of the wireless communications between the roadside and onboard equipments using the Denso radio modems is displayed in Figure 2.5. The communication distance of the DSRC modems ranges around 300 meters (1000 ft). The direct point to point configuration of communication provides relatively high speed of data communication.

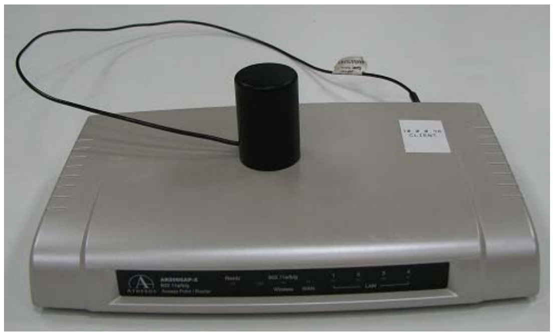


Figure 2.4 Denso DSRC Wireless Modem

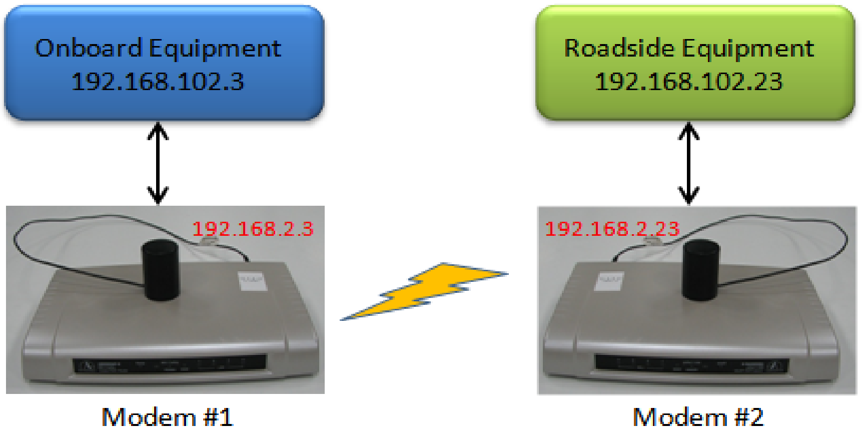


Figure 2.5 Wireless Communications Using the Denso Radio

2.2.2 802.11x Wireless Modules

In addition to the DSRC modems, two Ruckus (http://www.ruckuswireless.com/) MediaFlex Wi-Fi modems, as shown in Figure 2.6, was used to access to the Minneapolis wireless network. The RSE and OBE were each connected to a Ruckus modem to establish connection to the Internet through the Minneapolis Wi-Fi network as shown in Figure 2.7.

Figure 2.6 Ruckus Wi-Fi Modem

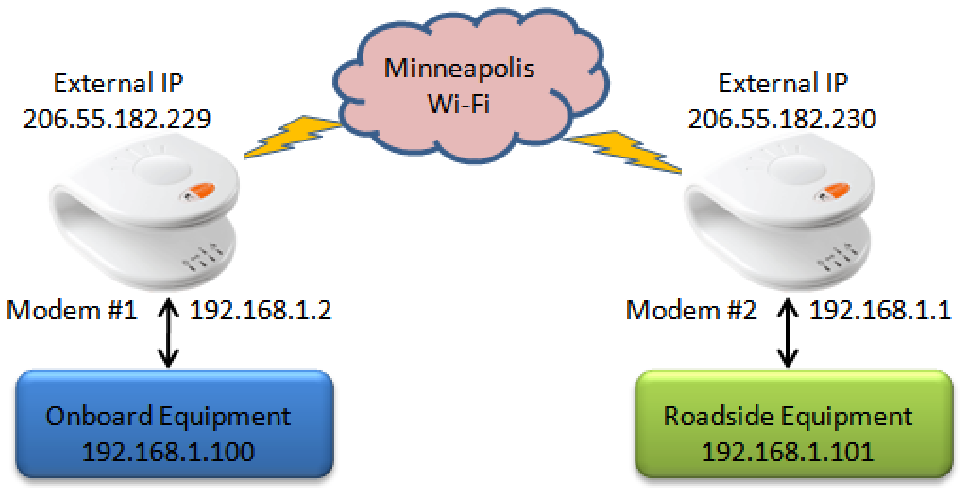


Figure 2.7 Wireless Communications Using the Ruckus Modem

Since Minneapolis wireless network does not cover the University of Minnesota (UMN) campus area, a pair of LinkSys (http://www.linksys.com/) Wireless-N USB adapters, as shown in Figure 2.8, was also used during the development phase to test the wireless communication systems using the University of Minnesota wireless network from the lab. The RSE and OBE were each connected to a adapter to establish connections through the UMN wireless network as shown in Figure 2.9. USB wireless adapters are usually plug and play after installing the device drivers in Windows operation system. However, many vendors do not release specifications of the hardware or provide a Linux driver for their wireless network cards. An NDISwrapper (http://ndiswrapper.sourceforge.net/joomla/) open source project implements Windows kernel Application Programming Interface (API) and Network Driver Interface Specification (NDIS) API within Linux kernel. A Windows driver for wireless network card is then linked to this implementation so that the driver runs natively, as though it is in Windows, without binary emulation. With the NDISwrapper, most miniPCI (builtin), PCI, PCMCIA (Cardbus only) or USB wireless network cards work in Linux with x86 or x86-64. Although NDISwrapper is intended for wireless network cards, other devices are known to work according the NDISwrapper project website: for example, Ethernet cards, USB to serial port device, home phone network device and so on.

In order to keep the Linux kernel to a minimal size and allow the system to be bootable from a CompactFlash memory, no Graphical User Interface (GUI) was installed on the Linux-based embedded target systems. A text-based web browser called Lynx (http://lynx.isc.org/) was then installed on the embedded computer to submit authentication scripts and passphrases to the University of Minnesota wireless network or the Minneapolis Wi-Fi network when using the USB wireless adapters. The Ruckus modems do not require additional authentication to access the Minneapolis Wi-Fi network since the Media Access Control (MAC) addresses on the Ruckus modems were previously registered to the Minneapolis Wi-Fi network server. Dynamic Host Configuration Protocol (DHCP) was used to obtain IP address dynamically when the wireless modem detects the network access point. Detail information regarding the NDIS wrapper for the wireless adapter and the lynx text-based web browser are documented in Appendix E.

Figure 2.8 LinkSys Wireless-N USB Network Adapter

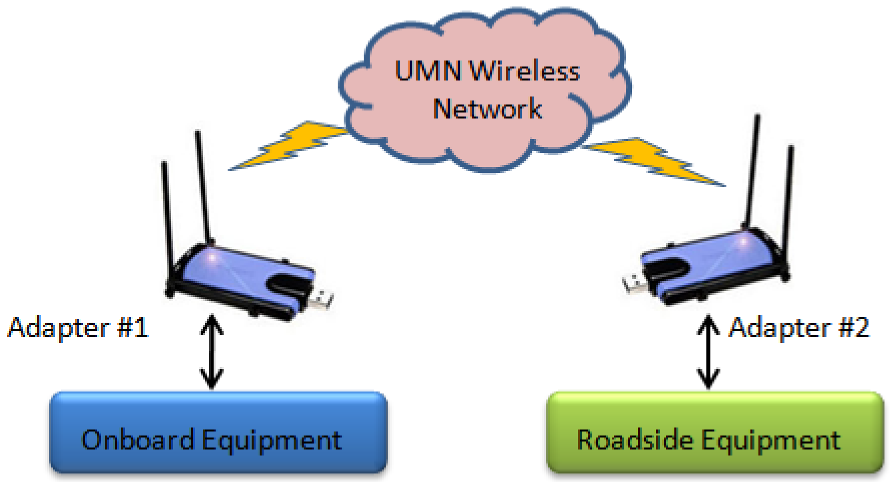


Figure 2.9 Wireless Communications Using the WUSB-N Wireless Adapter

2.2.3 Wireless Router

Another configuration for our wireless testing is to communicate between the RSE and OBE though a private network. A LinkSys WRT310N wireless router as shown in Figure 2.10 was used as a gateway to test the data communication between the embedded target computers. According to the product specification from LinkSys (http://www.linksys.com/), the access point built into the WRT310N router uses the Wireless-N (draft 802.11n) wireless networking technology. The IEEE 802.11n builds on previous 802.11 standards by adding multiple-input multiple-output (MIMO) and 40 MHz operation to the physical (PHY) layer. MIMO uses multiple transmitter and receiver antennas to improve the system performance. The 40 MHz operation uses wider bands, compared to 20 MHz bands in previous 802.11 operations, to support higher data rates. Wider bandwidth channels are cost effective and easily accomplished with moderate increases in digital signal processing.

By overlaying the signals of multiple radios, WRT310N router's MIMO technology multiplies the effective data rate. Unlike ordinary wireless networking technologies that are confused by signal reflections, MIMO actually uses these reflections to increase the range and reduce "dead spots" in the wireless coverage area. The robust signal travels farther, maintaining wireless connections much farther than standard Wireless-G. The Wireless-N USB adapters were used to evaluate the performance of the wireless router in the outdoor environment. The RSE and OBE were each connected to the wireless-N adapters and established communications to each other through the WRT310N access point as illustrated in Figure 2.11.

Figure 2.10 Linksys Wireless-N Gigabit Wireless Router

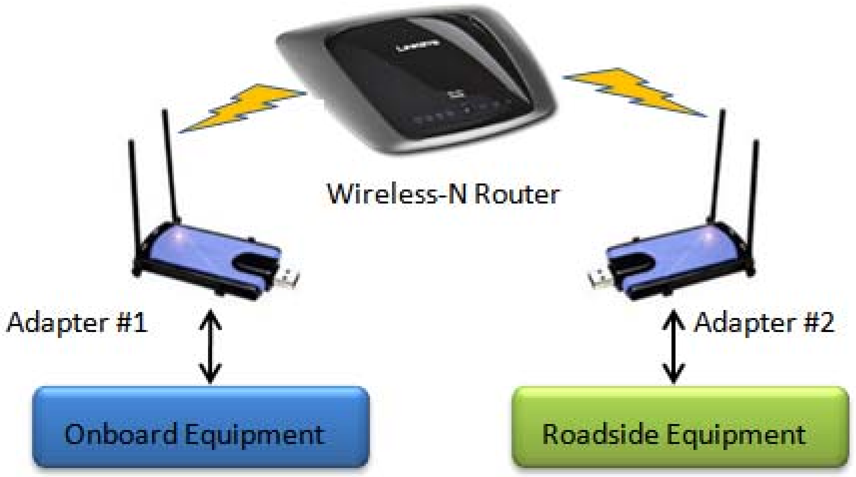


Figure 2.11 Wireless Communications Using the WUSB-N Wireless Adapter and Router

2.3 Wireless Signal Priority System Integration

System integration of the embedded TSP system and software design and development are the key elements in developing the wireless signal priority system as shown in Figure 2.12. The design of the OBE includes the wireless communication modules and the interfaces to the GPS receiver and other transit vehicle information such as passenger count and door opening status. The RSE include the signal priority algorithm, wireless communication module and the interface to traffic signal controller.

2.3.1 Hardware Design and Integration

A Garmin GPS 18 5Hz unit is used provide vehicle location as part of the wireless transit signal priority system. The GPS 18 receiver stores configuration information in its non-volatile memory which allows the GPS unit to start up quickly. It also has a real-time clock and raw measurement output data for sophisticated, high-precision dynamic applications. For extra precision, it offers 5 Hz measurement pulse output with rising edges that align to precise 0.2 second increments of UTC time, as long as the receiver has reported a valid and accurate position within the past 4 seconds. Graphical User Interface (GUI) was previously developed to test the performance of the GPS 18n unit. Detail information about the Garmin GPS receiver is included in Appendix G.

The mobile embedded signal priority system is packaged in a NEMA enclosure, as shown in Figure 2.13. This design allows us to easily deploy the prototype system to various field testing and validation at different intersections or on different buses. The wireless signal priority strategy will be tested using the Minneapolis Wi-Fi network and the 5.9 GHz DSRC radio. Detail testing results are discussed in Chapter 4.

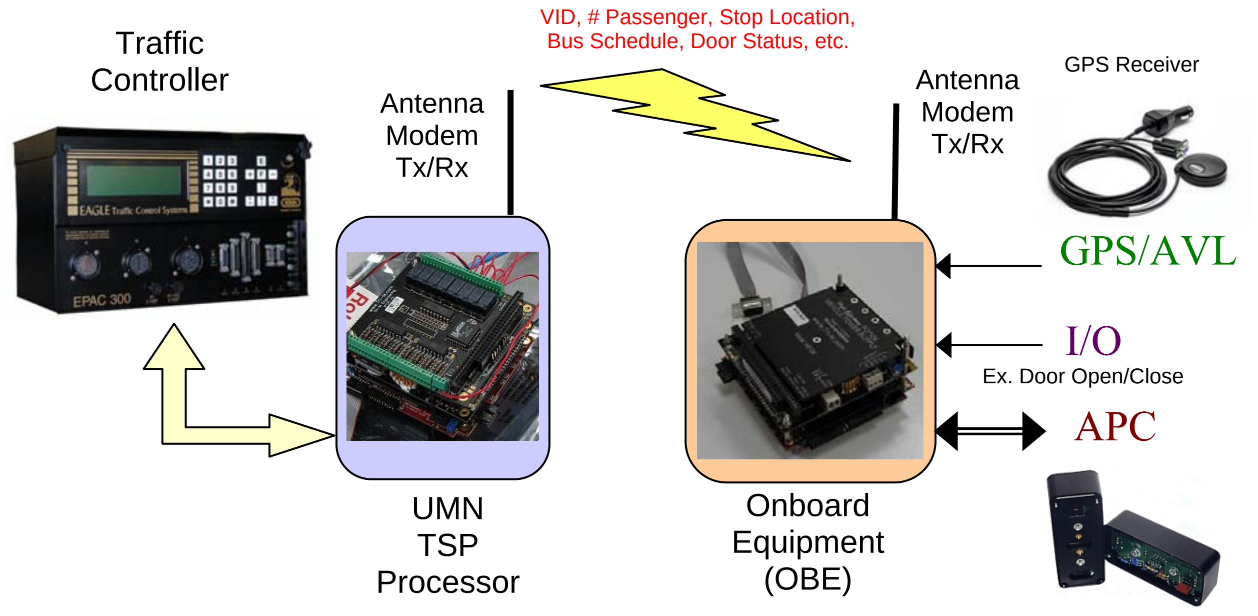


Figure 2.12 GPS and Wireless-Based Signal Priority System

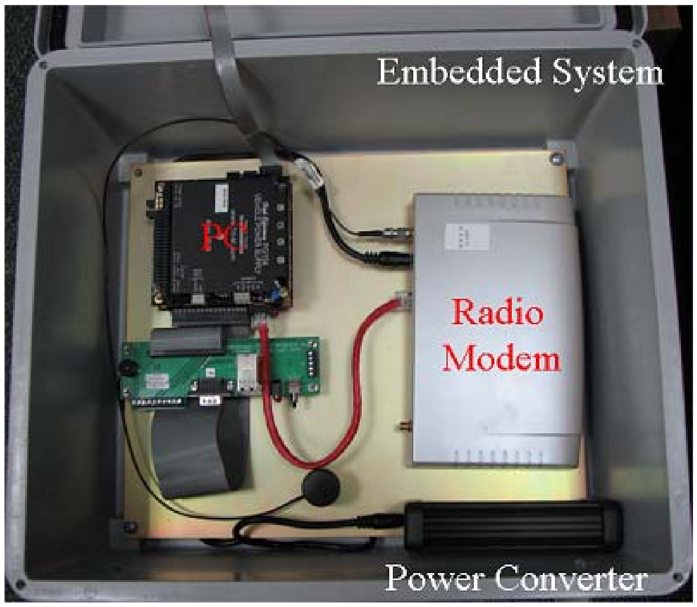


Figure 2.13 The Embedded Signal Priority System Packaged in a NEMA Enclosure

2.3.2 Software Design and Implementation

Software design of the OBE includes three major processes, GPS string processing, OBE wireless communications, and bus computer interface as shown in Figure 2.14. The GPS data processor parses the GPS sentences every 200 ms since the GPS receiver updates its location five times per second. Software design of the OBE includes the signal priority algorithm, RSE wireless communications, traffic controller interfaces. The signal priority algorithm developed in the phase one simulation study was ported to the host machine, recompiled and downloaded to the target computers for testing.

Transmission Control Protocol (TCP) is optimized for accurate delivery rather than timely delivery, TCP sometimes incurs relatively long delays (in the order of seconds) while waiting for out-of-order messages or retransmissions of lost messages, and it is not particularly suitable for real-time applications. The User Datagram Protocol (UDP) does not guarantee reliability or ordering in the way that TCP does. UDP, faster and more efficient, is suitable for time-sensitive applications that do not need guaranteed delivery. UDP is used to establish the data communication between the OBE and RSE.

UDP uses a connectionless communication setup. A process using UDP does not need to establish a connection before sending data and when two processes stop communicating there are no, additional, control messages. Communication consists only of the data segments themselves. A network node can communicate with another network node using UDP without first negotiating any kind of handshaking or creating a connection. Because of this, UDP is very efficient for protocols that send small amounts of data at irregular intervals. UDP provides a message-oriented interface. Each message is sent as a single UDP segment, which means that data boundaries are preserved. However, this also means that the maximum size of a UDP segment depends on the maximum size of an IP datagram. More detail information regarding the UDP protocol can be found at Internet Engineering Task Force (IETF, http://www.ietf.org/rfc/rfc768.txt).

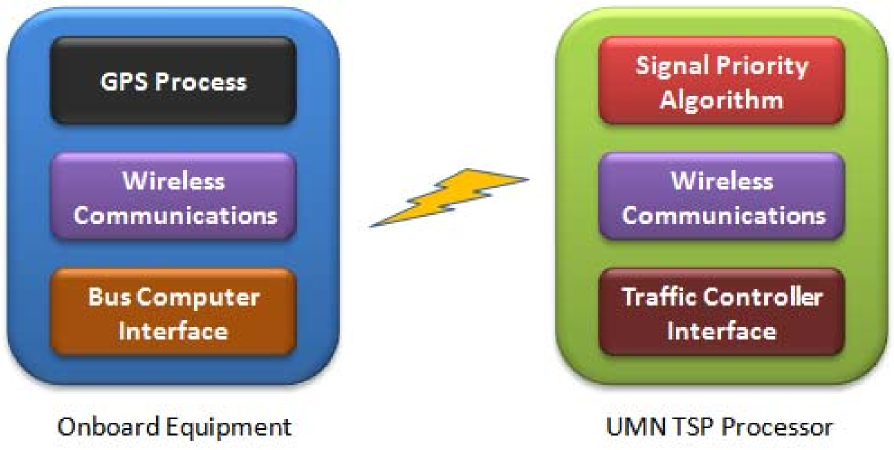


Figure 2.14 Software Design of the Signal Priority System

2.4 Signal Control Interface

Signal priority request is sent from the RSE to the signal controller through the digital I/O board. The traffic signal controller needs to be programmed and configured to accept the external input for priority requests. Priority phase assignments and bus route information are also needed to help RSE determine where is bus coming from and which phase to provide green extension or red truncation.

2.4.1 Signal Priority

The Eagle EPAC traffic controller, as shown in Figure 2.15, includes provisions for internal preemptors with the capability of handling six unique preempt sequences. The preemption program accepts commands from 6 preempt inputs and provides the timing and signal display programmed to occur in response to each. Preemption controls are internally applied. Internally applied preempt controls will have priority. Each preempt input provides two modes of priority control based on the form of the input signal. The standard input form is a continuous ground true logic input. The alternate input form, for low priority, is a pulsating (1~30 Hz) ground true logic input. When the preempt link value in the PREEMPT→MISCALLENAEOUS menu equals to the preempt command, then a constant input actuation will place a call for low priority routine.

According to the Eagle SEPAC manual, enabling the low priority routine will insert a delay of 500 milliseconds into the recognition of a standard preempt routine. This delay will allow the traffic controller to determine whether the request is a low priority or preemption call. When a low priority routine is enabled, the preempt call for the same input is a pulse signal and the duration of the pulse signal must be longer than 1 second. Preempt channel #5 was configured as low priority channel to accept inputs from the roadside computer.

Figure 2.15 Eagle EPAC M40 Traffic Signal Controller

2.4.2 Wiring Diagram of Priority Input

There are several ways to initiate TSP request on the signal controller. An external request from the digital input is the simplest way to initiate the request. However, there will be no TSP responses from the signal controller. The RSE has no information whether the request was granted or not. Another way to initiate the TSP request is to interface with the controller serial interface (RS-232) or communicate through the NTCIP interface (for example, Los Angeles Metro TSP project) as illustrated in Figure 2.16. TSP reuqets were sent directly to the controller using the proprietary commands. Signal controller firmware usually needs to be modified by the controller manufacturer in order to accept the external commands. It is very difficult to obtain the communication protocol of the traffic controller due to the proprietary nature.

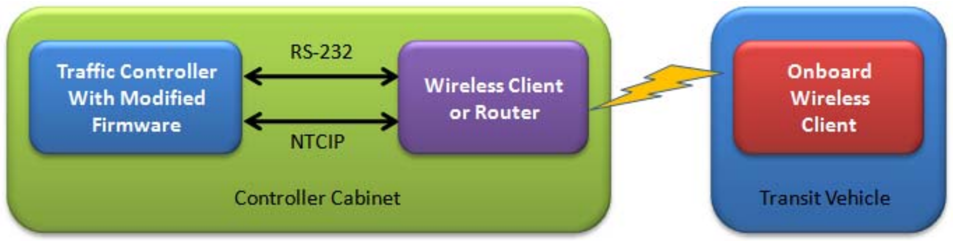


Figure 2.16 TSP Initiation Thrugh Serial or NTCIP Interface

Wiring diagram of a single preemption channel is illustrated in Figure 2.17. Two wires from the normally closed output of the R104 digital I/O board were connected to the preemption input and the 24VDC logic common, respectively. NEMA controllers require a standard 6.25 Hz signal at 50% duty cycle, for the low priority input logic circuits and a ground true logic for the high priority or preemption. A continuous 6.25 Hz pulse signal (low-priority call) for transit vehicle priority calls was generated from the RSE when bus is ready to pass through upcoming intersection.

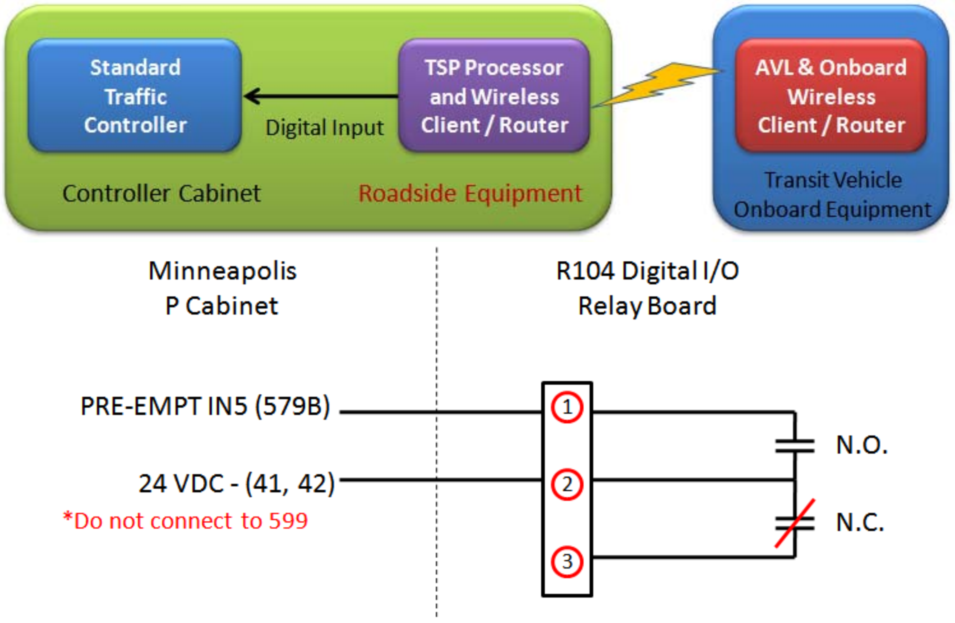

Standard Traffic Controller
Digital Input
TSP Processor and Wireless Client / Router
AVL & Onboard Wireless Client / Router
Controller Cabinet
Roadside Equipment
Transit Vehicle Onboard Equipment
Minneapolis P Cabinet
R104 Digital I/O Relay Board
PRE-EMPT IN5 (579B)
24 VDC - (41, 42)
*Do not connect to 599
1
2
3
N.O.
N.C.

Figure 2.17 Wiring Diagram from R104 I/O Board to Controller Cabinet

2.4.3 Priority Phase Selection and Configuration

A priority phase selection table is configured in the RSE to determine which phase and in what direction will the transit vehicle need signal priority. The standard NEMA phase assignment for a main street in east/west direction is shown in Figure 2.18. Sample priority phase selections and configuration is shown in Table 2.1 where the I/O channels and priority inputs are specified.

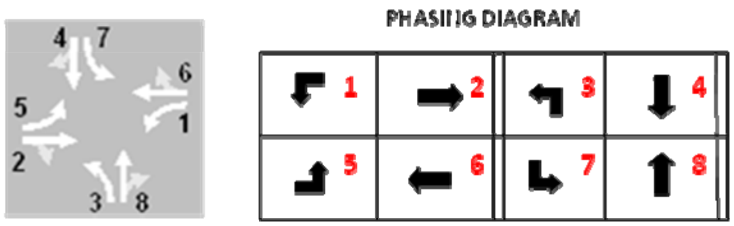


Figure 2.18 NEMA Phase Assignments

Table 2.1 Priority Phase Selections and Configuration

Heading	Phase	I/O Output	Preempt/Priority
East	2	1	5
East - LT	5	3	3
West	6	1	5
West - LT	1	3	3
North	4	2	6
North - LT	3	4	4
South	8	2	6
South - LT	7	4	4

3. ADAPTIVE TRANSIT SIGNAL PRIORITY STRATEGY

To illustrate our priority strategy, consider a simple eastbound/westbound corridor as shown in Figure 3.1. For a bus approached a bus stop or signalized intersection, there are basically two scenarios, a nearside bus stop or a far-side bus stop. For the nearside bus stop, a bus will stop for boarding/alighting before passing the signalized intersection, as illustrated in Figure 3.1 by the eastbound bus approaching stop j and intersection *i*. Estimated bus dwell time at the nearside bus stop needs to be considered by the signal controller to provide signal priority to the bus in a timely manner. For the far-side bus stop, a bus passes through the intersection first before its arrival at the stop (see Figure 3.1 westbound bus approaching intersection *i* and bus stop *k*). Bus travel time to the intersection needs to be considered when providing priority.

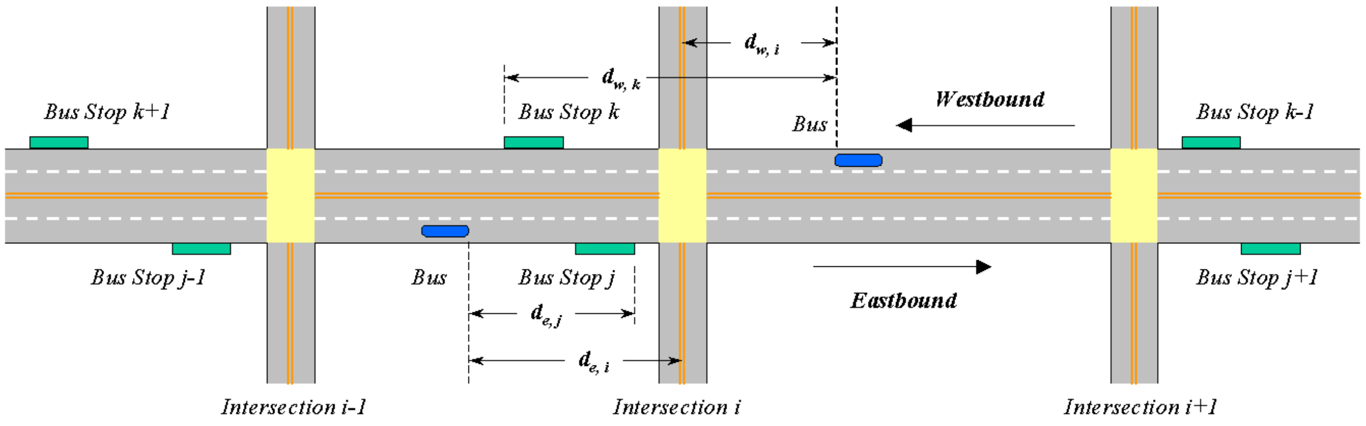


Figure 3.1 An East-West Corridor Example for Signal Priority

3.1 Bus Stop Location Consideration

3.1.1 Nearside Bus Stop

Consider the bus traveling in the eastbound as shown in Figure 3.1. Expected bus dwell time, T_{dj}, at bus stop j can be forecasted using historical dwell time statistics. Expected bus travel time, T_{aj}, from its current location to bus stop can be calculated via,

$$T_{aj} = \frac{d_{e,j}}{v_b} + T_{br} + T_{delay} \qquad \text{(Eq. 1)}$$

Where,

v_b: is bus speed,

$d_{e,j}$: is the distance from the current bus location to bus stop *j*,

T_{br} : is bus braking/stopping time, and

T_{delay} : is the traffic delay on bus route.

The expected bus travel time (T_{ji}) from bus stop j to intersection *i* can also be calculated as follows, assuming the distance from the nearside bus stop to the intersection is relatively short compared to the distance needed to accelerate to running speed.

$$T_{ji} = \sqrt{\frac{2(d_{e,i} - d_{e,j})}{a}} + T_{bc} \qquad \text{(Eq. 2)}$$

Where,

$d_{e,i}$: is the distance from eastbound bus to intersection *i*,

$d_{e,j}$: is the distance from eastbound bus to bus stop j,

a : is the bus acceleration, and

T_{bc} : is the bus clearance time.

Therefore the predicted time at which the eastbound bus passes intersection *i* can be calculated as follows.

$$\hat{t}_{ei} = t + T_{aj} + T_{dj} + T_{ji} \qquad \text{(Eq. 3)}$$

Where,

t : is the current time, sec.

And estimated time for the bus leaving stop *j* is,

$$\hat{t}_{lj} = t + T_{aj} + T_{dj} \qquad \text{(Eq. 4)}$$

The desired signal priority request should then be sent at δ_n seconds prior to the bus departure time at stop *j*. That is, at time $\hat{t}_{lj} - \delta_n$, where

$$\delta_n = t_{cp} + t_{comm} + t_{const} \qquad \text{(Eq. 5)}$$

t_{cp} : is the controller processing time,

t_{comm} : is the communication latency time, and

t_{const} : is an additional time constant.

The signal priority service should be ended at $\hat{t}_{ei} + T_{xi}$, where T_{xi} is the time for the bus to cross intersection *i*. If both beginning ($\hat{t}_{lj} - \delta_n$) and ending ($\hat{t}_{ei} + T_{xi}$) of the estimated priority service fall within the green split, no action needs to be taken at the controller. If $\hat{t}_{lj} - \delta_n$ falls in the green split and $\hat{t}_{ei} + T_{xi}$ falls in the red split, extended green time is needed to ensure that bus could pass the intersection. However, if the estimated beginning of priority service time ($\hat{t}_{lj} - \delta_n$) falls within the red light period, red signal truncation or early green light treatment is needed to provide bus signal priority.

3.1.2 Far-side Bus Stop

For a bus approaching an intersection prior to its arrival at next bus stop, for example, the bus traveling in westbound as shown in Figure 3.1, signal priority should be provided based on bus traveling speed and traffic conditions. The estimated time (T_{ai}) to arrive at intersection i can be calculated as,

$$T_{ai} = \frac{d_{w,i}}{v_b} + T_{delay} \qquad \text{(Eq. 6)}$$

Where,

$d_{w,i}$: is the distance from westbound bus to intersection *i*,

v_b : is bus speed, and

T_{delay} : is the traffic delay on bus route.

Therefore the estimated time for westbound bus passing intersection *i* can be calculated as follows.

$$\hat{t}_{wi} = t + T_{ai} \qquad \text{(Eq. 7)}$$

Where,

t: is the current time, sec.

The desired signal priority would need to begin at δ_n seconds prior to the bus arriving intersection *i* ($\hat{t}_{wi} - \delta_n$), where δ_n is defined as equation (5). The signal priority service can be ended at $\hat{t}_{wi} + T_{xi}$, where T_{xi} is the time for bus to cross intersection *i*. If both beginning ($\hat{t}_{wi} - \delta_n$) and ending ($\hat{t}_{wi} + T_{xi}$) of the estimated priority service fall within the green split, no action needs to be taken by the controller. If $\hat{t}_{wi} - \delta_n$ falls in the green split and $\hat{t}_{wi} + T_{xi}$ falls in the red split, extended green time is need to ensure bus could pass the intersection. However, if the estimated beginning of priority service time ($\hat{t}_{wi} - \delta_n$) falls within the red light period, red signal truncation or early green light treatment is needed to offer bus priority.

3.2 Estimation of Bus Dwell Time at Bus Stop

Ghanim et al. (2007) developed an artificial neural network modeling tool to predict the bus arrival time on approaches with nearside bus stops based on observed travel time, boarding and alighting demand, and current traffic condition. We used a simpler linear regression model to predict dwell time based on the number of boarding and alighting passengers, average headway between buses, schedule adherence, number of door on the vehicle, fare collection method, and bus type. Estimated passenger arrival rates will be used to forecast bus dwell time at each stop. Based on the collected data, we assume the passenger arrivals at each stop follow a Poisson distribution with an arrival rate, λ, calculated from the mean of the collected passenger arrival rate. A Poisson process subroutine was developed to generate numbers of passengers boarding and alighting at each stop during the simulation.
Bus dwell time at a bus stop for boarding can be estimated using the following equation.

$$T_{dj}^{B} = \lambda_j(t) \times \left[t_k(j) - t_{k-1}(j)\right] \times T_{boarding} \qquad \text{(Eq. 8)}$$

Where,

T_{dj}^{B} is the bus dwell time for boarding at stop j,

$\lambda_j(t)$ is the passenger arrival rate for stop j,

$t_k(j)$ is the arrival time of bus k at stop j,

$t_{k-1}(j)$ is the arrival time of bus k-1 at stop j, and

$T_{boarding}$ is the average boarding time per passenger.

3.3 Priority Acknowledgement Rules

After receiving a signal priority request from a bus, the signal controller has to determine whether or not to grant the request. Only one bus will get the priority service if there are multiple requests at the same intersection from buses on different approaches. The signal controller will ignore all bus priority requests if there is an emergency vehicle preemption request. The signal controller will consider the following three components when determining which bus will receive the priority service.

3.3.1 Priority Request Time, Time Factor (TF)

$$TF(A,B)=\begin{cases} A=W_T, B=1 & t_A<t_B \\ A=1, B=W_T & t_A>t_B \end{cases}$$

Bus *A* wins if it requests earlier than bus *B* does, where W_T is the request time weighting factor ($W_T \geq 1$).

3.3.2 Bus Schedule Adherence, Lateness Factor (LF)

$$LF = W_L \times T_{Late}$$

Where W_L is the bus late time weighting factor ($W_L \geq 1$) and T_{Late} is the number of minute the bus was late. $LF = 0$ when bus is ahead of its schedule.

3.3.3 Number of Passengers, Passenger Factor (PF)

$$PF = W_P \times N_{passenger}$$

Where W_P is the bus passenger count weighting factor ($W_P \geq 1$) and $N_{passenger}$ is the number of passengers on the bus.
The priority acknowledgement functions for bus *A* and *B* are defined as follows.

$$\begin{aligned} f(A) &= TF(A,B)\times\{LF(A)+PF(A)\} \\ f(B) &= TF(A,B)\times\{LF(B)+PF(B)\} \end{aligned} \qquad \text{(Eq. 9)}$$

If the priority acknowledgement function, *f(A)* is greater than *f(B)*, bus A will be granted signal priority. No signal priority request is granted if the acknowledge function *f* equals zero, which means there are no passengers on the bus and no delay on bus schedule adherence.

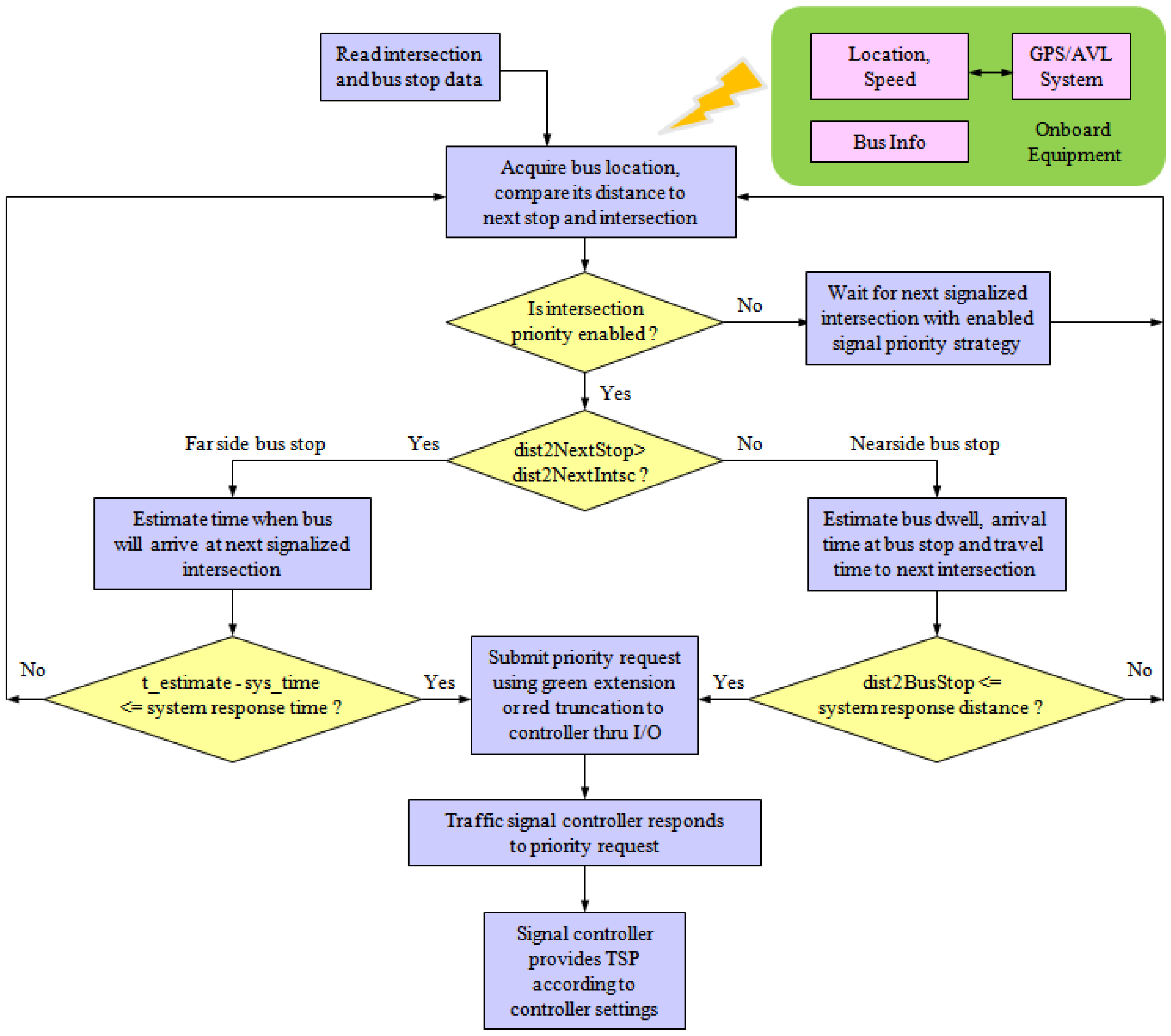
3.4 Signal Timing Treatment

The projected signal phase estimated arrival time for a bus passing a signalized intersection can be calculated using the equations discussed in the previous section. When the projected signal phase coincides with the priority phase, which is the phase where a bus requires passing through an intersection, green extension is considered if the remaining green time is insufficient. However, if the projected arriving phase is different from the priority phase, phase arrangement, such as phase suppression or red truncation, is needed to provide green time to the buses. A minimum green time has to be served prior to terminating the phase.

There has been some concern about returning the intersection timing to its original coordination after providing signal priority to buses. Some priority strategies require many cycles before the signal timing is resynchronized to its regional coordination (Siemens 2002). Recently, an advanced controller provides the signal priority recovery with a cycle by including optional transit phases in the timing plan (Siemens). The bus signal priority strategy will resynchronize to its neighbor intersections in the next cycle by reducing the amount of green time extended in the next cycle priority phase. Signal priority requests in the following cycle will be ignored in order to facilitate coordination recovery. For example, if the request from bus *A* or *B* in cycle *i* was granted at an intersection, priority requests from bus *C* and *D* will not be considered because cycle *i+1* will be used for coordination recovery.

3.5 Signal Priority Implementation

The priority strategy was implemented using the C programming language and compiled on a Linux host machine. Executable binary code was then downloaded to each OBE and RSE. When a bus travels within the wireless communication range, the signal priority program will continuously monitor the bus location and speed. Bus location and its distance corresponding to the next bus stop and signalized intersection were calculated to identify a nearside versus a far side bus stop scenario. The control diagram for the priority strategy is shown in Figure 3.2. Bus dwell time at each stop was computed based on the passenger arrival using the Poisson distribution. Bus travel times to the intersection and the bus stop were calculated to determine when to submit priority request prior to its arrival at the signalized intersection. Signal priority settings in the controller were programmed to provide green extension or red truncation. The EPAC controller is running on a background coordination cycle to ensure that the intersection returns back to its timing and stays coordinated with the neighboring intersections.



Read intersection and bus stop data
Location, Speed
GPS/AVL System
Bus Info
Onboard Equipment
Acquire bus location, compare its distance to next stop and intersection
Is intersection priority enabled ?
No
Wait for next signalized intersection with enabled signal priority strategy
Yes
Far side bus stop
Yes
dist2NextStop> dist2NextIntsc ?
No
Nearside bus stop
Estimate time when bus will arrive at next signalized intersection
Estimate bus dwell, arrival time at bus stop and travel time to next intersection
No
t_estimate - sys_time <= system response time ?
Yes
Submit priority request using green extension or red truncation to controller thru I/O
Yes
dist2BusStop <= system response distance ?
No
Traffic signal controller responds to priority request
Signal controller provides TSP according to controller settings

Figure 3.2 Block Diagram of Transit Signal Priority Strategy

4. EXPERIMENT SETUP AND TESTING

Performance of wireless communication is highly affected by the changing environment in which transmission errors are unavoidable and quite common. Wireless signals suffer attenuations as they propagate through space and other obstacles cause absorptions and reflections. Communication coverage and latency were tested for both DSRC and 802.11x Wi-Fi modules to better understand the performance of each system and potential constraints while requesting for signal priority in real-time applications.

4.1 Wireless Communication Testing

Wireless communication testing for Denso DSRC radios and Wi-Fi module were tested at two different test sites, East Franklin Avenue at 22nd Avenue and Como Avenue at 29th Avenue in Minneapolis. A pair of data communication programs using User Datagram Protocol (UDP) were written in C language and running on both roadside and onboard embedded computers. The onboard computer receives the vehicle location from the GPS receiver every 200 ms (5 Hz) and sends vehicle ID, passenger counts, location, priority request and other information to the roadside computer wirelessly. The roadside equipment immediately returns the data string received from onboard computer. Wireless communication latency is calculated from the time difference between the data string sent to RSE and received back on the onboard computer.

4.1.1 DSRC Communication Latency

As shown in Figure 4.1, the roadside equipment is placed at location A where latency testing begins along the East Franklin Avenue. The onboard equipment is placed inside a passenger vehicle. The onboard computer continuously sends out UDP data to the roadside unit through the Denso DSRC radio modem as the vehicle traverses from location A to B then turns around at B. The test vehicle passes through location C, and turns around again at location D then returns back to starting location A through location E. The vehicle lost communication nearby location B and during the CDE curve. The UDP protocol allows the vehicle to re-establish the communication with roadside computer as soon as it enters the wireless communication coverage range. Wireless signal coverage of the DSRC radio and vehicle GPS data were plotted in Figure 4.1 where X and Y represent the coordinate of the Stake Plane Coordinate System (SPSC) of Minnesota South FIPSZONE 2203. The wireless communication distance of the DSRC radio is about 650 meters (or 325 m radius) at 22nd Ave and East Franklin Avenue.

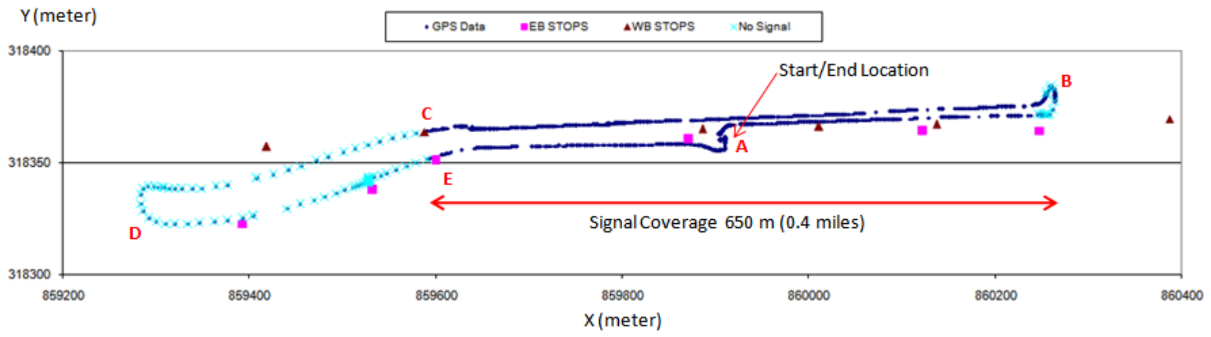


Figure 4.1 DSRC Wireless Coverage at 22nd and Franklin Avenue

The average wireless data communication latency using the Denso DSRC radio ranges between 4 and 6 milliseconds as shown in Figure 4.2. The onboard computer lost it UDP data packets periodically around 39:44. The wireless link was totally lost between 40:05 and 40:10.

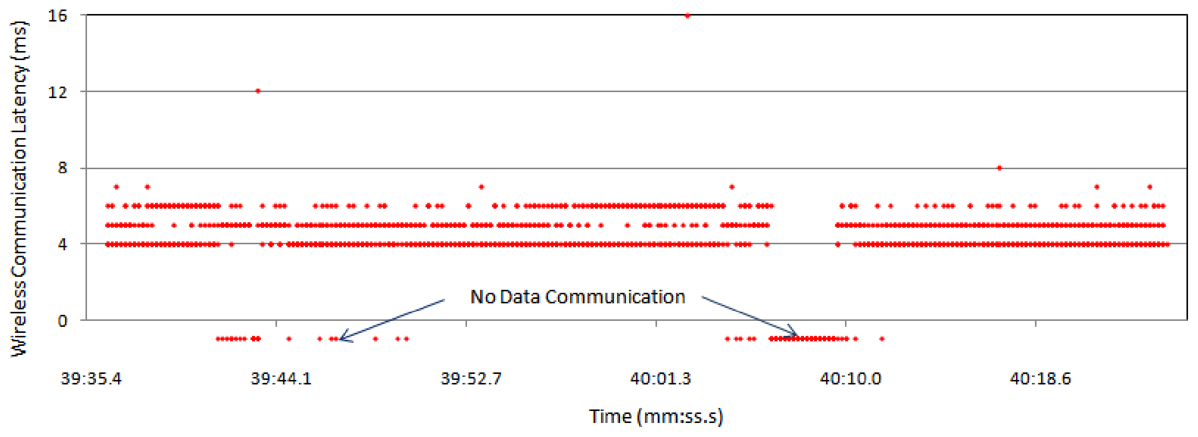


Figure 4.2 Latency of DSRC Wireless Communication at 22nd and Franklin Avenue

Similar testing was performed at the intersection of Como and 29th Avenue to compare the performance of DSRC radio at different location. As shown in Figure 4.3, the wireless coverage range at Como test site is much shorter than that at Franklin Avenue. The shorter communication range was probably caused by the significant amount of trees along the Como Avenue which might contribute additional reflections, absorptions and refractions. The average wireless data communication latency using the Denso DSRC radio ranges between 3 and 5 milliseconds as shown in Figure 4.4 at Como and 29th Avenue.

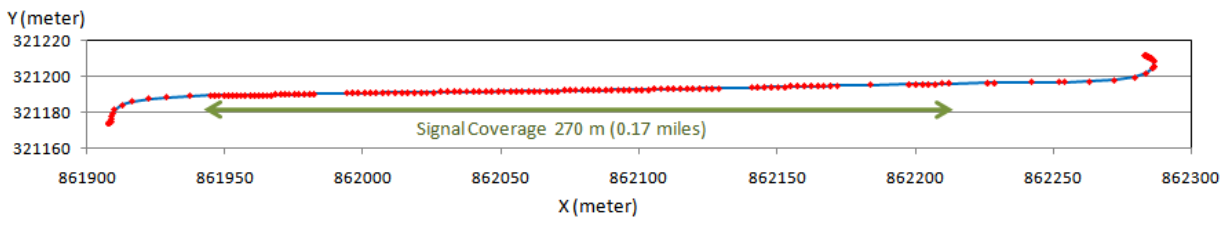


Figure 4.3 DSRC Wireless Coverage at Como and 29th Avenue

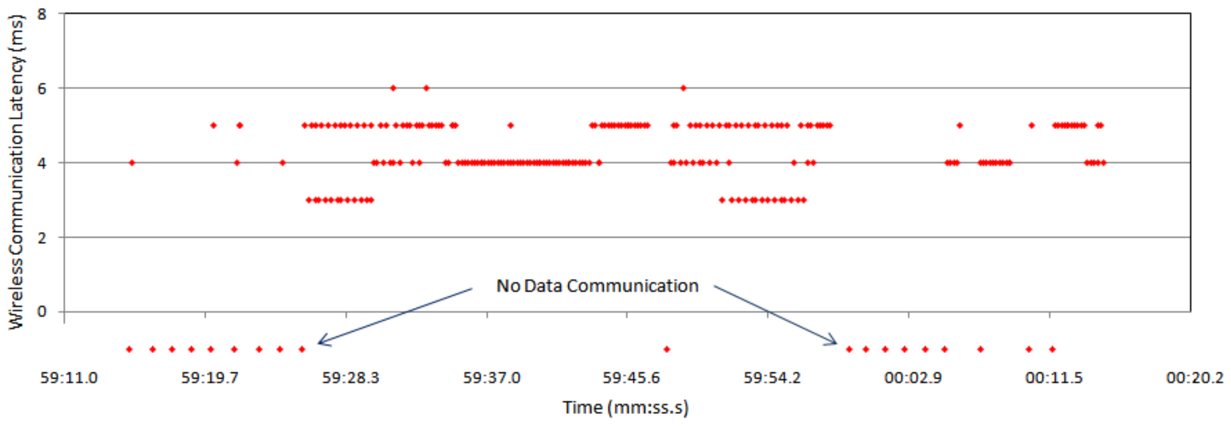


Figure 4.4 Latency of DSRC Wireless Communication at Como and 29th Avenue

4.1.2 802.11x Wi-Fi Communication Latency

Additional testing was also conducted using the Wi-Fi adapter through a LinkSys WRT310N router at Como test site. The average wireless data communication latency using the Linksys Wireless-N adapter is about 23 milliseconds as shown in Figure 4.5. Test vehicle initially established wireless communication with the RSE at 55:35. As the vehicle travelled away from the RSE, the OBE lost connection between 56:05 and 56:38. Wireless communication was re-established as the test vehicle turned around and traveled within the wireless coverage distance. The coverage distance of the Wi-Fi system is about 100 meters.

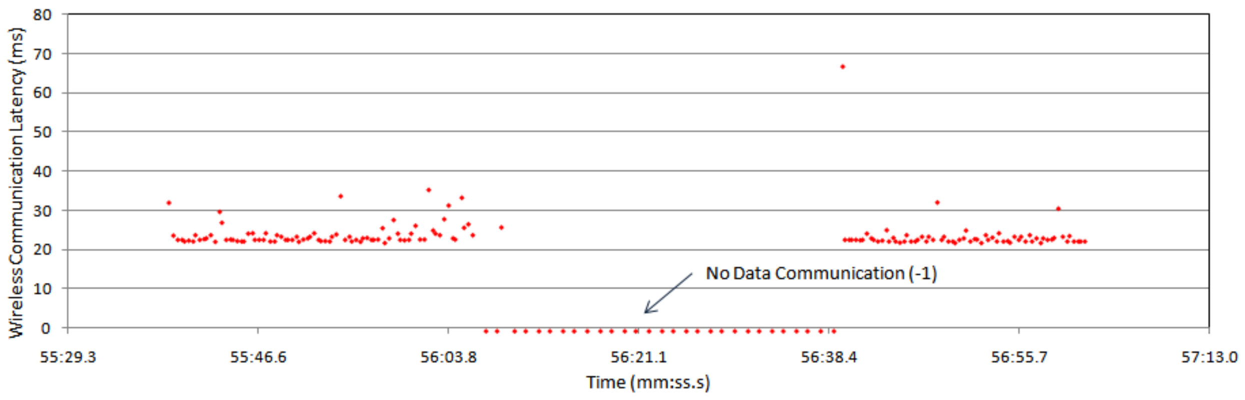


Figure 4.5 Latency of 802.11x Wireless Communication at Como and 29th Avenue

The wireless prototype system was also tested using the University of Minnesota (UMN) Wi-Fi network. The average wireless data communication latency using the Linksys Wireless-N adapter (WUSB300) is about 15 milliseconds as shown in Figure 4.6. Wireless communication was established as long as the test vehicle stays within the area covered by the wireless network.

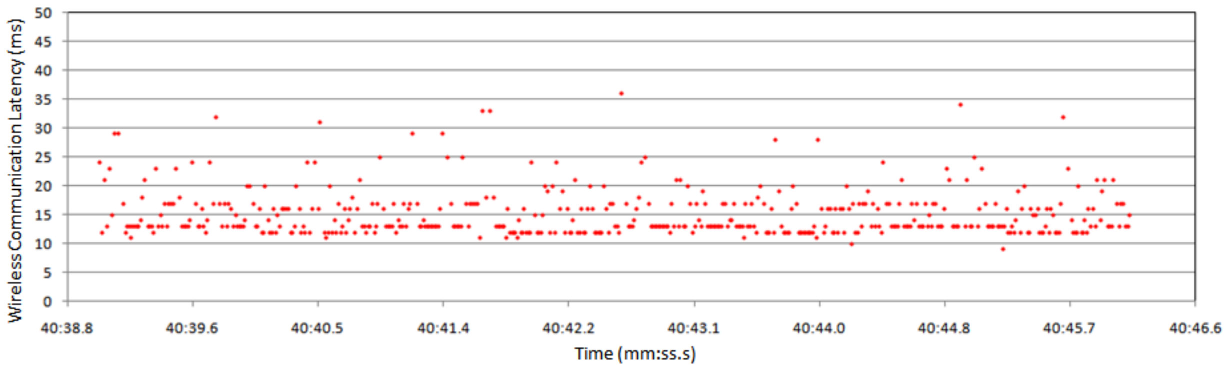


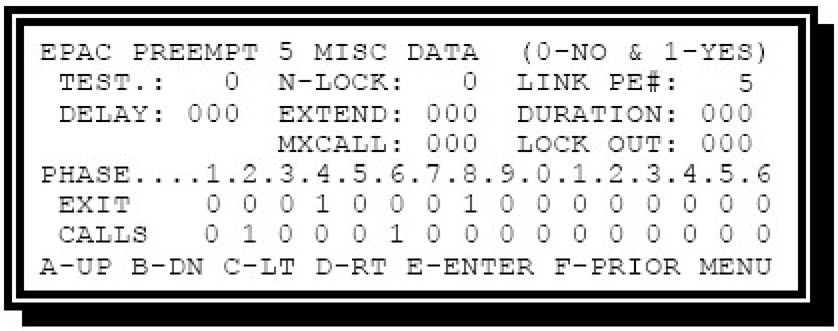
Figure 4.6 Latency of Wireless Communication Using UMN Wi-Fi Network

4.2 Program Signal Controller and Signal Priority Interface

Output of the signal priority request from the roadside computer was connected to the pre-emption input channel on the signal controller through wirings in the controller cabinet. Traffic signal controller was configured and activated to accept external pre-emption inputs. The traffic signal controller was programmed by the City of Minneapolis traffic engineer to specify corresponding delay, dwell, maximum call, and extension time.

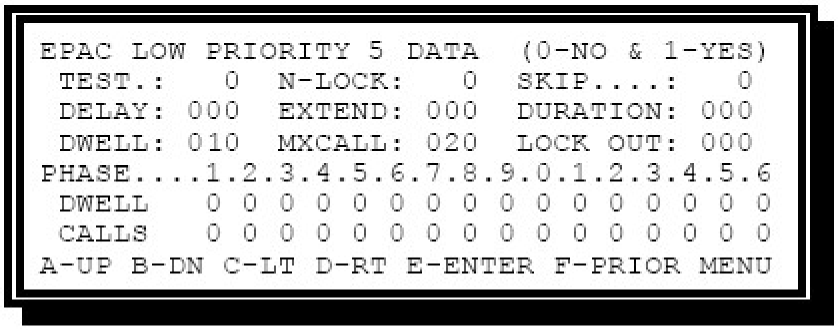
4.2.1 Program Low Priority Pre-Emption Input

Traffic signal at the intersection of Como and 29th Avenue is controlled by an Eagle M10 NEMA traffic controller housing in a P-type cabinet. The NEMA controller allows up to six pre-empt inputs from external calls. Each pre-emption input can operate in high or low priority mode. Preemption input #5 in low priority mode was configurred to provide green extension or red truncation to the main street (Como Ave.) in signal phase 2 and 6 for our field testing. The low priority input and its settings can be programmed through the LCD interface (miscellaneous and low priority menu) of the Eagle controller as shown in Figure 4.7 and 4.8.



```
EPAC PREEMPT 5 MISC DATA   (0-NO & 1-YES)
 TEST.:    0  N-LOCK:    0  LINK PE#:    5
 DELAY: 000   EXTEND: 000   DURATION: 000
              MXCALL: 000   LOCK OUT: 000
PHASE....1.2.3.4.5.6.7.8.9.0.1.2.3.4.5.6
 EXIT    0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 0
 CALLS   0 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0
A-UP B-DN C-LT D-RT E-ENTER F-PRIOR MENU
```

Figure 4.7 Preempt #5 Miscellaneous Menu



```
EPAC LOW PRIORITY 5 DATA   (0-NO & 1-YES)
 TEST.:    0  N-LOCK:    0  SKIP....:    0
 DELAY: 000   EXTEND: 000   DURATION: 000
 DWELL: 010   MXCALL: 020   LOCK OUT: 000
PHASE....1.2.3.4.5.6.7.8.9.0.1.2.3.4.5.6
 DWELL   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 CALLS   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
A-UP B-DN C-LT D-RT E-ENTER F-PRIOR MENU
```

Figure 4.8 Preempt #5 Low Priority Menu

The low priority menu includes options to specify the dwell, delay, and extend settings. DELAY is the waiting time that the low priority actuation must be activated prior to normal signal controller operation being interrupted for the low priority routine. EXTEND is the additional time that the low priority actuation should be extended from the termination of the actuation. DURATION is the time required by the preemption prior to a transition back to normal controller operation. DWELL is the time offered to provide green on the priority phase. MAXCALL is the time that a low priority call can remain active and be considered valid. Figure 4.9 illustrates the corresponding priority settings of the Eagle M40 signal controller. Figure 4.10 shows that traffic engineer (Scott Tacheny) from the City of Minneapolis programmed signal priority settings in the controller prior to the field testing.

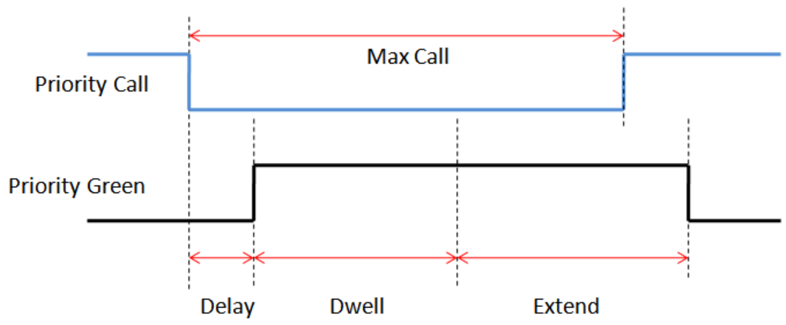


Figure 4.9 Low Priority Signal Priority Request

Figure 4.10 Program Eagle Traffic Signal Controller

4.2.2 Signal Priority Request Simulation

Vehicle location was recorded in previous experiment to evaluate the data communication latency. A simulation program was developed to read the recorded GPS data from a text file and test signal priority request output through wireless communications in the Minnesota Traffic Observatory at University of Minnesota. Figure 4.11 illustrates the diagram of the signal priority request by including both roadside and onboard hardware in the simulation. This setup provides the flexibility of performing system functional test without interrupting traffic in the field during the system verification process. As the vehicle approaches an intersection in the simulation, the signal priority request is sent through the digital I/O interface in the roadside equipment in this hardware-in-the-loop simulation setup. Detail information regarding the R104/88 digital I/O board is included in Appendix C.2. Similar simulation testing using the roadside unit to investigate and evaluate the response from the signal control was also performed in the traffic signal shop in the City of Minneapolis Public Works department. This is to perform the system reliability test and ensure that traffic controller will recover from signal priority requests.

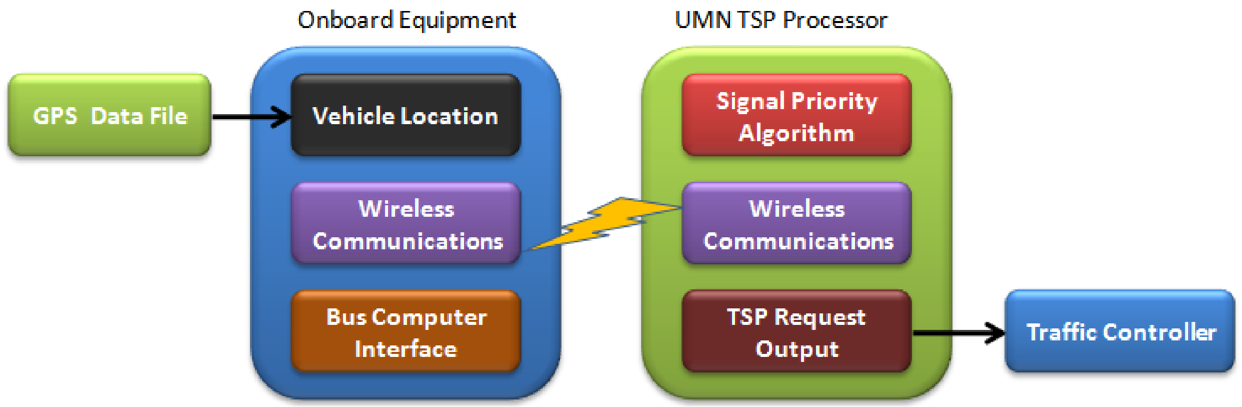


Figure 4.11 Block Diagram of Signal Priority Request Simulation

4.3 Field Testing - Como Avenue and 29th Avenue SE

Como and 29th Avenue, as shown in Figure 4.12, was selected by the City of Minneapolis and Metro Transit as our test site. The selected intersection, located relatively far away from nearby signal intersections, operates as a standalone intersection with no coordination with nearby signalized intersections. The isolated characteristic of the intersection offers great opportunity to perform functional test for the wireless-based signal priority system. Aerial photo of the test site is shown in Figure 4.13. Bus route #3 operates along Como Avenue and carries significant amount of riders each day. There are 220 bus trips along Como Avenue on a regular weekday. Detail trip count information and route map of bus route #3 is included in Appendix D. The test vehicle will traverse between the 27th and 31st Avenue along Como Avenue during the testing. Vehicle location, speed, priority request status, time were recorded on a USB memory stick on the onboard computer. Detail information regarding the phasing and timing settings at Como and 29th Avenue is included in Appendix A. Traffic count and turning movement collected by the City of Minneapolis in 2006 is also included in Appendix B.

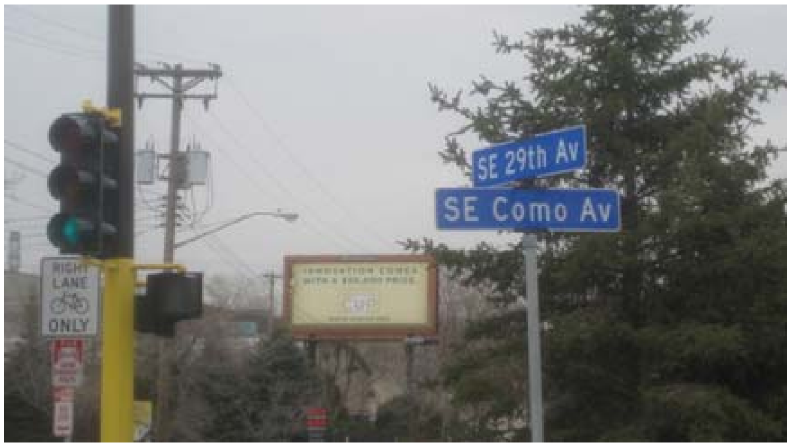


Figure 4.12 Transit Signal Priority Test Site

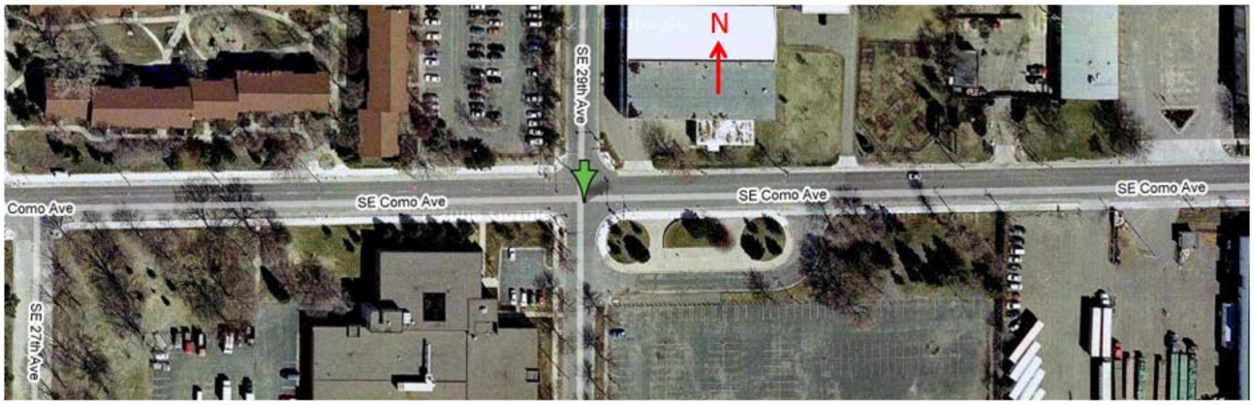


Figure 4.13 Aerial Map of Como and 29th Avenue SE in Minneapolis (from Google.com)

The developed prototype systems as described previously were deployed at Como and 29th Avenue test site to validate the bus signal priority algorithm using wireless communication technology. The mobile design of the wireless transit signal priority system allows us to test the prototype at different intersection or on different vehicle easily. The Onboard Equipment (OBE) as illustrated in Figure 4.14 was placed inside a minivan with GPS receiver and radio antenna mounted on the roof of the vehicle to represent a transit vehicle. The onboard embedded system interfaces with the GPS and wireless communication systems to transmit vehicle location and other information (for example, vehicle ID, route ID, passenger counts, door opening status and so on) to the roadside equipment. The Roadside Equipment (RSE) continuously monitors the vehicle location when the test vehicle travels within the range of the wireless communication and then generates a signal priority request to traffic signal controller as iuulstrated in Figure 4.15.

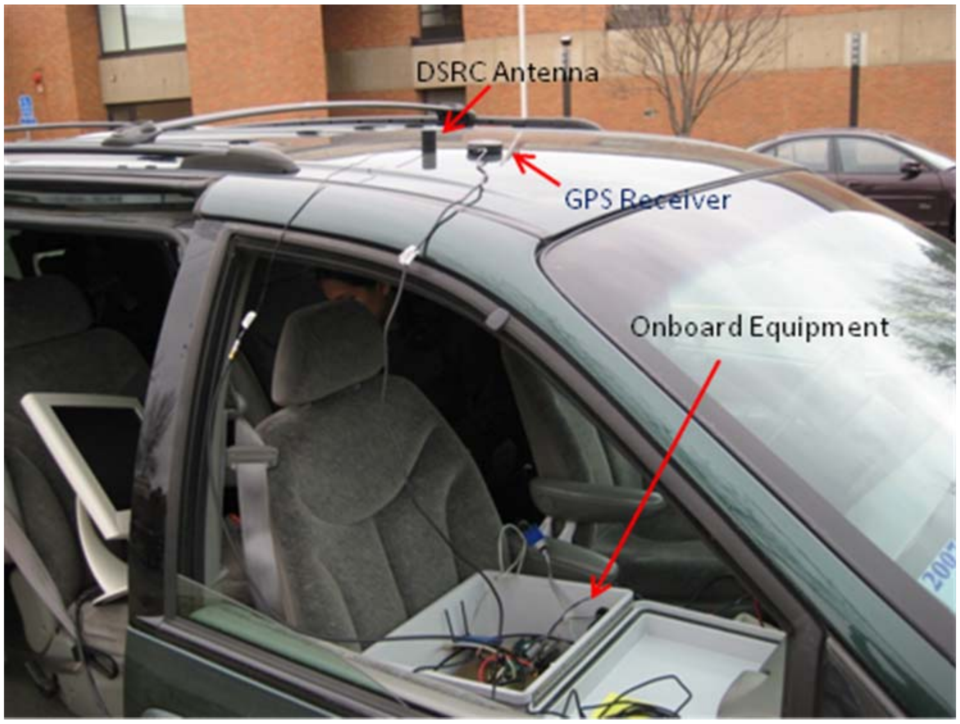


Figure 4.14 Onboard Equipment Setup

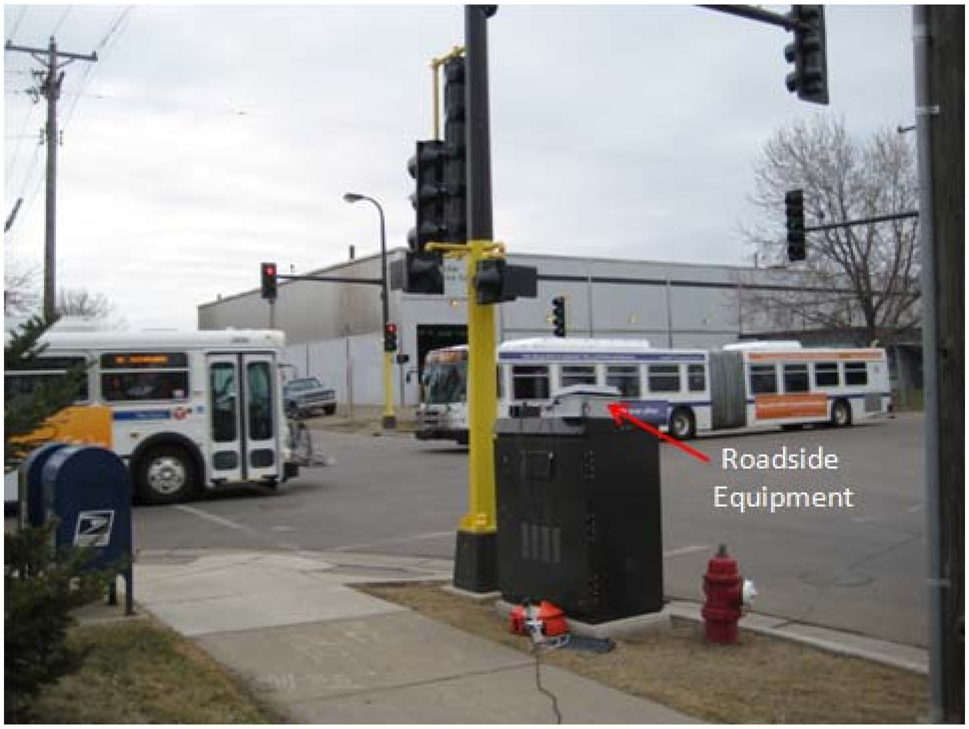


Figure 4.15 Roadside Equipment Setup

5. RESULTS AND DATA ANALYSIS

Vehicle location and timing of signal priority request were collected during the field testing. Data analysis and problem encountered during the field testing were discussed in this chapter. Figure 5.1illustrates a bus receives green signal extension along Como Avenue.

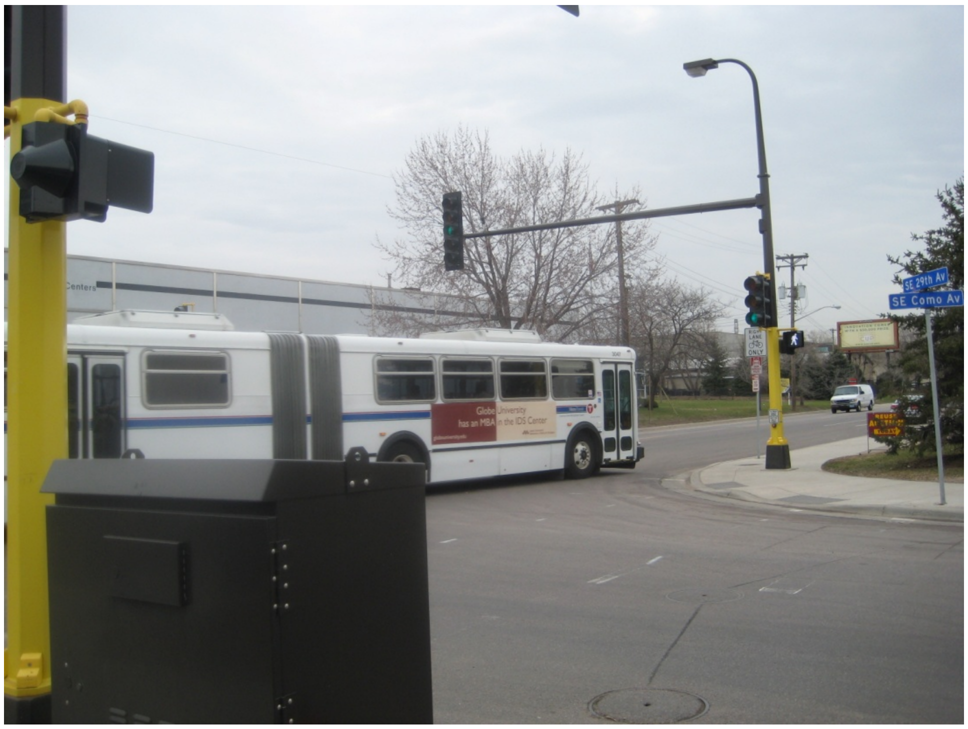


Figure 5.1 Bus Receives Signal Priority

5.1 Analyze Data Collected From Onboard Equipment

Vehicle location, speed, time and priority request status were recorded while the test vehicle was traveling from the 27th to 31st Avenue along the Como Avenue. As shown in Figure 5.2, each red dot represents one wireless communication string recorded from onboard computer. Signal priority data string was collected at every 200 milliseconds since the Garmin GPS receiver can only provide position update at 5 Hz when the onboard equipment establishes communication with the roadside equipment. The onboard equipment will record GPS data string after one second of timeout period if the wireless communication link was lost in the vehicular environment.

5.1.1 Signal Priority Request for Green Extension

Signal priority request for green extension on the main street (Como Avenue) was analyzed in this experiment. In Figure 5.2, the vehicle started at location A outside the coverage range of wireless communications. The DSRC wireless communication was established between location B and F. However, during this particular testing, there were communication gaps nearby location C, D and E where the communication between the vehicle and the roadside equipment was lost ocassionally. Figure 5.3 shows the distance from the test vehicle to the intersection over test period. The test vehicle was initially idling at about 180 meters upstream away from the intersection. The vehicle gradually moved within the wireless communication range at 25:32 when the adaptive signal priority algorithm began monitoring the location and speed of the test vehicle. Priority request was sent at around 25:36 to the roadside equipment to request for green extension as the vehicle approaching the intersection. The test vehicle arrived at the intersection around 25:46 as illustrated in Figure 5.3.

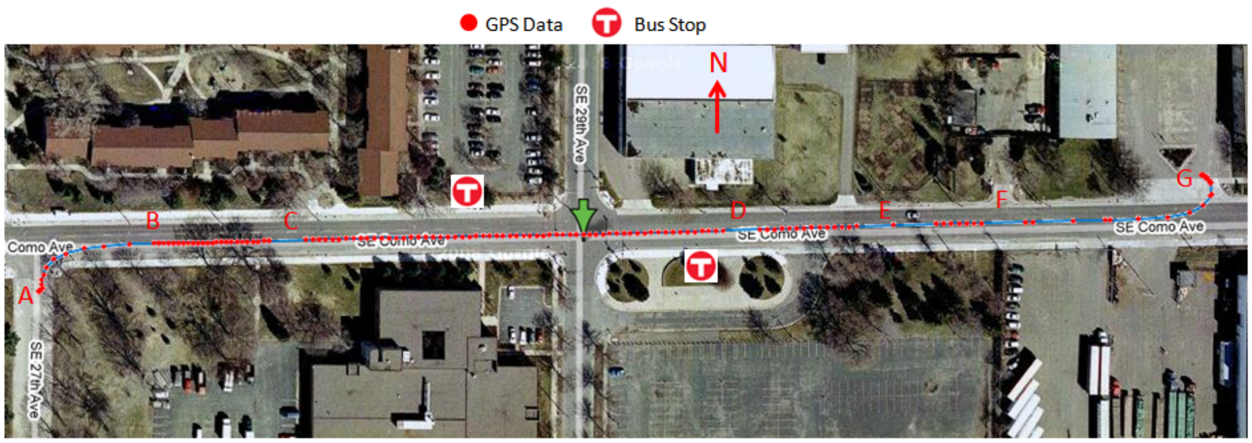


Figure 5.2 Recorded GPS Data Point Along Como Ave. SE (Eastbound)

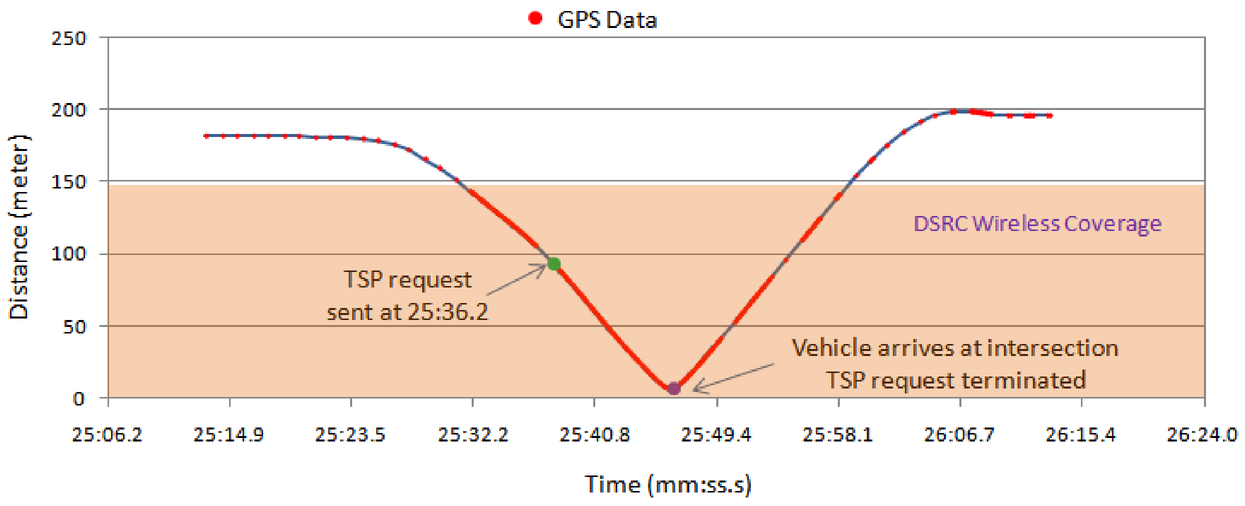


Figure 5.3 Vehicle Distance to Intersection and DSRC Wireless Coverage (Eastbound Test #1)

Vehicle speed versus time was also analyzed as plotted in Figure 5.4. The posted speed limit at the test site is 35 MPH. We drive the test vehicle at a relative lower speed to represent the lower average bus traveling speed at the test site. The test vehicle was traveling with the wireless communication established from 25:32 to 25:56 (24 seconds). The vehicle was travelling at an average speed of 25 MPH from the time when priority request was sent (25:36) to the time when vehicle passed through the intersection (25:46). There were 4 vehiles in front of the test vehicle during the experiment. But detail traffic condition in front of the test vehicle was not captured due to the insufficient data from the loop detectors.

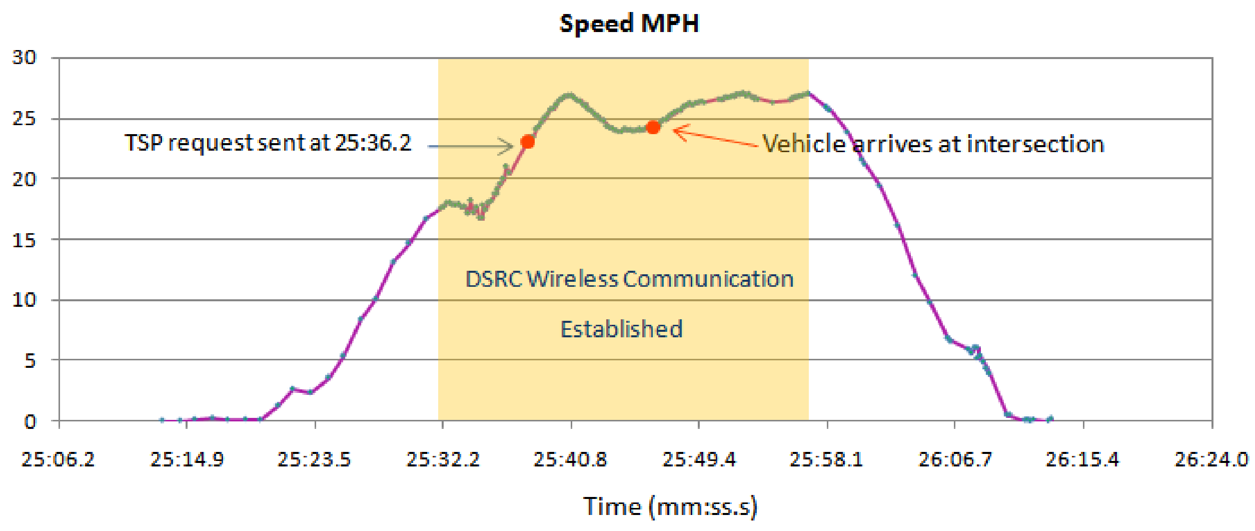


Figure 5.4 Vehicle Speed Profile and TSP Request (Eastbound Test #1)

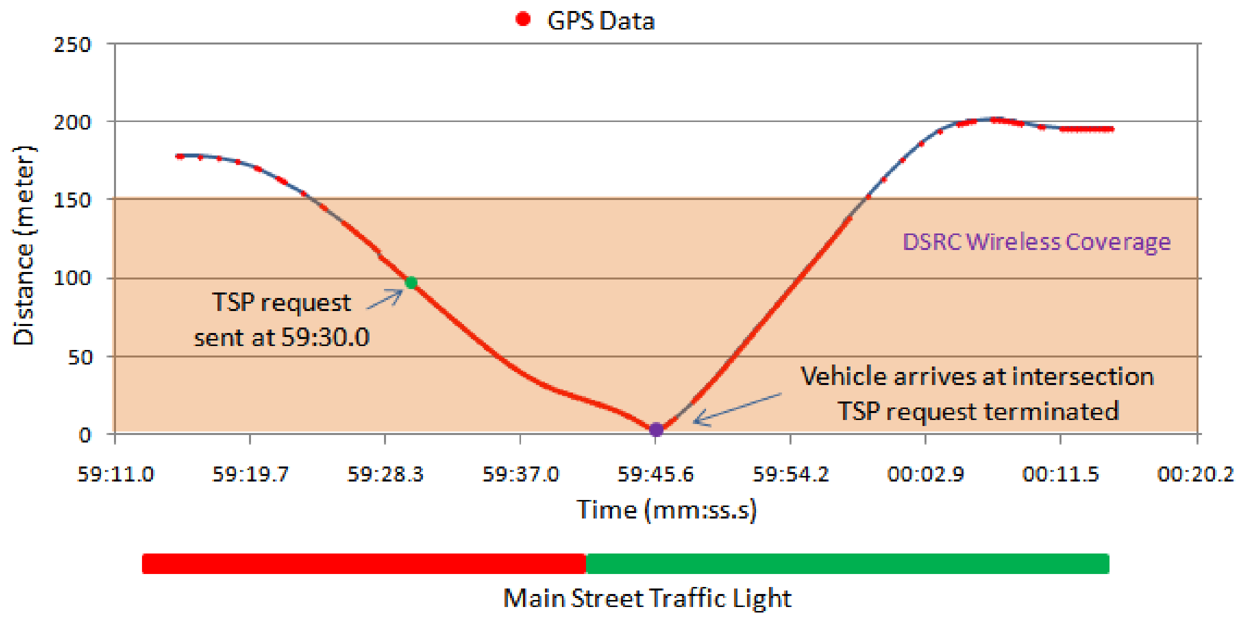


Figure 5.5 Vehicle Distance to Intersection and DSRC Wireless Coverage (Eastbound Test #2)

5.1.2 Eastbound Signal Priority Request for Early Green (Red Truncation)

Another scenario was also tested to evaluate the controller's response to priority request for early green. In Figure 5.5, the vehicle was intentionally started when the signal on Como Avenue turned red. The DSRC wireless communication was established from 59:24 to 59:56. Signal light on Como Avenue was red as the test vehicle approaching the intersection. Signal priority was requested through the wireless communication at 59:30.

Figure 5.5 shows the distance from the test vehicle to the intersection versus time. The test vehicle was initially idling at about 180 meters upstream away from the intersection. The adaptive signal priority algorithm began monitoring the location nand speed of the test vehicle at 59:24.

Priority request was sent at around 59:30 to the roadside equipment to request for early green (or red truncation) as the vehicle approaching the intersection. Priority request was granted and the signal turned green around 59:40. The test vehicle arrived at the intersection at around 59:45as shown in Figure 5.5.

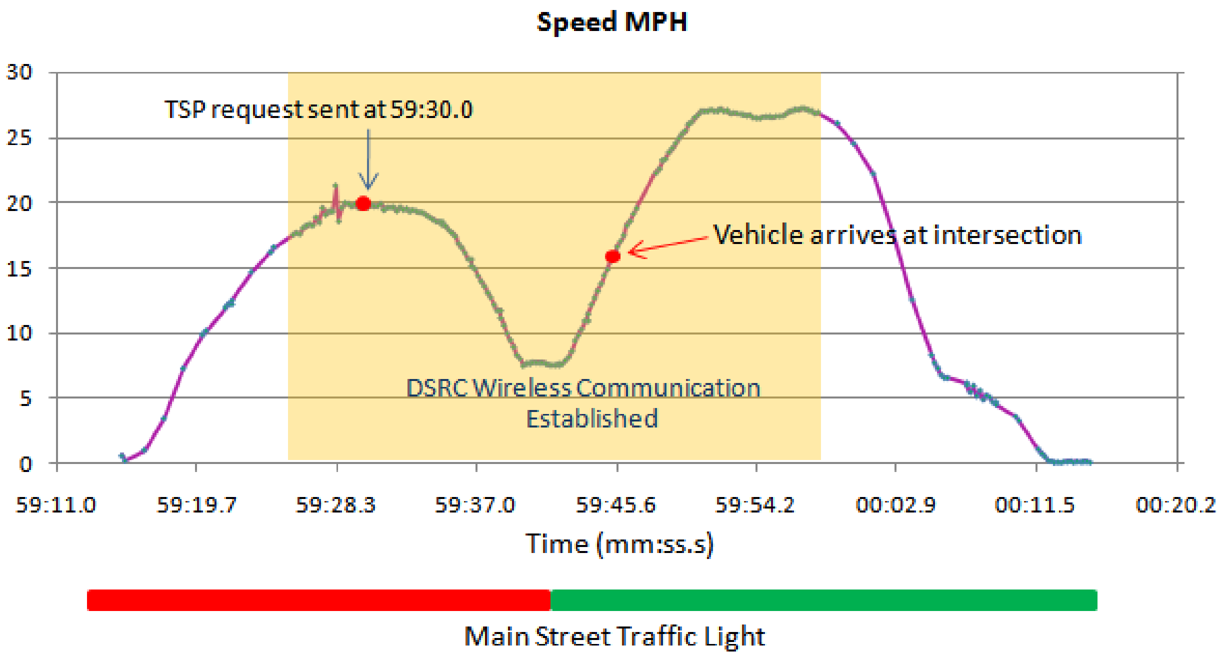


Figure 5.6 Vehicle Speed Profile and TSP Request (Eastbound Test #2)

Vehicle speed versus time for the early green scenario was analyzed as plotted in Figure 5.6. The test vehicle was traveling within the wireless communication range from 59:24 to 59:56 (duration of 32 seconds). The vehicle was travelling toward the signalized intersection when the signal light is red. Signal priority was requested when the test vehicle began to slow down due to the queue in front of the test vehicle. Traffic controller acknowledged the priority request and provided an early green around 59:41. After receiving the green light on the main approach, the speed of the test vehicle increased as the queue in front began to discharge. Test vehicle left the intersection around 59:45 at speed around 16 MPH. The average wireless data communication latency is about 4.1 ms for the eastbound test #2 using the DSRC radio.

5.1.3 Westbound Signal Priority Request for Early Green (Red Truncation)

Signal priority request for red truncation from westbound approach was analyzed in this experiment. In Figure 5.7, the vehicle started at location A. The DSRC wireless communication was established from location A to C. However, during this particular testing, there were communication gaps nearby location B where the communication link between the vehicle and the roadside equipment was lost ocassionally.

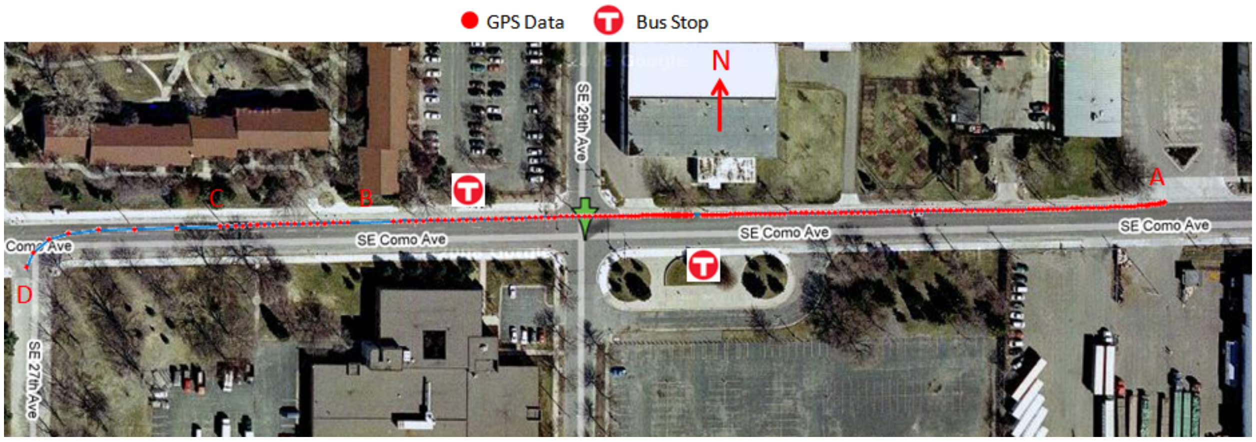


Figure 5.7 Recorded GPS Data Point Along Como Ave. SE (Westbound)

Figure 5.8 shows the distance from the test vehicle to the intersection versus time. The test vehicle was initially idling at about 175 meters upstream away from the intersection at location A. The vehicle moved within the wireless communication range at 02:38 when the adaptive signal priority algorithm began monitoring the location and speed of the test vehicle. Priority request was sent at around 02:48 to the roadside equipment to request for early green as the vehicle approaching the intersection. The test vehicle arrived at the intersection at around 03:04 as illustrated in Figure 5.8. The vehicle was intentionally started when the traffic signal on Como Avenue became red. The DSRC wireless communication was established from 02:38 to 03:15. Signal light on Como Avenue was red as the test vehicle approaching the intersection. Signal priority was requested through the wireless communication interface at 02:48.

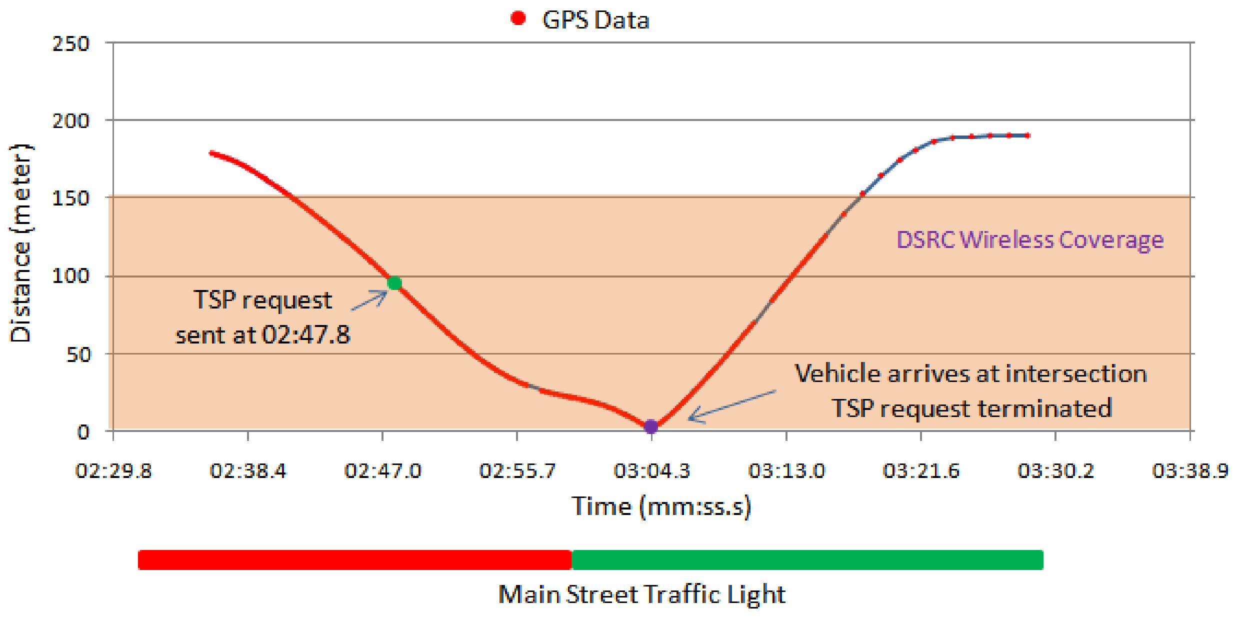


Figure 5.8 Vehicle Distance to Intersection and DSRC Wireless Coverage (Westbound)

Vehicle speed versus time for the early green scenario in the westbound approach was analyzed as shown in Figure 5.9. The test vehicle was traveling with the wireless communication connection from 02:38 to 03:15 (duration of 37 seconds). The vehicle was travelling toward the signalized intersection when the light is red. Signal priority was requested when the test vehicle began to slow down due to the queue in front of the test vehicle. Traffic controller acknowledged the priority request and provided an early green around 02:59. After receiving the green light on the main approach, the speed of the test vehicle increased as the queue in front began to discharge. Test vehicle left the intersection around 03:04 at speed around 17 MPH. The average wireless data communication latency is about 4.3 ms for the westbound testing using the DSRC radio.

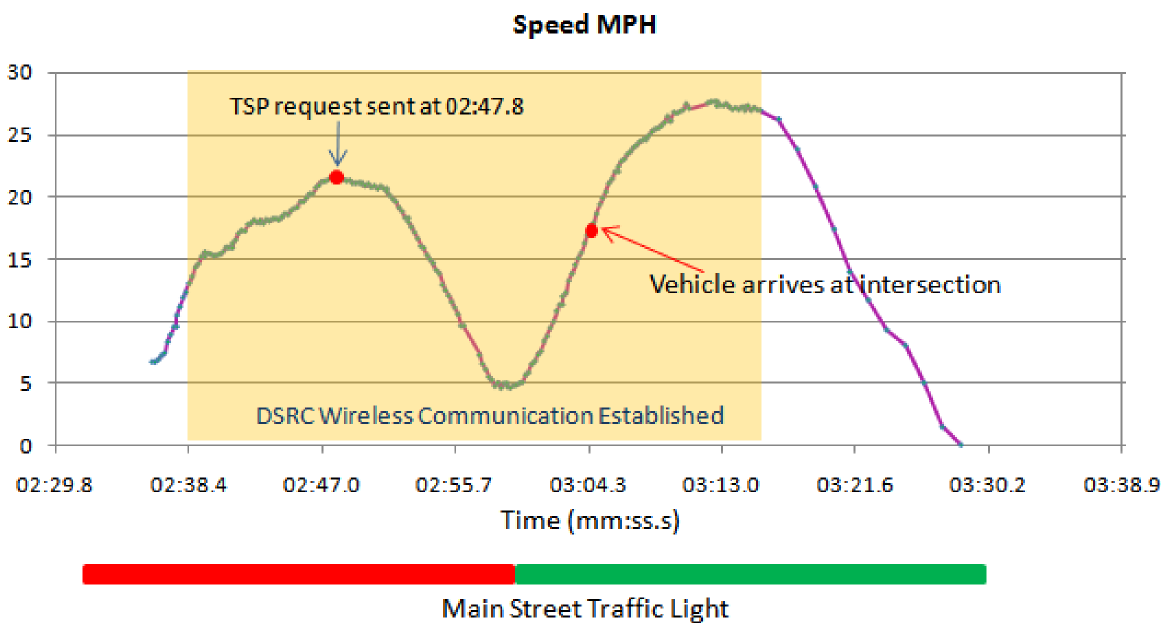


Figure 5.9 Vehicle Speed Profile and TSP Request (Westbound)

5.2 Phasing and Timing Information from Signal Controller

We tried to obtain real-time signal timing and phasing information from the EPAC traffic controller through the the serial communication interface on the traffic controller. A serial communication analyzer was utilized to monitor the serial port activities. Detail information regarding the serial analyzer and the signal controller serial communication are included in Appendix F. It is difficult to find out the timing and phasing commands without the knowledge of the serial communication commands. Signal controller vendor uses special software (MarcNX, www.itssiemens.com) to communicate with the traffic controller though the serial communication interface. MarcNX software allows monitoring and controlling of traffic from a central computer center in the Microsoft Windows™ environment. Due to the proprietary nature of the communication protocol, the vendor is unwilling to share the information with us.

One possible solution to get the controller timing and phasing information is to tap onto the controller cabinet back panel with a simple circuitry design as shown in Figure 5.10. The data collection system as shown in Figure 5.10 was developed by Professor Henry Liu and his research group at University of Minnesota. The SMART-SIGNAL systems were deployed on over a dozen of actuated intersections in the Twin Cities area to collect traffic event data triggered by inductive loop detector, pedestrian calls and phasing changes. Similar data collection system can be used to obtain the current active phases and timing of the active phases. Collected data can then be processed by the roadside equipment to adjust the appropriate timing for signal priority request.

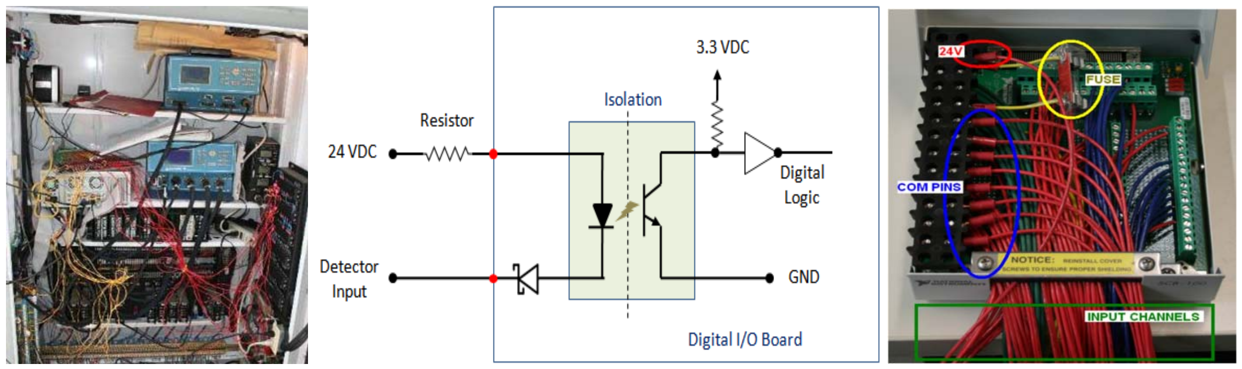


Figure 5.10 Controller Data Collection Interface from SMART-SIGNAL Project

5.3 Wireless Connection

To further investigate the feasibility of using Wi-Fi for transit signal priority, we also set up a private wireless network to test the communication between the OBE and RSE using the 802.11x protocol. The DSRC radios were replaced by a pair of Wi-Fi USB adapters each connected to the OBE and RSE and a wireless router. When wireless communication was initially established prior to the test vehicle traveling outside the communication range, the communication link will be temporary lost as the test vehicle traveling out of the Wi-Fi coverage. However, the communication link will be re-established as the departing vehicle turned around and re-entered into the wireless coverage range as shown in Figure 5.11a. If the communication between the OBE and RSE was not established as the vehicle traveling from upstream intersection to the next, wireless communication was not established automatically when the vehicle traveling within the communication range of the wireless network as shown in Figure 5.11b. An automation program is need to continuously look for authenticated access point and establish communication as the OBE travels toward the upcoming intersection. The wireless network needs to have the capability to establish communication in a timely manner in order for the TSP algorithm to process the priority request efficiently and effectively.

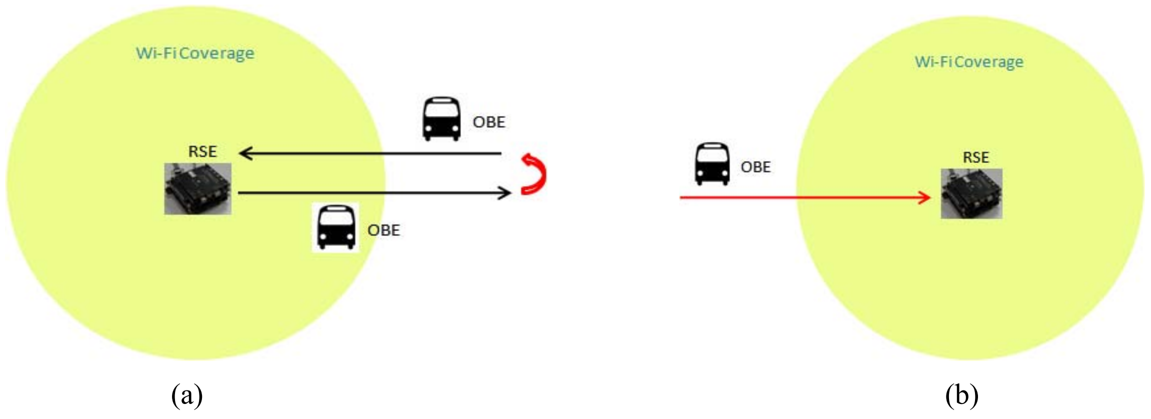


Figure 5.11 Establish Wi-Fi Connections

5.4 Minneapolis Wireless Network

In 2006 the City of Minneapolis signed a 10-year contract with USI Wireless of Minnetonka (http://www.usiwireless.com/) to provide city-wide wireless broadband technology. According to the City of Minneapolis, the Minneapolis wireless network will cover all 59 square miles of Minneapolis providing residents, businesses and visitors with wireless broadband access anywhere in the city. The network will allow the city to deliver services more efficiently and effectively.

We would like to investigate the possibility of using the USI wireless services for providing transit signal priority through the Minneapolis Wi-Fi network. We subscribed couple lines of services and purchased two wireless modems for testing. The configuration and design of current Minneapolis Wi-Fi network does not allow direct TCP/UDP communications through their Wi-Fi network between the OBE and RSE. As illustrated in Figure 5.12, both OBE and RSE receive dynamic IP addresses assigned under a private network (for example, IP: 192.168.1.xxx) connected to the wireless modems or adapters. OBE and RSE reside in their own intranet as configured by the Wi-Fi network server. The OBE or RSE can freely communicate to the world through the Minneapolis Wi-Fi network. However, the OBE cannot communicate with the RSE directly through the Wi-Fi network due to security settings from the USI wireless servers. We also investigated other options as recommended by USI wireless to use port forwarding and Network Address Translation (NAT) for wireless communications between OBE and RSE. Because both the onboard and roadside computers reside with their own private domain, the NAT settings configured within each Ruckus modem only allow intranet communication within the private domain. The translated network address cannot pass though the barriers imposed by the DHCP settings of the USI wireless servers and modem settings.

USI wireless technical support later confirmed that the wireless communication between two clients within their network was not possible under the current network configuration. We were then advised by the USI wireless to use third-party software to achieve communications between our onboard and roadside equipment. The data communication latency might be increased significantly when introducing additional software for wireless communication through the USI wireless network. The Minneapolis Wi-Fi network currently does not offer static IP assignment for each subscriber. This could cause communication issues for TSP applications whenever a unit has to recycle power. USI wireless will need to modify the network connection settings in order to allow static IP address assignment and direct wireless communications between the RSE and OBE in the vehicular environment.

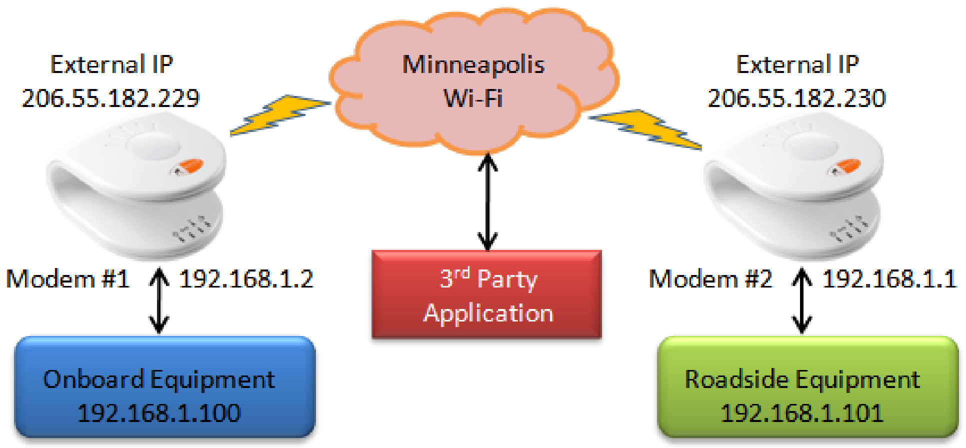


Figure 5.12 Wireless Data Communication through a 3rd Party Application

6. FUTURE WORK

We would like to meet with USI wireless to pursue possible modification of network access with special IP assignment or other options for wireless connectin to OBE and RSE. The phase III wireless TSP project was awarded by ITS institute. Phase III project proposed to instrument four to six intersections with RSEs and install OBEs on a few buses with interface to the bus AVL/GPS system. The proposed phase III research project will evaluate the impact of TSP deployment along a selected corridor.

We would like to evaluate the tSP performance along a corridor as compared to the results from other deployments (e.g. LA, Chicago, etc.). We will invtigate the reliability and explore the limitation of our TSP system. We plan to examine and evaluate the existing transit control systems (SMARTCoM AVL system and WLAN radio) that are already installed on the Metro Transit buses. We plan to identify potential software or firmware changes that are needed to allow wireless communications between the bus onboard computer and other roadside equipment using the 802.11x wireless communication protocols. Unprotected Wi-Fi networks pose multiple threats to the transit system. Data encryption, access authentication and dedicated Virtual Private Networks (VPNs) will be investigated and evaluated as potential solutions to protect the transit wireless network. We also would like develop a communication framework between the buses and the roadside infrastructure for ITS applications that can potentially be deployed by Metro Transit region wide. Our intent is to investigate the feasibility and reliability of implementing a vehicle-to-infrastructure wireless communication framework for the various intelligent transit applications described in the study.

Minnesota is one of five communities nationwide to receive funding through the U.S. Department of Transportation's Urban Partnership Agreement (UPA) program to develop strategies and to implement and deploy applications to reduce traffic congestions in the Twin Cities. As part of the UPA program, Metro Transit is working with consultants to design concept of operation to provide transit signal priority (TSP) along Central or Nicollet Avenue running in parallel with I-35W. The idea of the wireless-based TSP approach is to utilize as much as information from the existing AVL system and bus mobile infrastructure in order to reduce intsllation and maintenance cost and implementation time. We would like to build upon our previous research effort on wireless TSP and work together with the City of Minneapolis and Metro Transit to improve the transit reliability and run time adherence in the Twin Cities.

7. SUMMARY AND DISCUSSION

The objective of the phase II study is to develop a wireless-based transit signal priority system that will incorporate the Global Positioning System/Automated Vehicle Location (GPS/AVL) system on the buses while determing when to submit priority request to signal controller. An adaptive signal priority strategy developed from phase I study was implemented to consider the bus schedule adherence, its number of passengers, location and speed. Buses can communicate with intersection signal controllers using wireless technology to request for signal priority or other ITS applications. Communication with the roadside unit (e.g., traffic controller) for signal priority was tested using the available 802.11x WLAN and the DSRC (Dedicated Short Range Communication) prototype system for wireless access in vehicular environment.

A set of PC/104 stand-alone Single Board Computer (SBC) was used for the embedded system development. Additional I/O modules were integrated to the embedded system to perform data communication between the traffic signal controller and a transit vehicle. A pair of DSRC WAVE radios and 802.11x wireless modems were used for testing wireless communications between the onboard equipment (OBE) and the roadside equipment (RSE). Communication coverage and latency were measured for both DSRC and 802.11x Wi-Fi adapters to better understand the performance of each system and the potential constraints while requesting for signal priority in real-time applications. The performance evaluation of the wireless communication using the Denso DSRC radios and Wi-Fi module were tested at two different test sites, East Franklin Avenue at 22nd Avenue and Como Avenue at 29th Avenue in Minneapolis. The DSRC system was tested at both test sites. The wireless performance testing using the Minneaplis Wi-Fi network was performed at Franklin test site due to the USI wireless access point/router was not yet installed at the Como test site. A pair of data communication programs using User Datagram Protocol (UDP) were written in C language and running in both roadside and onboard embedded computers.

Signal priority request output on the roadside equipment was connected to a pre-emption input channel on the signal controller through wirings in the controller cabinet. Program of the traffic controller was also configured and activated to accept external pre-emption inputs. The traffic signal controller was programmed by the City of Minneapolis traffic engineer to specify corresponding delay, dwell, maximum call and extension time. Developed prototype systems were deployed and tested at the intersection of Como and 29th Avenue nearby the University of Minnesota campus to validate the bus signal priority algorithm with green extension and red truncation (early green) strategy. The mobile design of the wireless TSP system allows us to easily test the prototype system at different intersection and on different vehicle. The OBE was placed inside a minivan with GPS receiver and radio antenna mounted on top of the vehicle to represent a transit vehicle. The onboard embedded system interfaces with the GPS and wireless communication systems to transmit vehicle location and other information (for example, vehicle ID, route ID, passenger counts, door opening status and so on) to the roadside equipment. The RSE continuously monitors the vehicle location when it travels within the communication range of the wireless network. The RSE will generate signal priority request to traffic signal controller as governed by the TSP strategy implemented in the RSE.

The field test results demonstrate that the test vehicle is able to successfully submit signal priority request through the wireless network as it is traveling toward the intersection instrumented with roadside equipment. The vehicle is initially traveling from a location outside the DSRC WAVE radio coverage range. As soon as the vehicle moves within the wireless communication range, the adaptive signal priority algorithm begins to monitor the location and speed of the test vehicle and submits request for priority through the roadside interface to the traffic signal controller. Traffic signal controller is capable of providing green extension or red truncation (or early green) to the qualified vehicle as it is approaching the intersection. The signal priority request is dropped when the test vehicle passes the intersection or when the call duration reaches the maximum call setting.

An experiment to test the signal priority systems using the Minneapolis Wi-Fi network was also attempted. But the configuration of current Minneapolis Wi-Fi network does not allow direct TCP/UDP communications through their network servers between the OBE and RSE. Both OBE and RSE receive dynamic IP addresses assigned under the private network connected through to the wireless modems or adapters. The OBE or RSE can freely communicate to the world through the Minneapolis Wi-Fi network. However, the OBE cannot communicate with the RSE directly through the Wi-Fi network due to security settings from the USI wireless servers. We were advised by the USI wireless technical support to use third-party software to communicate between our onboard and roadside equipment through Minneapolis Wi-Fi network. The data communication latency might be increased significantly when introducing additional layer of data communication. However, the variation of the network latency plays a more importance role for realtime application using wireless communication.

Using the Minneapolis Wi-Fi network for TSP application can certainly reduce cost by taking advantage of the existing infrastructure. However, availability of data bandwidth and quality of service, concern of network reliability and data security need to be addressed when choosing the Wi-Fi technology. The DSRC radio is potentially good with excellent performance (short range with fast data communication rate), but the availability of DSRC is currently limited. We certainly don’t know whether there will be national “rollout”. The UMN TSP system uses wireless technology to establish data communication between transit vehicles and roadside systems. It is not limited to any particular wireless technology.

REFERENCES

3M™ Opticom™ Priority Control System, (http://solutions.3m.com/wps/portal/3M/en_US/Traffic_Safety/TSS/Offerings/Systems/Opticom/, accessed October 1, 2007).

Ahmed, H., EL-Darieby, M., Abdulhai, B., Morgan, Y., 2008. "Bluetooth- And Wi-Fi-Based Mesh Network Platform for Traffic Monitoring". Transportation Research Board 87th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

Alexander, L., Cheng, P., Gorjestani, A., Menon, A., Newstrom, B., Shankwitz, C., Donath, M., 2006. "The Minnesota Mobile Intersection Surveillance System". Proceedings of 9th International IEEE Conference on Intelligent Transportation Systems, Toronto, Canada, pp. 139-144.

Biswas, S., Tatchikou, R., Dion, F., 2006. „Vehicle-to-Vehicle Wireless Communication Protocols for Enhancing Highway Traffic Safety". *IEEE Communications Magazine*, Volume 44, Issue 1, pp. 74-82.

Böhm, M., Pfliegl, R., Frötscher, A., 2008. "Wireless Infrastructure-To-Vehicle Communication Technologies to Increase Road Safety Along Motorways". Transportation Research Board 87th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

Bretherton, R.D., Hounsell, N.B., Radia, B., 1996. "Public Transport Priority in SCOOT". Proceedings of the 3rd Annual World Congress on ITS Systems, Orlando, FL.

Collura, J., Rakha, H., and Gifford, J., 2003. *Guidelines for the Planning and Development of Emergency Vehicle Preemption and Transit Priority Strategies*, Prepared by the Virginia Tech Transportation Institute, Blacksburg, VA, and George Mason University School of Public Policy, Arlington, VA.

Crout, D.T., 2005. "Evaluation of Transit Signal Priority at the Tri-County Metropolitan Transportation District of Oregon (TriMet)". Proceedings of the 12th Annual World Congress on ITS Systems, Nov. 6-10, San Francisco, CA.

Dion F., Rakha H., 2005. "Integration of Transit Signal Priority Within Adaptive Traffic Control Systems". Transportation Research Board 84th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

Farradyne, P. B., 2005. *VII Architecture and Functional Requirements, Version 1.1*. U.S. Department of Transportation. (www.vehicle-infrastructure.org/documents/VII%20Architecture%20version%201%201% 202005_07_20.pdf, accessed November 1, 2007).

Federal Highway Administration (FHWA), 2004. Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software. FHWA-HRT-04-040, McLean, VA.

Fitzmaurice, M., 2005. "Use of Wireless Local Area Networks in Rail and Urban Transit Environments". *Transportation Research Record*, No. 1916, pp. 42-46.

Furth, P.G., Mueller, T.H., 2000. "Conditional Bus Priority at Signalized Intersections, Better Service with Less Traffic Disruption". *Transportation Research Record*, No. 1731, pp. 23-30.

Furth, P.G., SanClemente, J.L., 2006. "Near Side, Far Side, Uphill, Downhill, Impact of Bus Stop Location on Bus Delay". *Transportation Research Record*, No. 1971, pp. 66-73.

Ghanim, M., Dion, F., Abu-Lebdeh, G., 2007. "Projected Transit Arrival Time Prediction Tool for Transit Signal Priority with Nearside Bus Stops". Transportation Research Board 86th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

Hourdakis, J., Michalopoulos, P., J. Kottommannil, 2003. “Practical procedure for calibrating microscopic traffic simulation models”. *Transportation Research Record*, No. 1852, pp. 130-139.

ITS America, 2002. *An Overview of Transit Signal Priority*, prepared by Advanced Traffic Management Systems Committee and Advanced Public Transportation Systems Committee of the ITS America, Washington, D.C.

ITS America, 2004. *An Overview of Transit Signal Priority – revised and updated*, prepared by Advanced Traffic Management Systems Committee and Advanced Public Transportation Systems Committee of the ITS America, Washington, D.C.

Jarmar Technologies, JAMAR Hand-held traffic data collector, DB-400, Horsham, PA. (http://www.jamartech.com/, accessed November 1, 2007).

Kim, W. and Rilett, L.R., 2005. “An Improved Transit Signal Priority System for Networks With Nearside Bus Stops”. Transportation Research Board 84th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

King County Department of Transportation, 2002. *An Evaluation of Transit Signal Priority in Aurora Avenue North, Transit Speed and Reliability Program*, King County Department of Transportation, King County, WA.

Kittelson & Associates, Inc., 2006. *LADOT/County Transit Signal Priority System*. Technical report. Kittelson & Associates, Inc., Portland, OR.

Li, M., Wu, G., Li, Y.I., Bu, F., Zhang, W.B., 2007. “Active Signal Priority for Light-Rail Transit at Grade Crossings”. TRB 86th Annual Meeting Compendium of Papers CD-ROM. Washington, D.C.

Li, M., Yin, Y., Zhou, K., Zhang, W.B., Liu, H., and Tan, C.W., 2005. “Adaptive Transit Signal Priority on Actuated Signalized Corridors”. Transportation Research Board 84th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

Liao, C.F., Davis, G.A., 2006. *Bus Signal priority Based on GPS and Wireless Communications, Phase I: Simulation Study*. Final Report, ITS Institute, CTS, University of Minnesota, Minneapolis, MN, CTS 06-07.

Liu, H., Skabardonis, A., Zhang, W.B., 2003. “A Dynamic Model For Adaptive Bus Signal Priority”. Transportation Research Board 82nd Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

Liu, H., Skabardonis, A., Zhang, W.B., Li, M., 2004. “Optimal Detector Location for Bus Signal Priority”. *Transportation Research Record*, No. 1867, Washington, D.C.

Marca, J.E., 2006. “Mobile throughput of 802.11b from a moving vehicle to a roadside access point”. Transportation Research Board 85th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

McLeod, F., Hounsell, N., 2003. “Bus Priority at Traffic Signals – Evaluating Strategy Options”. *Journal of Public Transportation*, Volume 6, No.3. pp. 1-14. (http://www.nctr.usf.edu/jpt/pdf/JPT%206-3.pdf, accessed October 1, 2007).

McNally, M.G., Marca, J.E., Rindt, C.R., Koos, A.M., 2003. *TRACER: In-vehicle, GPS-based, Wireless Technology for Traffic Surveillance and Management*. California PATH Research Report, UCB-ITS-PRR-2003-23. (http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/2003/PRR-2003-23.pdf, accessed October 1, 2007).

Metro Transit, 2006. Bottineau Corridor Transit Signal Priority: Conceptual Design. Minneapolis, MN.

Mirchandani, P.B., Head, K.L., 2001. "A real-time traffic signal control system: Architecture, algorithms and analysis". Transportation Research Part C: Emerging Technologies, Vol. 9, No. 6, Elsevier, pp. 415-432.

Mirchandani, P.B., Knyazyan, A., Head, K.L., Wu, W., 2001. "An Approach Towards the Integration of Bus Priority, Traffic Adaptive Signal Control, and Bus Information/Scheduling Systems", Computer-Aided Scheduling of Public Transport, *Journal of Scheduling*, Springer-Verlag, Germany, pp. 319-334.

Mirchandani, P.B., Lucas, D.E., 2004. "Integrated Transit Priority and Rail/Emergency Preemption in Real-Time Traffic Adaptive Signal Control". *Journal of Intelligent Transportation Systems Technology*, Planning and Operations, Vol. 8 Issue 2, pp. 101-115. (http://www.informaworld.com/smpp/content~content=a713904020~db=all~order=page, accessed October 1, 2007).

Rakha, H., Ahn K., Collura J., 2006. *Transit Signal Priority Project Along Route 1: Lessons Learned*. Virginia Transportation Research Council, Charlottesville, VA, VTRC 06-CR.

Saint Cloud Metropolitan Transit Commission, 2000. *Transit Priority Evaluation Report*, Final Report, St. Cloud, MN.

Siemens Traffic Controls, SCOOT, Split Cycle Offset Optimisation Technique (www.scoot-utc.com, accessed October 1, 2007).

Siemens Intelligent Transportation Systems, 2002. SEPAC Actuated Signal Control Software, User's manual. (http://www.itssiemens.com/en/t_nav228.html, accessed October 1, 2007).

Siemens Intelligent Transportation Systems. Eagle EPAC M50 Traffic Control Unit, (http://www.itssiemens.com/en/u_nav2131.html, accessed October 1, 2007).

Skabardonis, A., 2000. "Control Strategies for Signal Priority". *Transportation Research Record*, No. 1727, pp. 20-26.

Skabardonis, A., Geroliminis, N., 2008. "Real-Time Monitoring and Control on Signalized Arterials". *Journal of Intelligent Transportation Systems*, Volume 12, Issue 2, pp. 64-74.

Stibor, L., Zang, Y., Reumerman, H., 2007. "Neighborhood evaluation of vehicular ad-hoc network using IEEE 802.11p". Compendium of 13th European Wireless Conference, Paris, France, April 1-4, 2007 (http://www.ew2007.org/papers/1569014956.pdf, accessed October 1, 2007).

Torrent-Moreno, M., Jiang, D., Hartenstein, H., 2004. "Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc networks". Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, Association for Computing Machinery, New York, NY, pp. 10-18.

Trafficware Corporation, *Synchro, traffic signal coordination software*, Albany, CA. (http://www.trafficware.com/, accessed October 1, 2007).

Transportation Research Board, 2003. *Transit Cooperative Research Program (TCRP) Report 100*: Transit Capacity and Quality Service Manual, 2nd Edition – Part 4: Bus Transit Capacity, Chapter 1, Bus Capacity Fundamentals, pp. 4-3~4-9. (http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp100/part%200.pdf, accessed October 1, 2008).

Transport Simulation Systems, 2002. *AIMSUN Version 4.1 User's Manual*. Transport Simulation Systems (TSS), Barcelona, Spain. (http://www.aimsun.com/site/, accessed October 1, 2007).

Transport Simulation Systems, 2002. *GETRAM Extensions Version 4.1 User's Manual*. TSS, Barcelona, Spain.

Wadjas, Y., Furth, P.G., 2003. “Transit Signal priority Along Arterials Using Advanced Detection”. *Transportation Research Record*, No. 1856, pp. 220-230.

Wischhof, L., Ebner, A., Rohling, H., Lott, M., Hafmann, R., 2003. “Adaptive Broadcast for Travel and Traffic Information Distribution Based on Inter-Vehicle Communication”. Proc., IEEE Vehicular Technology Conference (VTC) 2003, Orlando, FL.

Wu, H., Lee, J., Hunter, M., Fujimoto, R., Guensler, R., Ko., J., 2005. “Efficiency of Simulating Vehicle-Vehicle Message Propagation in Atlanta, Georgia, I-75 Corridor”. *Transportation Research Record*, No. 1910, pp. 82-89.

Xu, Q., Hedrick, K., Sengupta, R., VanderWerf, J., 2002. “Effects of Vehicle-vehicle/ roadside-vehicle Communication on Adaptive Cruise Controlled Highway Systems”. Proceedings of IEEE 56th Vehicular Technology Conference, Birmingham, AL, Volume: 2, pp. 1249- 1253.

Zhang, J., 2003. “Zero Public Infrastructure Vehicle-Based Traffic Information System”. Transportation Research Board 82nd Annual Meeting Compendium of Papers CD-ROM, Washington, D.C.

Zheng, J., Wang, Y., Liu, H., Hallenbeck, M. E., 2007. “Modeling Impact of Near-Side Bus Stop on Transit Delays at Transit Signal Priority Enabled Intersections”. TRB 86th Annual Meeting Compendium of Papers CD-ROM. Washington D.C.

APPENDIX A

SIGNAL PHASING AND TIMING INFORMATION OF COMO & 29TH AVENUE

A.1 Geometry Layout and Phase Assignment

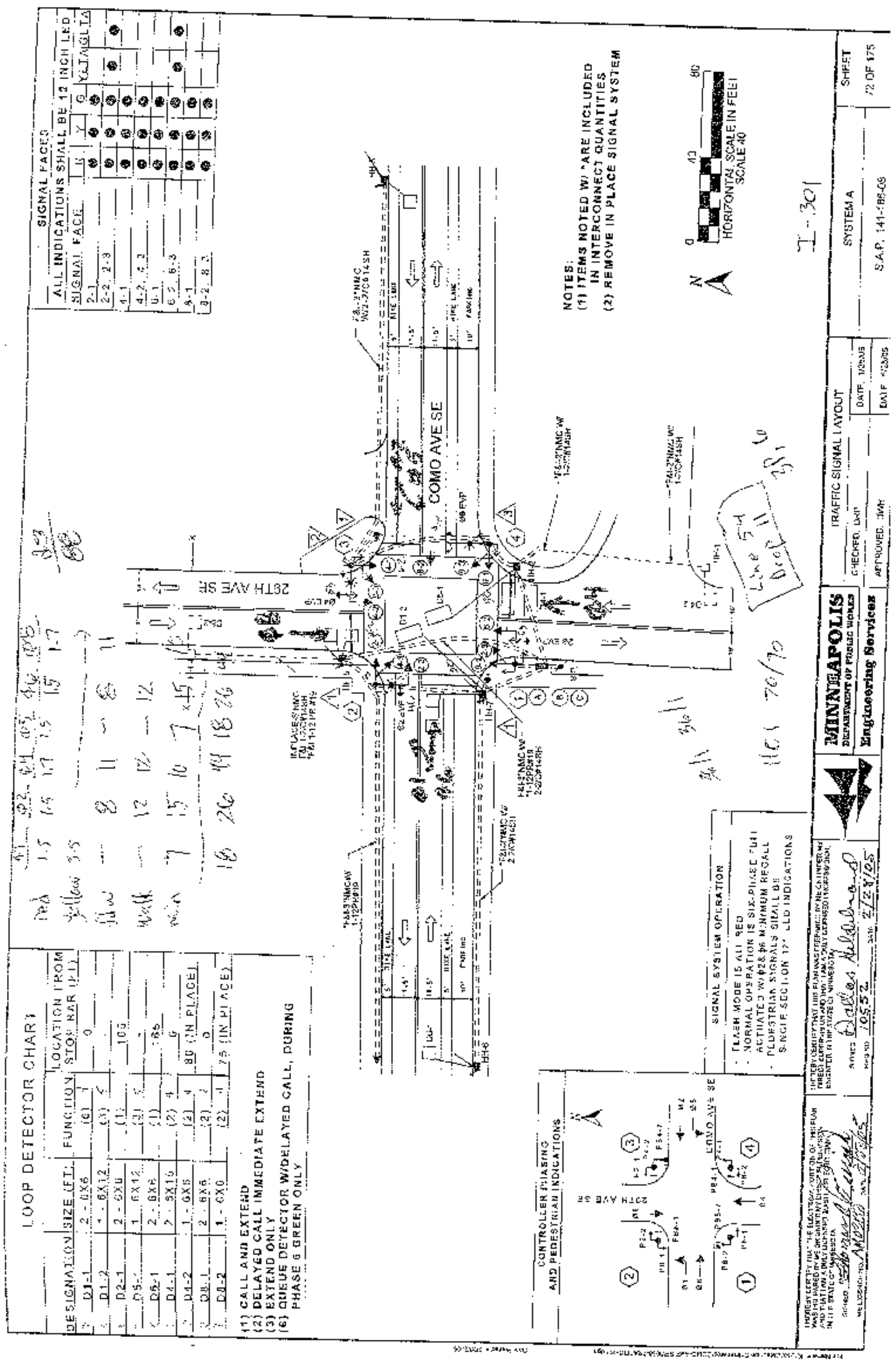
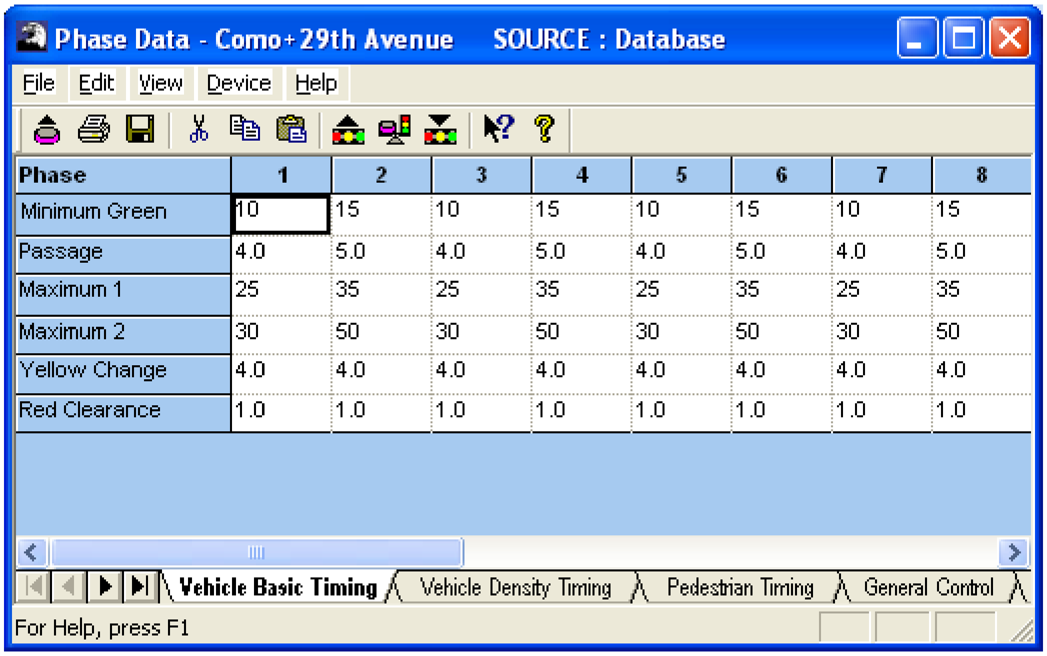


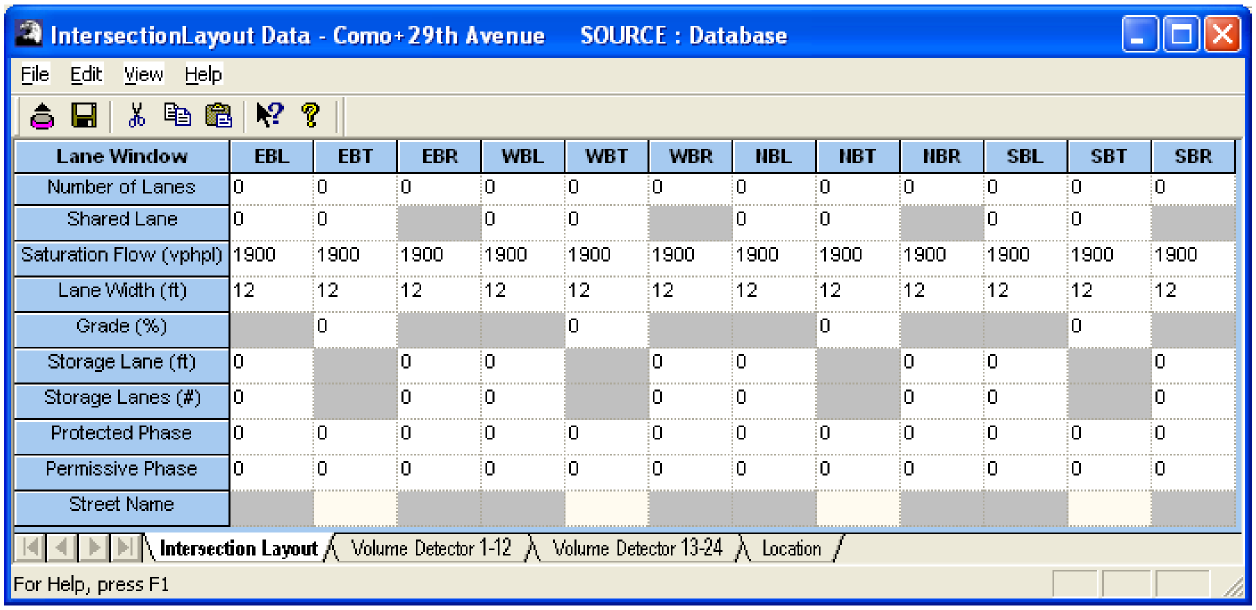
Figure A.1 Como and 29th Avenue Geometry Layout and Phase Assignment

A.2 Signal Timing Data



Phase	1	2	3	4	5	6	7	8
Minimum Green	10	15	10	15	10	15	10	15
Passage	4.0	5.0	4.0	5.0	4.0	5.0	4.0	5.0
Maximum 1	25	35	25	35	25	35	25	35
Maximum 2	30	50	30	50	30	50	30	50
Yellow Change	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Red Clearance	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Figure A.2 Signal Timing Data (from MarcNX Software)



Lane Window	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Number of Lanes	0	0	0	0	0	0	0	0	0	0	0	0
Shared Lane	0	0		0	0		0	0		0	0	
Saturation Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Lane Width (ft)	12	12	12	12	12	12	12	12	12	12	12	12
Grade (%)		0			0			0			0	
Storage Lane (ft)	0		0	0		0	0		0	0		0
Storage Lanes (#)	0		0	0		0	0		0	0		0
Protected Phase	0	0	0	0	0	0	0	0	0	0	0	0
Permissive Phase	0	0	0	0	0	0	0	0	0	0	0	0
Street Name												

Figure A.3 Intersection Data (from MarcNX Software)

APPENDIX B

TRAFFIC VOLUME AT COMO & 29TH AVE.

The following are the traffic counts collected by the City of Minneapolis in 2006 at Como and 29th Avenue.

Table B.1 Traffic Counts at Como and 29th Avenue

	29th Av SE From North				Como Av SE From East				29th Av SE From South				Como Av SE From West				
Start Time	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Int. Total
Factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
06:30 AM	0	34	6	0	6	9	14	0	6	2	0	4	2	9	1	4	97
06:45 AM	1	54	5	3	11	3	31	4	5	7	1	3	4	11	1	3	147
Total	1	88	11	3	17	12	45	4	11	9	1	7	6	20	2	7	244
07:00 AM	5	23	16	3	11	21	10	0	28	9	8	2	0	6	0	1	143
07:15 AM	6	14	13	3	7	18	13	1	5	8	12	2	0	15	0	1	118
07:30 AM	6	14	15	3	11	18	11	0	11	4	3	0	2	23	0	1	122
07:45 AM	4	12	17	5	10	24	11	0	12	5	13	0	3	23	1	2	142
Total	21	63	61	14	39	81	45	1	56	26	36	4	5	67	1	5	525
08:00 AM	3	17	21	3	23	23	10	0	14	5	3	0	2	28	0	0	152
08:15 AM	8	13	16	2	13	16	7	1	9	8	2	1	2	17	0	1	116
08:30 AM	5	6	16	3	12	17	10	0	5	5	1	0	4	25	0	0	109
08:45 AM	0	7	23	1	18	24	7	1	9	7	2	0	3	22	0	0	124
Total	16	43	76	9	66	80	34	2	37	25	8	1	11	92	0	1	501
09:00 AM	4	7	12	2	15	18	33	1	12	5	4	1	6	26	0	0	146
09:15 AM	1	15	14	5	18	23	12	1	12	5	6	2	7	24	2	0	147
09:30 AM	4	2	10	3	21	19	10	1	22	3	1	1	4	20	1	0	122
09:45 AM	2	5	8	1	15	15	11	1	11	3	5	0	4	14	2	2	99
Total	11	29	44	11	69	75	66	4	57	16	16	4	21	84	5	2	514
10:00 AM	4	4	9	7	12	10	15	1	9	10	3	0	2	11	3	1	101
10:15 AM	0	9	10	3	11	15	7	1	14	8	4	0	5	22	3	3	115
10:30 AM	3	6	6	3	11	26	9	1	12	11	4	2	3	20	1	4	122
10:45 AM	2	11	8	3	13	14	12	0	12	6	6	1	5	11	1	0	105
Total	9	30	33	16	47	65	43	3	47	35	17	3	15	64	8	8	443
11:00 AM	1	8	13	0	10	17	2	0	15	10	2	2	2	10	1	1	94
11:15 AM	1	7	7	2	17	17	14	0	10	9	3	0	7	16	2	1	113
11:30 AM	1	9	9	3	11	30	8	2	5	17	4	1	6	20	3	0	129
11:45 AM	2	4	10	1	17	15	7	3	16	8	10	1	5	18	0	0	117
Total	5	28	39	6	55	79	31	5	46	44	19	4	20	64	6	2	453
12:00 PM	3	12	12	1	15	24	7	2	18	12	6	0	2	18	1	2	135
12:15 PM	1	16	15	0	11	20	8	0	9	15	2	3	4	16	1	2	123
12:30 PM	0	10	0	0	0	76	0	0	0	16	0	0	1	65	0	0	168
12:45 PM	1	23	19	0	14	27	11	0	10	13	3	0	2	11	7	0	141
Total	5	61	46	1	40	147	26	2	37	56	11	3	9	110	9	4	567
	29th Av SE From North				Como Av SE From East				29th Av SE From South				Como Av SE From West				
Start Time	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Int. Total
Factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
01:00 PM	2	18	16	0	20	16	10	3	22	19	2	0	7	21	1	0	157
01:15 PM	4	14	20	1	22	26	7	2	8	6	6	1	6	13	1	2	139
01:30 PM	2	16	20	0	23	26	18	0	15	15	6	1	10	28	5	0	185
01:45 PM	4	9	15	1	24	26	16	2	10	9	2	0	4	24	0	2	148
Total	12	57	71	2	89	94	51	7	55	49	16	2	27	86	7	4	629
02:00 PM	1	22	13	2	30	22	18	0	23	13	2	3	4	40	3	7	203
02:15 PM	0	15	11	2	13	21	18	1	14	20	3	0	4	22	0	1	145
02:30 PM	3	18	18	0	26	23	14	2	35	42	3	3	4	16	0	1	208
02:45 PM	2	11	7	0	20	17	18	1	38	25	3	0	6	20	5	3	176
Total	6	66	49	4	89	83	68	4	110	100	11	6	18	98	8	12	732
03:00 PM	2	16	18	0	12	11	17	0	9	15	1	3	11	32	2	10	159
03:15 PM	2	8	10	0	21	26	7	0	27	43	5	2	16	20	3	11	201
03:30 PM	2	4	16	3	21	34	7	0	38	24	5	1	3	45	4	1	208
03:45 PM	1	5	17	2	17	21	8	0	15	15	3	4	2	15	8	3	136
Total	7	33	61	5	71	92	39	0	89	97	14	10	32	112	17	25	704
04:00 PM	1	7	14	1	15	15	4	2	13	13	2	2	3	22	2	1	117
04:15 PM	0	3	5	0	10	13	4	0	2	3	0	1	0	18	1	0	60
04:30 PM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04:45 PM	0	19	9	0	19	23	2	5	10	11	0	0	1	18	1	0	118
Total	1	29	28	1	44	51	10	7	25	27	2	3	4	58	4	1	295
05:00 PM	4	13	12	1	42	31	1	2	15	17	0	0	1	20	8	2	169
05:15 PM	2	4	13	1	27	24	1	3	8	5	3	0	1	23	3	3	121
05:30 PM	2	2	13	3	15	24	1	0	5	3	0	0	1	31	1	1	102
05:45 PM	5	1	10	0	9	22	0	1	2	2	1	0	1	29	2	5	90
Total	13	20	48	5	93	101	3	6	30	27	4	0	4	103	14	11	482
06:00 PM	3	6	13	3	14	28	0	2	9	2	0	3	2	26	2	7	120
06:15 PM	0	4	14	0	8	24	1	7	1	3	0	0	2	27	1	1	93
06:30 PM	0	0	10	0	11	23	4	0	2	2	0	0	0	23	0	4	79
06:45 PM	4	3	2	0	17	29	1	0	0	0	0	0	2	20	1	0	79
Total	7	13	39	3	50	104	6	9	12	7	0	3	6	96	4	12	371
Grand Total	114	560	606	80	769	1064	467	54	612	518	155	50	178	1054	85	94	6460
Apprch %	8.4	41.2	44.6	5.9	32.7	45.2	19.8	2.3	45.8	38.8	11.6	3.7	12.6	74.7	6	6.7	
Total %	1.8	8.7	9.4	1.2	11.9	16.5	7.2	0.8	9.5	8	2.4	0.8	2.8	16.3	1.3	1.5	

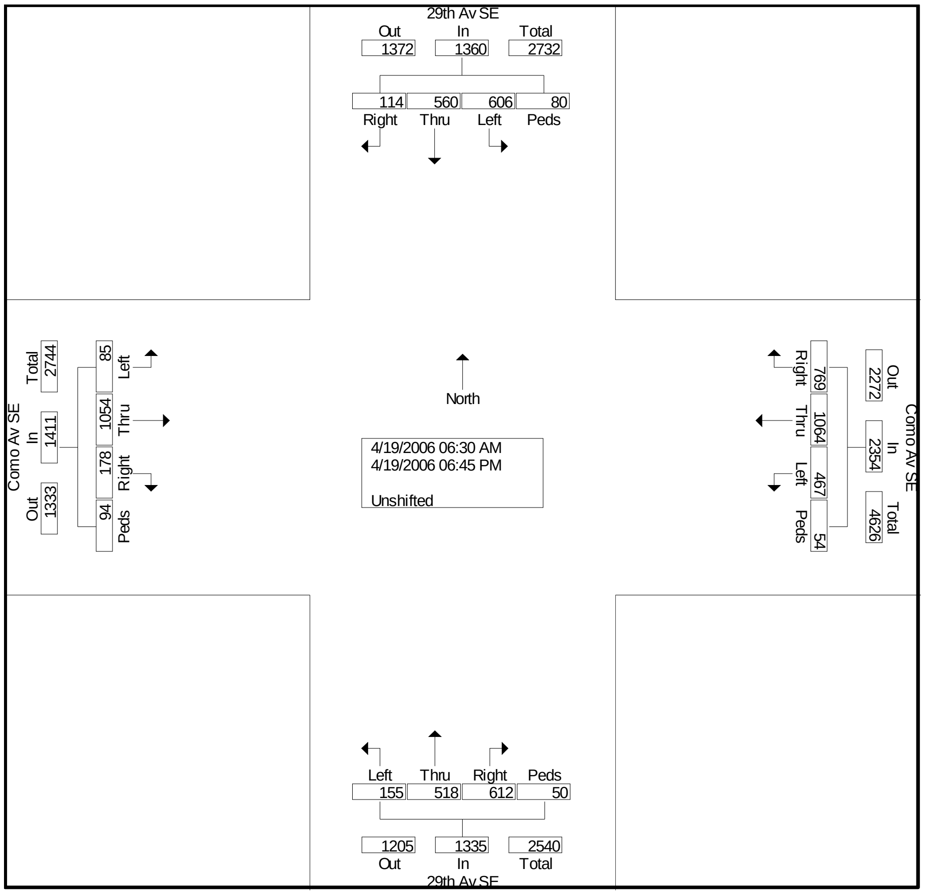


Figure B.1 Average Volume at Como and 29th Avenue

APPENDIX C

EMBEDDED COMPUTER SYSTEMS

C.1 CPU Board

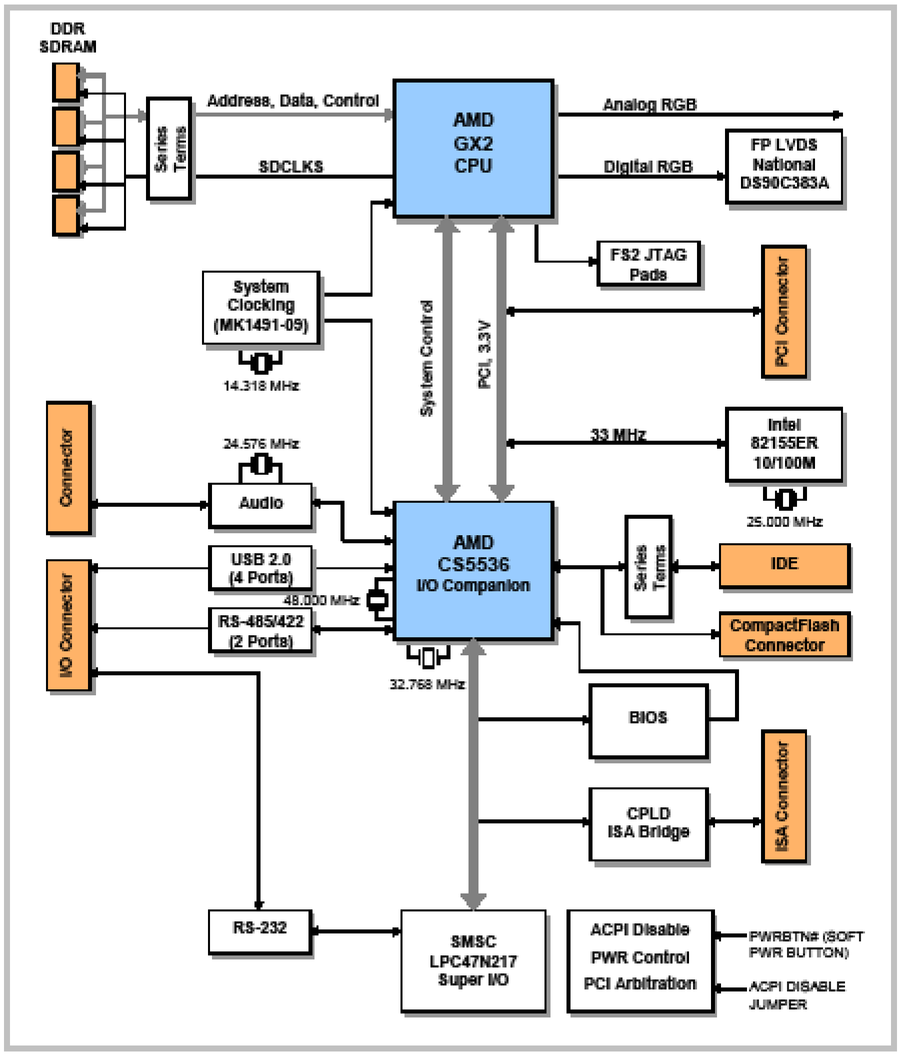


Figure C.1 EPM-5 Block Diagram (VersaLogic EPM-5 Reference Manual)

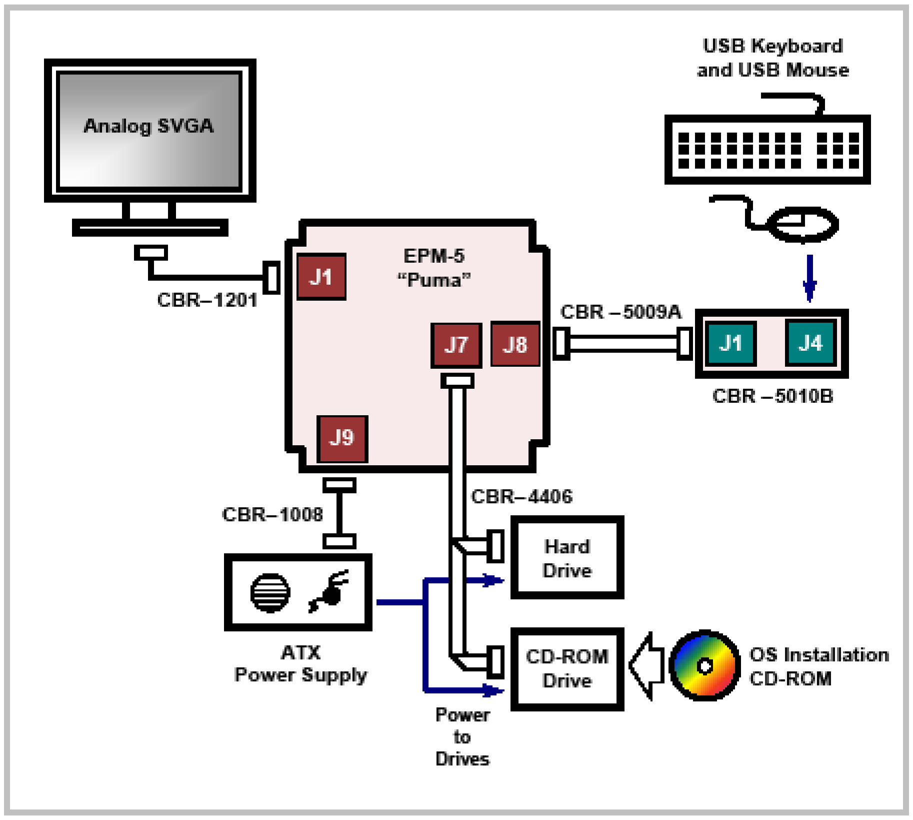


Figure C.2 EPM-5 Start Configuration (VersaLogic EPM-5 Reference Manual)

C.2 Digital I/O Board – R104-88

C.2.1 Relay Output Control

The 8 relays are accessed through I/O memory writes. The relays are grouped in set of four and the group I/O memory address is an offset from the base decode address. Relays are grouped as follows.

Group 1: Output DO1 to DO4	I/O address = Base Address
Group 2: Output DO5 to DO8	I/O address = Base Address + 1

The relays are bit mapped to the lower four data lines in each group as follows.

Relay	SD3	SD2	SD1	SD0
Group 1	Relay4	Relay3	Relay2	Relay1
Group 2	Relay8	Relay7	Relay6	Relay5

C.2.2 Digital Input Reading

The 8 digital inputs are accessed though I/O memory reads. The inputs are grouped in sets of four and the group I/O memory address is an offset from the base address. Inputs are grouped as follows.

Group 1: Output DI1 to DI4	I/O address = Base Address + 2
Group 2: Output DI5 to DI8	I/O address = Base Address + 3

The inputs are bit mapped to the lower four data lines in each group as follows.

Digital Input	SD3	SD2	SD1	SD0
Group 1	Input4	Input3	Input2	Input1
Group 2	Input8	Input7	Input6	Input5

<u>C.2.3 Base Address Settings</u>

There are four decode base addresses, which are jumper selectable from the address select block J18.

Base Address	J18-1	J18-2
240H	Jumper Not Installed	Jumper Not Installed
260H	Jumper Installed	Jumper Not Installed
280H	Jumper Not Installed	Jumper Installed
300H	Jumper Installed	Jumper Installed

C.3 Connection to Signal Controller Cabinet

The wiring diagram of the connection between the relay output and the controller cabinet is illustrated in Figure C.3.

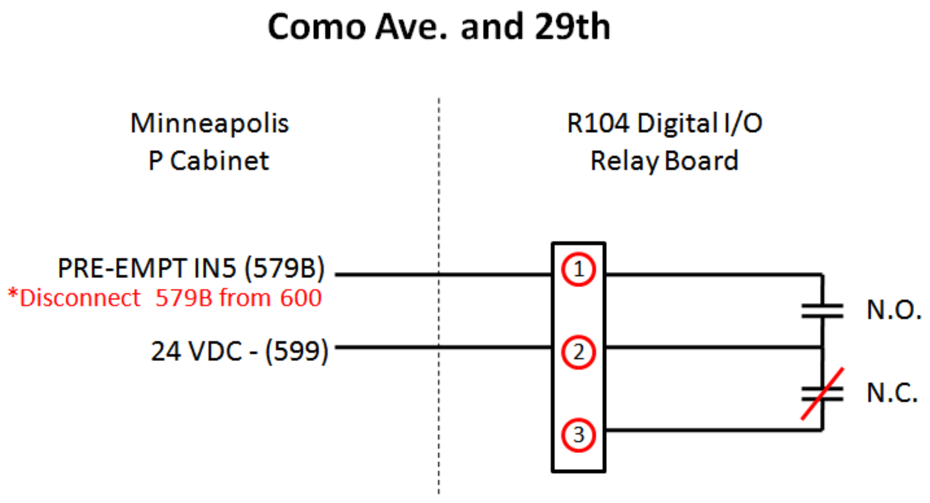
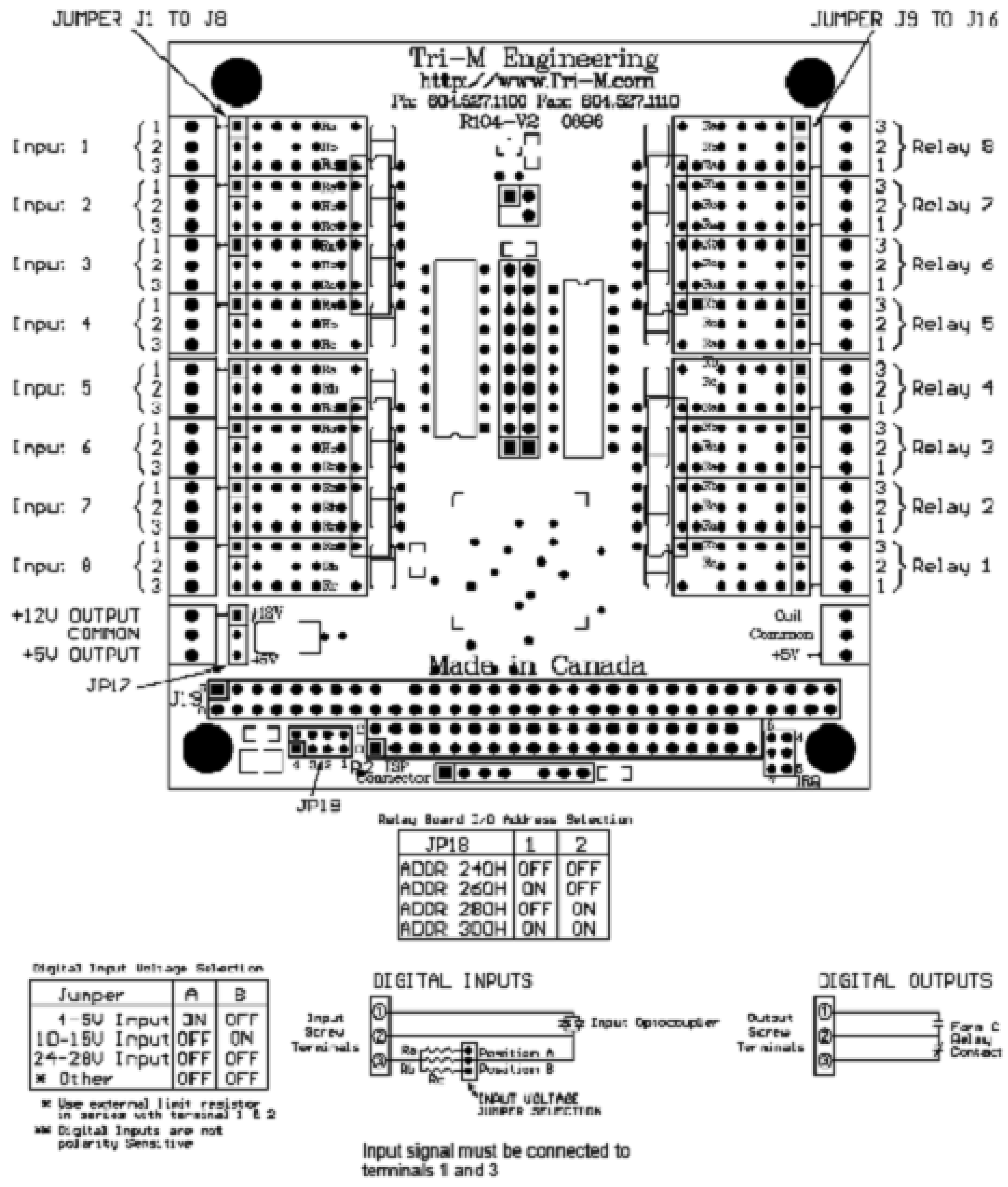


Figure C.3 Connect Relay Output to Controller Cabinet



Relay Board I/O Address Selection

JP18	1	2
ADDR 240H	OFF	OFF
ADDR 260H	ON	OFF
ADDR 280H	OFF	ON
ADDR 300H	ON	ON

Digital Input Voltage Selection

Jumper	A	B
4-5V Input	ON	OFF
10-15V Input	OFF	ON
24-28V Input	OFF	OFF
* Other	OFF	OFF

* Use external limit resistor in series with terminal 1 & 2

** Digital Inputs are not polarity Sensitive

Input signal must be connected to terminals 1 and 3

Figure C.4 R104 Digital I/O Relay Board Layout (Tri-M Engineering R104-88 User Guide)

C.4 Instructions to Build Debian Linux Kernel

1. Install Debian Linux on a development PC

2. apt-cache -search debootstrap
   apt-cache -install debootstrap

3. cd debian_bus
   run ./buildroot hud   # build kernel image script

4. edit files after finished without error

   edit(vim) device.map and menu.list under ~debian_bus/hud-root/boot/grub/ directory

   edit(vim) fstab under ~debian_bus/hut-root/etc/
   change "defaults,ro" to "defaults,errors=remount-ro"
   with corresponding boot drive /dev/hda1 (PUma board), (or /dev/hdc1 for Cobra)

5. modify ~debian_bus/hud-root/etc/rc.local for program execution after bootup

6. format CF disk
   mount CF, #mount /dev/sda1 /media/usbdisk

   format CF, use command #gparted, if auto mounted, unmount first
   GNOME File menu, Partition->umount
   delete old fat16 partition, , Partition->delete
   check "boot" in Partition->manage flags
   create new partition to EXT3 as Primary partition
   if error, unmount and reformat again

   use "df -h" to view disk files

7. copy directories
   cp -r ~hud-root/* /media/usbdisk/
   sync   # sync flash with CF

8. remove the /media/usbdisk/boot/grub/devices.map
   rm /media/usbdisk/boot/grub/devices.map

9. install grub loader
   sudo grub-install --root-diectory=/media/usbdisk /dev/sda1

   # Note: grub-install wants to install on the computer running it
   and the devices.map does not match the running computer, so it
   complains. If you look at the devices.map file right after grub install
   it will match your computer. - compare /boot/grub/devices.map
   to /media/usbdisk/boot/grub/devices.map. Which is wrong, so you have to
   recopy the file from hud-root/boot/grub to the usbdisk.

10. cp ~debian_bus/hud-root/boot/grub/devices.map /media/usbdisk/boot/grub/.

APPENDIX D

BUS ROUTE #3 TRIP DATA

D.1 Route #3 Trip Counts

Table D.1 Bus Route #3 Trip Counts

	Count of Trips								
	SUN			SAT			WK		
hour	East	West	SUN Total	East	West	SAT Total	East	West	WK Total
0	1	1	2	1	1	2	1	1	2
1	1		1	1	1	2	1	1	2
4							1		1
5				2		2	2	1	3
6	1	1	2	2	1	3	4	4	8
7	2	1	3	2	2	4	4	13	17
8	2	1	3	2	2	4	3	13	16
9	2	2	4	2	2	4	4	12	16
10	2	2	4	2	2	4	5	9	14
11	2	2	4	2	2	4	7	6	13
12	2	2	4	2	2	4	7	7	14
13	2	2	4	2	2	4	7	6	13
14	2	2	4	2	2	4	8	5	13
15	2	2	4	2	2	4	10	5	15
16	2	2	4	2	2	4	9	6	15
17	2	2	4	2	2	4	11	5	16
18	2	2	4	2	2	4	6	5	11
19	2	2	4	2	2	4	4	4	8
20	2	2	4	2	2	4	5	4	9
21	2	2	4	2	2	4	4	2	6
22	1	2	3	2	2	4	2	2	4
23	1	1	2	1	2	3	2	2	4
Grand Total	35	33	68	39	37	76	107	113	220

D.2 Map of Bus Route #3

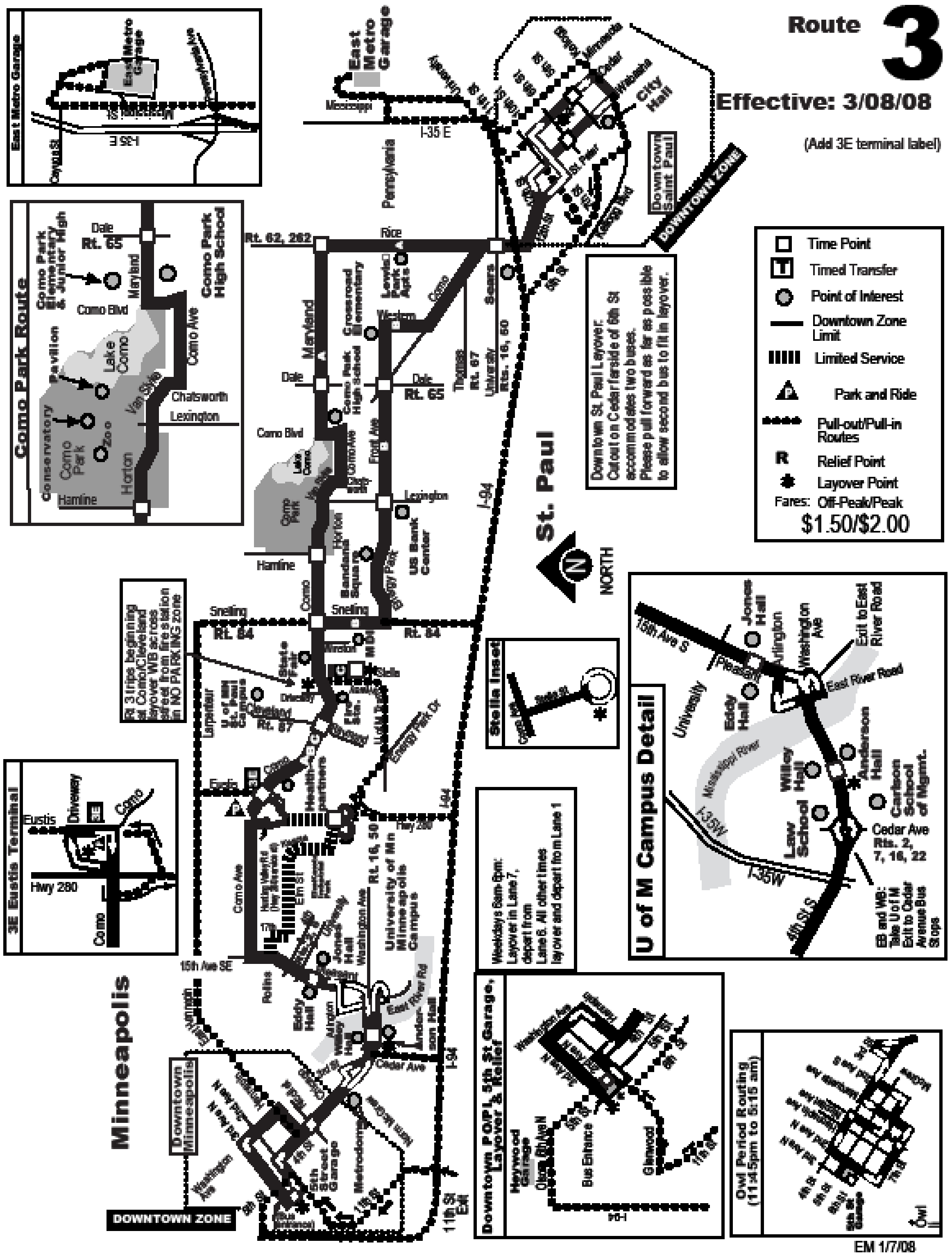

Route 3
Effective: 3/08/08
(Add 3E terminal label)
Time Point
Timed Transfer
Point of Interest
Downtown Zone Limit
Limited Service
Park and Ride
Pull-out/Pull-in Routes
Relief Point
Layover Point
Fares: Off-Peak/Peak
$1.50/$2.00
St. Paul
Minneapolis
DOWNTOWN ZONE
Downtown Saint Paul
Downtown Minneapolis
East Metro Garage
Como Park Route
3E Eustis Terminal
Stella Inset
U of M Campus Detail
Owl Period Routing (11:45pm to 5:15 am)
Downtown POP/ 5th St Garage, Layover & Relief
Downtown St Paul Layover: Cutout on Cedar farside of 6th St accommodates two buses. Please pull forward as far as possible to allow second bus to fit in layover.
Rt 3 trips beginning at Como/Cleveland layover WB across street from fire station in NO PARKING zone
Weekdays 6am-6pm: Layover in Lane 7, depart from Lane 8. All other times layover and depart from Lane 1
EB and WB: Take U of M Exit to Cedar Avenue Bus Stops
Rt. 62, 262
Rt. 65
Rt. 84
Rt. 87
Rts. 16, 50
Rts. 2, 7, 16, 22
I-94
I-35 E
I-35W
NORTH
EM 1/7/08

Figure D.1 Map of Route #3

APPENDIX E

WIRELESS DEVICES

E.1 Denso DSRC Wireless Modems

Figure E.1 Denso DSRC Prototype

E.2 LynkSys 802.11 Wireless Modules

Figure E.2 LinkSys Wireless-N USB Network Adapter

E.3 Steps to Install Module Assistant and Ndiswrapper

E.3.1 Modify the sources files

```
/etc/apt/sources.list

deb http://http.us.debian.org/debian etch main contrib non-free
deb http://security.debian.org stable/updates main contrib non-free
```

E.3.2 Install/compile ndiswrapper

Code:
```
su
apt-get update
```

```
apt-get dist-upgrade
apt-get install module-assistant ndiswrapper-source ndiswrapper-utils
m-a prepare
m-a a-i ndiswrapper
```

E.3.3 Install the driver

Code:

```
ndiswrapper -i /home/student/Driver/xp_2k/<name>.inf
ndiswrapper -m
ndiswrapper -l
```

E.3.4 Insert the module

Code:

```
modprobe ndiswrapper
```

There should be no error messages from the modprobe command. If necessary, add ndiswrapper to /etc/modules for automatic insertion at boot. Next insert the wireless device, if you haven't already, and watch what happens with one or more of the commands

```
iwconfig
iwlist scan
ifconfig
exit
```

That ifconfig command should show the wireless wlan0 (or ra0, etc) interface, although not yet configured... but that's another story. Just a hint: if you plan on using WPA security (you really should), then specify the wext driver with wpa_supplicant, not the ndiswrapper driver...

E.3.5 Command samples

- Configure wlan0 interface to connect to UMN-TSP network
  `iwconfig wlan0 essid “UMN-TSP”`
- Scan and list available wireless network
  `iwlist wlan0 scan`
- Request for IP through wlan0 interface
  `dhclient wlan0`
- Remove dhclient file/process
  `dhclient -r`

E.4 Test University Wireless Network Using WUSB300N Adapters

Connect WUSB300N to the USB drive.
Ensure that there is enough signal strength and verify by looking at the blue signal shown in the device

E.4.1 Authentication Script for connecting with U of M wireless network

In the connection script, after line key <space> specify your student id and password for every alphabets.

Below is the example for following user ID:

Username: xxx
Password: xxx

```
# Command logfile created by Lynx 2.8.5rel.1 (04 Feb 2007)
# Arg0 = lynx
# Arg1 = -accept_all_cookies
# Arg2 = -cmd_script = myCommandScript
# Arg3 = www.google.com
key y
key <space>
key s
key t
key u
key d
key x
key 0
key 8
key ^J
key t
key s
key p
key P
key r
key o
key j
key %
key 1
key ^J
key ^J
key y
key Down Arrow
key Right Arrow
key :
key q
key ^J
key y
```

Save the above script in a file called connect.
After receiving an IP address from the UofM wireless network, execute command at the prompt

```
lynx -accept_all_cookies -cmd_script = myConnectScript www.google.com
```

This should allow you to connect to the UofM Wireless network.

E.4.2 Automatic script generated by the lynx

Go to /home/scripts. If scripts directory does not exists then create a folder under home.
After receiving an IP address from the UofM wireless network, execute command at the prompt :~$>. The user could also create a new connection script by specifying the following command.

```
:-~$> lynx -accept_all_cookies -cmd_log = myLogScript  www.google.com
```

Note: When invoking the google.com link, the connection could automatically bring the wireless network access authentication UI.

Specify UMN X500 Userid and Password when prompted.

This should allow you to connect to the UofM Wireless network.
All the logging sequence of commands would be saved in the filename as specified with the option *myLogScript*.

Next time after rebooting, use the same script for calling the command

```
:~$> lynx -accept_all_cookies -cmd_script = myLogScript www.google.com
```

User can also execute the following script file, myExtIP.sh, to obtain external IP address when using the Minneapolis wireless network.

```
#!/bin/bash
wget www.whatismyip.com/automation/n09230945.asp -O - -o /dev/null
echo
exit 0
```

Execute this at the command prompt of the target machine.

This would allow you to get the external IP address

Start the communication between both the devices.

E.5 Test Minneapolis Wi-Fi Network Using Ruckus Modems

Steps:

Connect the ruckus modem to the Ethernet port.

Ensure that the modem is powered on and has enough strength.
Note that this modem would work only for USI wireless network.

Ensure that the interfaces file has the following details.

```
# This file describes the network interfaces available on your system
# and how to activate them. For more information, see interfaces(5).

# The loopback network interface
auto lo
iface lo inet loopback

# The primary network interface

auto eth0
iface eth0 inet dhcp
```

After starting the machine, one should notice that the machine gets connected to the USI wireless network automatically.

After this create a file called myExtIP.sh

```
#!/bin/bash
wget www.whatismyip.com/automation/n09230945.asp -O - -o /dev/null
echo
exit 0
```

Execute this at the command prompt of the target machine.

This would allow you to know the IP address

Start the communication between both the devices.

APPENDIX F

SERIAL COMMUNICATION WITH THE EPAC-M40 TRAFFIC CONTROLLER

In order to communicate with the traffic controller and read its data, we monitored the serial communication carried out by the MarcNX software with the device. The MarcNX software was provided by the SEIMENS Ltd.

MarcNX software obtains phase data by carrying out multiple combinations of commands (namely Write, Set RTS, Clear RTS, Read and Set timeouts) within an iterative loop.

The communication for obtaining phase data is a 2-way mode where in the software performs the "write operation" by writing a certain data characters and waits for the device to write the same piece of information. This whole operation happens in a timeout mode. However the serial monitor software which i am using can capture only the first 100 bytes of data in every operation.

Due to loss of the protocol information describing the frame format, memory location, command, checksums etc, and our study could not reveal the proper commands to communicate with the device. We captured new upload session for Phase Value of 6s and 7s. The “Advanced Serial Port Monitor” tool from AGG Software is used to check the flow of data through computer’s serial COM port. The serial port analyzer is used to control and monitor serial devices right from the PC. It supports data input and monitoring in Hexadecimal, Decimal, Octal, Binary and ASCII formats. It also allows user to change or monitor RS-232's line states.

Serial Port Monitor:
http://www.aggsoft.com/serial-port-monitor.htm

232 Analyzer for sending the commands:
http://www.232analyzer.com/232default.htm

Here is the Hex data for the above communication along with the difference in the packet content.

F.1 Hex Dump for Phase Value of Six

```
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX>#2F<DLE><ETX>#5C#31
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#25#D1<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#3F#29
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4>#2F<DLE><ETX><ESC>#69
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#25#D1<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#3F#29
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><NUL><DLE><ETX>#B8#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><NUL><NUL>#3C<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<DLE><DLE><NUL><NUL>#40#40<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#B7#F3
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
```

```
<DLE>#30
<DLE><STX><EM><DC4><ACK><SOH><DLE><ETX>#B9#A2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><SOH><NUL>#78<NUL><NUL><NUL>#96<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX
>#84<ETX>#84<NUL>#50<NUL>#8C<NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL>#4F<DLE><DLE>#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#2D#44
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><STX><DLE><ETX>#B9#52
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><STX><NUL>#96<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH>
#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>#
20<NUL><NUL>#40#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#A3#F7
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><ETX><DLE><ETX>#B8#C2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><ETX><NUL>#78<NUL><NUL><NUL>#64<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX>
#84<ETX>#84<NUL>#50<NUL>#8C<NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL>#4F<DLE><DLE>#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#C1#68
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><EOT><DLE><ETX>#BA#F2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><EOT><NUL>#3C<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
#30<NUL><NUL>#40#40<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#22#5C
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><ENQ><DLE><ETX>#BB#62
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><ENQ><NUL>#96<NUL><NUL><NUL>#96<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX
>#84<ETX>#84<NUL>#50<NUL>#8C<NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL>#4F<DLE><DLE>#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#32#B7
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><ACK><DLE><ETX>#BB#92
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><ACK><NUL>#3C<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
#40<NUL><NUL>#40#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#77#82
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><BEL><DLE><ETX>#BA<STX>
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><BEL><NUL>#3C<NUL><NUL><NUL>#64<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX
>#84<ETX>#84<NUL>#50<NUL>#8C<NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL>#4F<DLE><DLE>#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#DF#71
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
```

```
<DLE>#30
<DLE><STX><EM><DC4><ACK><BS><DLE><ETX>#BF#F2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><BS><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#F6#83
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><HT><DLE><ETX>#BE#62
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><HT><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#3E#7A
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><LF><DLE><ETX>#BE#92
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><LF><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#2D#78
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><VT><DLE><ETX>#BF<STX>
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><VT><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#E5#81
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><FF><DLE><ETX>#BD#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><FF><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#43#34
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><CR><DLE><ETX>#BC#A2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><CR><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#8B#CD
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><SO><DLE><ETX>#BC#52
<DLE>#31
<EOT>#61#30#30<ENQ>
```

```
<DLE><STX><ACK><SO><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#98#CF
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><SI><DLE><ETX>#BD#C2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><SI><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#50#36
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#20<DLE><ETX>#A1#F2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#20<NUL><NUL><NUL><NUL><BS><NUL><NUL><NUL><NUL><NUL><DLE><DLE><NUL><NUL><N
UL><NUL><NUL><CAN><NUL><NUL><NUL><NUL><NUL>#20<NUL><NUL><NUL><NUL><NUL>#28<NUL><NUL><NUL>
<NUL><NUL>#30<NUL><NUL><NUL><NUL><NUL>#38<NUL><NUL><NUL><NUL><NUL>#40<NUL><DLE><ETX>#CC#A5
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#21<DLE><ETX>#A0#62
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#21<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#C5#8D
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#22<DLE><ETX>#A0#92
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#22<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#F2#AB
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#23<DLE><ETX>#A1<STX>
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#23<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX><RS>#76
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#24<DLE><ETX>#A3#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#24<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#9C#E7
<DLE>#30
```

```
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#25<DLE><ETX>#A2#A2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#25<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#70#3A
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#26<DLE><ETX>#A2#52
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#26<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#47<FS>
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#27<DLE><ETX>#A3#C2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#27<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#AB#C1
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#28<DLE><ETX>#A6#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#28<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#40#7F
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#29<DLE><ETX>#A7#A2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#29<NUL><NUL><NUL><NUL>#78<EOT><NUL><NUL><NUL><NUL><DLE><DLE><EOT><NUL><NU
L><NUL><NUL><CAN><EOT><NUL><NUL><NUL><NUL>#20<EOT><NUL><NUL><NUL><NUL>#28<EOT><NUL><NUL><
NUL><NUL>#30<EOT><NUL><NUL><NUL><NUL>#38<EOT><NUL><NUL><NUL><NUL>#40<EOT><DLE><ETX>#4A#35
<DLE>#30
<EOT>
```

F.2 Hex Dump for Phase Value Seven

```
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX>#2F<DLE><ETX>#5C#31
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#2F#AB<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#C6#D2
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
```

```
<DLE><STX><EM><DC4>#2F<DLE><ETX><ESC>#69
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#2F#AB<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#C6#D2
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><NUL><DLE><ETX>#B8#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><NUL><NUL>#46<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<DLE><DLE><NUL><NUL>#40#40<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#5C#A2
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><SOH><DLE><ETX>#B9#A2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><SOH><NUL>#78<NUL><NUL><NUL>#96<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX
>#84<ETX>#84<NUL>#50<NUL>#8C<NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL>#4F<DLE><DLE>#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#2D#44
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><STX><DLE><ETX>#B9#52
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><STX><NUL>#96<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH>
#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>#
20<NUL><NUL>#40#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#A3#F7
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><ETX><DLE><ETX>#B8#C2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><ETX><NUL>#78<NUL><NUL><NUL>#64<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX>
#84<ETX>#84<NUL>#50<NUL>#8C<NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL>#4F<DLE><DLE>#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#C1#68
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><EOT><DLE><ETX>#BA#F2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><EOT><NUL>#3C<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
#30<NUL><NUL>#40#40<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#22#5C
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><ENQ><DLE><ETX>#BB#62
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><ENQ><NUL>#96<NUL><NUL><NUL>#96<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX
>#84<ETX>#84<NUL>#50<NUL>#8C<NUL>
#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>#4F<DLE><DLE>#20<NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#32#B7
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
```

```
<DLE><STX><EM><DC4><ACK><ACK><DLE><ETX>#BB#92
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><ACK><NUL>#3C<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
#40<NUL><NUL>#40#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#77#82
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><BEL><DLE><ETX>#BA<STX>
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><BEL><NUL>#3C<NUL><NUL><NUL>#64<NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><ETX
>#84<ETX>#84<NUL>#50<NUL>#8C<NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL>#4F<DLE><DLE>#20<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#DF#71
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><BS><DLE><ETX>#BF#F2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><BS><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#F6#83
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><HT><DLE><ETX>#BE#62
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><HT><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
N
UL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#
3E#7A
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><LF><DLE><ETX>#BE#92
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><LF><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#2D#78
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><VT><DLE><ETX>#BF<STX>
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><VT><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#E5#81
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><FF><DLE><ETX>#BD#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><FF><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#43#34
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><CR><DLE><ETX>#BC#A2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><CR><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#8B#CD

<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><SO><DLE><ETX>#BC#52
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><SO><NUL><DC4><NUL><NUL><NUL><NUL><NUL><RS><NUL><NUL><NUL><NUL><NUL><NUL>
<NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#98#CF
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK><SI><DLE><ETX>#BD#C2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK><SI><NUL><DC4><NUL><NUL><NUL><NUL><NUL><LF><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><DC4><NUL><DC4><NUL><NUL><NUL><NUL><NUL>#28<NUL><DC4><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX
>#50#36
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#20<DLE><ETX>#A1#F2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#20<NUL><NUL><NUL><NUL><BS><NUL><NUL><NUL><NUL><NUL><DLE><DLE><NUL><NUL><N
UL><NUL><NUL><CAN><NUL><NUL><NUL><NUL><NUL>#20<NUL><NUL><NUL><NUL><NUL>#28<NUL><NUL><NUL>
<NUL><NUL>#30<NUL><NUL><NUL><NUL><NUL>#38<NUL><NUL><NUL><NUL><NUL>#40<NUL><DLE><ETX>#CC#A5
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#21<DLE><ETX>#A0#62
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#21<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#C5#8D
<DLE>#30
<EOT>

<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#22<DLE><ETX>#A0#92
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#22<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#F2#AB
<DLE>#30
```

```
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#23<DLE><ETX>#A1<STX>
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#23<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX><RS>#76
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#24<DLE><ETX>#A3#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#24<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#9C#E7
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#25<DLE><ETX>#A2#A2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#25<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#70#3A
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#26<DLE><ETX>#A2#52
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#26<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#47<FS>
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#27<DLE><ETX>#A3#C2
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#27<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#AB#C1
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#28<DLE><ETX>#A6#32
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#28<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><
NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL
><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><E
TX>#40#7F
<DLE>#30
<EOT>
<EOT>#41#30#30<ENQ>
<DLE>#30
<DLE><STX><EM><DC4><ACK>#29<DLE><ETX>#A7#A2
```

```
<DLE>#31
<EOT>#61#30#30<ENQ>
<DLE><STX><ACK>#29<NUL><NUL><NUL><NUL>#78<EOT><NUL><NUL><NUL><NUL><DLE><DLE><EOT><NUL><NU
L><NUL><NUL><CAN><EOT><NUL><NUL><NUL><NUL>#20<EOT><NUL><NUL><NUL><NUL>#28<EOT><NUL><NUL><
NUL><NUL>#30<EOT><NUL><NUL><NUL><NUL>#38<EOT><NUL><NUL><NUL><NUL>#40<EOT><DLE><ETX>#4A#35
<DLE>#30
<EOT>
```

F.3 Difference in Above Two Dumps

```
Compare: (<)C:\TSP\EagleController\9th Jan\10th Jan\New Record\HexVal7.txt (10757 bytes)
   with: (>)C:\TSP\EagleController\9th Jan\10th Jan\New Record\HexVal6.txt (10757 bytes)

6c6
<
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#2F#AB<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#C6#D2
---
>
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#25#D1<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#3F#29
14c14
<
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#2F#AB<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#C6#D2
---
>
<DLE><STX>#2F<NUL><DC4>#33#31#33<DC1>#5C#25<NUL><NUL><NUL><NUL><FF>#25#D1<SOH>#39<NUL><NUL>
<NUL><NUL><DLE><ETX>#3F#29
22c22
<
<DLE><STX><ACK><NUL><NUL>#46<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<DLE><DLE><NUL><NUL>#40#40<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#5C#A2
---
>
<DLE><STX><ACK><NUL><NUL>#3C<NUL><NUL><NUL>#3C<NUL><RS><NUL><NUL><NUL><NUL><NUL><RS><SOH
>#2C<SOH>#2C<NUL><NUL><NUL><NUL><NUL>#23<NUL><GS><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL>
<DLE><DLE><NUL><NUL>#40#40<NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><NUL><DLE><ETX>#B7#F3
```

F.4 Device Communications

We tried with the following values for communicating with the traffic controller

```
<EOT>A00<ENQ>
Got Reply as
<DLE>0<DLE>

<EOT><a00><ENQ>
Got Reply as
0

<STX>/<DLE><ETX>\1
No Reply.
```

APPENDIX G

GARMIN GPS RECEIVER

G.1 Garmin GPS 18 Descriptions

The GPS 18 5Hz is an OEM, GPS sensor for use in machine control, guidance and agricultural applications that require 5 Hz position and velocity reports from a small, highly accurate GPS receiver. This 12-parallel-channel, WAAS-enabled GPS comes with an integrated magnetic base for easy mounting. The puck-like receiver is 2.4 inches in diameter and weighs just a few ounces, making it an ideal solution for applications where space is at a premium. The GPS 18 5Hz stores configuration information in non-volatile memory so it starts up quickly each time you use it. It also has a real-time clock and raw measurement output data for sophisticated, high-precision dynamic applications. For extra precision, it offers 5 Hz Measurement Pulse Output with rising edges that align to precise 0.2 second increments of UTC time, as long as the receiver has reported a valid and accurate position within the past 4 seconds.

Figure G.1 Garmin GPS 18 5Hz Unit

G.2 Test Interface

A test program with Graphical User Interface (GUI), as shown in Figure G.2, was initially developed to test and validate the features and functionalities of the Garmin 18 5 Hz GPS receiver. The Garmin 18 receiver has the following National Marine Electronics Association (NMEA) 0183 output sentences including GPALM, GPGGA, GPGSA, GPGSV, GRMC, GPVTG, GPGLL, PGRME, PGRMF, PGRMT, PGRMV, and PGRMB (Garmin proprietary sentences). Two sentences, GPGGA and GPVTG are used in this project to get the GPS position and ground speed. Please refer to Garmin user maul for more detail (http://www8.garmin.com/manuals/425_TechnicalSpecification.pdf).

G.2.1 Global Positioning System Fix Data (GGA)

Table G.1 GGA Sentence

$GPGGA,<1>,<2>,<3>,<4>,<5>,<6>,<7>,<8>,<9>,M,<10>,M,<11>,<12>*hh<CR><LF>

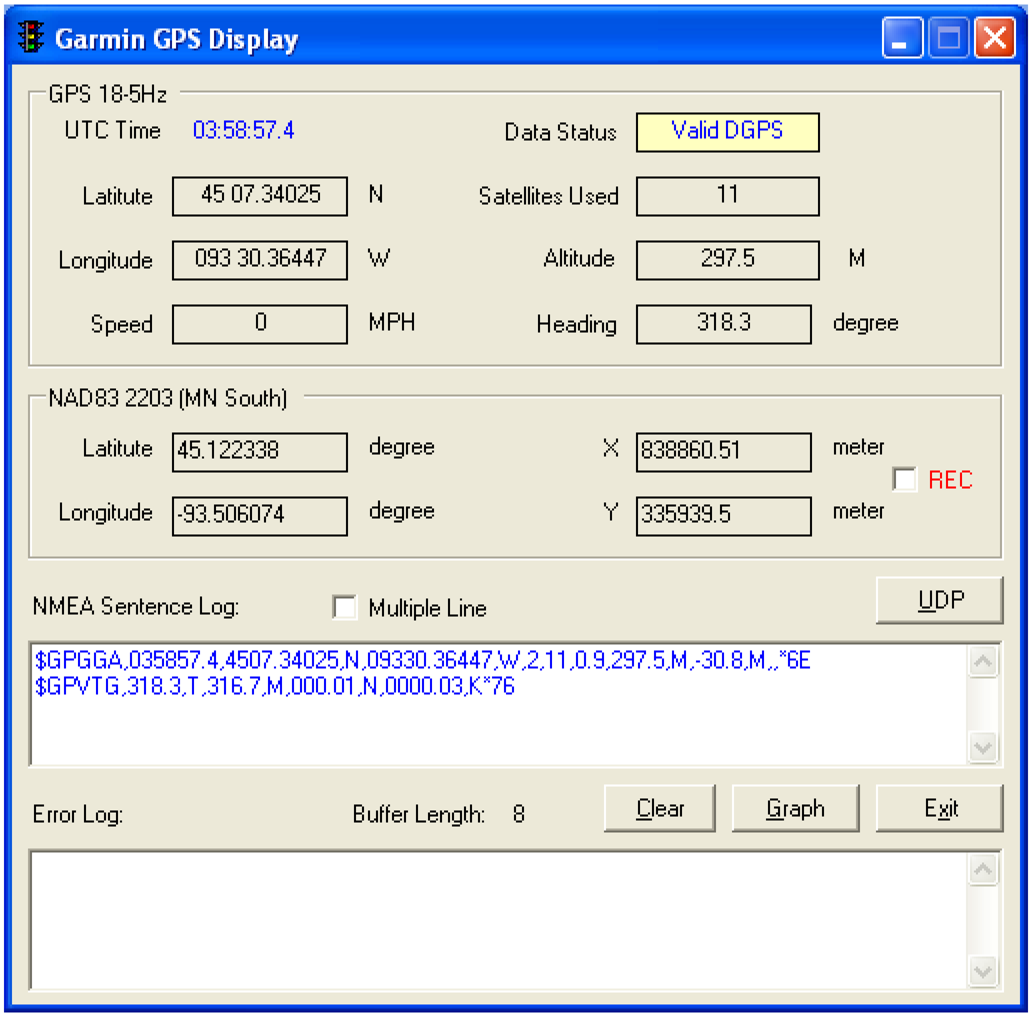
<1>	UTC time of position fix, hhmmss format for GPS 18 PC or LVC; hhmmss.s format for GPS 18-5Hz
<2>	Latitude, ddmm.mmmm format for GPS 18 PC/LVC; ddmm.mmmmm for GPS 18-5Hz (leading zeros will be transmitted)
<3>	Latitude hemisphere, N or S
<4>	Longitude, dddmm.mmmm format for GPS 18 PC/LVC; dddmm.mmmmm for GPS 18-5Hz (leading zeros will be transmitted)
<5>	Longitude hemisphere, E or W
<6>	GPS quality indication, 0 = fix not available, 1 = Non-differential GPS fix available, 2 = Differential GPS (WAAS) fix available, 6 = Estimated
<7>	Number of satellites in use, 00 to 12 (leading zeros will be transmitted)
<8>	Horizontal dilution of precision, 0.5 to 99.9
<9>	Antenna height above/below mean sea level, -9999.9 to 99999.9 meters
<10>	Geoidal height, -999.9 to 9999.9 meters
<11>	Null (Differential GPS
<12>	Null (Differential Reference Station ID)

G.2.2 Track Made Good and Ground Speed (VTG)

Table G.2 VTG Sentence

$GPVTG,<1>,T,<2>,M,<3>,N,<4>,K,<5>*hh<CR><LF>

<1>	True course over ground, GPS 18 PC and LVC: 000 to 359 degrees, GPS 18-5Hz: 000.0 to 359.0 degrees(leading zeros will be transmitted)
<2>	Magnetic course over ground, 000 to 359 degrees, GPS 18-5Hz: 000.0 to 359.0 degrees(leading zeros will be transmitted)
<3>	Speed over ground, GPS 18 PC and LVC: 000.0 to 999.9 knots, GPS 18-5Hz: 000.00 to 999.99 knots (leading zeros will be transmitted)
<4>	Speed over ground, GPS 18 PC and LVC: 0000.0 to 1851.8 kilometers per hour, GPS 18-5Hz: 0000.00 to 1851.89 (leading zeros will be transmitted)
<5>	Mode indicator (only output if NMEA 0183 version 2.30 active), A = Autonomous, D = Differential, E = Estimated, N = Data not valid



UTC Time 03:58:57.4
Data Status: Valid DGPS

Latitute	45 07.34025	N	Satellites Used	11	
Longitude	093 30.36447	W	Altitude	297.5	M
Speed	0	MPH	Heading	318.3	degree

Latitute	45.122338	degree	X	838860.51	meter
Longitude	-93.506074	degree	Y	335939.5	meter

NMEA Sentence Log:

```
$GPGGA,035857.4,4507.34025,N,09330.36447,W,2,11,0.9,297.5,M,-30.8,M,,*6E
$GPVTG,318.3,T,316.7,M,000.01,N,0000.03,K*76
```

Error Log:

Buffer Length: 8

Figure G.2 GPS Receiver Test Interface

G.2.3 GPS Test Interface GUI Source Code

```
Imports System.IO
Public Class GpsDisplay
    Inherits System.Windows.Forms.Form
    '    Dim dataRcvd(DATA_SIZE + 2) As Byte
    Public UTC_str As String
    Dim NMEA_type, Lat_str, NS_str, Long_str, EW_str As String
    Dim PFix_str, SatUsed_str, Alt_str, AltUnit_str As String
    Dim GPVTG_str, Heading_str, Knot_str As String
    Dim rcvdBuffer As String
    Dim gpsLat, gpsLong As Double
    Dim gpsLatLong As New Point2D
    Dim sentenceSize As Integer = 2

    'Dim recordSize As Integer
    '    Dim SPCS_XY As New Point2D

    Private Sub GpsDisplay_Load(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles MyBase.Load
        SPCS_XY = New Point2D
        rcvdBuffer = ""
        Timer1.Enabled = True
        recLatLongStr = ""
    End Sub

    Private Sub Timer1_Tick(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Timer1.Tick
        ' read serial buffer
        Dim header_i, header_j As Integer
        ' Read the NetworkStream into a byte buffer.
        ' Output the data received from iServer
        Dim iBytes, sent_i As Integer
        Dim receivedSentence, tmpStr As String
        For sent_i = 1 To sentenceSize
            iBytes = moRS232.Read(DATA_SIZE)
            rcvdBuffer += moRS232.InputStreamString
            header_i = rcvdBuffer.IndexOf("$")
            header_j = rcvdBuffer.IndexOf("$", header_i + 1)
            If header_i >= 0 And header_j > 0 And header_j > header_i Then
                receivedSentence = rcvdBuffer.Substring(header_i, header_j - header_i)
                rcvdBuffer = rcvdBuffer.Substring(header_j)
                lblBufLen.Text = rcvdBuffer.Length
            Else
                Exit Sub
            End If
            'dataRcvd = moRS232.InputStream
            If CheckBoxLog.Checked Or sent_i > 1 Then
                NMEAStr_Box.Text += receivedSentence
            Else
                NMEAStr_Box.Text = receivedSentence
            End If
            'NMEAStr_Box.SelectionStart = NMEAStr_Box.TextLength

            ' parse lat, long, alt etc.
            Dim st_idx, en_idx, i As Integer

            Try
                st_idx = 0
                en_idx = receivedSentence.IndexOf(",", st_idx)
                NMEA_type = receivedSentence.Substring(st_idx, en_idx - st_idx)
                If NMEA_type.IndexOf("GPRMC") > 0 Then
                    For i = 2 To 9
                        st_idx = en_idx + 1
                        en_idx = receivedSentence.IndexOf(",", st_idx)
                        If en_idx > 0 And st_idx <> en_idx Then
                            Select Case i
                                Case 1  ' sentence ID
                                    'NMEA_type = receivedSentence.Substring(st_idx, en_idx - st_idx)
                                Case 2  ' UTC time
                                    UTC_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    lblTime.Text = UTC_str.Substring(0, 2) + ":" + UTC_str.Substring(2, 2) + ":" + UTC_str.Substring(4)
                Case 3  'status
                    PFix_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    Select Case PFix_str
                        Case "V"
                            txtPFix.ForeColor = Color.Red
                            txtPFix.Text = "Invalid"
                        Case "A"
                            txtPFix.ForeColor = Color.Blue
                            txtPFix.Text = "Valid"
                    End Select
                Case 4  ' latitude
                    Lat_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    tmpStr = Lat_str.Substring(0, 2)
                    gpsLat = Convert2Double(tmpStr)
                    tmpStr = Lat_str.Substring(2)
                    gpsLat += Convert2Double(tmpStr) / 60
                    txtLat.Text = Lat_str.Substring(0, 2) + " " + Lat_str.Substring(2)
                Case 5  ' N/S indicator
                    NS_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    lblNS.Text = NS_str
                    If NS_str.IndexOf("S") >= 0 Then
                        gpsLat = -1 * gpsLat
                    End If
                Case 6  ' Longitude
                    Long_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    tmpStr = Long_str.Substring(0, 3)
                    gpsLong = Convert2Double(tmpStr)
                    tmpStr = Long_str.Substring(3)
                    gpsLong += Convert2Double(tmpStr) / 60
                    txtLong.Text = Long_str.Substring(0, 3) + " " + Long_str.Substring(3)
                Case 7  ' E/W indicator
                    EW_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    lblEW.Text = EW_str
                    If EW_str.IndexOf("W") >= 0 Then
                        gpsLong = -1 * gpsLong
                    End If
                Case 8  ' Speed
                    Knot_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    vehSpeed = Convert2Double(Knot_str) * 1.150779448 ' convert from knot to MPH
                    txtSpeed.Text = Convert.ToString(Convert.ToUInt16(vehSpeed))
                Case 9  ' course
                    Heading_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    txtHeading.Text = Heading_str

            End Select
        End If
    Next i
ElseIf NMEA_type.IndexOf("GPGGA") > 0 Then
    For i = 2 To 11
        st_idx = en_idx + 1
        en_idx = receivedSentence.IndexOf(",", st_idx)
        If en_idx > 0 Then
            Select Case i
                Case 1  ' sentence ID
                    'NMEA_type = receivedSentence.Substring(st_idx, en_idx - st_idx)
                Case 2  ' UTC time
                    UTC_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    lblTime.Text = UTC_str.Substring(0, 2) + ":" + UTC_str.Substring(2, 2) + ":" + UTC_str.Substring(4)
                Case 3  ' latitude
                    Lat_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    tmpStr = Lat_str.Substring(0, 2)
                    gpsLat = Convert2Double(tmpStr)
                    tmpStr = Lat_str.Substring(2)
                    gpsLat += Convert2Double(tmpStr) / 60
                    txtLat.Text = Lat_str.Substring(0, 2) + " " + Lat_str.Substring(2)
                Case 4  ' N/S indicator
                    NS_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                    lblNS.Text = NS_str
                    If NS_str.IndexOf("S") >= 0 Then
```

```
                                    gpsLat = -1 * gpsLat
                                End If
                            Case 5  ' Longitude
                                Long_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                                tmpStr = Long_str.Substring(0, 3)
                                gpsLong = Convert2Double(tmpStr)
                                tmpStr = Long_str.Substring(3)
                                gpsLong += Convert2Double(tmpStr) / 60
                                txtLong.Text = Long_str.Substring(0, 3) + " " + Long_str.Substring(3)
                            Case 6  ' E/W indicator
                                EW_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                                lblEW.Text = EW_str
                                If EW_str.IndexOf("W") >= 0 Then
                                    gpsLong = -1 * gpsLong
                                End If
                            Case 7  'Positioin Fix
                                PFix_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                                Select Case PFix_str
                                    Case "0"
                                        txtPFix.ForeColor = Color.Red
                                        txtPFix.Text = "Invalid"
                                    Case "1"
                                        txtPFix.ForeColor = Color.Blue
                                        txtPFix.Text = "Valid SPS"
                                    Case "2"
                                        txtPFix.ForeColor = Color.Blue
                                        txtPFix.Text = "Valid DGPS"
                                    Case "3"
                                        txtPFix.ForeColor = Color.Blue
                                        txtPFix.Text = "Valid PPS"
                                End Select

                            Case 8  ' Satellite used
                                SatUsed_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                                txtSatUsed.Text = SatUsed_str
                            Case 9
                                ' HDOP - Horizontal dilution of precision
                            Case 10
                                ' alittude
                                Alt_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                                txtAlt.Text = Alt_str
                            Case 11
                                ' altitude unit
                                AltUnit_str = receivedSentence.Substring(st_idx, en_idx - st_idx)
                                lblAltUnit.Text = AltUnit_str

                        End Select
                    End If
                Next i
            ElseIf NMEA_type.IndexOf("GPVTG") > 0 Then
                Timer2.Enabled = True
                GPVTG_str = receivedSentence
            End If  ' sentence type
            txtLongDeg.Text = Convert.ToString(Math.Round(gpsLong * 1000000) / 1000000)
            txtLatDeg.Text = Convert.ToString(Math.Round(gpsLat * 1000000) / 1000000)

            ' convert lat-long to XY
            gpsLatLong.setLatLong(gpsLat, gpsLong)
            SPCS_XY = convert2XY(gpsLatLong)
            txtPosX.Text = Convert.ToString(Math.Round(SPCS_XY.getX * 100) / 100)
            txtPosY.Text = Convert.ToString(Math.Round(SPCS_XY.getY * 100) / 100)
        Catch ie As Exception
            txtError.Text += ie.Message + "," + tmpStr + vbNewLine
        End Try
    Next sent_i
End Sub

Public Function Convert2Double(ByVal str As String) As Double
    Dim retVal As Double
    retVal = 0
```

```
        If IsNothing(str) Then
            Return 0
        End If
        If str.Length > 0 Then
            retVal = Convert.ToDouble(str)
        End If
        Return retVal
    End Function

    Private Sub btnExit_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles btnExit.Click
        recTimer.Enabled = False
        Timer2.Enabled = False
        Timer1.Enabled = False
        moRS232.Close()
        Application.Exit()
    End Sub

    Private Sub GpsDisplay_Closing(ByVal sender As Object, ByVal e As System.ComponentModel.CancelEventArgs) Handles
MyBase.Closing
        moRS232.Close()
        Application.Exit()
    End Sub

    Private Sub NMEAStr_Box_TextChanged(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles
NMEAStr_Box.TextChanged

    End Sub

    ' convert lat_long to XY
    Public Function convert2XY(ByVal myLatLong As Point2D) As Point2D
        Dim sin_phi0, sin_phi As Double
        Dim gamma, Ln1, Ln2, R, Q As Double
        Dim DEG_2_RAD As Double = Math.PI / 180.0
        Dim constants As Coord_Const = New Coord_Const
        constants.setZone(2203)     '// NAD83 MN South zone
        Dim mySPCSxy As Point2D = New Point2D

        sin_phi0 = Math.Sin((constants.phi_zero * DEG_2_RAD))
        gamma = (constants.lambda_zero + myLatLong.getY()) * sin_phi0 * DEG_2_RAD
        sin_phi = Math.Sin(myLatLong.getX() * DEG_2_RAD)
        Ln1 = Math.Log((1.0 + sin_phi) / (1.0 - sin_phi))
        Ln2 = Math.Log((1.0 + constants.E * sin_phi) / (1.0 - constants.E * sin_phi))
        Q = 0.5 * (Ln1 - constants.E * Ln2)
        R = constants.K / Math.Exp(Q * sin_phi0)
        mySPCSxy.setX(constants.E_zero + R * Math.Sin(gamma))
        mySPCSxy.setY(constants.Rb + constants.Nb - R * Math.Cos(gamma))
        Return mySPCSxy
    End Function

    Private Sub btnUDP_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles btnUDP.Click
        If frmUdpComm Is Nothing Then
            frmUdpComm = New UDPComm
            frmUdpComm.Show()
        End If

    End Sub

    Private Sub Timer2_Tick(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Timer2.Tick
        ' parse lat, long, alt etc.
        Dim st_idx, en_idx, i As Integer

        For i = 1 To 6
            st_idx = en_idx + 1
            en_idx = GPVTG_str.IndexOf(",", st_idx)
            If en_idx > 0 And st_idx <> en_idx Then
                Select Case i
                    Case 2  ' course
                        Heading_str = GPVTG_str.Substring(st_idx, en_idx - st_idx)
                        txtHeading.Text = Heading_str
                    Case 3  ' reference, T=true heading
                    Case 4  ' course
                    Case 5  ' M = magnetic heading
                    Case 6  ' Speed
                        Knot_str = GPVTG_str.Substring(st_idx, en_idx - st_idx)
                        vehSpeed = Convert2Double(Knot_str) * 1.150779448 ' convert from knot to MPH
                        txtSpeed.Text = Convert.ToString(Convert.ToUInt16(vehSpeed))
                    Case 7  ' unit, N Knot
                    Case 8  ' speed
                    Case 9  ' speed unit K, Km/h
                End Select
            End If
        Next i

    End Sub

    Private Sub btnGraph_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles btnGraph.Click

        If IsNothing(frmGraph) Then
            frmGraph = New GraphXY
            'Display the new form.
            frmGraph.Show()
        Else
            If Not frmGraph.IsDisposed Then
                frmGraph.WindowState = FormWindowState.Normal
                frmGraph.BringToFront()
            Else
                frmGraph = New GraphXY
                frmGraph.Show()
            End If

        End If

    End Sub

    Private Sub chkRec_CheckedChanged(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles
chkRec.CheckedChanged
        If chkRec.Checked Then
            recLatLongStr = ""
            recDataSize = 0
            recTimer.Enabled = True
        Else
            recTimer.Enabled = False
            Dim result As DialogResult
            result = MessageBox.Show("Save " + recDataSize.ToString + " recorded data?", "Record Lat/Long data",
MessageBoxButtons.YesNo, MessageBoxIcon.Question, MessageBoxDefaultButton.Button1)
            If result = DialogResult.Yes Then
                Dim myStream As System.IO.Stream
                If SaveFileDialog1.ShowDialog() = DialogResult.OK Then
                    myStream = SaveFileDialog1.OpenFile()
                    Dim w As New BinaryWriter(myStream)
                    If Not (myStream Is Nothing) Then
                        w.Write(recLatLongStr)
                    End If

                End If
            End If
        End If
    End Sub

    Private Sub recTimer_Tick(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles recTimer.Tick
        recLatLongStr += SPCS_XY.toStr() + "$"
        recDataSize += 1
        'txtError.Text += "rec-" + recDataSize.ToString + ";"
    End Sub

    Private Sub btnClear_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles btnClear.Click
        rcvdBuffer = ""
    End Sub
End Class
```

APPENDIX H

SAMPLE SOURCE CODE

H.1 Bus Onboard Unit Sample Source Code

/etc/rc.local script file

```
#!/bin/sh -e
# rc.local
su - root -c "/etc/init.d/runrsu start" &
exit 0
```

/etc/init.d/runrsu script file

```
#! /bin/sh
#
# PATH should only include /usr/* if it runs after the mountnfs.sh script
PATH=/sbin:/usr/sbin:/bin:/usr/bin
DESC="Daemon for running the RSU unit"
NAME=prog_rsu_udp
DAEMON=/usr/sbin/$NAME
DAEMON_ARGS="--options args"
PIDFILE=/var/run/$NAME.pid
SCRIPTNAME=/etc/init.d/$NAME

# Exit if the package is not installed
[ -x "$DAEMON" ] || exit 0

# Read configuration variable file if it is present
[ -r /etc/default/$NAME ] && . /etc/default/$NAME

# Load the VERBOSE setting and other rcS variables
. /lib/init/vars.sh

# Define LSB log_* functions.
# Depend on lsb-base (>= 3.0-6) to ensure that this file is present.
. /lib/lsb/init-functions

#
# Function that starts the daemon/service
#
do_start()
{
        # Return
        #   0 if daemon has been started
        #   1 if daemon was already running
        #   2 if daemon could not be started
        start-stop-daemon --start --quiet --pidfile $PIDFILE --exec $DAEMON --test > /dev/null \
                || return 1
        start-stop-daemon --start --quiet --pidfile $PIDFILE --exec $DAEMON -- \
                $DAEMON_ARGS \
                || return 2
        # Add code here, if necessary, that waits for the process to be ready
        # to handle requests from services started subsequently which depend
        # on this one.  As a last resort, sleep for some time.
}

#
# Function that stops the daemon/service
#
do_stop()
{
        # Return
        #   0 if daemon has been stopped
        #   1 if daemon was already stopped
        #   2 if daemon could not be stopped
        #   other if a failure occurred
       #kill  `cat $PIDFILE`
        start-stop-daemon --stop --quiet --retry=TERM/30/KILL/5 --pidfile $PIDFILE --name $NAME
        RETVAL="$?"
        [ "$RETVAL" = 2 ] && return 2
        # Wait for children to finish too if this is a daemon that forks
        # and if the daemon is only ever run from this initscript.
        # If the above conditions are not satisfied then add some other code
        # that waits for the process to drop all resources that could be
        # needed by services started subsequently.  A last resort is to
        # sleep for some time.
        start-stop-daemon --stop --quiet --oknodo --retry=0/30/KILL/5 --exec $DAEMON
        [ "$?" = 2 ] && return 2
        # Many daemons don't delete their pidfiles when they exit.
        rm -f $PIDFILE
        return "$RETVAL"
}
```

```
// gps.h file
#include <math.h>
#define MN_STATE_SOUTH          2203
#define COORDINATE_SYS          MN_STATE_SOUTH
#define DEG_2_RAD       M_PI/180.0

typedef struct {
   double  gpstime;           /* UTC */
   short   gps_month;
   short   gps_day;
   short   gps_year;
   short   gps_hh;                            /* time hour */
   short   gps_mm;                            /* time minute */
   double  gps_ss;                            /* time second ss.ss */
   double  latitude;
   double  longitude;
   double  altitude;
   char    lat_dir;                /* hemisphere N/S */
   char    long_dir;               /* E or W */

   double  cartesian_x;                       /* state plane in meters, east */
   double  cartesian_y;                      /* state plane in meters, north */
   double  height;            /* antenna height in meters */
   double  hdop;              /* < 4 is good, > 5 bad */
   double  diff_age;                          /* age of differential GPS data record */
   double  speed;                             /* gps speed in m/s */
   double  heading;                           /* heading angle in radians measured
                               /* from north (0) to east */
   double  dt;                /* time (sec) between gps strings */
   int     position_fix;      /* 0 = invalid, 1=valid SPS,
                               /* 2 = valid DGPS  3=valid PPS */
   int     num_satellites;
} gps;
```

```
/*
 * bus_obu.c
 * This is the bus onboard unit (OBU) to acquire GPS/AVL data and send bus
 * data through radio to roadside unit (RSU) residing in traffic control
 * cabinet for priority request.
 *
 * Created on May 20, 2007, 3:06 PM
 * Copyright  ©  Regents of the University of Minnesota.
 * All rights reserved.
 */

/*
 * Chen-Fu Liao
 * Sr. Systems Engineer
 * Minnesota Traffic Observatory (MTO)
 * ITS Institute, CTS / Department of Civil Engineering
 * University of Minnesota
 * 500 Pillsbury Drive SE
 * Minneapolis, MN 55455
 */
```

```
// ===============================================================================
#include <asm/io.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <errno.h>
#include <pthread.h>
#include <time.h>
#include "bus_obu.h"

// ===============================================================================
// main
// ===============================================================================
int main(int argc, char *argv[])
{
        int portnum ;
        char buffer[BUFFER_SIZE] ;
        char text[20] ;
        int nbytes = 0 ;
        char dataStr[BUFFER_SIZE] ;
        int strPtr=0, i=0;

        /* initialize NMEA_fields */
        NMEA_fields = (char **)malloc(NMEA_FIELD_SIZE*sizeof(char*)) ;
        for (i=0; i<NMEA_FIELD_SIZE; i++) {
                NMEA_fields[i] = (char*)malloc(32*sizeof(char)) ;
        }

        // init myGPS
        myGPS = (gps *)malloc(sizeof(gps)) ;

        // initialize serial port
        if((fd=open_port(1))==-1) {     //open serial port COM1
           printf("Error opening COM1\n") ;
           return (1);
        }

        init_port(&fd,38400);                   //set serial port to 38400,8,n,1

        // thread 1 - read gps sentences
        pthread_t thread1 ;
        char *message1 = "read GPS" ;
        int  iret1 ;

        // Create independent threads each of which will execute function
        iret1 = pthread_create( &thread1, NULL, readGPSStr, (void*) message1);

        // thread 2 - communicate with RSU server
        pthread_t thread2 ;
        char *message2 = "client" ;
        int  iret2 ;

        // Create independent threads each of which will execute function
        iret2 = pthread_create( &thread2, NULL, clientComm, (void*) message2);

        pthread_join( thread1, NULL);
        pthread_join( thread2, NULL);

        if (argc>1) {
           while(1)             // infinite loop
           {
                if (*argv[1]=='t') {  // transmit
                        // read GPS sentences
                        fputs("Enter text: ", stdout) ;
                        fflush(stdout) ;
                        fgets(text, 20, stdin) ;
                        sendSerial(&fd,text);
                        //printf("done!\n");
                } else if (*argv[1]=='r') {  // receive
```

```
                        while ((nbytes=read(fd, buffer, 255))>0)
                        {
                                printf("%d bytes received.\n", nbytes) ;
                                for (i=0; i<nbytes; i++) {
                                dataStr[strPtr] = buffer[i] ;
                                        strPtr++ ;
                                        if (buffer[i] == '\n')
                                        {
                                   printf("Data received = %s\n", dataStr) ;
                                           strPtr = 0 ;
                                        }
                                }   // for
                        }   // while
                    }
            }  // while(1)

        } else if (argc==1) { // argc=1, debug/testing

            char *testStr;
            strcpy(testStr,"$GPGGA,053856.0,4507.34256,N,09330.37989,W,1,05,2.5,283.4,M,-30.8,M,,*6F") ;
            //printf("test str=%s\n",testStr) ;
            parseGPSStr(testStr) ;
            printf("----------\n") ;

            strcpy(testStr,"$GPVTG,317.8,T,316.1,M,000.24,N,0000.45,K*71") ;
            //printf("test str=%s\n",testStr) ;
            parseGPSStr(testStr) ;

            //printf("loop here\n") ;

        } // if

        return (0);
} // end of main

// ==========================================================================
// communicate with RSU server, bus_rsu
// ==========================================================================
void *clientComm(void *data)
{
        char buf[BUFFER_SIZE] ;
        int num_char ;

        while(1) // infinite loop
        {
                num_char = sprintf(buf, "%d,%d,%02d:%02d:%04.1f,%lf,%lf,%lf",
                                BUS_ID,
                                APC_COUNT,
                                myGPS->gps_hh,myGPS->gps_mm,myGPS->gps_ss,
                                myGPS->cartesian_x,
                                myGPS->cartesian_y,
                                myGPS->speed) ;
                send2RSU(buf, "128.101.111.119") ;

                msleep(20) ;
        } // end of while

} // end of clientComm

// ==========================================================================
// delay # millisecond, sleep function
// ==========================================================================
int msleep(unsigned long milisec)
{
    struct timespec req={0};
    time_t sec=(int)(milisec/1000);
    milisec=milisec-(sec*1000);
    req.tv_sec=sec;
    req.tv_nsec=milisec*1000000L;
    while(nanosleep(&req,&req)==-1)
```

```
         continue;
    return 1;
}

// ==============================================================================
// read GPS sentences through COM port
// ==============================================================================
void *readGPSStr(void *data)
{
        int nbytes = 0 ;
        char dataStr[BUFFER_SIZE] ;
        char buffer[BUFFER_SIZE] ;
        int strPtr=0, i=0;
        while(1)
        {
                        while ((nbytes=read(fd, buffer, BUFFER_SIZE))>0)
                        {
                            for (i=0; i<nbytes; i++) {
                                dataStr[strPtr] = buffer[i] ;
                                        strPtr++ ;
                                        if (buffer[i] == '\n')
                                        {
                                            dataStr[strPtr] = '\0' ;            // terminate string
                                            strPtr = 0 ;
                                            parseGPSStr(dataStr) ;
                                        }
                            }   // end for

                        }   // end while

        }  // end while(1)

}   // end of readGPSStr routine

// ==============================================================================
// send command/data thru serial port
// ==============================================================================
void sendSerial(int *fd, char *text)
{
        int num;
        num = write(*fd,text,strlen(text)); //send packet
        printf("%d bytes sent!\n",num) ;
} // end of sendSerial

// ==============================================================================
// identify GPS sentence ID
// ==============================================================================
int getSentenceID() {
     int sID = -1 ;

           // extract data from each parsed text field
           if (strcmp(NMEA_fields[0], "$GPGGA")==0) {
                        sID = GPGGA_ID ;
           } else if (strcmp(NMEA_fields[0], "$GPVTG")==0) {
                        sID = GPVTG_ID ;
           }
     return (sID) ;

} // end of getSentenceID

// ==============================================================================
// parse GPS sentence fields and save data in myGPS class
// ==============================================================================
int parseGPSField(int sentenceID, int field_index) {
        double data, data_deg ;
        char *txt ;
        int int_data ;
        time_t now ;
        struct tm *local_time ;
        switch (sentenceID) {
                case GPGGA_ID:  // update GPGGA sentence
                        switch(field_index) {
                                case 2:
                                        myGPS->gpstime = atof(NMEA_fields[field_index-1]) ;
                                        myGPS->gps_hh = floor(myGPS->gpstime/10000.0) ;
                                        myGPS->gps_mm = floor((myGPS->gpstime-myGPS->gps_hh*10000.0)/100.0) ;
                                        myGPS->gps_ss = myGPS->gpstime - myGPS->gps_hh*10000.0 - myGPS-
>gps_mm*100.0 ;
                                        now = time(0) ;
                                        local_time = localtime(&now) ;
                                        myGPS->gps_year = 1900+local_time->tm_year ;
                                        myGPS->gps_month = 1+local_time->tm_mon ;
                                        myGPS->gps_day = local_time->tm_mday ;

                                        break ;
                                case 3:    // latitude
                                        data = atof(NMEA_fields[field_index-1]) ;
                                        data_deg = floor(data/100.0) ; // degree
                                        myGPS->latitude = data_deg+(data-data_deg*100.0)/60.0 ;
                                        break ;
                                case 4:    // N/S indicator
                                        myGPS->lat_dir = NMEA_fields[field_index-1][0] ;
                                        if (myGPS->lat_dir=='S') {
                                           myGPS->latitude = -myGPS->latitude ;
                                        }
                                        break ;
                                case 5:    // longitude
                                        data = atof(NMEA_fields[field_index-1]) ;
                                        data_deg = floor(data/100.0) ; // degree
                                        myGPS->longitude = data_deg+(data-data_deg*100)/60.0 ;
                                        break ;
                                case 6:    // E/W indicator
                                        myGPS->long_dir = NMEA_fields[field_index-1][0] ;
                                        if (myGPS->long_dir=='W') {
                                           myGPS->longitude = -myGPS->longitude ;
                                        }
                                        break ;
                                case 7:    // Position fix
                                        myGPS->position_fix = atoi(NMEA_fields[field_index-1]) ;
                                        break ;
                                case 8:    // Satellite used
                                        myGPS->num_satellites = atoi(NMEA_fields[field_index-1]) ;
                                        break ;
                                case 9:    // HDOP
                                        myGPS->hdop = atof(NMEA_fields[field_index-1]) ;
                                        break ;
                                case 10:   // Altitude, meter
                                        myGPS->altitude = atof(NMEA_fields[field_index-1]) ;
                                        break ;
                                case 14:   // checksum, convert to XY
                                        convert_to_cartesian(myGPS) ;
                                        break ;
                        }               //// end of switch field_index
                        break ;

                case GPVTG_ID:  // update GPVTG sentence
                        //printf("GPVTG %d = %s\n", field_index, NMEA_fields[field_index-1]) ;
                        switch(field_index) {
                                case 8:    // speed, Km/h
                                        myGPS->speed = 1000.0/3600.0*atof(NMEA_fields[field_index-1]) ;
                                        break ;
                        }               // end of switch field_index
                        break ;

                default:
                        break ;
        }       // end of switch(sentenceID)

        return (0) ;
```

```
} // end of parseGPSField
```

```
/*
 * clientUDP.c
 *
 * Created on July 20, 2007, 3:06 PM
 * Copyright  ©  Regents of the University of Minnesota.
 * All rights reserved.
 */
/*
 * Minnesota Traffic Observatory (MTO)
 * ITS Institute, CTS / Department of Civil Engineering
 * University of Minnesota
 * 500 Pillsbury Drive SE
 * Minneapolis, MN 55455
 */

/*** a stream socket client function ***/

#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <errno.h>
#include <string.h>
#include <netdb.h>
#include <sys/types.h>
#include <netinet/in.h>
#include <sys/socket.h>
#include <signal.h>
#include <setjmp.h>
#include <sys/time.h>
#include "clientTCP.h"

#define RECV_TIMEOUT 1            /* timeout in seconds */

static sigjmp_buf recv_timed_out;

/* timeout handler */
void timeout_handler (int signum)
{
    signal(SIGALRM, SIG_DFL);
    siglongjmp(recv_timed_out, 1);
}

int send2RSU(char* message, char* hostname)
{
        int sockfd, numbytes;
        char buf[MAXDATASIZE];
        struct hostent *he;

        //connector's address information
        struct sockaddr_in their_addr, cliAddr;


        //get the host info
        if((he=gethostbyname(hostname)) == NULL) {
                perror("gethostbyname()");
                exit(1);
        }

        // create a socket for connection
        if((sockfd = socket(AF_INET, SOCK_DGRAM, 0)) == -1)
        {
                perror("socket()");
                exit(1);
        }
        //host byte order
        their_addr.sin_family = he->h_addrtype;

        their_addr.sin_port = htons(PORT);
        memcpy ((char *) &their_addr.sin_addr.s_addr, he->h_addr_list[0], he->h_length);

        //zero the rest of the struct
        memset(&(their_addr.sin_zero), '\0', 8);

        /* bind any port */
          cliAddr.sin_family = AF_INET;
          cliAddr.sin_addr.s_addr = htonl(INADDR_ANY);
          cliAddr.sin_port = htons(0);

        if(bind(sockfd, (struct sockaddr *) &cliAddr, sizeof(cliAddr)) == -1) {
                perror("Client-bind() error");
                exit(1);
        }

        int sin_size = sizeof(their_addr);

        // send message to remote server
        if(sendto(sockfd, message, strlen(message), 0,(struct sockaddr *)&their_addr, sin_size) == -1) {
                        perror("Client-sendto() error lol!");
        }


        if (sigsetjmp(recv_timed_out, 1)) {
                        printf("recvfrom() timed out\n\n");
                        return -1;
        }

        /* set timer and handler */
        signal(SIGALRM, timeout_handler);
        alarm(RECV_TIMEOUT);

        // receive
        numbytes = recvfrom(sockfd, buf, MAXDATASIZE-1, 0,(struct sockaddr *)&their_addr, &sin_size);


        /* clear timer and handler */
        alarm(0);
        signal(SIGALRM, SIG_DFL);

        if (numbytes == -1)
        {
                        perror("recvfrom()");
                        exit(1);
        }
        buf[numbytes] = '\0';// add end of data
        printf("Client-Received: %s\n", buf);

        close(sockfd);

        return 0;
}
```

```
/*
 * mySerial.c
 *
 * Created on May 20, 2007, 3:06 PM
 * Copyright  ©  Regents of the University of Minnesota.
 * All rights reserved.
 */

/*
 * Author  Chen-Fu Liao
 * Sr. Systems Engineer
 * Minnesota Traffic Observatory (MTO)
 * ITS Institute, CTS / Department of Civil Engineering
 * University of Minnesota
 * 500 Pillsbury Drive SE
 * Minneapolis, MN 55455
 */

#include <stdio.h>
#include <string.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#include <termios.h>

// ============================================================================
// open serial port
// ============================================================================
int open_port(int portnum)
{
	int fd;
	char portfile[20]={'\0'};
	if(portnum==1)
			sprintf(portfile,"/dev/ttyS0");
	else if(portnum==2)
			sprintf(portfile,"/dev/ttyS1");
	else if(portnum==3)
			sprintf(portfile,"/dev/ttyS2");
	else if(portnum==4)
			sprintf(portfile,"/dev/ttyS3");
	else
	{
			printf("open_port: unrecognized port number\n");
			return (-1);
	}
	if((fd=open(portfile, O_RDWR | O_NOCTTY | O_NDELAY))==-1)
			perror("open_port: unable to open /dev/ttyS0 - ");
	return (fd);
}

// ============================================================================
// init serial port
// ============================================================================
void init_port(int *fd, unsigned int baud)
{
	struct termios options;
	//note: the termios structure does not support a baud rate of 14400
	tcgetattr(*fd,&options);
	switch(baud)
	{
	case 9600:
			cfsetispeed(&options,B9600);
			cfsetospeed(&options,B9600);
			break;
	case 19200:
			cfsetispeed(&options,B19200);
			cfsetospeed(&options,B19200);
			break;
	case 38400:
			cfsetispeed(&options,B38400);
			cfsetospeed(&options,B38400);
			break;
	default:
			cfsetispeed(&options,B9600);
			cfsetospeed(&options,B9600);
			break;
	}
	options.c_cflag |= (CLOCAL | CREAD);
	options.c_cflag &= ~PARENB;
	options.c_cflag &= ~CSTOPB;
	options.c_cflag &= ~CSIZE;
	options.c_cflag |= CS8;
```

```
        tcsetattr(*fd,TCSANOW,&options);
}
```

H.2 Bus Roadside Unit Sample Source Code

```
// =============================================================================
/*
 * bus_rsu_udp.c
 * This is the roadside unit (RSU) interface to communicate with bus onboard
 * unit (OBU) through radio to get bus GPS/AVL data and process signal
 * priority request to traffic signal controller.
 *
 * Created on July 30, 2007, 5:36 PM
 * Copyright  ©  Regents of the University of Minnesota.
 * All rights reserved.
 */

/*
 * Chen-Fu Liao
 * Sr. Systems Engineer
 * Minnesota Traffic Observatory (MTO)
 * ITS Institute, CTS / Department of Civil Engineering
 * University of Minnesota
 * 500 Pillsbury Drive SE
 * Minneapolis, MN 55455
 */

// =============================================================================
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <errno.h>
#include <string.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>
#include <arpa/inet.h>
#include <sys/wait.h>
#include <signal.h>
#include "bus_rsu.h"

// =============================================================================
int main(int argc, char *argv[])
{
        // thread 1 - communicate with OBU client
        pthread_t thread1 ;
        char *message1 = "UDPserver" ;
        int  iret1 ;

        // Create independent threads each of which will execute function
        iret1 = pthread_create( &thread1, NULL, serverComm, (void*) message1);

        pthread_join( thread1, NULL);

        return (0);
} // end of main


// =============================================================================
// communicate OBU client
// =============================================================================
void *serverComm(void *data)
{
        /*listen on sock_fd, new connection on new_fd*/
        int sockfd, new_fd;

        /*my address information*/
        struct sockaddr_in my_addr;
```

```
/*connector's address information*/
struct sockaddr_in their_addr;

int sin_size;
struct sigaction sa;
int yes = 1;
int numbytes;
char buf[MAXDATASIZE];

if ((sockfd = socket(AF_INET, SOCK_DGRAM, 0)) == -1) {
        perror("Server-socket() error lol!");
        exit(1);
} else {
        printf("Server-socket() sockfd is OK...\n");
}

/* host byte order*/
my_addr.sin_family = AF_INET;

/* short, network byte order*/
my_addr.sin_port = htons(MYPORT);

/* automatically fill with my IP*/
my_addr.sin_addr.s_addr = htonl(INADDR_ANY);

printf("Server-Using %s and port %d...\n", inet_ntoa(my_addr.sin_addr), MYPORT);


/* zero the rest of the struct*/
memset(&(my_addr.sin_zero), '\0', 8);

if(bind(sockfd, (struct sockaddr *)&my_addr, sizeof(struct sockaddr)) == -1) {
        perror("Server-bind() error");
        exit(1);
} else {
        printf("Server-bind() is OK...\n");
}

/*clean all the dead processes*/
sa.sa_handler = sigchld_handler;
sigemptyset(&sa.sa_mask);
sa.sa_flags = SA_RESTART;

if(sigaction(SIGCHLD, &sa, NULL) == -1) {
        perror("Server-sigaction() error");
        exit(1);
}


while(1)
{
    sin_size = sizeof(their_addr);
        if((numbytes = recvfrom(sockfd, buf, MAXDATASIZE-1, 0,(struct sockaddr *)&their_addr, &sin_size)) == -1)
        {
                perror("recvfrom()");
                exit(1);
        }
        else
        {
                printf("Server-The recv() is OK...\n");
        }

        buf[numbytes] = '\0';
        printf("Server-Received: %s\n", buf);

        /* this is the child process */
        if(!fork())
        {
                /* child does not need the listener */
```

```
                        close(sockfd);
                        printf("Reached Inside !");

                        if(sendto(sockfd, buf, numbytes, 0,(struct sockaddr *)&their_addr, sin_size) == -1)
                        perror("Server-sendto() error lol!");

                        close(sockfd);
                        exit(0);
                }
                else
                {
                        //printf("Server-send is OK...!\n");
                }

                /* parent does not need this*/
                close(sockfd);
        }  // while
        return 0;
}
```

APPENDIX I

INDEMNITY LETTER

LETTER OF INDEMNITY FOR

"BUS SIGNAL PRIORITY BASED ON GPS AND WIRELESS COMMUNICATIONS PHASE II"

WHEREAS, the University of Minnesota, Center for Transportation Studies, is undertaking a research program for bus signal priority based on GPS and wireless communications, which has advanced to Task 4, system validation;

WHEREAS, the GPS Bus Priority System may represent a significant advancement over bus priority systems currently in use in various cities;

WHEREAS, all Metro Transit busses currently are equipped with GPS, and a validated system could rapidly be implemented with the current Metro Transit fleet;

WHEREAS, traffic simulation has demonstrated that the GPS system would not cause traffic problems for non-bus vehicles and would significantly improve transit performance: reducing delays, improving adherence to schedules, reducing fuel costs and greenhouse gas emissions, making transit a more attractive option; and,

WHEREAS, the City of Minneapolis is willing to participate as a validation site, using a limited number of intersections, provided that it is assured that any damages caused to Minneapolis property shall be the responsibility of the University of Minnesota;

THEREFORE: The University of Minnesota hereby provides the following indemnification to the City of Minneapolis: In consideration for the City of Minneapolis' participation as a validation site, the University of Minnesota hereby accepts responsibility for any and all loss, injury or damage to the property of the City of Minneapolis that results from the City of Minneapolis' participation as a validation site, including without limitation any damage to or negative effect on the Eagle traffic control system firmware used in the validation intersections; and the University of Minnesota shall pay and indemnify the City of Minneapolis from any and all costs or expenses associated with such damage, including costs of replacement or repair, material and labor costs, and shipping costs, including priority shipping. Excluded from this indemnity are damages or costs caused by the willful or wanton conduct of employees of the City of Minneapolis; however, this exclusion applies only to the extent that the costs or damages are attributable to such willful or wanton conduct.

This letter of indemnity has been approved by an authorized representative of the Regents of the University of Minnesota.

Regents of the University of Minnesota

By: ____

Name: ____

Title: ____

Date: ____