Simulation Study of a Bus Signal Priority Strategy Based on GPS/AVL and Wireless Communications

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ABSTRACT
Providing signal priority for buses has been proposed as an inexpensive way to improve transit efficiency, productivity and reduce operation costs [1]. Bus signal priority has been implemented in several US cities to improve schedule adherence, reduce transit operation costs, and improve customer ride quality [2]. 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 take advantage of the already equipped GPS/AVL system on the buses in Minneapolis and develop an adaptive signal priority strategy 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 signal priority. Communication with the roadside unit (e.g., traffic controller) for signal priority may be established using the readily available 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. This paper describes our proposed priority logic, and its evaluation using microscopic traffic simulation. Simulation results indicate that a 12-15% reduction in bus travel time during AM peak hours (7AM-9AM) and 4-11% reduction in PM peak hours (4PM-6PM) could be achieved by providing signal priority for buses. Average bus delay time was reduced in the range of 16-20% and 5-14% during AM and PM peak periods, respectively.

KEYWORDS
Transit Signal Priority, GPS/AVL, Wireless Communication, Vehicle to Roadside Communication
INTRODUCTION

Signal Priority for transit has been studied and proposed as an efficient way to improve transit travel and 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 [1], but the transit travel time reduction varies considerably across studies [2]. Unlike signal preemption, which interrupts 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 [3].

Metro Transit in Twin Cities Metro area (http://www.metrotransit.org/) previously performed an evaluation of providing signal priority for buses on Lake Street in Minneapolis, using Opticom™ systems [4]. 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. Results from the previous evaluation study were not promising.

Bus signal priority has also been implemented in several US cities (Seattle, Portland, Los Angeles, Chicago) as well as in Europe. Various technologies have been deployed for bus priority including Opticom™ (St. Cloud) [5], Loopcom (Los Angeles), and RF tag (Seattle, King County) [6]. Recently, Crout [7] 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.

With the installation of GPS system on its fleet, Metro Transit now constantly monitoring buses locations in relation to their schedules, in order to provide more reliable transit services and enhance transit operation and management. Bus location, travel time information and other traffic information can also be integrated and provided for traffic operations or to the traveling public. Metro Transit would prefer to use the already installed GPS/AVL system as the basis of a TSP system. 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. These TSP strategies do not consider the bus’s speed and its distance from intersection when determining the appropriate time to request signal priority.

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) for 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.

Literature Review

A research group at California PATH (Partners for Advanced Transit and Highways) is pursuing a study titled “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 [8]. Yin et al proposed a heuristic TSP algorithm to provide signal priority to buses as well as limit negative impact on cross-street traffic [9]. Traditional TSP strategies implemented in other cities are fixed-location detection systems and implemented with time-of-day signal control systems. TSP systems using fixed-location detection mostly do not work well with nearside bus stops, due to the uncertainty in bus dwell time. Kim and Rilett [10] proposed a weighted least squares regression model in simulation to estimate bus dwell time in order to overcome nearside bus stop challenges. Rakha
et al. [11] performed field and simulation evaluation along US Route 1 corridor. They recommended further consideration on existence of queues in transit signal priority strategy and not implementing near-side bus stops.

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) [12] traffic signal control system was conducted by Bretherton et al in 1996 [13]. 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 [14] 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 [15] conducted a field study with three priority conditions (no priority, absolute priority, 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 [16] 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 [17] 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) [18]. “Weighted bus” and “phase constrained” approaches were developed for providing transit priority through the RHODES-CAPRI framework. Mirchandani et al [19] 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).

Los Angeles County Metropolitan Transportation Authority (MTA) has implemented wireless technology in a transit signal priority system along a corridor using IEEE 802.11b standard. The wireless card on each bus sends IP addressable message to an access point which covers 3~4 intersections. A wireless client installed in the signal cabinet communicates with modified traffic controller to request for signal priority. King County MTA in Washington is also designing wireless TSP system similar to that in LA County.

Objective

With GPS/AVL system on the bus, we believe we can provide signal priority to buses with minimal impact on other traffic because GPS offers better information regarding bus trajectory than the sensors used previously to provide traffic signal priority. Our objective is to investigate the performance of GPS and a wireless-based adaptive signal priority strategy to provide reliable and efficient bus transit services with minimal impact on traffic flow. The improved service will hopefully make the transit system more attractive to the public and increase ridership. Simulation studies and field measurements will be used to estimate changes in bus travel time, as well as effects on other traffic.

DEVELOPMENT OF TRAFFIC SIMULATION MODEL

Study Site Selection

Bus route #2, operating on Franklin Ave from S Dupont Ave to S 27th Ave in City of Minneapolis, was selected for the bus signal priority study after discussions with City of Minneapolis and Metro Transit. The Franklin corridor, located south of downtown Minneapolis, runs in an east-west direction parallel to interstate highway I-94, as shown in Figure 1. The study section of the Franklin Corridor consisted of 22 signalized intersections with total travel distance of about 3 miles. On the west end, at Hennepin and Lyndale Ave, Franklin Avenue provides connection to the interstate I-94 & I-394. Toward the east side, the bus stop at south 17th Ave connects the bus route #2 to the recently opened Minnesota Hiawatha Light Rail Transit (LRT) line, which in turn connects the traffic from downtown Minneapolis to the Minneapolis-St. Paul (MSP) international airport, and to the Mall of America.

Intersection Capacity Analysis

Intersection capacity analyses were performed at several major intersections on the study corridor, in order to better understand the existing traffic condition. The intersection capacity of the following intersections was
Liao and Davis identified and analyzed: Hennepin, Lyndale, Nicollet, Chicago, 11th, Cedar, and Minnehaha Avenue. Traffic volume, turning movements and signal timing data for each intersection were entered in Synchro [20] to calculate intersection delay and Level Of Service (LOS). For the intersections currently having significant delay, the effect on cross street traffic needs to be carefully analyzed when providing bus signal priority on Franklin Ave.

**Bus Travel Time**

Current average travel time for buses was computed using the per-minute bus GPS data. The data set from Metro Transit included 5 days of bus GPS data of route #2. A computer program was developed to extract the data collected on Franklin Ave. during the AM and PM peak hours. In addition to the estimates of the bus travel times from the GPS data, field observations were performed by taking several bus trips during both peak hours, along Franklin Ave. The collected data were also used to calculate average travel times. These measured bus travel times were compared to those produced by the simulation model in order to verify the accuracy of the public transit model used in the simulator.

**Bus Intersection Delay**

The purpose of providing signal priority to a transit vehicle is to minimize its waiting time at intersections. It is important to know how much time buses spend waiting at red lights as compared to their total travel times. Collecting the bus delay times at red signals will provide information on the degree of improvement that bus signal priority could provide to the existing bus operation. Based on the collected data buses traveling westbound require on average about 18 minutes to traverse study site with approximately 210 seconds of delay at red signals. Buses traveling in the eastbound direction spend about 20 minutes in average, including about 260 seconds of signal delay per trip. By comparing the average intersection delay to the average bus travel time, a bus generally spent on average around 18% to 23% of its travel time (3.3~4.8 minutes) waiting for green lights at intersection along Franklin Avenue.

**Bus Dwell Time**

Bus dwell time at each bus stop consists of the boarding/alighting of passengers, door opening/closing and clearance time. The per-minute bus GPS data provided by Metro Transit does not provide sufficient resolution for us to calculate and estimate the bus dwell time at each bus stop. Also, Metro Transit was not able to provide passenger counts at the time of this study using the APC (automatic passenger count) unit integrated with the bus GPS/AVL data collection system along Franklin Avenue. However, Metro Transit conducted passenger boarding/alighting counts at every bus stop along bus route #2 from 6AM to 12AM during 2000 and 2001. Bus dwell time at each stop can therefore be calculated using the recommended formulas from Transit Capacity and Quality of Service Manual [21].

**Traffic Simulation**

A microscopic traffic simulation package, AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks, http://www.aimsun.com [22]) was selected for this study. AIMSUN includes an Application Programming Interface (API) to allow interfacing to other simulation or assignment models. An additional library of DLL (Dynamic Link Library) functions enables the system to communicate with external applications [22, 23]. AIMSUN has been used successfully for several large-scale traffic modeling research projects [24] and provides a well-documented API to access and modify all elements of the simulation state (signal control, sensing, vehicle characteristics and state), while the simulation is running. A C++ program was developed to interface with the microsimulator through the API. Bus location, speed, and bus stop information can be sent to the external bus signal priority application, and a priority request can be sent back to the simulator, in real-time.

Digital Orthophotos Quad aerial images (DOQs) around Franklin Avenue were acquired from Twin Cities Metropolitan Council (http://www.datafinder.org/metadata/orthos2000.htm). The aerial images were then used to create the arterial network geometry for the AIMSUN simulation model. Bus route and bus stop locations were selected and specified in the network geometry and bus dwell time statistics were entered in the transit model. Intersection signal timing and phase assignments were specified in the signal control model. Three different vehicle types, passenger car, light truck, and bus, were included in the simulation model. The 15-minute traffic volume and turning proportions collected at each intersection were entered. Before entering the traffic volume inputs at the boundary links and the turning ratio at each intersection, the collected traffic counts were adjusted to satisfy the traffic flow conservation principle. Signalized intersection traffic counts were obtained from City of Minneapolis, while traffic volumes at un-signalized intersection were collected on 20 different weekdays for this study. The
inconsistencies between the network inflow and outflow must then be “balanced” before applying the data to any traffic operation analysis.

An arterial traffic volume balance technique is used by Minnesota Department of Transportation (MnDOT), includes intersections on both sides of an on-ramp or off-ramp intersection, when conducting highway traffic simulation. Traffic volume and turning movements at arterial intersections are often collected on different days and different days of the week, and these traffic volumes need to be adjusted to conserve the inflow and outflow traffic at each link. By adjusting the arterial traffic volume from upstream to downstream intersections in both directions recursively, the arterial network traffic volume will reach an equilibrium state. A Java program was developed to read a text file with intersection traffic volume data filenames listed sequentially. The program then reads all intersection traffic volume data in JAMAR [25] data format from a specified directory and automatically computes the adjustments iteratively until the total traffic volume balanced.

When the intersection traffic data were balanced and entered in the AIMSUN simulation model for each 15-minute interval, an error-checking task was performed by running a trial simulation in order to visually identify any unusual traffic conditions. For example, incorrect intersection signal phasing or offset may cause unusual queue buildup. A working model of Franklin Avenue is available for calibration upon the completion of the error-checking tasks. The traffic simulation model can only include a portion of all parameters that affect the real-world traffic conditions. The calibration process helps improve the ability of traffic model to accurately reproduce the local traffic conditions [26].

**ADAPTIVE BUS SIGNAL PRIORITY STRATEGY**

To illustrate our priority strategy, consider a simple eastbound/westbound corridor as shown in Figure 2. For a bus approaching 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 2 by the eastbound bus approaching stop j and intersection i. Estimated bus dwell time at the near side 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 2 westbound bus approaching intersection i and bus stop k). Bus travel time to the intersection needs to be considered when providing priority.

**Nearside Bus Stop**

Consider the bus traveling in the eastbound as shown in Figure 2. 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,

$$ T_{aj} = \frac{d_{e,j}}{1.467 \times v_b} + T_{br} + T_{delay} $$  \hspace{1cm} (1)

Where,

- $v_b$: is bus speed, in MPH,
- $d_{e,j}$: is the distance from the current bus location to bus stop $j$, in feet,
- $T_{br}$: 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.
\[ T_{ji} = \sqrt{\frac{2(d_{e,i} - d_{e,j})}{a}} + T_{bc} \]  

Where,

- \( d_{e,i} \): is the distance from eastbound bus to intersection \( i \) (ft),
- \( d_{e,j} \): is the distance from eastbound bus to bus stop \( j \) (ft),
- \( a \): is the bus acceleration in ft/s/s, 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.

\[ \hat{t}_{ei} = t + T_{aj} + T_{dj} + T_{ji} \]  

Where,

- \( t \): is the current time, sec.

And estimated time for the bus leaving stop \( j \) is,

\[ \hat{t}_{lj} = t + T_{aj} + T_{dj} \]  

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

\[ \delta_n = t_{cp} + t_{comm} + t_{const} \]  

- \( t_{cp} \): 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 \( \hat{t}_{ei} + T_{si} \), where \( T_{si} \) is the time for the bus to cross intersection \( i \). If both beginning (\( \hat{t}_{lj} - \delta_n \)) and ending (\( \hat{t}_{ei} + T_{si} \)) 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 \( \hat{t}_{ei} + T_{si} \) 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.

**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 2, 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,

\[ T_{ai} = \frac{d_{w,i}}{1.467 \times v_p} + T_{delay} \]  

Where,

- \( d_{w,i} \): is the distance from westbound bus to intersection \( i \) (ft),
- \( v_p \): is bus speed in MPH, 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.
\[ \hat{t}_{wi} = t + T_{wi} \]  

(7)

Where, 
\[ t \] is the current time, sec.

The desired signal priority would need to begin at \( \delta_n \) seconds prior to the bus arriving intersection \( i \) 
\( (\hat{t}_{wi} - \delta_n) \), where \( \delta_n \) is defined as equation (5). The signal priority service can be ended at \( \hat{t}_{wi} + T_{wi} \), where \( T_{wi} \) is the time for bus to cross intersection \( i \). If both beginning \( (\hat{t}_{wi} - \delta_n) \) and ending \( (\hat{t}_{wi} + T_{wi}) \) 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 \( \hat{t}_{wi} + T_{wi} \) 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.

**Estimation of Passenger Arrival Rate at Bus Stop**

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, \( \lambda \), 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.

**Estimation of Bus Dwell Time at Bus Stop**

Bus dwell time at a bus stop for boarding can be estimated using the following equation.

\[ T_{dj}^B = \lambda_j(t) \times [t_k(j) - t_{k-1}(j)] \times T_{boarding} \]  

(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.

**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.

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 (\( W_T \geq 1 \)).

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. **Number of passengers on the bus, 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.

$$f(A) = TF(A, B) \times \{LF(A) + PF(A)\}$$

$$f(B) = TF(A, B) \times \{LF(B) + PF(B)\}$$

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

**Green Extension and Red Truncation**

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.

**Signal Recovery/Resynchronization Consideration**

It has been a concern to return the intersection timing back to its coordination often providing signal priority to buses. Some priority strategies require many cycles before the signal timing is resynchronized to its regional coordination [27]. Recently, an advanced controller provides the signal priority recovery with a cycle by including optional transit phases in the timing plan [28]. Our 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.

**Bus Signal Priority Modeling in the Simulator**

The priority strategy was implemented using the C++ programming language and integrated with the simulator through the AIMSUN API interface. At each simulation step, the 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. 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 Control Model**

An external signal control logic was programmed to emulate the green extension and red truncation functionality. In order to ensure that the intersection returns back to its timing plan prior to the priority request and remains coordinated with the neighboring intersections, signal timing recovery and resynchronization were also considered. For example, extend green and maintain coordination, early green or red truncation, and phase insertion and coordination recovery in the next cycle.

**SIMULATION RESULTS ANALYSIS**

Traffic data produced by the simulation model were used to compare the measures of effectiveness of the signal priority strategy. System statistics as described in the AIMSUN User’s Manual are defined as follows.
Flow: Average number of vehicles per hour that have passed through the network during the simulation period.

Average Travel time: Average time a vehicle needs to travel one kilometer inside the network.

Average Delay Time: Average delay time per vehicle per kilometer. This is the difference between the expected travel time (the time it would take to traverse the system under ideal conditions) and actual travel time.

Average Stops: Average number of stops per vehicle per kilometer.

The overall statistics of the simulation network without applying signal priority strategy were first collected. During the PM peak period (4 - 6PM), traffic is much heavier than that in the morning hours (7 - 9AM). There were about 40% increases of traffic flow in PM peak hours. The PM average speed in the system dropped by 9%, from 19.8 to 18 MPH, as compared to the AM peak period. The average travel time, delay time and number of stops per vehicle in the afternoon rush hours also increased by about 21%, 31.7%, and 25% respectively.

Bus Measures of Effectiveness (MOE) Analysis

Bus average speed, travel time, and stop time were collected during simulations to measure the effectiveness with and without priority strategy. These measures are defined as follows.

Bus Travel time: Average time it takes for a bus to travel along a public transport line. This is the mean of all the single travel times for each bus.

Bus Delay Time: Average delay time per bus to make the trip. This is the difference between the expected travel time (time it takes to go from the origin to the destination under ideal conditions) and the actual travel time.

Bus Stop Time: Average time spent at a stop per bus during the trip.

AM Peak

By applying the signal priority strategy, the bus travel time was reduced by about 12% in EB and 14% in WB, respectively. Bus delay time was reduced by about 16%~19% and the stop time was reduced around 18% as well.

PM Peak

There was about a 40% increase in traffic flow during the PM peak hours. Bus statistics from the simulation with and without signal priority strategy are listed in Table 1 for PM peak hours. Bus travel time and speed are also plotted in Figure 4. In the PM peak hours, it took about 22(23) minutes for a EB (WB) bus to travel between Hennepin Ave and 27th Ave on Franklin Ave without signal priority. By applying the signal priority strategy for the buses, the bus travel time was reduced by about 2 minutes in EB and 1.5 minutes in WB direction, or 10.5% in EB and 7% in WB, respectively. Bus delay time was reduced by about 9%~14% and the stop time was reduced around 10%~14% as well.

As the simulation results show, the signal priority strategy during the PM peak hours provided relatively less travel time reduction in WB (about 1-minute less) as compared to the AM scenario. There were mostly nearside bus stops at our study site. During the PM peak hours, there were longer queues at intersections from 11th Ave to Cedar Avenue, so that a bus was not able to get in to its service bay when it approached a queue at the intersection. The bus stuck behind the queue had to wait until the queue cleared at the next green in order to provide service. Also, when there was a queue built up during the bus service period at a nearside bus stop, the bus had to wait to find an acceptable gap in order to join the traffic. The priority request will help clear the queue to reduce bus clearance time. However, if knowledge of the queue length could be obtained and processed to submit a priority request earlier, the bus waiting time could be reduced during the busier PM period. Future enhancements to the priority strategy can include consideration of queue detection at the intersection.

Overall Network System MOE Analysis

The measures of effectiveness for the whole network were obtained for the simulation period.

AM Peak

Network system statistics from the simulation with and without the signal priority strategy are listed in Table 2 for the AM peak hours. There was about a 7 seconds increase in average travel time. Average delay increased by 6 seconds for the 15-sec extension scenario. The average number of stops per vehicle was increased by 0.1 stop per vehicle for both cases.

PM Peak
As a result of heavier traffic flow during the PM peak hours, the overall network statistics from the simulation with and without signal priority strategy generated longer delay and more vehicle stops. As listed in Table 2, the travel time during the PM period was increased by 22 seconds per kilometer when providing signal priority. Average delay was increased by 23 seconds while average stops increased by 0.6 stop per vehicle with the priority strategy.

FUTURE WORK

We would like to investigate the 800 MHz radios and WLAN (Wireless Local Area Networks) systems already equipped on the bus. A voice radio on the bus is linked to a regional 800MHz digital voice communication system. Metro Transit Control Center uses another analog 800 MHz radio to poll bus GPS data every minute. In addition, each bus has a wireless communication system that is used to download/upload files between the central server and the bus computer when the bus is within proximity of the bus garage. We would like to investigate the possibility of integrating a signal priority strategy using one of the existing communication systems on the bus with the traffic controller. We also plan to develop a prototype system to validate the bus signal priority algorithm using wireless communication technology in the second phase study. We also would like to work with Metro Transit and City of Minneapolis to discuss the potential opportunity of bus signal priority deployment. Metro Transit is planning the Northwest Corridor (Bottineau Corridor) project so as to include a bus way that will offer high-quality transit service from downtown Minneapolis through Crystal, Brooklyn Park, Maple Grove and Rogers (http://www.metrotransit.org/improvingTransit/northwestCorridor.asp). In this project, bus signal priority will be considered in order to improve bus travel time and reduce bus delay at signalized intersections. Transit Signal Priority conceptual design along Bottineau Corridor is currently being investigated by SEH Inc. (http://www.sehinc.com/).

The vision of the VII (Vehicle Infrastructure Integration, http://www.its.dot.gov/vii/index.htm) is to deploy a nationwide network that enables communications between vehicles and roadside infrastructure for various transportation operations and applications. Signal priority requests for transit or emergency vehicles can potentially be sent to the signal controller through the vehicle-to-infrastructure communication architecture described in VII. Communication with the roadside unit (e.g., traffic controller) for signal priority may be established using the existing 802.11x WLAN on the bus or the DSRC (Dedicated Short Range Communication) 802.11p protocol currently under development for wireless access to and from the vehicular environment. Work in next phase will concentrate first on the more readily available protocols. However the system will be designed so that it can be ported to the new 802.11p protocol when it becomes more readily available.

ACKNOWLEDGEMENT

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Figure 2. An East-West Corridor Example for Signal Priority

* Map adopted from MapQuest, Inc. (http://www.mapquest.com/)
Figure 3. Control Diagram of Bus Signal Priority Strategy
Figure 4. AM and PM Peak Bus Speed and Travel Time
### Public Transit, Priority Extension Time = 15 sec

#### AM PEAK

<table>
<thead>
<tr>
<th>Bus Statistics</th>
<th>Speed</th>
<th>Bus Travel Time</th>
<th>Bus Delay Time</th>
<th>Bus Stop Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB No Priority</td>
<td>9.1</td>
<td>0:19:53</td>
<td>0:14:49</td>
<td>0:10:05</td>
</tr>
<tr>
<td>WB No Priority</td>
<td>9.2</td>
<td>0:19:08</td>
<td>0:14:08</td>
<td>0:09:30</td>
</tr>
<tr>
<td>EB With Priority</td>
<td>10.4</td>
<td>0:17:30</td>
<td>0:12:26</td>
<td>0:08:17</td>
</tr>
<tr>
<td>WB With Priority</td>
<td>10.7</td>
<td>0:16:27</td>
<td>0:11:27</td>
<td>0:07:50</td>
</tr>
</tbody>
</table>

| Average EB     | 1.30  | -0:02:23        | -0:02:23       | -0:01:48     |
| Change EB      | 1.50  | -0:02:41        | -0:02:41       | -0:01:40     |

#### PM PEAK

<table>
<thead>
<tr>
<th>Bus Statistics</th>
<th>Speed</th>
<th>Bus Travel Time</th>
<th>Bus Delay Time</th>
<th>Bus Stop Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB No Priority</td>
<td>8.3</td>
<td>0:21:58</td>
<td>0:16:55</td>
<td>0:10:14</td>
</tr>
<tr>
<td>WB No Priority</td>
<td>7.7</td>
<td>0:22:41</td>
<td>0:17:41</td>
<td>0:10:10</td>
</tr>
<tr>
<td>EB With Priority</td>
<td>9.2</td>
<td>0:19:39</td>
<td>0:14:35</td>
<td>0:09:15</td>
</tr>
<tr>
<td>WB With Priority</td>
<td>8.3</td>
<td>0:21:03</td>
<td>0:16:02</td>
<td>0:08:47</td>
</tr>
</tbody>
</table>

| Average EB     | 0.90  | -0:02:19        | -0:02:20       | -0:00:59     |
| Change EB      | 0.60  | -0:01:38        | -0:01:39       | -0:01:23     |

#### Average Change

| EB Change % | 14.29% | -11.99% | -16.09% | -17.85% |
| WB Change % | 16.30% | -14.02% | -18.99% | -17.54% |

### Overall Network System, Priority Extension Time = 15 sec

#### AM PEAK

<table>
<thead>
<tr>
<th>Network Statistics</th>
<th>Speed</th>
<th>Avg. Travel Time</th>
<th>Avg. Delay Time</th>
<th>Avg. Stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Priority</td>
<td>19.8</td>
<td>0:01:35</td>
<td>0:01:00</td>
<td>1.60</td>
</tr>
<tr>
<td>Priority</td>
<td>19.1</td>
<td>0:01:42</td>
<td>0:01:06</td>
<td>1.70</td>
</tr>
<tr>
<td>Average Change</td>
<td>-0.70</td>
<td>0:00:07</td>
<td>0:00:06</td>
<td>0.10</td>
</tr>
</tbody>
</table>

#### PM PEAK

<table>
<thead>
<tr>
<th>Network Statistics</th>
<th>Speed</th>
<th>Avg. Travel Time</th>
<th>Avg. Delay Time</th>
<th>Avg. Stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Priority</td>
<td>18.1</td>
<td>0:01:55</td>
<td>0:01:19</td>
<td>2.00</td>
</tr>
<tr>
<td>Priority</td>
<td>16.0</td>
<td>0:02:17</td>
<td>0:01:42</td>
<td>2.60</td>
</tr>
<tr>
<td>Average Change</td>
<td>-2.10</td>
<td>0:00:22</td>
<td>0:00:23</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 1. AM and PM Peak Bus Statistics

Table 2. Overall Network Statistics