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Comprehensive Evaluation on Transit Signal Priority System Impacts Using Field Observed Traffic Data

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16. ABSTRACT

To improve the level of service for Community Transit (CT) buses, the South Snohomish Regional Transit Signal Priority (SS-RTSP) project has been launched. To understand the overall benefit of this project, the SS-RTSP system was tested and evaluated after the completion of the hardware and software installations on the 164th Street SW street corridor (phase-one) and the SR-99 corridor (phase-two) in Snohomish County, Washington State.

In this study, impacts of the SS-RTSP system on both transit and local traffic operations were quantitatively evaluated based on field observed data. Simulation models were also built and calibrated to compute measures of effectiveness that cannot be obtained from field-observed data. With simulation models and field observed data, the impacts of the SS-RTSP system on both transit and local traffic operations were quantitatively evaluated. Our evaluation results showed that the SS-RTSP system introduced remarkable benefits to transit vehicles, with insignificant negative impacts to local traffic on cross streets. The overall impact of the SS-RTSP system on local traffic of each entire intersection was not statistically significant at the p=0.05 level.

To improve the performance of the current SS-RTSP system, more transit vehicles can be made TSP eligible. The average number of granted TSP trips was only 16.96 per day per intersection during the phase-one test and 14.40 during phase-two test. Considering that negative impacts of the SS-RTSP on local traffic were not significant, more transit trips can be granted with proper TSP treatments to generate more benefits from the SS-RTSP system. Also, near-side bus stops were found to introduce extra transit delays when TSP was provided under certain conditions. Our recommendation is that the TSP treatment of extended green be disabled at intersections with near-side bus stops to avoid introducing negative impacts on transit vehicles.

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EXECUTIVE SUMMARY

Transit signal priority (TSP) is an operational strategy that facilitates the movements of in-service transit vehicles through signalized intersections. To improve the level of service for Community Transit (CT) buses, the South Snohomish Regional Transit Signal Priority (SS-RTSP) project has been launched. To understand the overall benefit of this project, the SS-RTSP system was tested and evaluated after the completion of the hardware and software installations on the 164th Street SW corridor (phase-one) and the SR-99 corridor (phase-two) in Snohomish County. This comprehensive evaluation was based on a large amount of field observed traffic data and real-world traffic control settings. These data included 11,448 hours of traffic video tapes and over 3.74 GB of raw traffic data (excluding the video data). They were collected through nine traffic control/operation systems across six transportation agencies.

This study quantitatively evaluated impacts of the SS-RTSP system on both transit and local traffic operations based on field-observed data. Simulation models were also built and calibrated to compute measures of effectiveness that cannot be obtained from field-observed data. With the simulation model and field-observed data, we quantitatively evaluated the impacts of the SS-RTSP system on both transit and local traffic operations. Our evaluation results showed that the SS-RTSP system introduced remarkable benefits to transit vehicles, with insignificant negative impacts to local traffic on cross streets. The overall impact of the SS-RTSP system on local traffic of each entire intersection was not statistically significant at the p=0.05 level.

With the SS-RTSP system, transit vehicles can be operated more reliably. The Measure of Effectiveness (MOE) of Transit Time Match indicated improvements of 1 minute and 34 seconds, or about 16.3 percent in the phase-one test, and 15 seconds, or about 6%, in the phase-two test. In the phase-one test, the mean eastbound corridor travel time of transit vehicles was

6.7 seconds or 4.9 percent shorter for granted trips than the average corridor travel time without TSP. Similarly, the average saved transit corridor travel time was 54 second, or 4.93 percent in the phase-two test. Because of the saved transit travel time, the SS-RTSP system decreased the overall personal delays. For all passengers who used the two test corridors, the average person delay reduced by 0.1 second in the phase-one test and 0.2 second in the phase-two test. The overall saved personal delay was 336,766 person-hours per year for only peak-hour travels at the two test corridors.

The impact of the SS-RTSP system on local traffic delay of an entire intersection was sometimes increasing and sometimes decreasing as observed from the simulation experiments. Paired t-tests on average vehicle delay and number of vehicle stops did not find any significant impacts from the SS-RTSP system at the p=0.05 level. Similarly, the SS-RTSP system impact on cross-street traffic was also analyzed. Our test data showed slight changes in vehicle delay, queue length, and signal cycle failure frequency on cross streets. However, the *t* tests indicated that these changes were not significant either at the p=0.05 level after the TSP implementation.

To improve the performance of the current SS-RTSP system, more transit vehicles can be enabled for TSP eligibility. The average number of granted TSP trips per day per intersection was only 16.96 in the phase-one test, and 14.40 in the phase-two test. Considering that the negative impact of the SS-RTSP on local traffic was not significant, more transit trips can be granted with proper TSP treatments and frequency of TSP requests can be increased to generate more benefits from the SS-RTSP system. Also, near-side bus stops were found to introduce extra transit delays when TSP was provided under certain conditions. Therefore, besides regular recommendations to avoid these extra delays, such as moving a near-side bus stop to the far side of the intersection, we recommend that the TSP treatment of extended green be disabled at intersections with near-side bus stops to avoid introducing negative impacts on transit vehicles.

CHAPTER 1 INTRODUCTION

1.1 Research Background

Transit signal priority (TSP) is an operational strategy that facilitates the movement of in-service transit vehicles through signalized intersections. Since delays incurred by transit vehicles at signalized intersections typically account for 10 to 20 percent of transit vehicle running times, TSP promotes transit utilization through improving service reliability (Baker, 2002). As an important ITS technology, TSP systems use sensors to detect approaching transit vehicles and alter signal timings, if necessary, to prioritize transit vehicles and improve their performance. For example, a green signal can be extended for a late transit vehicle to avoid further delay at the intersection. By reducing waiting time of transit vehicles at intersections, TSP can reduce transit delay and travel time, thereby increasing quality of service. Implementation of TSP gives transit customers more dependable service through greater schedule adherence and a more comfortable ride due to decreased number of stops and braking at signalized intersections. Transit riders who have experienced smoother and more comfortable rides are more likely to continue using transit services.

A transit agency has two objectives for using TSPs: improve service and decrease costs (Garrow and Machemehl, 1997). Through customer service enhancements, the transit agency could ultimately attract more customers. Fewer stops also mean reductions in drivers' workload, travel time, fuel consumption, vehicle emissions, and maintenance costs. Greater fuel economy and reduced maintenance costs can increase the efficiency of transit operations. TSP can also help reduce transit operation costs, as reductions in transit vehicle travel times may allow a given level of service to be offered with fewer transit vehicles. Reductions in bus running time and number of stops may also lower vehicle wear and tear, and consequently lead to deferred vehicle maintenance and new vehicle purchases (Garrow and Machemehl, 1997). Local transportation agencies also can benefit from TSP strategies when improved transit service encourages more auto users to switch to public transportation. Finally, reduced demand for personal car travel will help improve roadway service level.

Due to the rapid population and economic growth in the Greater Seattle area, traffic congestion has become an increasingly important issue. Improving transit services to reduce personal car travel demand are considered an effective countermeasure against traffic congestion. The South Snohomish Regional Transit System Priority (SS-RTSP) system was launched to improve the level of services for Community Transit (CT) buses and, therefore, would help solve traffic congestion problems in the Greater Seattle area.

1.2 Problem Statement

In the past two decades, TSP systems have been deployed in many cities worldwide. However, enthusiasm for TSP in North America has been tempered with concerns that overall traffic performance may be unduly compromised when signal timing plans intended to optimize traffic flow are overridden to provide a travel advantage to transit vehicles (Chang and Ziliaskopoulos, 2002). Several recent studies (see, for example, Abdulhai et al., 2002, and Dion et al., 2002) have quantitatively evaluated the effect of TSP. While these studies generally agree on the benefits for transit operations, the overall impacts of TSP on local traffic networks remain unclear. Also, since performance of a signal control strategy is closely related to traffic conditions, surrounding land use, traffic regulations, and roadway network geometry, comprehensive impacts of TSP systems on transit and other vehicles are case specific and difficult to generalize. This implies that TSP effects on a particular network need to be evaluated based on field-observed data.

Therefore, a comprehensive evaluation on the SS-RTSP system is of academic interest and practical significance.

The SS-RTSP system installation and evaluation comprises two phases. Phase-one involves four intersections on SW 164th Street in south Snohomish County. Phase-two covers thirteen intersections on SR-99 in the City of Lynnwood. This report summarizes both phase-one and phase-two evaluation.

1.3 Research Objective

This study uses field-observed data to quantitatively evaluate impacts of the SS-RTSP project on both transit and local traffic operations. We developed a series of measures of effectiveness (MOE) to measure the traffic performance. Specifically, this research has three major objectives:

- Quantitatively evaluate the TSP system benefits for transit operations;
- Calculate the overall impacts of the TSP system on local traffic networks; and
- Understand how TSP effects change with traffic conditions and signal control strategies.

CHAPTER 2 STATE OF THE ART

Interests in TSP date back to the 1970s. Typical performance measures used for TSP evaluation include changes in transit travel times, intersection delay, average vehicle delay, average vehicle stops, average person delay, and average person stops. The work of Ludwick (1975) was among the first TSP studies in the United States. It evaluated the initial Urban Traffic Control System - Bus Priority System (UTCS-BPS) in Washington, D.C., and used a microscopic simulation model, UTCS-1, for the evaluation. With this model Ludwick simulated a network with unconditional preemption for transit buses, applying the early green or extended green logic. The early green logic shortens the green times of conflicting phases so that a transit vehicle can receive green indication early. The extended green logic holds the green signal for an extra time period so that a transit vehicle can clear the intersection without stop.

Sunkari et al. (1995) developed a model to evaluate a bus priority strategy for one signalized intersection in a coordinated signal system. The model used the delay equation employed by the Highway Capacity Manual (2000) for signalized intersections and adapted the equation to calculate person delays for cases with and without priority strategies. Al-Sahili and Taylor (1996) used the NETSIM microscopic model to analyze Washtenaw Avenue in Ann Arbor, Michigan. A decease of 6 percent in bus travel time was the maximum benefit found. The authors suggested that the most suitable TSP plan for each intersection should be integrated and implemented as a system to maximize the benefit. Garrow and Machemehl (1997) evaluated the 2.5-mile-long Guadalupe N. Lamar arterial in Austin, Texas. The main objective of this study was to evaluate performance of different TSP strategies under peak and off-peak traffic conditions and also different saturation levels for side-street approaches (Chada and Newland, 2002).

Field evaluations reported by Chang et al. (1995) and Collura et al. (2000) indicated that reductions in average intersection delays ranged from 6 to 42 percent, and reductions in average bus travel times were from 0 to 38 percent. Some studies (for example, Yand, 2004) found that vehicles sharing the same signal phase with transit vehicles also occasionally benefited from TSP treatments. While a number of deployments produced no significant impacts on general traffic, others yielded stop and delay increases as high as 23 percent (Baker et al., 2002).

The Transit Capacity and Quality of Service Manual (TCQSM, 2003) provides guidance to practitioners seeking to evaluate the impact of a TSP system. The TCQSM recommends using person-delay as the unit of measurement for comparing the benefits and costs of TSP implementation. The person-delay approach assumes that the value of time for a bus passenger is the same as for an auto passenger. This assumption allows use of the same scale to evaluate the benefits and costs of TSP and provides flexibility to practitioners by allowing variable auto occupancy and bus occupancy rates.

According to the study by Casey (2002), the number of transit agencies with operational TSP systems increased 87 percent from 1998 (16 agencies) to 2000 (30 agencies). New and rapid advances in traffic/bus detection and communication technologies and well-defined priority algorithms have made TSP more appealing or acceptable to more road users of all modes.

CHAPTER 3 PROJECT OVERVIEW

3.1 Major Components

The SS-RTSP project employed the TSP system developed by McCain. It has three major subsystem components, including in-vehicle subsystem, road-side subsystem, and center subsystem. Figure 3-1 illustrates the subsystems in the field of the SS-RTSP system. When an equipped transit vehicle approaches a TSP-enabled intersection, the in-vehicle device communicates with the road-site antenna. A reader sends the transit vehicle's electronic ID and trip information to the traffic signal controller for the transit vehicle's eligibility evaluation. If the transit is qualified to receive TSP and no other TSP has been issued in the current signal control cycle, a TSP treatment may be provided to reduce delay of the transit vehicle (McCain Traffic Supply. 2004). The field equipments are connected with the center subsystem and can be remotely monitored, debugged, and updated.

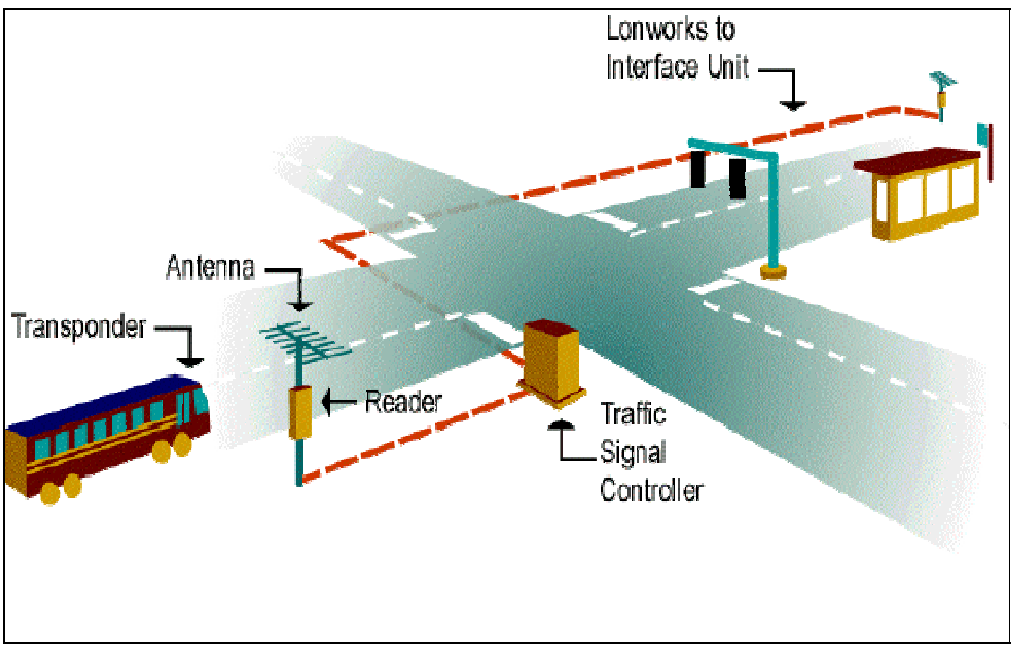

Figure 3-1 Field Equipment for TSP System Operation

(Source: King County Department of Transportation, 2002)

A transponder installed on the front end of the transit vehicle provides the coach number, route number, trip number, and transit system operator ID (such as Community Transit or Metro). The road-side subsystem includes Radio Frequency (RF) antennas mounted upstream of the traffic signals on mast arms, power sources for reader units, and the Transit Priority Request Generator (TPRG). A TPRG contains a microprocessor and a communication device connected with the traffic signal controller via 24 VDC logic inputs.

3.2 Priority Strategies

The SS-RTSP system applies active priority strategies, which are dynamic signal timing enhancements that modify the signal phases upon detection of a transit vehicle. These strategies provide efficient operation of traffic signals by responding to a transit TSP call and then returning to normal operation after the call is serviced or has expired. Although several active TSP strategies are available, such as phase insert and phase suppression (Baker et al., 2002), only two active transit signal priority strategies are used in the SS-RTSP system:

- Early Green (Early Start or Red Truncation of Priority Phase);
- Extended Green (or Phase Extension of Priority Phase).

Early green and extended green are the most common TSP treatments for transit vehicles. The early green strategy indicates a green light prior to the normal start of a priority movement phase. This process is implemented by shortening the green time of the conflicting phase(s), without violating the minimum green time and clearance intervals, so that the green time for the priority phase can start early.

The extended green strategy is typically used when a transit vehicle arrives near the end of the green indication of a priority phase. When extended green is applied, traffic signal holds the green signal of the priority phase for additional seconds to facilitate eligible vehicles to pass the intersection without further delay. Depending on the signal control policy, green times for conflicting phases may or may not be shortened to compensate for the extended green for the priority phase. In the latter case, a constant signal control cycle length is not enforced. Both the early green and extended green strategies are intended to lower transit vehicle delays at TSP-enabled intersections. Depending upon the arrival time of a TSP-eligible transit vehicle, early green or extended green may be used to provide an appropriate TSP treatment to the transit vehicle.

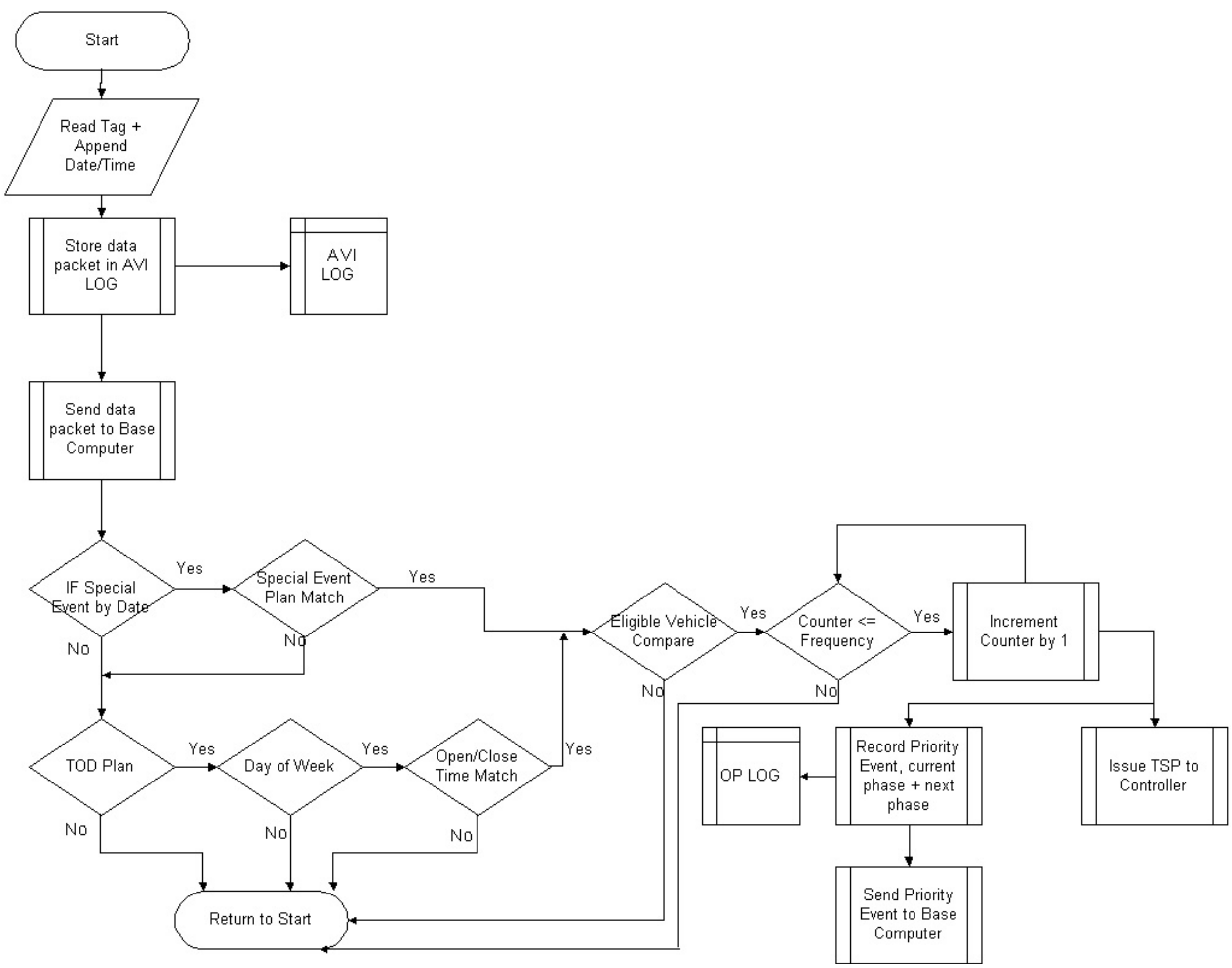

Figure 3-2 Priority Logic Flowchart

The basic priority logic flowchart of the TPRG is shown in Figure 3-2. Some intersections may have additional logic, or conduct the eligibility tests in the readers. The TPRG sends a transit priority request to the traffic controller only for an eligible bus when and only when the bus is:

- operating on one of the three test routes (114, 115, and 116);
- equipped with Keypad;
- 0–30 minutes behind its scheduled time.

Keypad is a device installed beside the bus driver’s seat to input the route number and trip number data to the transponder.

CHAPTER 4 METHODS

4.1 Major Measures of Effectiveness

To provide a comprehensive evaluation of TSP strategy impacts, we used several Measures of Effectiveness (MOEs) to regularly assess impacts on traffic and transit operations. Each MOE reflects the impact of the TSP system from a certain perspective, and they jointly provide a relatively complete assessment on the SS-RTSP project. In this study, we separate the chosen MOEs into two categories: the main MOEs and the secondary ones. The main MOEs address our major concerns about the SS-RTSP project and can be calculated using field-observed data. The secondary MOEs are useful for in-depth understanding of TSP performance but cannot be derived from field-observed data. We rely on microscopic simulation models to calculate secondary MOEs.

The main MOEs chosen for this evaluation study are as follows:

Transit Time Match

TSP systems are designed to help transit vehicles adhere to their schedules. A high on-schedule rate can result in increased ridership and reduced operation cost. In this study, we define the variable of Transit Time Match (TTM) as the difference between actual transit arrival time and scheduled arrival time at each timing point on the test routes. If the mean of TTM is close to zero, then the transit vehicles adhere to their schedules very well. The actual arrival times can be extracted from Global Positioning Systems (GPS).

Transit Travel Time

Transit travel time data are collected to evaluate whether the TSP system has caused a significant change in travel time on the test routes. Decreases in transit vehicle travel time can result in a lower operation cost and emission level. In-vehicle GPS data loggers record vehicle locations periodically. Such vehicle location data can be used to generate accurate transit travel time data.

Traffic Queue Length

A major concern about a TSP system is whether or not a TSP treatment can cause excessive delay for other intersection movements. To address this concern, a key MOE is chosen as the size of traffic queue for each conflicting phase and the delays associated with those queues. Before and after analysis on traffic queue length helps answer whether queues significantly lengthen for movements not receiving the benefits of TSP treatments. Also, it helps understand TSP impacts on streets crossing the TSP corridors. In this study, we manually collected sample traffic queue length data from recorded video images at TSP-enabled intersections of the SS-RTSP project.

Signal Cycle Failures

Signal cycle failures refer to the specific delay condition in which vehicles must sit through at least one complete signal cycle to pass through an intersection. This condition leads to considerable public frustration, and increased occurrence is likely to result in more substantial "public resistance" to TSP than will a minor increase in intersection delay. Thus, it is a key measure reported to public officials. Signal cycle failures are extracted manually from recorded video data.

Frequency of TSP "Calls"

This MOE monitors how frequently (calls per hour) the TSP system requests signal priority, and how often those calls result in a "denied" priority request (a priority request may not be granted at a given condition due to the TSP policy). This information will be used along with the intersection delay information to determine the need for any changes to the TSP policy. If

TSP calls are causing further intersection delay, the number of allowable priority calls may need to be reduced. Conversely, if intersection delays are not deteriorating and desirable priority calls are not resulting in changes in signal timing, then additional priority calls should be allowed. Frequency of TSP calls is calculated from the TPRG-logged TSP requests from transit vehicles.

In addition to the above primary MOEs, the following secondary MOEs are also important. Since these MOEs cannot be calculated from field-observed data, a microscopic traffic simulation model is built to derive them.

Average Person Delay

This MOE is commonly adopted to reflect the performance of a roadway system. If the average person delay for the whole network is reduced by the SS-RTSP project, then we can conclude a net benefit from the TSP system.

Vehicle Delays and Stops

Average delay per vehicle is the MOE used for intersection level of service evaluation in HCM (2000). In this study, we use averaged vehicle delay and number of vehicle stops to reflect the time loss of vehicles at intersections. Changes of this MOE set before and after the SS-RTSP system indicate the impacts of the TSP system on the performance of the intersections. Additionally, it can also be used to quantify the impacts of the SS-RTSP system on side streets crossing the TSP corridors.

4.2 Database Design and Implementation

The large amount of complex data collected for analysis requires a well-designed and organized database. The database design in this study followed the Entity/Relationship (E/R) diagram approach. A detailed introduction of the E/R diagram approach is available in Garcia-Molina et al. (2002). Figure 4-1 shows the E/R diagram design of the database. According to Figure 4-1, the following database objects are needed:

Entities:

- Bus location
- Bus assignment information
- Bus operation information
- TSP calling

Relationships:

- Belong to: binary, many-one
- Related to: binary, many-one

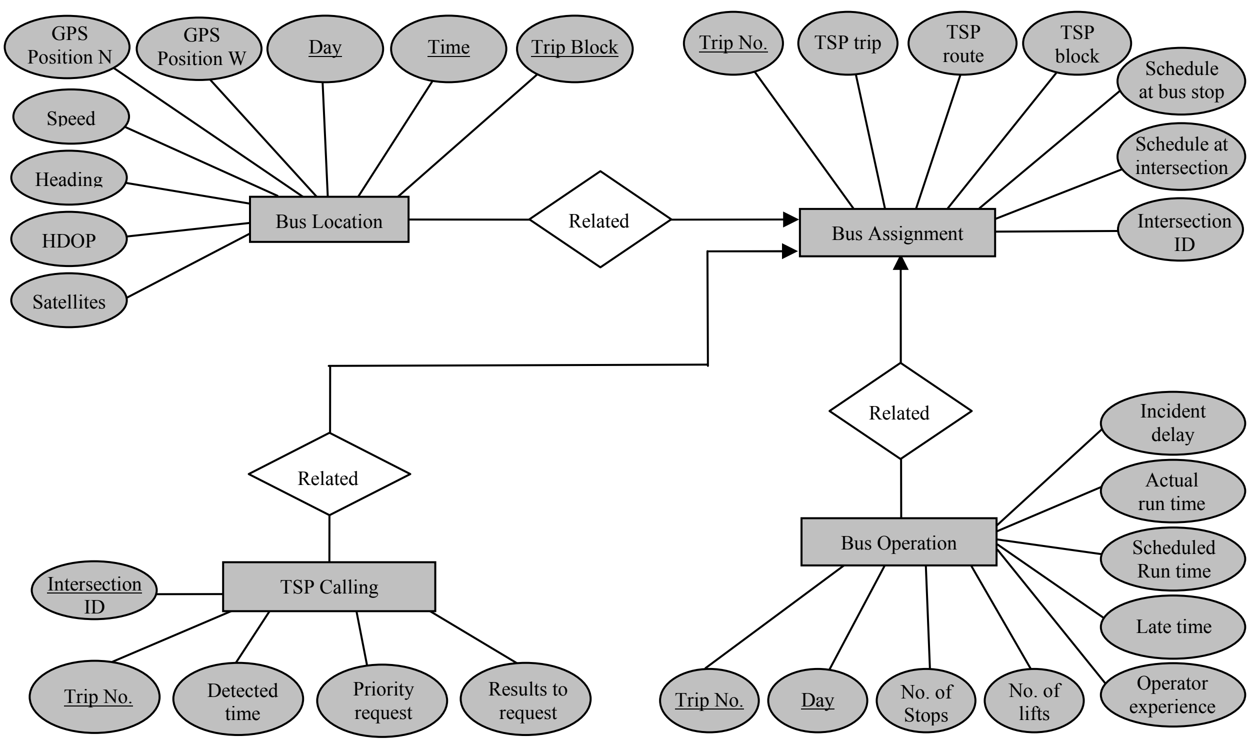

Figure 4-1 E/R Diagram of Database

Relational schemas:

- Bus location (Trip block, Time [hhmmss], Day [mmddyy], GPS coordination N, GPS coordination W, Speed, Heading, HDOP, Satellites)
- Bus Assignment Information (Trip No., TSP trip, Route No., Trip block, schedule at each time-points on weekday/ Saturday/ Sunday and holiday, schedule at each intersection with TSP sensor on weekday/ Saturday/ Sunday and holiday, Intersection ID)
- Bus Operation Information (Trip No., Day, No. of stops at bus stops, No. of wheel chair/bicycle lifts, operator experience [year], late time at the first bus stop [second], scheduled running time [second], actual running time [second], incident delay [second])
- TSP Calls (Intersection ID, coordination N, coordination W, Trip No., Bus detected time, Day, Priority request made, Results to request)

Foreign Keys:

- (Buslocation.Tripblock, Buslocation.Time, Buslocation.Day) references BusAssignmentInformation.TripNo.
- (BusOperationInformation.TripNo, BusOperationInformation.Day) references BusAssignmentInformation.TripNo.
- (TSPCalls.IntersectionID) references BusAssignmentInformation.TripNo..

In this study, we use Structured Query Language (SQL) for data management. This database is implemented in the Microsoft SQL Server 2000.

CHAPTER 5 PHASE-ONE FIELD TEST

The phase-one test of the SS-RTSP project lasted two weeks, from April 4 to April 17, 2005. The TSP system was turned off in the first week, and on in the second week. TSP was turned on or off on Monday mornings between 1:00 AM and 4:00 AM, when no CT vehicles were in operation. Although TSP was off in the first week, we still collected all the data in the week in order to conduct a before and after analysis for the SS-RTSP project.

5.1 Corridor

The phase-one test was performed on the 164th Street SW corridor, between 36th Avenue W and 25th Avenue W (or NorthPoint). Figure 5-1 shows the map of the test corridor and its location.

The tested corridor is about 3600 feet long and has four signalized intersections. All four intersections on the test corridor are equipped with TSP devices. One or two approaches of the four intersections are equipped with TSP readers and can detect transit vehicles with TSP tags. Table 5-1 shows the TSP approaches tested in this project.

Table 5-1 TSP Approaches of the Phase-One Test

Intersection	36th Avenue	Park & Ride	Alderwood Mall Parkway	NorthPoint
TSP approaches	Eastbound	Eastbound, Westbound	Westbound	Eastbound, Westbound
TPRG Unit	15010	15000	15020	15030
Reader Unit	15014	15003, 15004	15023	15033, 15034

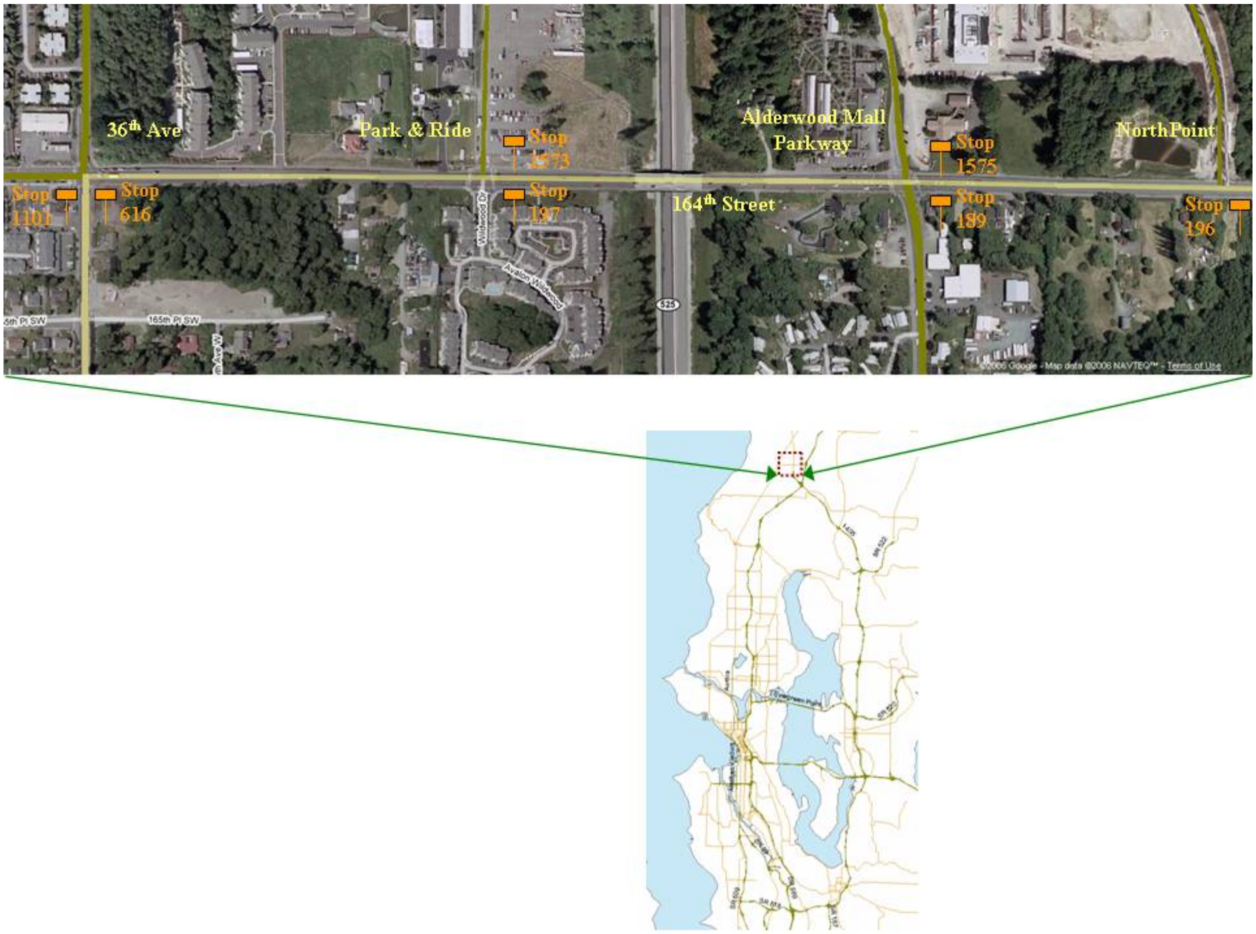

Figure 5-1 Phase-One Test Corridor

(Map and image source: http://maps.google.com/maps.)

5.2 Transit Service

The tested transit routes were CT 114, 115, and 116. All the test routes run through 164th Street SW between NorthPoint and 36th Avenue, and turn on 36th Avenue, as shown in Figure 5-1. This corridor has seven bus stops, including three near-side stops: stop 616 (eastbound), stop 1573 (westbound), and stop 1575 (westbound). Most of coaches on the test routes are equipped with Keypad and eligible for receiving TSP. Table 5-2 summarizes the number of the eligible TSP trips on the test corridor in one week.

Table 5-2 Number of Eligible TSP Trips on Phase-One Test Routes

	Per Weekday	Saturday	Sunday	One Week Total
Eastbound	58	25	14	329
Westbound	57	25	14	324
Total	115	50	28	653

5.3 Data source

5.3.1 TSP logs

TPRG records transit vehicle detection, TSP request, and traffic signal status in real time. A TPRG generates two types of log files: AVI (Automatic Vehicle Identification) logs and OP (operation) logs. AVI logs collect information from the TSP readers about detected transit vehicles. The following are several example rows in an AVI log file.

06:04:11,15003,1,1,2,7602,0,0,115,2018,21515 ,

06:13:30,15003,1,1,2,5827 ,

06:19:51,15003,1,1,2,9158 ,

Commas are used to separate fields in the log files. From left to right, the data fields are: detection time, reader unit, antenna, system, agency, vehicle, unused field, unused field, route, run, trip number, and some undefined fields reserved for future usage. Data in fields 3 ~ 6 are static, and those in fields 9~11 dynamic. The TSP system may also detect and record transit coaches not in the three tested routes but equipped with TSP tags. These vehicles can be easily recognized from the lack of dynamic data.

Examples of OP logs are as follows:

06:27:03,15000,Checkout (25),Phase 6 Green to Red: 0

06:27:17,15000,Checkout (25),Phase 6 Red to Green: 0

06:27:38,15000,Checkout (25),Priority Denied - Trip: 9163

06:33:31,15000,Checkout (25),Priority Denied - Phase: 7640

06:29:41,15000,Checkout (25),Priority granted for trip: 21500

06:29:41,15000,Checkout (25),: 7617

The first two fields are the same with the AVI logs. The third field is always the same for all the recorded rows in a TPRG. The fourth field records the change of traffic signal lights in given phases, such as those in the first two rows, or the TPRG treatments applied to detected buses. A TSP request may be denied for two reasons: "trip" or "phase." "Trip" means the detected bus is not serving TSP-eligible trips of the three test routes. "Phase" indicates the eligible bus does not need a TSP treatment because it is estimated to arrive at the intersection when signal is in green, or the bus is not late at all. If a TSP request is denied, the reason, together with the coach number, will be logged in the fourth field, as shown in the third and fourth rows of the example. If a bus is given a priority, its trip number will be logged in the fourth field, with its coach number saved in the following row, as shown in the fifth and sixth rows of the example.

5.3.2 GPS data

GPS data were logged by the GeoStats In-Vehicle GeoLogger™ systems installed on transit coaches. GeoLogger can track up to 12 satellites and update data every second, with position accuracy of 15 meters in root-mean-square (RMS). Thirteen GeoLoggers were installed on test coaches. All the GeoLoggers were preset to record data every second when the vehicle speed exceeds 1.15 miles per hour. The following is an example of logged GPS data:

A,47.81633,N,122.29803,W,133813,110405,004.7,317,,05.8,04

The first field shows the working status of GPS. If the status is okay, the GeoLogger records an "A." The next four fields are the coordinates of vehicle position shown in longitude and latitude. The fifth field shows time in the "hhmmss" format. The sixth field represents the date in the "ddmmyy" format. The seventh filed is the speed in miles per hour. The eighth field is the heading of the vehicle in degrees. The last two fields relate to the satellite signal quality, showing Horizontal Dilution of Precision (HDOP) and number of satellites, respectively. To analyze position data more conveniently, we wrote a piece of MATLAB™ code to transfer the positions from the longitude and latitude coordinate system into the Carter coordinate system defined for North American Datum (NAD) 1927 State Plane Washington North FIPS 4601.

5.3.3 Traffic controller logs

A traffic controller monitors detector calls and makes signal timing decisions in real-time. For approaches with advance detectors, traffic volume data can be collected and logged periodically. Table 5-3 provides an example of traffic volume data logged by a traffic controller.

Table 5-3 Example of Traffic Controller Logs in the Phase-One Test

Date Time	Name	Det1	Det2	Det3	Det4	Det5	Det6	Det7	Det8	…
4/14/05 11:30	060 164th SW & Alderwood/Manor	67	35	14	11	52	50	4	24	…

Depending on controller type, model, and the operating traffic management system, other event data such as changes of signal control phases and time-stamped traffic calls may be recorded. Phase change times are very valuable data for understanding signal controller decisions. However, such phase change data were not available for the phase-one test due to constraints of the traffic management system used by Snohomish County. Fortunately, some phase change information is logged by TPRG. Through analyzing the TPRG logs, we were able to understand the time associated with each priority phase change during the test period.

5.3.4 Traffic video data

All four intersections included in this study use Video Image Processors (VIPs) for traffic detection. These detection cameras are typically fixed to cover a designated area for vehicle detection. For recording traffic video, we split the video channel from a detection camera into two channels; one goes to the VIP card and the other to our Video Cassette Recorder (VCR). Twelve VCRs were configured to record traffic images for the 36th Avenue intersection (all four approaches), the Alderwood Mall Parkway intersection (all four approaches), the Park & Ride intersection (the eastbound and westbound approaches), and the 25th Avenue intersection (the eastbound and westbound approaches). Six hours of video data were collected for each recording approach every day during the two weeks for the phase-one test. The six-hour video includes two hours during the morning peak (6:30A–8:30 AM), two hours during non-peak (12:30–2:30 PM), and two hours during the afternoon peak (4:30–6:30 PM). On Sundays, the six-hour video was recorded in two time periods: 6:30–8:30 AM and 2:30–6:30PM.

5.3.5 Other data

Unusual transit vehicle delays may be introduced by incidents, special events, or inclement weather conditions. To capture impacts from these factors, we designed a data log form for transit drivers to record reasons for usual delays (Figure 5-2). Since unusual delays may introduce serious errors to TSP evaluation, data associated with unusual delays were removed from analysis.

Date ____________ **Transit Signal Priority Log** Route 114/115/116

Run Number ____________________ Years Driving w/CT ________________

Trip Number	Delay (minute)	Major Reason for the Delay						
		Wheel Chair	Traffic	Weather	Incident	Accident	Reroute	Other
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	
		☐	☐	☐	☐	☐	☐	

Notes: 1. Please only record delays on 164th Street SW between 36th Ave W and 22nd Ave W.
2. If there is more than one wheelchair operation on the test corridor, please indicate the number of operations beside the checked box. If the delay reason is not listed, please indicate it in the "other" column.

Figure 5-2 Log Form for Bus Drivers

Additionally, CT provided bus schedule data and also trip assignment records, which listed trip numbers assigned to each coach every day during the test period.

All the discussed data, except for the traffic video data, were stored in the designed database described in Section 4.2 in a Microsoft SQL Server database. SQL can be used to query and analyze the data.

CHAPTER 6 PHASE-TWO FIELD TEST

The phase-two test of the SS-RTSP project lasted six weeks, from January 8th to February 18th, 2007. However, only data collected in weeks three and four were used. There was a strong snow storm occurred in the first week of the test that severely affected traffic pattern on the test corridor for the first two weeks. The last two weeks' data could not be used either because of a transit schedule change that made the data incomparable. Therefore, only data from January 22nd to February 4th could be used for the phase-two evaluation. The TSP system stayed on in the week of January 22nd to 28th, and turned off in the week of January 29th to February 4. The data collection method used for the phase-one test was also applied in this test.

6.1 Corridor

The phase-two test was performed on the SR-99 corridor, between 238th Street SW and 164th Street SW. A map of this corridor is shown in Figure 6-1. This corridor is about 5.3 miles long with 13 signalized intersections. All the intersections are equipped with TSP for both the northbound and the southbound traffic.

6.2 Transit Service

On the SR-99 corridor, the tested transit routes were CT 100 and 101. Both test routes run south-north directions without turning. There are 33 bus stops on this corridor, and none of them are near-side bus stops. A summary on eligible TSP trips for each direction are provided in Table 6-1.

Table 6-1 Number of Eligible TSP Trips on Phase-Two Test Routes

		Per Weekday	Saturday	Sunday	One Week Total
SR-99	Northbound	72	46	37	443
	Southbound	74	47	35	452
	Total	146	93	72	895

Figure 6-1 Phase-Two Test Corridor

(Map and image source: http://maps.google.com/maps.)

6.3 Data Source

6.3.1 TSP logs

The TSP logs were generated by exactly the same devices used for the phase-one test. Please refer to Section 5.3.1 for detailed information on those TSP logs and their data formats.

6.3.2 GPS data

The GPS logs were provided by exactly the same devices and in the same way as in phase-one test. Please refer to section 5.3.2 for detailed information on TSP logs.

6.3.3 Traffic controller logs

The phase-two test corridor is in the territory of the City of Lynnwood. The City of Lynnwood uses the Naztec traffic control system for traffic management and control. With the Naztec TMC (Traffic Management Center) software, many event data, such as the split change and time-stamped traffic calls, can be monitored. The traffic detection systems on the SR-99 corridor are Traficon's Video Image Processors (VIPs). Virtual loops were setup at mid-blocks to detect traffic volume. The TMC server archives and reports traffic volume data periodically.

6.3.4 Traffic video data

All TSP-enabled intersections on the phase-two test corridor use VIPs for traffic detection. Video signals from these detection cameras were recorded as ground-truth data for traffic queue length and cycle failure analysis. In addition to the VIPs, some intersections also have a surveillance video camera that can be re-oriented to collect extra video data at locations of interest.

Twenty-eight VCRs were employed to record traffic video data from all the thirteen intersections on the SR-99 test corridor. The intersections at the 196th Street SW, the 200th Street SW, and the 220th Street SW are very busy on all approaches. Hence, each approach of the three intersections had a VCR dedicated to its video data collection. For each of the other ten intersections, video inputs from the four approaches were combined into a quad format and one VCR was used to record the quad video streams. Several surveillance cameras were also used to provide video data at advanced positions. In each weekday, the VCR recorded six hour video data, including two hours of the morning peak (6:30AM-8:30 AM), two hours of off-peak (3:00PM-4:00PM and 6:00PM-7:00PM), and two hours of the afternoon peak (4:00PM-6:00 PM).

6.3.5 Other data

Based on our experience of analyzing the phase-one test data, the transit drivers' logs were not accurate and could not be applied. Therefore, we eliminated drivers' log in the phase-two test.

Bus schedule, bus stop location, and transit ridership data were provided by CT. Trip assignment records were not collected in the phase-two test because these data can be extracted from the TSP logs generated by TPRG.

All the discussed data, except for the traffic video data, were stored in the phase-two database created following the design described in Section 4.2 and implemented in Microsoft SQL Server 2000.

CHAPTER 7 SIMULATION ANALYSIS

7.1 Simulation Tool

Average person delays, vehicle delays, and stops are several important performance measures for evaluating the system. As mentioned earlier, these MOEs are not directly calculable from the field-observed data; hence, we developed simulation models to compute them. Traffic simulation software VISSIM version 4.10 was exploited to emulate traffic operations with or without the functions of the TSP system. VISSIM is a microscopic behavior-based traffic simulation tool that can model integrated roadway networks and various modes including general-purpose traffic, buses, high-occupancy vehicles (HOV), light rail, trucks, bicyclists, and pedestrians. VISSIM can also implement some advanced traffic systems and control strategies such as TSP systems, provide effective measures to assess their benefits and costs, and then further optimize system operations (VISSIM User's Manual, 2004).

7.2 Phase-One Simulation Modeling and Experience

7.2.1 Modeling 164th Street SW

The section of 164th Street SW between 36th Avenue W and 25th Avenue W (or NorthPoint) in the City of Lynnwood was modeled to simulate the corresponding practical test sites. The simulation model was configured by actual layout of the corridor and traffic control parameters. Field-observed traffic volumes, transit ridership estimates, and vehicle occupancy data were used to calibrate the model. Details of model setup and calibration are described as follows.

To model the phase-one test corridor, we obtained arterial geometric characteristics and transit stop coordinates from construction designs and the GPS systems used by Snohomish County in addition to practical observations (Snohomish County, 2003). Traffic control and operational parameters at the test corridor were collected from the Snohomish County Department of Transportation.

In accordance with the practical test situation, the TSP function was enabled in the control strategies for the four intersections, 164th Street and 36th Avenue, 164th Street and Park and Ride, 164th Street and Alderwood Mall Parkway, and 164th Street and NorthPoint, on the phase-one test corridor. The emulated NEMA controller in VISSIM can be properly configured as a standard NEMA controller to satisfy requirements of fully actuated signal control and basic TSP operations. Thus, in this study we applied the emulated NEMA controllers in the simulation model to implement the real signal control plans in operation for each intersection. A basic TSP routine is supported by NEMA controller. A transit call detected by sensors may generate a request for early green or extended green operation that is consistent with the logic in the SS-RTSP system.

7.2.2 Simulation model calibration

We set traffic volumes for the approaches based on actual volumes observed by traffic sensors. Some traffic volume data were double-checked by ground-truth video tapes recorded at the test intersections to enhance to reliability of the model calibration process. Traffic flows of intersection approaches generated by the simulation program reasonably distributed in the range from 50 vehicle-per-hour-per-lane (vphpl) to 1250 vphpl and matched field observed volumes very well.

We estimated the passenger ridership on buses based on annual ridership of CT (National Transit Database, 2004). In our model we selected 12 ppv (passengers per vehicle) as the ridership. The average vehicle occupancy for general-purpose vehicles was estimated to be 1.2

occupants per vehicle, as determined by King County Metro based on field observations (King County Department of Transportation, 2002). Additionally, the generation rate of passengers is set as 10 persons per hour (pph) based on the number of boarding at each stop (Community Transit, 2005). Other parameters, such as bus headways, locations of bus stops and so on, were calibrated according to the real values. Figure 7-1 shows a snapshot of the simulation model for the intersection of 164th Street and 36th Avenue.

Figure 7-1 A Snapshot of the Phase-One Simulation Model

We also calibrated traffic control settings of the simulation model by using actual traffic operation parameters and control plans. Internal parameters for the simulation model were properly adjusted to ensure the model's appropriateness to the corresponding application. After the simulation model was properly calibrated, we conducted a six-hour simulation test: three hours for TSP-on and the other three hours for TSP-off.

7.3 Phase-Two Simulation Modeling and Experience

7.3.1 Modeling the SR-99 corridor

The SR-99 section between 238th Street SW and 164th Street SW was modeled to simulate the phase-two test corridor. The VISSIM model was configured using the actual layout of the corridor and traffic control parameters. Field-observed traffic volumes, transit ridership estimates, and vehicle occupancy data were used to calibrate the model.

The simulation software VISSIM provides a flexible and powerful platform for user-specific development. The emulated NEMA controller provided by VISSIM can properly function as a standard NEMA controller to satisfy requirements of actuated signal control and basic TSP operations. However, the traffic controllers on this corridor are Naztec, which provide some different TSP functions compared with those by the NEMA controller. Therefore, an external controller was established for each intersection using the vehicle actuated programming (VAP) language. The control logic and transit priority strategies of the phase-two test intersections can be implemented by using the VAP programming language. Thus, a total of thirteen external VAP controllers were developed, one for each intersection, for the SR-99 test corridor. Control parameters and TSP strategies were extracted from the real control system settings and applied to the calibration of the simulation models. Details of the calibration process are described in the following section.

7.3.2 Simulation model calibration

Traffic volumes in each approach were collected from the virtual loops at mid-block using the VIPs. Directional volumes were manually extracted from video tapes recorded at the test intersections on typical weekdays. These volume data were used to configure the simulation model for traffic generation. Traffic volumes generated by our VISSIM simulation model reasonably distributed in the range from 30 vphpl to 980 vphpl, which matched our field observations very well. Traffic control parameters used by the VISSIM model was calibrated using the actual control plans and timing parameters.

We estimated the passenger ridership on buses based on CT's annual ridership data (National Transit Database, 2004). Consequently, we used 12 ppv (Passengers Per Vehicle) as the ridership for our simulation model. The average vehicle occupancy for general-purpose vehicles was configured to be 1.2 occupants per vehicle based on field observations by King County Metro (King County Department of Transportation, 2002). Additionally, the generation rate of passengers is set as 20 persons per hour (pph) in our simulation model according to CT's study on the number of boardings at each stop (Community Transit, 2005). The other parameters, such as bus headways, bus stops' locations and so on, were calibrated according to the real values. Since the corridor is very long, we only show a snapshot of the simulation model at one example intersection of 196th Street and SR-99 in Figure 7-2. Figure 7-3 provides a 3D view of the simulation model at the intersection of 200th Street SW and SR-99.

Due to these stochastic features of the simulation models, multiple simulation iterations are essential to enhance the reliability of simulation results. By changing the VISSIM simulation random seeds, the random vehicle generation can be realized. In this analysis, a total of 20 iterations were conducted, ten scenarios with TSP functions and ten without TSP functions. The test period was 3 hours for each scenario.

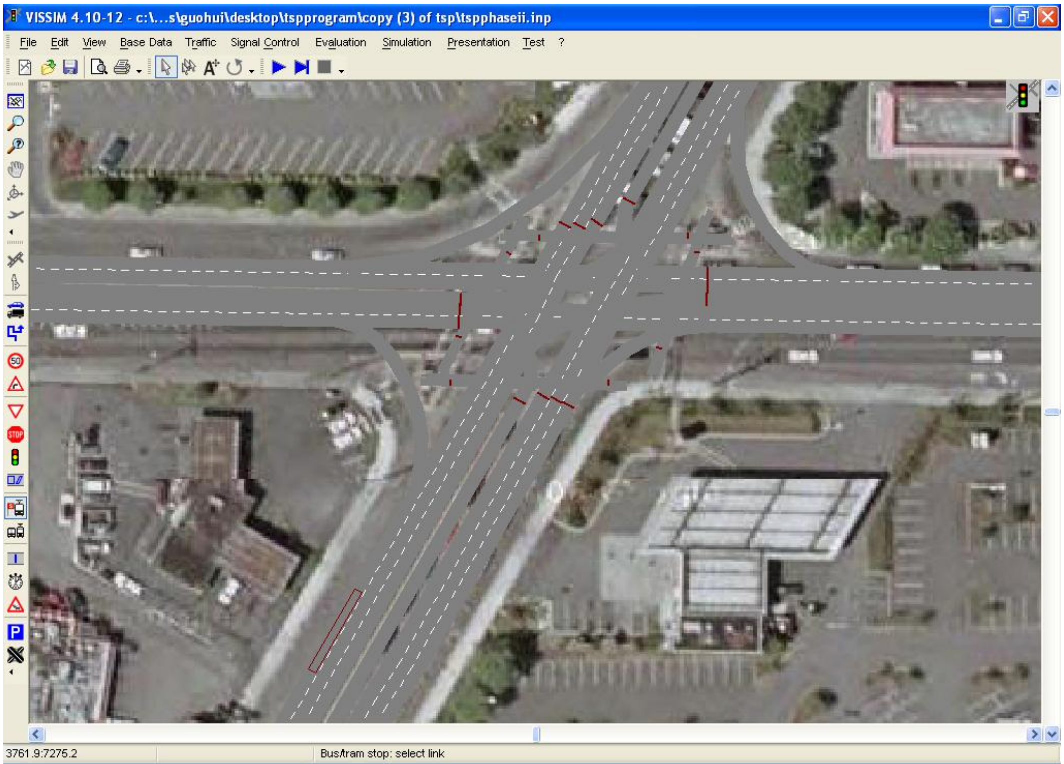

Figure 7-2 A Snapshot of the Phase-Two Simulation Model

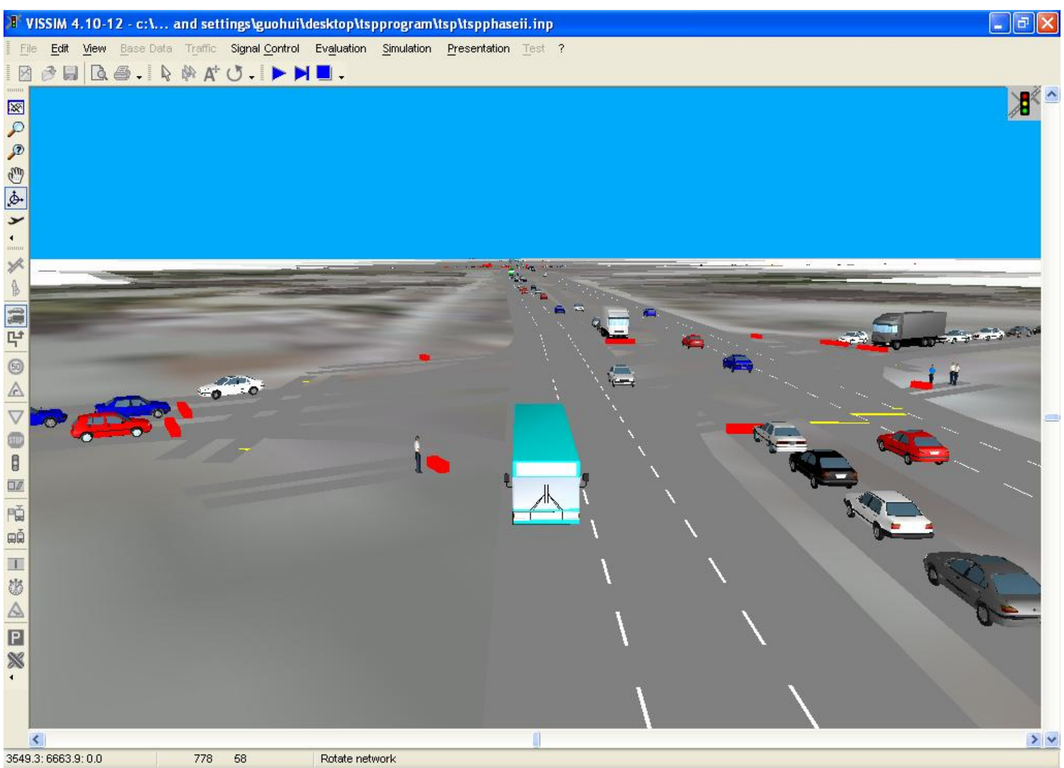

Figure 7-3 A 3D Snapshot of the Phase-Two Simulation Model

CHAPTER 8 PHASE-ONE RESULTS AND DISCUSSION

8.1 Statistics for Granted TSP Trips

Table 8-1 shows the number and percentage of granted TSP trips based on the TSP log files. When a TSP-eligible trip was granted for priority treatment, TPRG sent a priority requests to the traffic controller. Then the traffic controller issues proper TSP treatment to the bus. The percentage data in Table 8.1 shows the share of granted trips in all the scheduled trips of the test rout 114, 115 and 116. The number of granted TSP trips differed from day to day and from intersection to intersection. The average number of granted TSP trips per intersection per day was 16.96, or about 18.19 percent in all scheduled trips.

Table 8-1 Number and Percentage of Granted TSP Trips in the Phase-One Test

TPRG / Date	Number and Percentage of Granted TSP Trips									
	15010		15000		15020		15030		Total	
2005/04/11	19	16.52%	25	21.74%	26	22.61%	43	37.39%	113	24.57%
2005/04/12	1	0.87%	0	0.00%	4	3.48%	5	4.35%	10	2.17%
2005/04/13	5	4.35%	20	17.39%	20	17.39%	25	21.74%	70	15.22%
2005/04/14	16	13.91%	29	25.22%	24	20.87%	32	27.83%	101	21.96%
2005/04/15	13	11.30%	34	29.57%	26	22.61%	48	41.74%	121	26.30%
2005/04/16	2	4.00%	5	10.00%	11	22.00%	19	38.00%	37	18.50%
2005/04/17	0	0.00%	4	14.29%	8	28.57%	11	39.29%	23	20.54%
Total	56	8.58%	117	17.92%	119	18.22%	183	28.02%	475	18.19%

8.2 Benefits

8.2.1 Transit time match

As defined in Section 4.1, transit time match refers to the absolute difference between the actual transit arrival time at the timing point and the scheduled arrival time. The test corridor has seven bus stops, and six are affected by the TSP system. The average transit time match results at these bus stops are shown in Table 8-2. We calculated arrival times of transit vehicles based on TSP reader logs. The first three bus stops are eastbound, and the others are westbound.

Table 8-2 Time Match at Bus Stops in the Phase-One Test

	Stop 197	Stop 189	Stop 196	Stop 1101	Stop 1573	Stop 1575
TSP off	10′12″	7′36″	7′54″	9′42″	12′24″	10′12″
TSP on	8′06″	7′18″	6′30″	9′18″	9′00″	9′12″

The transit time match results showed that when TSP was on, transit coaches were more reliable at each bus stop. The increase of on-time performance varied from 18 seconds to 3 minutes and 24 seconds, or 3.9 percent to 27.4 percent, compared to the scenario when TSP was off. The overall average improved time match at all the stops was 93.6 seconds, or about 16.3 percent compared with the scenario when TSP was off.

8.2.2 Transit travel time

Transit travel time data were calculated using GPS position data. Table 8-3 shows the descriptive statistics for transit travel time over the test corridor. The east end of the corridor was defined as the point on the center line of the 164th Street SW at TSP reader 15034; and the west end was on the center line of the 36th Avenue at the stop bar of the southbound approach.

Compared with the mean travel time of eligible trips with TSP off, the average travel time for the eastbound granted trips was 6.8 seconds shorter when TSP was on, which was 5.0 percent of the average eastbound travel time for eligible trips without TSP. The standard deviation of eastbound travel time was also lower for trips with granted signal priorities, which indicates that the travel time was more predictable when TSP was on.

Table 8-3 Transit Corridor Travel Time in the Phase-One Test

		Eligible Trips with TSP off	Eligible Trips with TSP on	TSP Granted Trips
Mean travel time (sec)	Westbound	142.9	144.4	146.7
	Eastbound	135.2	131.6	128.4
Standard deviation (sec)	Westbound	29.2	30.3	28.9
	Eastbound	32.6	32.8	30.4
Maximum (sec)	Westbound	210.0	233.0	233.0
	Eastbound	269.0	287.0	205.0
Minimum (sec)	Westbound	95.0	87.0	90.0
	Eastbound	85.0	79.0	82.0

For the westbound trips, the mean travel time was longer when the TSP was on, and even longer for the trips with granted priorities. This finding seemed controversial to our expectation. However, if we look at the locations of the westbound bus stops, the results are understandable. Of the three bus stops on the westbound corridor, two are near-side bus stops, which may have negative impacts on trips with granted priority. Section 7.3.2 provides a detailed analysis on TSP impacts of near-side bus stops on transit delay. Although the eastbound corridor also has a near-side bus stop, it was located at a corner of the intersection where transit vehicles turn right. Considering that right-turn movements may be conducted even on a red signal, the negative impact on travel time from this near-side bus stop was not as noticeable as the westbound ones. Therefore, the westbound average travel time of TSP-granted trips exceeded the mean travel time of all TSP-eligible trips collected when the TSP system was off, but the eastbound mean travel time did not have this problem.

Table 8-4 shows the mean and standard deviation of transit travel times at four intersections. The starting and ending points for intersection travel time calculation were defined as the points 200 ft upstream and 200 ft downstream from the intersection's center point, respectively. However, for intersections with a near-side bus stop, the starting point for the corresponding direction was re-defined as the mid point of the bus stop and the stop bar.

Table 8-4 Transit Intersection Travel Times in the Phase-One Test

			Eligible Trips with TSP off	Eligible Trips with TSP on	Granted Trips with TSP on
Travel time (sec)	36 Ave	Westbound	57.60	24.89	21.59
		Eastbound	21.18	18.41	19.43
	Park & Ride	Westbound	16.90	16.48	16.77
		Eastbound	10.56	12.38	12.10
	Alderwood Mall Parkway	Westbound	40.75	17.56	18.18
		Eastbound	22.20	16.03	18.18
	NorthPoint	Westbound	9.88	8.91	8.97
		Eastbound	9.00	8.81	9.11
Standard Deviation (sec)	36 Ave	Westbound	61.83	12.22	10.36
		Eastbound	15.68	8.38	8.90
	Park & Ride	Westbound	6.47	7.68	8.70
		Eastbound	1.74	5.30	4.43
	Alderwood Mall Parkway	Westbound	19.14	14.22	15.96
		Eastbound	14.55	13.12	15.39
	NorthPoint	Westbound	0.64	0.88	0.94
		Eastbound	1.41	1.12	1.25

In general, the SS-RTSP system decreased intersection travel time of transit vehicles. The only exception is the eastbound direction for the intersection of Park & Ride, where the mean travel time of TSP-eligible trips was 1.82 seconds higher with TSP-on than that with TSP-off. This location had exceptionally good traffic conditions in the TSP-off week when the data were collected. This inference was based on the small standard deviation of 1.74 seconds compared to that of 5.30 seconds when TSP was on. The transit travel time savings from the SS-RTSP system varied from intersection to intersection: at the intersections of the 36th Avenue SW and of the Alderwood Mall Parkway, the savings were significant for westbound travel. At the other two intersections, the savings were in the one to two-second range.

For most of the intersections, the standard deviation of intersection travel time also decreased when TSP was on. Smaller travel time deviation indicates more reliable transit trips. Readers may have noticed that, in many cases, the mean travel times for TSP-granted trips were higher than those for all TSP-eligible trips. TSP-granted trips are normally tough trips occurring in congested traffic condition. Therefore, it is very likely that TSP-granted trips experience a longer travel time compared to all TSP-eligible trips.

8.2.3 Average person delay

Based on the simulation model described in Chapter 7, we calculated average person delay from the simulation results. Delays for passengers in both transit vehicles and general purpose vehicles were included in the calculation. Table 8-5 shows calculated average delays per person at the test intersections for both the TSP-on and TSP-off conditions.

As we can see in Table 8-5, the average person delay was reduced by the SS-RTSP system. Over all four intersections, the TSP system saved an average of 0.1 second for all passengers. Although the 0.1-second time saving seems marginal to each person, the overall benefit of more than 48 person-hours over a three-hour period (peak hours) is significant. This indicates a total peak-hour time saving of 96 person-hours (here we assume six peak hours per day) or 25,056 person-hours per year. This benefit was achieved through only 18 bus runs over the three-hour period. During the same time period, 5000 regular vehicles were generated.

Considering that the sample size for passenger cars were much higher than that for transit vehicles, the average person delay decreased by the SS-RTSP system was remarkable.

Table 8-5 Simulation Results for Personal Delays in the Phase-One Test

		36^{th} Ave	Park & Ride	Alderwood Mall Parkway	NorthPoint	Total
TSP off	Personal Delay	16.9	3.0	10.3	2.0	8.7
	Number of Passengers	8271	6574	7854	6188	28887
TSP on	Personal Delay	16.7	2.9	10.1	2.0	8.6
	Number of Passengers	8252	6561	7858	6186	28857

8.3 Costs

8.3.1 Vehicle delays and stops

The control delay per vehicle is the only criterion representing the Level of Service (LOS) at signalized intersections (Transportation Research Board, 2000). Vehicle delays at major cross streets were manually collected from traffic video images. Table 8-6 shows the average vehicle delays calculated from the manually collected vehicle delay data for April 4 and 11, 2006.

We used a paired t-test to compare the cross-street vehicle delays before and after the SS-RTSP implementation. The t ratio was 1.799, which is smaller than the critical t ratio of 1.962 at p=0.05 level. Therefore, the change of control delay for vehicles on side streets was not significant at p=0.05 level after the SS-RTSP implementation.

Table 8-6 Vehicle Delays in the Phase-One Test

	Intersection	time period	Approach	Intersection Delay (Second)
TSP off	Alderwood	7:30am - 8:00am	North approach	25.09
	Alderwood	2:00pm - 2:30pm	North approach	41.84
	Alderwood	4:30pm - 5:00pm	North approach	42.50
	Alderwood	7:30am - 8:00am	South approach	26.47
	Alderwood	2:00pm - 2:30pm	South approach	37.30
	Alderwood	4:30pm - 5:00pm	South approach	35.94
	36th Ave.	7:30am - 8:00am	West approach	17.72
	36th Ave.	2:00pm - 2:30pm	West approach	18.12
	36th Ave.	4:30pm - 5:00pm	West approach	25.03
TSP on	Alderwood	7:30am - 8:00am	North approach	30.22
	Alderwood	2:00pm - 2:30pm	North approach	27.76
	Alderwood	4:30pm - 5:00pm	North approach	42.64
	Alderwood	7:30am - 8:00am	South approach	25.54
	Alderwood	2:00pm - 2:30pm	South approach	20.77
	Alderwood	4:30pm - 5:00pm	South approach	31.96
	36th Ave.	7:30am - 8:00am	West approach	11.83
	36th Ave.	2:00pm - 2:30pm	West approach	17.55
	36th Ave.	4:30pm - 5:00pm	West approach	23.96

The intersection control delays and numbers of vehicle stop for all approaches were also collected from the simulation experiments. Table 8-7 shows the average control delay and number of stops at each intersection. For three of the four intersections, the SS-RTSP system decreased average intersection control delay and number of stops. The only exception was the intersection of NorthPoint where both average control delay and number of stops increased slightly after the SS-RTSP implementation. Since this intersection is less busy than the other three, the negative impacts from the SS-RTSP system were probably not enough to offset the positive impacts at other intersections. However, paired t-tests on average control delays per vehicle and numbers of vehicle stops did not indicate significant impacts from the SS-RTSP project at the p=0.05 level.

Table 8-7 Simulation Results for Average Vehicle Delays and Stops in the Phase-One Test

		36^{th} Ave	Park & Ride	Alderwood Mall Parkway	NorthPoint	Total
TSP off	Control Delay	16.5	2.7	10.3	1.6	8.5
	Number of Stops	0.61	0.10	0.40	0.11	0.33
	Number of Vehicles	6728	5323	6399	4994	23444
TSP on	Control Delay	16.4	2.6	10.0	1.7	8.4
	Number of Stops	0.60	0.09	0.39	0.12	0.33
	Number of Vehicles	6725	5324	6400	4993	23442

8.3.2 Traffic queue length

We manually counted the traffic queue length in vehicles from field recorded video data. Table 8-8 shows the traffic queue length on cross streets. Due to time constraints, we analyzed and summarized only data from Mondays.

We also used a paired t-test to compare the average queue length before and after TSP implementation. The *t* ratio was -1.578, the absolute value of which is smaller than the critical *t* ratio of 2.920 at p=0.05. Therefore, the change of the average queue length on cross streets after the SS-RTSP implementation was not significant. The average traffic queue length slightly increased for about 0.07 vehicles per signal cycle when the TSP system was turned on. However, on the southbound corridor of the Alderwood Mall Parkway intersection, traffic queue length decreased for about 0.01 vehicles per cycle. This result may be due to regular traffic variations between the two study days. Standard deviations of queue length also increased a little for all three cross streets when TSP was on. The maximum queue length stayed at almost the same level after the TSP implementation. On the southbound corridor of the Alderwood Mall Parkway intersection, the maximum queue length even decreased for two vehicles per cycle when the TSP system was on. The median value of traffic queue length remained constant before and after the implementation of the TSP system.

Table 8-8 Traffic Queue Length on Cross Streets in Phase-One Test

	Intersection	Cross Street	Average Queue Length Per Cycle	Standard Deviation	Maximum	Median
TSP off	Alderwood Mall Parkway	South approach	2.65471	2.41476	14	2
	Alderwood Mall Parkway	North approach	1.56651	1.31575	7	1
	36^{th} Ave	West approach	3.20079	2.58121	16	3
TSP on	Alderwood Mall Parkway	South approach	2.64318	2.43128	12	2
	Alderwood Mall Parkway	North approach	1.63679	1.40252	7	1
	36^{th} Ave	West approach	3.27135	2.76868	16	3

8.3.3 Signal cycle failure

Signal cycle failure (or overflow) is an interrupted traffic condition in which a number of queued vehicles are unable to depart due to insufficient capacity during a signal cycle. From a motorist's point of view, cycle failure can be more easily perceived than average control delay or queue length. Signal cycle failure data were also manually collected from traffic video images. Table 8-9 shows the frequency of signal cycle failure at cross streets on the Mondays of the two study weeks.

Table 8-9 Signal Cycle Failure Occurred in the Phase-One Test

	Intersection	Cross Street	Signal Cycle Failure per Cycle	Standard Deviation	Maximum Number of Vehicles in a Failure
TSP off	Alderwood Mall Parkway	South approach	0.01121	0.12492	2
	Alderwood Mall Parkway	North approach	0.00229	0.04789	1
	36Ave	West approach	0.00000	0.00000	0
TSP on	Alderwood Mall Parkway	South approach	0.00909	0.19069	4
	Alderwood Mall Parkway	North approach	0.00000	0.00000	0
	36Ave	West approach	0.00413	0.11134	3

Again, we used the paired t-test to compare the average frequency of signal cycle failures before and after the TSP implementation. The *t* ratio was 0.044, which is much smaller than the critical value of 2.920 at p=0.05. Therefore, the change of the average number of signal cycle failures after the TSP implementation was not significant at p=0.05 level. The frequency of signal cycle failure may slightly increase or decrease depending on flow and signal control conditions after TSP was enabled. When TSP was on, the standard deviation of signal cycle failure may also increase or decrease in a narrow range. The maximum number of vehicles caught in one cycle failure may also increase or decrease after TSP was turned on. This is consistent with the cross-street queue length analysis described in Section 8.3.2.

8.4 Discussion on Possible Improvements for the SS-RTSP System

8.4.1 Frequency of TSP calls

As shown in Table 4 in Section 7.1, the distribution of TSP-granted trips during the week as well as across the corridor was not even. On average, the number of TSP-granted trips per day per intersection was about 16.96. This value is relatively low and the benefits from TSP could be limited because of the low TSP-granted trips. The low number of TSP-granted trips does not necessarily reflect good traffic conditions. Keypad was not installed on all transit vehicles using the three test routes when the test was conducted. Without a Keypad, a transit vehicle is not able to take advantage of the SS-RTSP system. More Keypads can be installed on these coaches to enable them to receive TSP when necessary. On the phase one test corridor, only three transit routes are eligible for TSP treatment, and more transit routes can be added into the TSP system.

8.4.2 Near-side bus stops

Many researchers have found that at intersections with a near-side bus stop and the transit detector upstream of the bus stop, the benefits from TSP decreases significantly (Baker et al. 2002, Ngan 2003, and Rakha and Zhang, 2004). The near-side bus stop makes it very difficult to accurately predict the travel time from the upstream transit vehicle detector to the stop bar. In addition to vehicle speed and the distance from the transit vehicle detector to the stop bar, several other factors impact the travel time, such as the number of passengers to load and to unload. These factors are typically random and are not known when a TSP treatment decision is made. TSP treatments based on wrong travel-time predictions will not only waste the valuable green time, but also decrease the expected transit benefits from TSP. Furthermore, extra delays to transit vehicles may be introduced by TSP treatments, compared with non-TSP, under certain conditions.

In this study, we proved that a near-side bus stop increases transit delays under certain conditions at TSP-enabled intersections, which seems against our intuition. To evaluate impacts of near-side bus stops on transit delay at intersections, Zheng et al. (2006) developed a theoretical model. The conditions studied in this research include: an upstream check-in transit vehicle detector, two TSP treatments of green extension and early green (also called red truncation), a fixed-time and uncoordinated traffic signal plan. Their approach compared bus movements with TSP on and off in time-space diagrams. Four scenarios were possible when a transit vehicle arrives at the stop line of a TSP-enabled direction: (1) the transit vehicle received a green extension and benefited from the treatment because it skipped the near-side bus stop; (2) the transit vehicle received a green extension but missed the treatment because of the dwell at the near-side bus stop; (3) the transit vehicle received an early green and skipped the near-side bus stop; (4) the transit vehicle received an early green and made a stop at the near-side bus stop. Transit delays were analyzed for all four scenarios. All the scenarios except number two benefit from the TSP treatments. However, the expected delay may still be a net increase because the cost for missing green extension is high. Most of our theoretical results were backed up with simulation data. With this model, the extra cost from the near-side bus stop can be calculated. For details of the model, please refer to Zheng et al. (2006).

The research results point to recommendations for improving the performance of the TSP system. Since scenario two is the only source of extra transit delays, green extension may not be a worthy treatment and can be disabled at intersections with near-side bus stops. The near-side bus stop can also be moved to the far side of the intersection if necessary.

CHAPTER 9 PHASE-TWO RESULTS AND DISCUSSION

9.1 Statistics for Granted TSP Trips

Table 9-1 shows the number of granted TSP trips based on the TSP log files. When a TSP-eligible trip was granted for priority treatment, TPRG sent a priority requests to the traffic controller. Then the traffic controller issues a proper TSP treatment to the bus. The number of granted TSP trips differed from day to day and from intersection to intersection. The average number of granted TSP trips per intersection per day was 14.4, or about 9.86 percent in all scheduled trips of route 100 and 101.

Table 9-1 Number of Granted TSP Trips in Phase-Two Test

Date	Number of Granted TSP Trips												Total
	12140	12150	12160	12170	12180	12190	12200	12210	12220	12230	12260	12750	
1/22/05	23	0	13	3	3	13	17	18	3	11	16	3	123
1/23/05	22	2	14	11	4	29	11	14	3	20	16	4	150
1/24/05	33	4	22	7	6	21	12	14	3	9	25	7	163
1/25/05	38	0	29	11	4	38	18	27	12	34	25	16	252
1/26/05	29	0	26	12	11	28	20	23	19	48	21	11	248
Total	145	6	104	44	28	129	78	96	40	122	103	41	936

9.2 Benefits

9.2.1 Transit time match

The transit time match is summarized in Table 9-2. The results show that a transit vehicle would arrive at a bus stop with a reduced delay when the TSP system is on. The reduction in arrival time delay varies from location to location, with the maximum reduction of to 5 minutes and 51 seconds at stop 1013, which locates near the 220th Street intersection. The average improvement of transit time match of all the bus stops is 15 second, or about 6%, compared with scenario when TSP was off.

Table 9-2 Time Match at Bus Stops in Phase-Two Test

Southbound			Northbound		
Stop ID	TSP off	TSP on	Stop ID	TSP off	TSP on
1499	9′30″	3′48″	1003	4′09″	4′34″
1500	4′04″	3′06″	1004	4′09″	5′29″
1501	4′27″	3′30″	1005	4′50″	4′42″
1502	5′47″	4′02″	1006	3′53″	3′25″
1503	3′58″	3′28″	1007	3′02″	4′21″
1504	3′16″	4′10″	1008	2′31″	2′30″
1506	4′17″	4′22″	1010	3′06″	5′04″
1507	4′59″	4′08″	1012	2′41″	2′43″
1508	3′56″	4′25″	1013	8′33″	2′42″
1509	3′56″	4′58″	1016	6′49″	2′13″
1510	4′43″	4′35″			
1517	3′59″	2′05″			

9.2.2 Transit travel time

Transit travel time data were calculated using GPS position data. Table 9-3 shows the travel time statistics for the SR-99 corridor during the phase-two test. The average transit travel time of eligible trip when TSP was on was 13~32 seconds shorter than that when TSP was off. Northbound and Southbound together, the TSP saved an average of 26 second of transit travel time per trip, which is about 2.47% of the total corridor travel time. The mean transit travel time for the granted trips was even longer than that for all eligible trips with TSP off. This seems controversial. However, considering that only late trips would be granted with TSP treatment, this result is not beyond our expectation. Another comparison between the late trips with TSP on and off was conducted. The result showed that TSP saved 54 second transit travel time (northbound and southbound together) for late trips, which is about 4.93% of the total corridor travel time.

Table 9-3 Transit Corridor Travel Time in Phase-Two Test

		Eligible Trips with TSP off	Eligible Trips with TSP on	TSP Granted Trips
Mean travel time	Northbound	17′36″	17′23″	18′24″
	Southbound	17′39″	17′07″	17′35″
Standard deviation	Northbound	2′08″	3′12″	3′12″
	Southbound	2′34″	2′20″	2′20″
Maximum	Northbound	22′47″	25′13″	25′13″
	Southbound	24′23″	24′16″	24′16″
Minimum	Northbound	12′13″	9′43″	9′43″
	Southbound	10′23″	12′26″	12′26″

Table 9-4 Transit Intersection Travel Times in Phase-Two Test

			Eligible Trips with TSP off	Eligible Trips with TSP on
Travel time (sec)	196th Street	Northbound	26	26
		Southbound	40	28
	200th Street	Northbound	33	20
		Southbound	34	31
	220th Street	Northbound	37	34
		Southbound	23	26
Standard Deviation (sec)	196th Street	Northbound	37	36
		Southbound	27	23
	200th Street	Northbound	25	14
		Southbound	24	19
	220th Street	Northbound	29	20
		Southbound	22	26

Table 9-4 shows the transit travel time across three biggest intersections on this corridor. The starting and ending points for intersection travel time calculation were defined as the points

100 ft upstream and 100 ft downstream of the intersection's center point, respectively. Note that this definition is different from the one used for the phase-one test. The fact to use 100ft upstream and downstream of the intersection's center point is to exclude all bus stops from the intersection travel time calculation. This was not possible for the phase-one test because several near-side bus stops are too close to the intersections. The phase-one test used 200 ft instead to completely include the near-side bus stops. All the bus stops on the phase-two test corridor are on the far side and over 200 ft away from the center of intersection.

As can be seen in Table 9-4, the SS-RTSP system saved transit travel times at all studied intersections except for the southbound direction of the 200th St intersection. The time savings varied from 0 to 12 seconds, or 30% of the travel time without TSP. The travel time increase at the southbound direction of the 200th St intersection is unknown, but it is very likely due to random variations of traffic condition between the two test weeks.

9.2.3 Average person delay

Based on the simulation model described in Chapter 7, we calculated average person delay from the simulation results. Delays for passengers in both transit vehicles and general purpose vehicles were included in the calculation. Table 9-5 shows calculated average delays per person at the test intersections for both the TSP-on and TSP-off conditions.

In Table 9-5, the average person delay was reduced by the SS-RTSP system. Over all thirteen intersections, the TSP system saved an average of 0.2 second for all passengers. Although the 0.2-second time saving seems marginal to each person, the overall benefit of more than 292 person-hours over a three-hour period (peak hours) on the whole corridor is significant. This indicates a total peak-hour time saving of 584 person-hours (here we assume six peak hours per day) per day or 311,710 person-hours per year. The overall person delay saved by the SS-RTSP system is remarkable.

Table 9-5 Simulation Results of Personal Delays in Phase-Two Test

	Average Personal Delay (sec)		Person Number	
Simulation Scenario	TSP on	TSP off	TSP on	TSP off
1	24.0	24.0	134245	134204
2	24.0	24.2	134947	134952
3	23.8	24.0	134377	134378
4	23.7	23.6	133622	133627
5	24.5	24.2	133942	133891
6	24.3	24.3	135750	135769
7	23.9	24.1	134499	134519
8	23.9	24.0	135140	135167
9	23.8	23.7	134016	134004
10	23.7	23.7	134909	134914
Average	23.96	23.98	134545	134543

9.3 Costs

9.3.1 Vehicle delays and stops

Control delays and vehicle stops were collected for all approaches from the simulation experiments. Table 9-6 shows the average control delay and number of stops at each intersection in one simulation scenario.

Considering that each simulation run is just a random sampling action from a stochastic process, no conclusion can be drawn from a single simulation scenario. To further examine the differences in vehicle delay and number of stops between the conditions of TSP on and TSP off, a total of ten simulation scenario were conducted. Each simulation scenario is associated with a unique random seed. Vehicle delays and stops were averaged for all the thirteen intersections under each test scenario. Table 9-7 presents the comparison results for all the ten simulation scenarios.

Table 9-6 Traffic Delays and Stops from One Simulation Scenario in Phase-Two Test

	TSP on			TSP off		
Intersections	AVD[1]	ANS[2]	VC[3]	AVD	ANS	VC
164th ST.	13	0.54	7332	13	0.55	7325
168th ST.	29.3	0.74	9494	29	0.75	9499
174th ST.	10.8	0.4	8516	10.7	0.42	8515
176th ST.	15.4	0.57	9730	15.3	0.56	9730
188th ST.	36.3	1.21	9820	35.8	1.23	9832
196th ST.	36.2	1.01	12324	36.6	1.03	12307
200th ST.	37.4	1.08	10441	38.4	1.03	10446
208th ST.	26.2	0.79	10656	25.9	0.79	10647
212th ST.	18.9	0.81	10876	18.9	0.78	10871
216th ST.	16.9	0.74	10267	16.9	0.72	10265
220th ST.	39.1	1.01	12226	38.5	1.05	12235
224th ST.	9.4	0.35	9806	9.1	0.39	9789
238th ST.	13.8	0.48	9677	13.5	0.5	9673
Total	24.1	0.77	131134	24.2	0.77	131165

[1] denotes Average Vehicle Delay; [2] denotes Average Number of Stops; [3] denotes Vehicle Count

Table 9-7 Traffic Delays and Stops from All Simulation Scenarios in the Phase-Two Test

	AVD[1]		ANS[2]		VC[3]	
Simulation Scenario	TSP-on	TSP-off	TSP-on	TSP-off	TSP-on	TSP-off
1	24.2	24.1	0.77	0.77	131165	131134
2	24.2	24.3	0.78	0.78	131877	131882
3	24.0	24.1	0.77	0.78	131307	131308
4	23.9	23.7	0.77	0.76	130552	130557
5	24.6	24.4	0.82	0.79	130872	130831
6	24.5	24.5	0.81	0.80	132680	132699
7	24.1	24.2	0.78	0.79	131429	131459
8	24.1	24.1	0.77	0.78	132060	132087
9	24.0	23.8	0.76	0.75	130936	130934
10	23.9	23.8	0.78	0.77	131839	131844
Total	24.2	24.1	0.78	0.78	131472	131474
Paired t-test at the p=0.05 level	Not significant		Not significant		Not applicable	

[1] denotes Average Vehicle Delay; [2] denotes Average Number of Stops; [3] denotes Vehicle Count

The average vehicle delays and the numbers of stop observed from the ten simulation scenarios varied slightly from scenario to scenario. TSP impacts on average vehicle delays were controversial: in some scenarios, the impacts were increasing, while in some other scenarios, the impacts were decreasing. Observations on numbers of vehicle stops in the ten simulation scenarios were similar. Paired t-tests were conducted to see if the difference between the TSP-on and TSP-off conditions in any of the MOEs provided in Table 9-7 was significant at the p=0.05 level. These t-tests concluded that the TSP implementation did not generate significant changes in average vehicle delay and number of vehicle stops for local traffic.

9.3.2 Traffic queue length

We manually counted the traffic queue length in vehicles from field recorded video tapes. Due to time constraints, this analysis was conducted on two representative intersections on the SR-99 corridor. Table 9-8 shows the statistics of traffic queue lengths on the cross streets of the two intersections.

As we can see in Table 9-8, when the TSP was turned on, the queue length decreased in some cases and increased in other cases. This is reflected by the unpredictable changes in queue length statistics, including standard variation, maximum, and median queue length, in Table 9-8. Again, a paired t-test was applied to compare the average queue lengths at the test intersections before and after TSP implementation. The t ratio was -1.663, the absolute value of which is smaller than the critical t ratio of 1.962 at p=0.05. Therefore, the change of the average queue length on cross streets after the SS-RTSP implementation was not significant.

Table 9-8 Traffic Queue Length On Cross Streets in Phase-Two Test

	Intersection	Approach	Average Queue Length Per Cycle	Standard Deviation	Maximum	Median
TSP off	164th Street	Westbound	4.877	3.116	14	4
	164th Street	Eastbound	4.412	2.377	12	4
	174th Street	Westbound – through	1.353	1.433	5	1
	174th Street	Westbound – Left turn	0.647	0.597	2	1
	174th Street	Eastbound– through	0.800	1.476	8	0
	174th Street	Eastbound– Left turn	3.983	2.344	12	4
TSP on	164th Street	Westbound	4.471	3.229	13	3
	164th Street	Eastbound	3.829	2.172	10	4
	174th Street	Westbound– through	1.909	1.258	6	2
	174th Street	Westbound– Left turn	0.338	0.553	2	0
	174th Street	Eastbound– through	1.722	1.944	9	1
	174th Street	Eastbound– Left turn	3.654	2.591	10	4

9.3.3 Signal cycle failure

Signal cycle failure (or overflow) is an interrupted traffic condition in which a number of queued vehicles are unable to depart due to insufficient capacity during a signal cycle. From a motorist's point of view, cycle failure can be more easily perceived than average control delay or queue length. Signal cycle failure data were also manually collected from traffic video images. Table 9-9 shows the frequency of signal cycle failure at cross streets.

We also applied paired t-test to compare the average frequency of signal cycle failures before and after TSP implementation. The *t* ratio was 0.450, which is much smaller than the critical value of 1.962 at p=0.05. Therefore, TSP implementation did not bring in significant changes in the average number of signal cycle failures at the p=0.05 significance level. The frequency of signal cycle failure may slightly increase or decrease depending on flow and signal control conditions after TSP was turned on. When TSP was on, the standard deviation, maximum and median of signal cycle failure occurrence may increase or decrease in a narrow range. This is consistent with the cross-street queue length analysis described in Section 9.3.2.

Table 9-9 Signal Cycle Failure in Phase-Two Test

	Intersection	Approach	Signal Cycle Failure Per Cycle	Standard Deviation	Maximum
TSP off	164th Street	Westbound	0.0077	0.0877	1
	164th Street	Eastbound	0.0294	0.2706	3
	174th Street	Westbound – through	0	0	0
	174th Street	Westbound – Left turn	0.0588	0.2388	1
	174th Street	Eastbound– through	0	0	0
	174th Street	Eastbound– Left turn	0.5000	1.2702	7
TSP on	164th Street	Westbound	0.0643	0.3640	3
	164th Street	Eastbound	0.0286	0.2667	3
	174th Street	Westbound– through	0	0	0
	174th Street	Westbound– Left turn	0.0260	0.2279	2
	174th Street	Eastbound– through	0	0	0
	174th Street	Eastbound– Left turn	0.5865	1.3034	8

CHAPTER 10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

In this study, the SS-RTSP system was evaluated with field-observed data. Simulation models were also built and calibrated to compute MOEs that cannot be obtained from field-observed data. With the simulation models and field observed data, the impacts of the SS-RTSP system on both transit and local traffic operations were quantitatively evaluated.

Our evaluation results showed that the SS-RTSP system introduced remarkable benefits to transit vehicles, with insignificant negative impacts to local traffic on cross streets. The overall impact of the SS-RTSP system on local traffic of an entire intersection was net benefit.

With the SS-RTSP system, transit vehicles can be operated more reliably. The MOE of Transit Time Match indicated improvements of 1.56 minute, or about 16.3 percent in the phase-one test, and 15 second, or about 6%, in the phase-two test. In the phase-one test, the mean eastbound corridor travel time of transit vehicles was 6.7 seconds or 4.9 percent shorter for granted trips than the average corridor travel time without TSP; and in the phase-two test, the average saved transit corridor travel time was 54 second, or 4.93 percent. Because of the saved transit travel time, the SS-RTSP system decreased the overall personal delays. For all passengers who used the TSP-enabled intersections, the average person delay was reduced by 0.1 second in the phase-one test and 0.2 second in the phase-two test. Phase-one and phase-two together, the overall saved personal delay was 336,766 person-hours per year for only peak-hour travels.

The impact of the SS-RTSP system on local traffic delay of an entire intersection was sometimes increasing and sometimes decreasing as observed from the simulation experiments. Paired t-tests on average vehicle delay and number of vehicle stops did not find any significant impacts from the SS-RTSP system at the $p=0.05$ level. Similarly, the SS-RTSP system impact on cross-street traffic was also analyzed. Our test data showed slight changes in vehicle delay, queue length, and signal cycle failure frequency on cross streets. However, the *t* tests indicated that these changes were not significant either at the p=0.05 level after the TSP implementation.

10.2 Recommendations

To improve the performance of the current SS-RTSP system, more transit vehicles can be enabled for TSP eligibility. The average number of granted TSP trips per day per intersection was only 16.96 in the phase-one test, and 14.40 in the phase-two test. Considering that the negative impact of the SS-RTSP on local traffic was not significant, more transit trips can be granted with proper TSP treatments and frequency of TSP requests can be increased to generate more benefits from the SS-RTSP system.

This research found that extra transit delays may be introduced by TSP, compared with non-TSP, at an intersection with a near-side bus stop under certain conditions. Besides regular recommendations to avoid these extra delays, such as moving a near-side bus stop to the far side of the intersection, our research also suggests that the TSP treatment of extended green be disabled at intersections with near-side bus stops to avoid introducing negative impacts on transit vehicles.

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