Final Technical Report
Agreement T2695, Task 60
SS-RTSP Evaluation

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

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Washington State Transportation Commission
Department of Transportation
Olympia, Washington 98504-7370

and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

June 2008

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
WA-RD 699.1/
TNW2007-06

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Comprehensive Evaluation of Transit Signal Priority System Impacts Using Field Observed Traffic Data

5. REPORT DATE
June 2008

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Transportation Northwest Regional Center X (TransNow)
Box 352700, 129 More Hall
University of Washington
Seattle, WA 98195-2700

10. WORK UNIT NO.

11. CONTRACT GRANT NO.
Agreement T2695, Task 60

12. SPONSORING AGENCY NAME AND ADDRESS
Washington State Department of Transportation
Transportation Building, MS 47372
Olympia, Washington 98504-7372
Kathy Lindquist, Project Manager, 360-705-7976

13. TYPE OF REPORT AND PERIOD COVERED
Final Technical Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was conducted in cooperation with the University of Washington and the US Department of Transportation

16. ABSTRACT

To improve the level of service for Community Transit (CT) buses, the South Snohomish Regional Transit Signal Priority (SS-RTSP) project was launched. To understand the overall benefit of this project, the SS-RTSP system was tested and evaluated after the hardware and software had been installed on the 164th Street SW 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 on the basis of field-observed data. Simulation models were also built and calibrated to compute measures of effectiveness that could not 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 provided remarkable benefits to transit vehicles, with insignificant negative impacts to local traffic on cross-streets under the current coordinated control strategy. The overall impact of the SS-RTSP system on local traffic at 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. Given that negative impacts of the SS-RTSP project on local traffic were not significant, more transit trips can be granted with proper TSP treatment to generate more benefits from the SS-RTSP system.

Further simulation-based investigations on TSP system operations and optimization were conducted. The research findings indicated that to achieve the best operation efficiency, the compatibility between TSP control schemes and signal control coordination should be strengthened to minimize transit disruption to signal coordination. TSP systems must be fully tested under different coordinated control plans prior to implementation.

17. KEY WORDS
transit signal priority, traffic delay, loop detectors, signalized intersections

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (OF THIS REPORT)
None

20. SECURITY CLASSIF. (OF THIS PAGE)
None

21. NO. OF PAGES

22. PRICE

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 was launched. To understand the overall benefit of this project, the SS-RTSP system was tested and evaluated after the hardware and software had been installed 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 number 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 in addition to the video data. They were collected by nine traffic control/operation systems within six transportation agencies.

This study quantitatively evaluated the impacts of the SS-RTSP system on both transit and local traffic operations on the basis of field-observed data. Simulation models were also built and calibrated to compute measures of effectiveness that could not be obtained from field-observed data. Our evaluation results showed that the SS-RTSP system provided 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 at 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 in transit vehicle adherence to their schedules by 1 minute and 34 seconds, or about 16.3 percent in the Phase One test, and 15 seconds, or about 6 percent, 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 seconds, or 4.93 percent, in the Phase Two test. Because of the saved transit travel time, the SS-RTSP system decreased overall personal delays. For all passengers who used the two test corridors, the average person delay decreased by 0.1 second in the Phase One test and 0.02 second in the Phase Two test, although these observations were not statistically significant at the p=0.05 level. Although such a delay decrease is trivial on a personal basis, it can be converted to an overall saved delay of 56,227 person-hours per year for peak-hour only travel along the two test corridors.

Simulation experiments showed that the impacts of the SS-RTSP system on local traffic delay at an entire intersection sometimes increased and sometimes decreased. 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. The SS-RTSP system's impacts 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 also not significant at the p=0.05 level after the TSP implementation.

To improve the performance of the current SS-RTSP system, more transit vehicles could 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. Given that the negative impacts of the SS-RTSP system on local traffic weres not statistically significant, more transit trips could be given proper TSP treatment, and the frequency of TSP requests could be increased to generate more benefits from the SS-RTSP system.

Simulation-based investigations of TSP system operations and optimization were conducted. The SR 99 corridor was selected as the test site, and three practical semi-actuated signal control plans were applied to examine TSP system performance. The simulation-based research findings indicated that to achieve the best operation efficiency, the compatibility between TSP control schemes and signal control coordination should be strengthened to minimize transit disruption to signal coordination. TSP systems must be fully tested under different coordinated control plans prior to implementation.

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. Because transit vehicle delays at signalized intersections typically account for 10 to 20 percent of transit vehicle running times, TSP promotes transit utilization by improving service reliability (Bakers 2002). Through customer service enhancements, the transit agency could ultimately attract more customers. As an important intelligent transportation systems (ITS) technology, TSP systems use sensors to detect approaching transit vehicles and alter signal timings, if necessary, to prioritize transit vehicle passage 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 the waiting time of transit vehicles at intersections, TSP can reduce transit delay and travel time, thereby increasing reliability and quality of service. Implementation of TSP gives transit customers more dependable service through greater schedule adherence and a more comfortable ride as a result of a 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.

Besides improving service, a second objective for using TSPs is to decrease costs (Garrow and Machemehl 1997). Fewer stops can mean reductions in drivers' workload, travel time, fuel consumption, vehicle emissions, and maintenance costs. Reductions in bus running times 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). 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.

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.

Because of 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 is considered an effective countermeasure against traffic congestion. The South Snohomish Regional Transit System Priority (SS-RTSP) system was launched to improve the level of service of Community Transit (CT) buses and, thus, to 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 2003). Several recent studies (see, for example, Abdulhai et al. 2002, and Dion et al. 2002) have quantitatively evaluated the effects of TSP. While these studies have generally agreed on the benefits for transit operations, the overall impacts of TSP on local traffic networks remain unclear. Also, because the performance of a signal control strategy is closely related to traffic conditions, surrounding land use, traffic regulations, and roadway network geometry, the comprehensive impacts of TSP systems on transit and other vehicles are case specific and difficult to generalize. This suggests that the effects of TSP on a particular network need to be evaluated on the basis of field-observed data. Therefore, a comprehensive evaluation of the SS-RTSP system is of both academic interest and practical significance.

The SS-RTSP system installation and evaluation comprised two phases. Phase One involved four intersections on SW 164th Street in south Snohomish County. Phase Two covered 13 intersections on SR 99 in the City of Lynnwood. This report summarizes both the Phase One and Phase Two evaluations.

1.3 RESEARCH OBJECTIVE

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

- quantitatively evaluate the TSP system benefits for transit operations
- calculate the overall impacts of the TSP system on local traffic networks
- understand how TSP effects changed 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. Using a microscopic simulation model, UTCS-1, it evaluated the initial Urban Traffic Control System-Bus Priority System (UTCS-BPS) in Washington, D.C. 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 extra time so that a transit vehicle can clear the intersection without stopping.

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* (Transportation Research Board 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, as well as different saturation levels for side-street approaches (Chada and Newland 2002).

Field evaluations reported by Chang et al. (1995) and Collura et al. (2003) 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) (TRB 2003) provides guidance to practitioners seeking to evaluate the impacts 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, as well as 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 an in-vehicle subsystem, road-side subsystem, and center subsystem. Figure 3-1 illustrates the subsystems in the field. 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 identification and trip information to the traffic signal controller for the transit vehicle's eligibility evaluation. If the transit vehicle 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 equipment is connected with the center subsystem and can be remotely monitored, debugged, and updated.

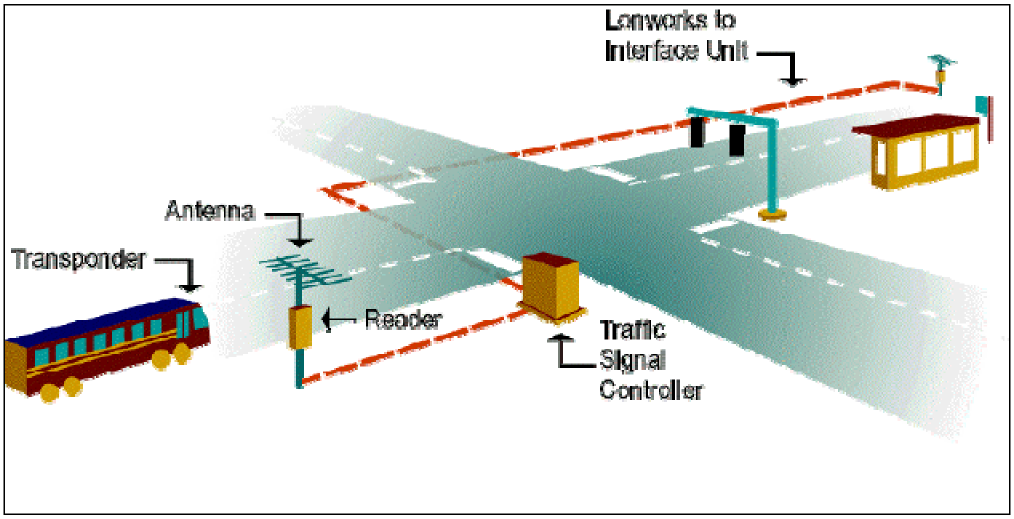

Figure 3-1   Field Equipment for TSP System Operation
(Source: King County Department of Transportation 2002)

A transponder installed on the front end of the transit vehicle provides the coach number, route number, trip number, and transit system operator identification (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 has been 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 before 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, the traffic signal holds the green signal of the priority phase for additional seconds to allow eligible vehicles to pass through 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 decrease 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.

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

- operating on one of the three test routes (114, 115, and 116)
- equipped with Keypad
- 0 to 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.

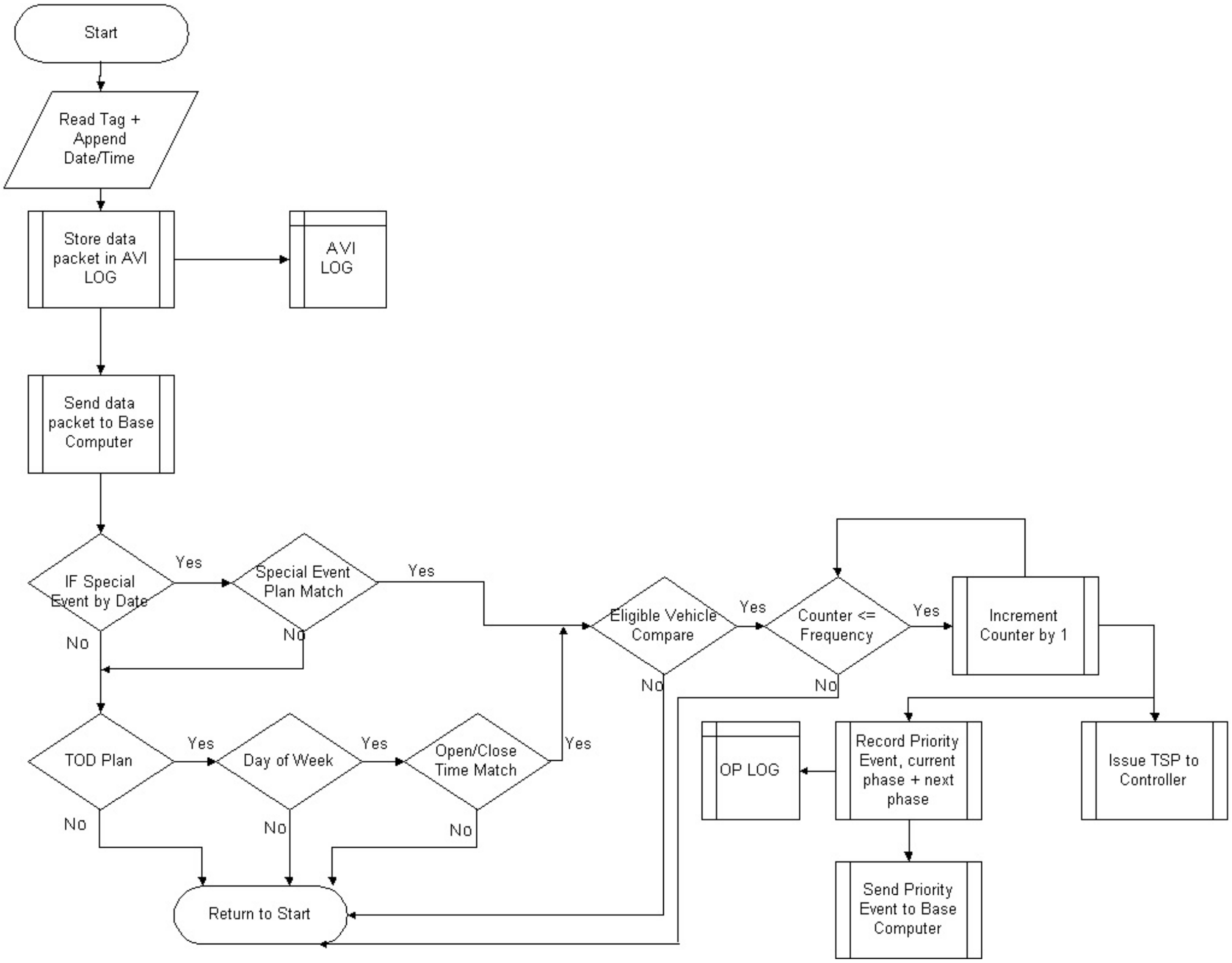

Figure 3-2 Priority Logic Flowchart

CHAPTER 4 METHODS

4.1 MEASURES OF EFFECTIVENESS

To provide a comprehensive evaluation of TSP strategy impacts, we used several MOEs to regularly assess impacts on traffic and transit operations. Each MOE reflected the impact of the TSP system from a certain perspective, and they jointly provided a relatively complete assessment on the SS-RTSP project. In this study, we separated the chosen MOEs into two categories: primary MOEs and secondary ones. The primary MOEs addressed our major concerns about the SS-RTSP project and could be calculated by using field-observed data. The secondary MOEs were useful for an in-depth understanding of TSP performance but could not be directly derived from field-observed data. We relied on microscopic simulation models to calculate the secondary MOEs.

4.1.1 Primary Measures of Effectiveness

The primary MOEs chosen for this evaluation study were 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 defined the variable of Transit Time Match (TTM) as the absolute difference between actual transit arrival time and scheduled arrival time at each timing point on the test routes. If the mean of TTM was close to zero, then the transit vehicles adhered to their schedules very well. The lower the TTM value, the higher the transit travel time reliability. The actual arrival times were extracted from global positioning systems (GPS).

Transit Travel Time

Transit travel time data were collected to evaluate whether the TSP system had caused a significant change in travel time on the test routes. Decreases in transit vehicle travel time could result in lower operation costs and emission levels. In-vehicle GPS data loggers recorded vehicle locations periodically. These vehicle location data were used to generate accurate transit travel time data.

Traffic Queue Length

A major concern about a TSP system is whether a TSP treatment will cause excessive delay for other intersection movements. To address this concern, a key MOE is the size of the traffic queue for each conflicting phase and the delays associated with those queues. Before and after analysis of traffic queue lengths can help 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 within 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 an increased occurrence of such failures 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 were 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 because of TSP policy). The purpose of this information, used along with the intersection delay information, is to determine the need for any changes to 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. The frequency of TSP calls was calculated from the TPRG-logged TSP requests from transit vehicles.

4.1.2 Secondary Measures of Effectiveness

In addition to the above primary MOEs, the following secondary MOEs were also important. Because these MOEs could not be calculated from field-observed data, a microscopic traffic simulation model was 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 was reduced by the SS-RTSP project, then we would be able to 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 the *HCM* (Transportation Research Board 2000). In this study, we used averaged vehicle delay and number of vehicle stops to reflect the time loss of vehicles at intersections. Changes in this MOE set before and after implementation of the SS-RTSP system would indicate the impacts of the TSP system on intersection performance. Additionally, it could 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 required 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 the report by Garcia-Molina et al. (2002). Figure 4-1 shows the E/R diagram of the database.

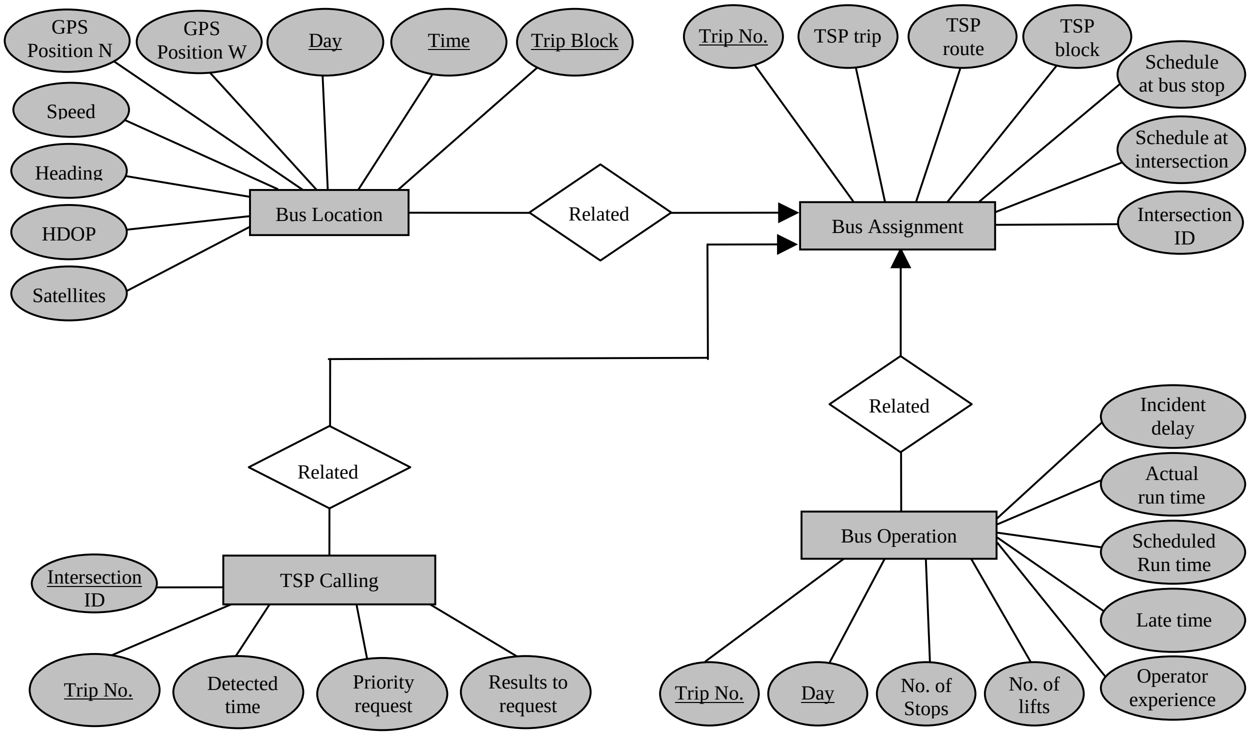

Figure 4-1 E/R Diagram of Database

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

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-point 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 used the Structured Query Language (SQL) for data management. This database was 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 data 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 was about 3600 feet long and had four signalized intersections. All four intersections on the test corridor were equipped with TSP devices. One or two approaches of the four intersections were equipped with TSP readers and could detect transit vehicles with TSP tags. Table 5-1 shows the TSP-enabled approaches tested in this project.

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

Intersection	36th Avenue	Park-and-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

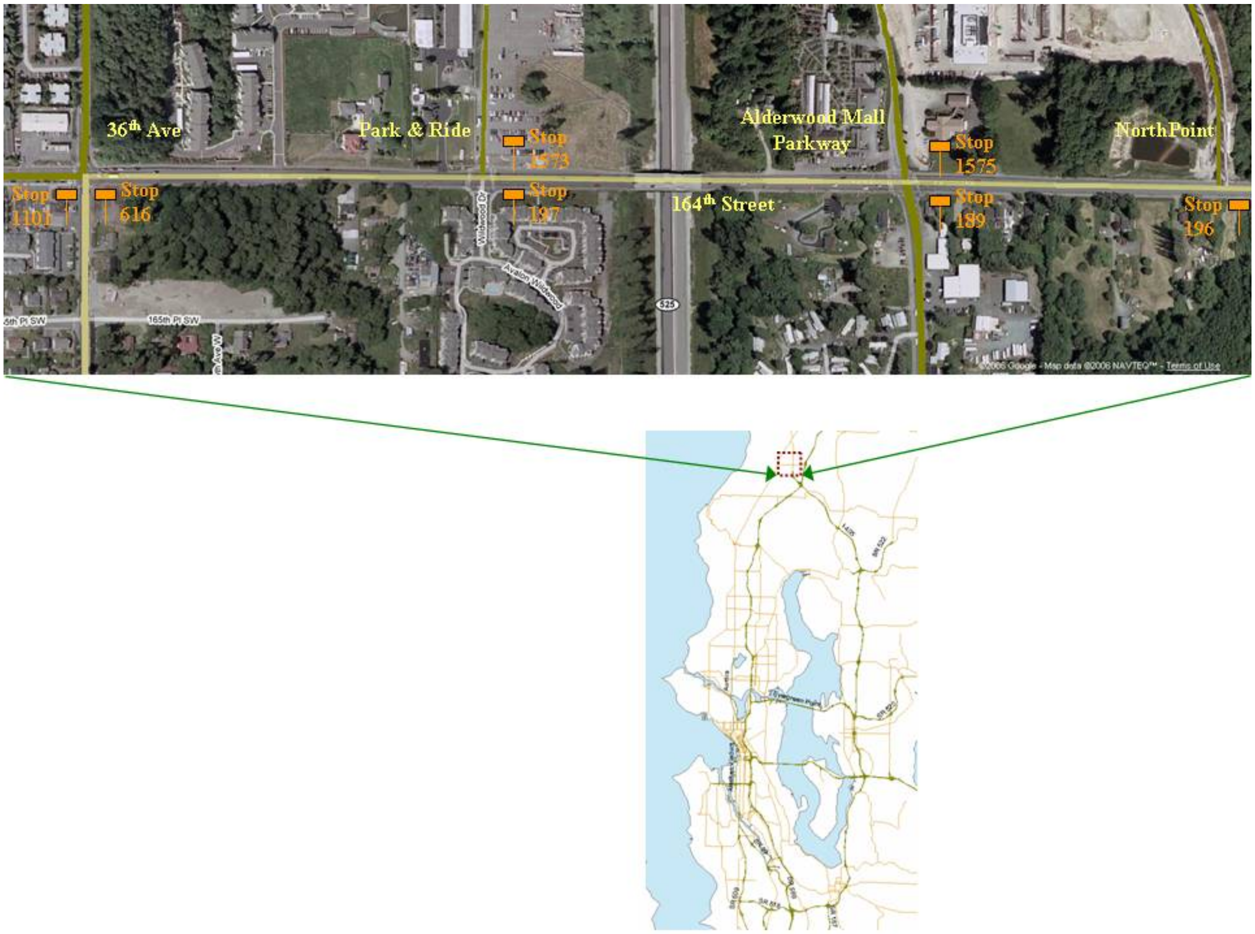

Figure 5-1 Phase One Test Corridor
(Map and image source: http://maps.google.com/maps.)

5.2 TRANSIT SERVICE

The tested transit routes were CT 114, 115, and 116. All the test routes ran through 164th Street SW between NorthPoint and 36th Avenue, then turned on 36th Avenue, as shown in Figure 5-1. This corridor had 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 were equipped with Keypad and eligible to receive 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 SOURCES

5.3.1 TSP Logs

The TPRG recorded transit vehicle detection, TSP requests, and traffic signal status in real time. The TPRG generated two types of log files: AVI (automatic vehicle identification) logs and OP (operation) logs. AVI logs collected 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 were used to separate fields in the log files. From left to right, the data fields were 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 through 6 were static, and those in fields 9 through 11 were dynamic. The TSP system was also able to detect and record transit coaches not in the three tested routes but equipped with TSP tags. These vehicles could 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 were the same as those of the AVI logs. The third field was always the same for all the recorded rows in the TPRG. The fourth field recorded 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 could be denied for two reasons: “trip” or “phase.” “Trip” meant the detected bus was not serving TSP-eligible trips on the three test routes. “Phase” indicated that the eligible bus did not need a TSP treatment because it was estimated to arrive at the intersection when the signal is in its green phase, or the bus was not late at all. If a TSP request was denied, the reason, together with the coach number, was logged in the fourth field, as shown in the third and fourth rows of the example. If a bus was given a priority, its trip number was 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^{TM} system installed on transit coaches. GeoLogger can track up to 12 satellites and update data every second, with a position accuracy of 15 meters in root-mean-square (RMS). Thirteen GeoLoggers were installed on the test coaches. All the GeoLoggers were preset to record data every second when the vehicle speed exceeded 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 showed the working status of GPS. If the status was okay, the GeoLogger recorded an “A.” The next four fields were the coordinates of vehicle position shown in longitude and latitude. The fifth field showed time in the “hhmmss” format. The sixth field represented the date in the “ddmmyy” format. The seventh filed was the speed in miles per hour. The eighth field was the heading of the vehicle in degrees. The last two fields related 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^{TM} 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 in 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 because of constraints in the traffic management system used by Snohomish County. Fortunately, some phase change information was logged by the TPRG. By 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 was 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-and-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 included two hours during the morning peak (6:30–8:30 AM), two hours during the 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 2:30–6:30 PM.

5.3.5 Other Data

Unusual transit vehicle delays may be caused by incidents, special events, or inclement weather conditions. To capture the impacts from these factors, we designed a data log form on which transit drivers could record reasons for usual delays (Figure 5-2). Because unusual delays could introduce serious errors to the 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 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 was 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 8 to February 18, 2007. However, only data collected in weeks three and four were used. A strong snowstorm that occurred in the first week of the test severely affected traffic patterns along the test corridor for the first two weeks. The last two weeks' data also could not be used 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 during the week of January 22nd to 28th, and was turned off during the week of January 29th to February 4th. The same data collection method used for the Phase One test was also applied during 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, with bus stops marked with cyan circles and the TPRG boxes marked with red squares. This corridor was about 5.3 miles long, with 13 signalized intersections. All the intersections were equipped with TSP for both 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 ran south-north without turning. There were 33 bus stops along this corridor, and none of them was a near-side bus stop. A summary of eligible TSP trips for each direction is provided in Table 6-1.

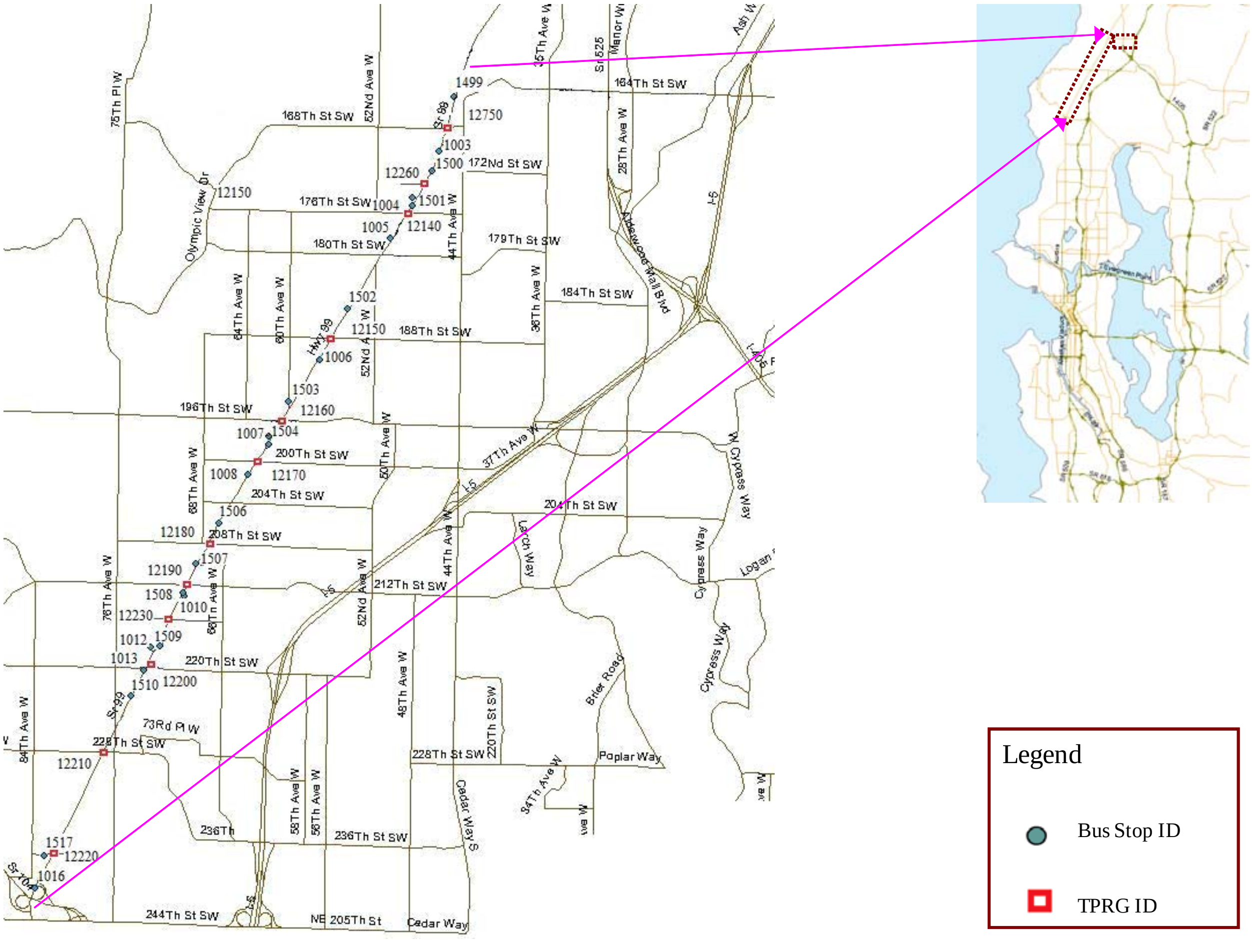

Figure 6-1 Phase Two Test Corridor

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

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

6.3 DATA SOURCE

6.3.1 TSP Logs

The TSP logs were generated by the same devices as 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 the same devices and in the same way as in the 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 was in 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 are deployed at mid-block 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 used 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 had a surveillance video camera that could be re-oriented to collect extra video data at locations of interest.

Twenty-eight VCRs were employed to record traffic video data from the 13 intersections on the SR 99 test corridor. The intersections at 196th Street SW, 200th Street SW, and 220th Street SW were very busy on all approaches. Hence, each approach of the three intersections had a VCR dedicated to 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. During each weekday, the VCR recorded six hours of video data, including two hours of the morning peak (6:30-8:30 AM), two hours of off-peak (3:00-4:00 PM and 6:00-7:00 PM), and two hours of the afternoon peak (4:00-6:00 PM).

6.3.5 Other Data

Our analysis of the Phase One test data showed that the transit drivers' logs were not accurate and could not be applied. Therefore, we eliminated the 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 could be extracted from the TSP logs generated by the 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 were several important performance measures for evaluating the system. As mentioned earlier, these MOEs were not directly calculable from the field-observed data; hence, we developed simulation models to compute them. The traffic simulation software VISSIM version 4.30 was utilized 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 Users 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 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 details of model setup and calibration are described below.

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—along the Phase One test corridor. The emulated NEMA controller in VISSIM can be properly configured as a standard NEMA controller to satisfy the 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. The basic TSP routine was supported by the NEMA controller. A transit call detected by sensors could generate a request for early green or extended green operation that would be consistent with the logic in the SS-RTSP system.

7.2.2 Simulation Model Configuration and 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 the reliability of the model calibration process. Traffic flows of intersection approaches generated by the simulation program were reasonably distributed in the range of 50 vehicle-per-hour-per-lane (vphpl) to 1250 vphpl and matched field observed volumes very well.

We estimated the passenger ridership on buses on the basis of annual CT ridership (National Transit Database 2004). In our model we selected 12 passengers per vehicle (ppv) 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 on the basis of field observations (King County Department of Transportation 2002). Additionally, the generation rate of passengers was set as 10 persons per hour (pph) on the basis of the number of boardings 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.

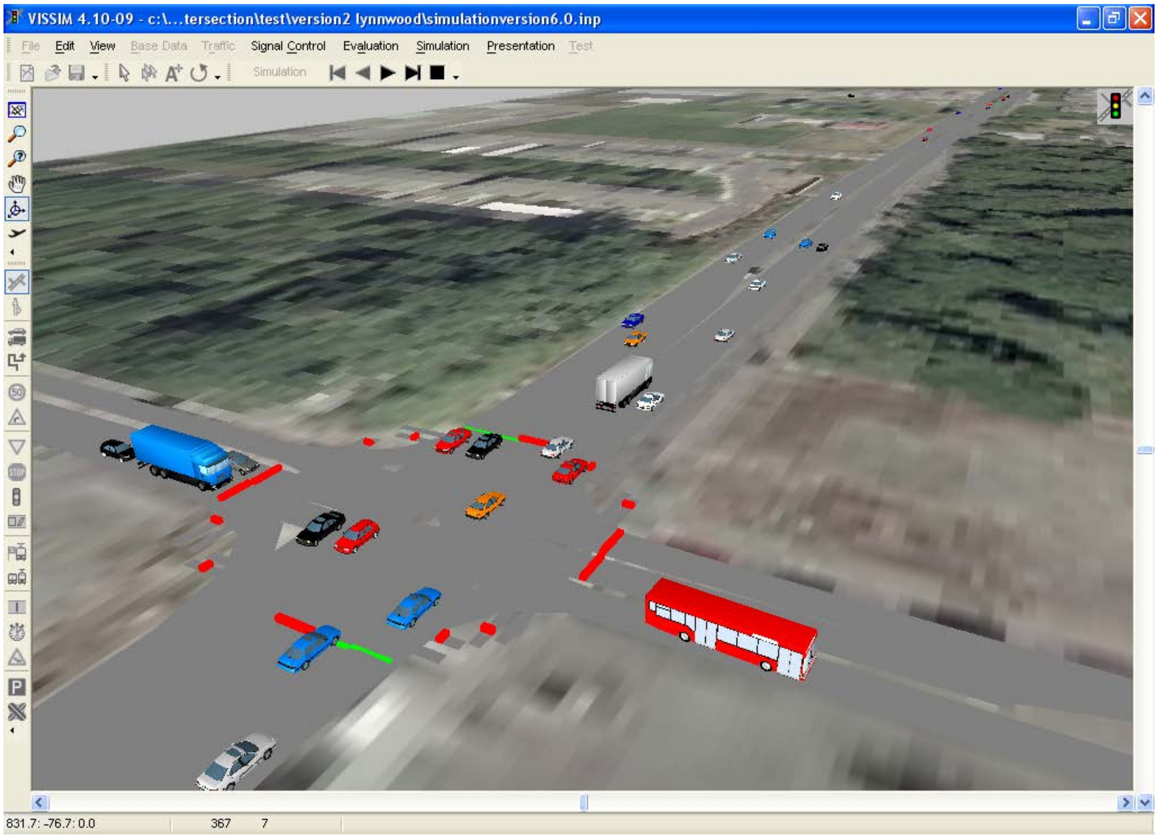

Figure 7-1 A Snapshot of the Phase One Simulation Model

We also calibrated the 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 by 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 the requirements of actuated signal control and basic TSP operations. However, the traffic controllers on this corridor were Naztec, which provide some different TSP functions than those provided by the NEMA controller. Therefore, an external controller was established for each intersection by using the vehicle actuated programming (VAP) language. The control logic and transit priority strategies of the Phase Two test intersections could be implemented by using the VAP programming language. Thus, a total of 13 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. The details of the calibration process are described below.

7.3.2 Simulation Model Configuration and Calibration

Traffic volumes in each approach were collected from mid-block virtual loops by 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 were reasonably distributed in the range of 30 vphpl to 980 vphpl, which matched our field observations very well. The traffic control parameters used by the VISSIM model were calibrated by using the actual control plans and timing parameters.

We estimated the passenger ridership on buses on the basis of CT's annual ridership data (National Transit Database 2004). Consequently, we used 12 ppv as the ridership for our simulation model. The average vehicle occupancy for general-purpose vehicles was configured to be 1.2 occupants per vehicle on the basis of field observations by King County Metro (King County Department of Transportation 2002). Additionally, the generation rate of passengers was set at 20 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 stop locations, and so on, were calibrated according to the real values. Because the corridor was very long, we show only 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 three-dimensional view of the simulation model at the intersection of 200th Street SW and SR 99.

Because of the stochastic features of the simulation models, multiple simulation iterations were essential to enhance the reliability of the simulation results. By changing the VISSIM simulation random seeds, the random vehicle generation could 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 three hours for each scenario.

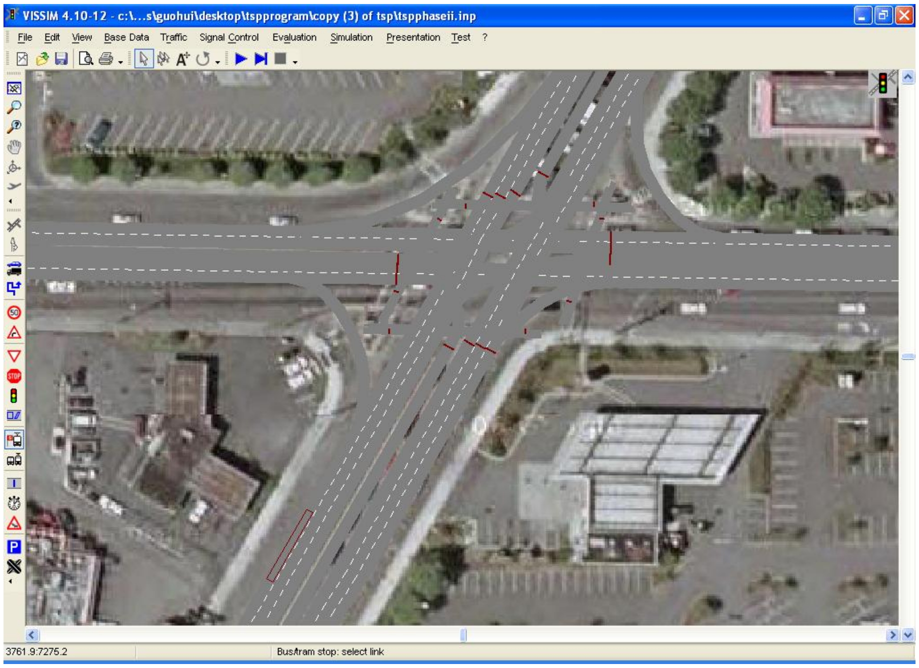

Figure 7-2 A Snapshot of the Phase Two Simulation Model

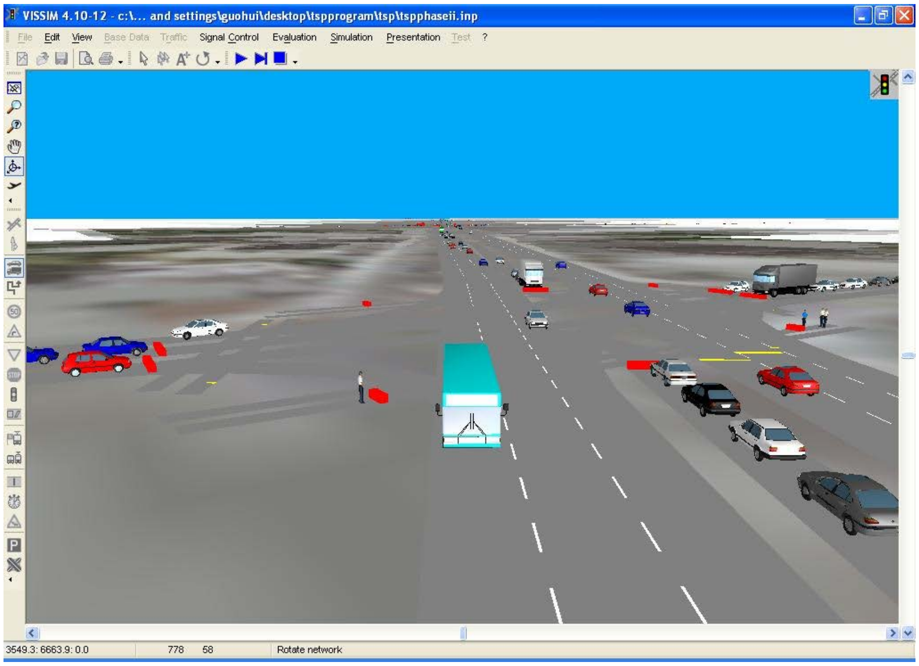

Figure 7-3 A Three-Dimensional Snapshot of the Phase Two Simulation Model

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 is granted for priority treatment, TPRG sends a priority requests to the traffic controller. Then the traffic controller issues a 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 routes 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 of 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 had seven bus stops, and six were affected by the TSP system. The average transit time match results at these bus stops are shown in Table 8-2. We calculated the arrival times of transit vehicles on the basis of TSP reader logs. The first three bus stops in the table 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, in comparison with the scenario in which TSP was off. The overall average improved time match at all the stops was 93.6 seconds, or about 16.3 percent in comparison with the scenario in which TSP was off.

8.2.2 Transit Travel Time

Transit travel time data were calculated by 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 36th Avenue at the stop bar of the southbound approach.

In comparison 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 to contradict our expectations. 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 were near-side bus stops, which may have had negative impacts on trips with granted priority. Section 8.4.2 provides further discussions on TSP impacts of near-side bus stops on transit delay.

Although the eastbound corridor also had a near-side bus stop, it was located at a corner of the intersection where transit vehicles turned right. Because 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.

In general, the SS-RTSP system decreased the intersection travel times of transit vehicles. The only exception was the eastbound direction for the intersection of Park-and-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 in comparison 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 with 36th Avenue SW and with Alderwood Mall Parkway, the savings were significant for westbound travel. At the other two intersections, the savings were in the 1- to 2-second range.

For most of the intersections, the standard deviation of intersection travel times 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 experienced longer travel times in comparison to all TSP-eligible trips.

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

8.2.3 Average Person Delay

On the basis of 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 for 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 with only 18 bus runs over the three-hour period. During the same time period, 5000 regular vehicles were generated. Given that the sample size for passenger cars was 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

		36th Ave	Park-and-Ride	Alderwood Mall Parkway	NorthPoint	Average
TSP Off	Personal Delay	16.9	3.0	10.3	2.0	8.7
	Number of Passengers	8271	6574	7854	6188	7222
TSP On	Personal Delay	16.7	2.9	10.1	2.0	8.6
	Number of Passengers	8252	6561	7858	6186	7214

8.3 COSTS

8.3.1 Vehicle Delays and Stops

The control delay per vehicle is the only measurement 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 was 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 number of vehicle stops 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. Because this intersection was 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

		36th Ave	Park-and-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 lengths on cross-streets. Because of time constraints, we analyzed and summarized data only from Mondays.

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
	36th 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
	36th Ave	West approach	3.27135	2.76868	16	3

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 was 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.

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 because of 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 was much smaller than the critical value of 2.920 at p=0.05. Therefore, the change in the average number of signal cycle failures after the TSP implementation was not significant at the p=0.05 level. The frequency of signal cycle failures may have slightly increased or decreased, depending on flow and signal control conditions after TSP was enabled. When TSP was on, the standard deviation of signal cycle failures may also have increased or decreased in a narrow range. The maximum number of vehicles caught in one cycle failure may also have increased or decreased after TSP was turned on. This was 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 8-4, 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 may have been limited because of the low number of 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 that used the three test routes when the test was conducted. Without a Keypad, a transit vehicle was not able to take advantage of the SS-RTSP system. More Keypads could be installed on these coaches to enable them to receive TSP when necessary. On the Phase One test corridor, only three transit routes were made eligible for TSP treatment, and more transit routes could be included in 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 affect travel time, such as the number of passengers to load and 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 in comparison with non-TSP intersections, 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 to contradict our intuition. To evaluate the 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 included an upstream check-in transit vehicle detector, two TSP treatments of green extension and early green (also called red truncation), and a fixed-time and uncoordinated traffic signal timing plan. Their approach compared bus movements with TSP on and off in time-space diagrams. Four scenarios were possible when a transit vehicle arrived 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. Zheng found that all the scenarios except number two benefited from TSP treatments. However, the expected delay might still be a net increase because the cost for missing a green extension would be high. Most of our theoretical results were backed up with simulation data. With this model, the extra cost from the near-side bus stop could be calculated. (For details of the model, please refer to Zheng et al. (2006).) However, Zheng assumed that the time of green extension was not stolen from conflicting phases, which resulted in a longer signal control cycle when the green extension treatment was provided. In practice, many signal control systems maintain a fixed cycle length for pre-timed traffic lights. The findings from Zheng et al. (2006) are not suitable for such TSP-enabled signals with a fixed cycle length.

The research results point to recommendations for improving the performance of the TSP system. Because scenario two has been shown to be the only source of extra transit delays, green extension may not be a worthy treatment at intersections with near-side bus stops and can be disabled. 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, the TPRG sent a priority request to the traffic controller. Then the traffic controller issued 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 for routes 100 and 101.

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

Date	Number of Granted TSP Trips by TPRG ID												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

Note: Locations of the TPRG can be found in Figure 6-1.

9.2 BENEFITS

9.2.1 Transit Time Match

The calculated TTM values are summarized in Table 9-2. The results show that transit vehicles would arrive at bus stops with reduced variability when the TSP system was on. The reduction in travel time variability varied from location to location, with a maximum reduction of 5 minutes and 51 seconds at stop 1013, located near the 220th

Street intersection. The average improvement in transit time matched for all the bus stops was 15 seconds, or about 6 percent, in comparison with the scenario when TSP was off.

Table 9-2 Time Match Results at Bus Stops in the 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″			

Note: The location of each bus stop is shown in Figure 6-1.

9.2.2 Transit Travel Time

Transit travel time data were calculated by 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 trips when TSP was on was 13 to 32 seconds shorter than that when TSP was off. With northbound and southbound together, the TSP saved an average of 26 seconds of transit travel time per trip, about 2.47 percent 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 contradictory. However, given that only late trips would be granted TSP treatment, this result is not beyond our expectation. Another comparison between late trips with TSP on and off was conducted.

The results showed that TSP saved 54 seconds of transit travel time (northbound and southbound together) for late trips, about 4.93 percent of the total corridor travel time.

Table 9-3 Transit Corridor Travel Time in the 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 shows the transit travel times across the 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 decision to use 100 ft upstream and downstream of the intersection’s center point was intended 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 were too close to the intersections. All the bus stops in the Phase Two test corridor were on the far side and over 200 ft away from the center of the intersection.

Table 9-4 Transit Intersection Travel Times in the 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

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 percent of the travel time without TSP. The reason for the travel time increase in the southbound direction of the 200th St intersection is unknown, but it is very likely due to random variations of traffic conditions between the two test weeks or bad TSP and traffic signal timing combinations, as will be discussed in Chapter 10.

9.2.3 Average Person Delay

On the basis of 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 13 intersections, the TSP system saved an average of 0.02 second for all passengers. Although the 0.02-second time saving seems trivial for each person, the overall benefit of more than 29.2 person-hours over a three-hour period (peak hours) for the whole corridor is noticeable. This indicates a total peak-hour time savings of 58.4 person-hours per day (here we assume six peak hours each day) or 31,171 person-hours per year. The overall person delay saved by the SS-RTSP system is remarkable. However, the reduced average person delay when TSP was on is not statistically significant from that when TSP was off at the p=0.05 level.

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

	Average Personal Delay (sec/intersection)		Average Hourly Person Number per Intersection	
Simulation Iteration	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 iteration.

Table 9-6 Traffic Delays and Stops from One Simulation Iteration in the 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

Given that each simulation run was just a random sampling action from a stochastic process, no conclusion can be drawn from a single simulation iteration. To further examine the differences in vehicle delay and number of stops between the conditions of TSP on and TSP off, ten simulation iterations were conducted. Each was associated with a unique random seed. Vehicle delays and stops were averaged for all 13 intersections under each test scenario. Table 9-7 presents the comparison results for all ten simulation iterations.

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

	AVD[1]		ANS[2]		VC[3]	
Simulation Iteration	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 number of stops observed from the ten simulation iterations varied slightly from iteration to iteration. TSP impacts on average vehicle delays were contradictory: for some iterations, vehicle delay increased, while for other iterations, the vehicle delay decreased. Observations on the number of vehicle stops in the ten simulation iterations were similar. Paired t-tests were conducted to determine whether the difference between the TSP on and TSP off conditions for 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 lengths from field recorded video tapes. Because of time constraints, this analysis was conducted on two representative intersections on the SR 99 corridor. Table 9-8 shows the statistics for traffic queue lengths on the cross-streets of the two intersections.

Table 9-8 Traffic Queue Length On Cross-Streets in the 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

As we can see in Table 9-8, when TSP was turned on, 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 queue length, 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 was smaller than the critical *t* ratio of 1.962 at p=0.05. Therefore, the change in average queue lengths on cross-streets after the SS-RTSP implementation was not significant.

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 because of 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 a paired t-test to compare the average frequency of signal cycle failures before and after the TSP implementation. The *t* ratio was 0.450, which was much smaller than the critical value of 1.962 at p=0.05. Therefore, TSP implementation did not result in significant changes in the average number of signal cycle failures. The frequency of signal cycle failures may have slightly increased or decreased, 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 have increased or decreased 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 the 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 SIMULATION-BASED INVESTIGATION OF TSP SYSTEM OPERATION AND OPTIMIZATION

TSP systems have been implemented in many urban areas in the U.S. and are regarded as one of the most applicable countermeasures against traffic congestion, particularly for metropolitan areas. Most of the relevant research has concentrated on system performance evaluations, with few studies emphasizing TSP operation strategies or system control optimization. This report lays out a series of theoretical and practical issues regarding TSP system control on the basis of observed field data and comprehensive analysis. Further research is desirable to improve the current state of the practice.

Traffic simulation is widely used in transportation engineering fields that include transportation system design, traffic operations, and management alternative evaluations because of its cost-effective and risk-free nature. VISSIM was developed to model urban traffic and public transit operations, and it can simulate and analyze traffic operations under various test scenarios. In this study, simulation-based investigations of TSP system operations and control strategy optimization were conducted. By using the real timing plans provided by the City of Lynnwood, a wide range of simulation scenarios were designed and tested. Optimal control strategy and parameter settings were explored, and potential problems were identified. These research findings are of practical importance for traffic engineers to optimize TSP systems in transportation applications.

10.1 SIMULATION EXPERIMENTAL DESIGN

To fully investigate TSP system performance under various traffic conditions, the Phase Two test corridor, i.e., the section of Washington SR 99 between 238th Street SW and 164th Street SW in Lynnwood, was selected as the simulation test site because of its large scale, complex traffic conditions, and diverse control strategies. There were 13 signalized intersections along this test corridor. Semi-actuated control strategies had been executed to coordinate signal control at these intersections. In our study, three typical signal plan groups were used to investigate TSP system operations. Each signal plan group consisted of 13 individual timing plans for the corresponding intersections. These signal plans included phase structures and timing parameters exported from the corresponding controllers. An individual VISSIM model was configured for each plan, including various field-observed traffic volumes, traffic control parameters, and so on. Because of consistent cycle lengths for all the intersections under the coordinated control mode, we were able to distinguish these signal groups by using their unique cycle length as follows: the 120-second signal plan group, the 130-second signal plan group, and 150-second signal plan group.

In TSP systems there are two important pre-specified control parameters, early green time and green extension time. In the SS-RTSP system, the early green time and green extension time were pre-set to 15 seconds. It is widely recognized that these two parameters have significant impacts on system performance because they indicate the extent of priority treatment for transit vehicles. Therefore, optimizing these two parameter settings is important for improving TSP system operation efficiency. Simulation experiments were conducted with different early green time and green extension time settings under different time plans. Various MOEs were applied to quantify their impacts on system performance, including delays, stops, and throughputs for both transit and general vehicles. Six simulation scenarios were established as follows to fully examine TSP system operations and explore the optimal control strategy settings:

Scenario 1: Fixed early green and green extension times of 15 seconds under 120-second-cycle signal plan

Scenario 2: Fixed early green and green extension times of 15 seconds under 130-second-cycle signal plan

Scenario 3: Fixed early green and green extension times of 15 seconds under 150-second-cycle signal plan

Scenario 4: Various early green and green extension times ranging from 6 to 30 seconds under 120-second-cycle signal plan

Scenario 5: Various early green and green extension times ranging from 6 to 30 seconds under 130-second-cycle signal plan

Scenario 6: Various early green and green extension times ranging from 6 to 30 seconds under 150-second-cycle signal plan.

In VISSIM, traffic generation is manipulated by a random seed number; by employing different random seeds, simulation results can be changed correspondingly, but within a certain range. To minimize the randomness of simulation results and enhance the credibility of simulation models, multiple simulation runs should be conducted. In this study, 20 simulation runs were conducted for each test scenario; among them were ten iterations with TSP functions and ten without TSP functions, each with a different random seed arbitrarily selected. The integrated results from these simulation runs were considered statistically reliable and unbiased.

On the basis of actual traffic conditions and control plans, the VISSIM model was configured and calibrated. Slight corrections were made to strengthen the model's appropriateness to the corresponding applications. Details of simulation model configuration and calibration are described in Chapter 7. The test period was specified as three hours. The outputs from the calibrated simulation models, including traffic volumes and speeds, reasonably matched our field observations. We believe that the simulation models were reasonably calibrated and did represent the real-world TSP system operations. Simulation results and discussions are provided in the next section.

10.2 SIMULATION TEST RESULTS AND DISCUSSION

10.2.1 Simulation Test under Scenario 1

In Scenario 1, transit vehicles operated under the 120-second-cycle signal plan, and 15-second early green and green extension times were used for TSP control strategies. To facilitate results analysis, several secondary MOEs, including the average person delay, intersection delays, and intersection stops, were collected for both transit and general traffic. Table 10-1 shows the average delays and stops for both southbound and northbound transit vehicles along the corridor. Comparisons between two systems, one with TSP active and the other without TSP, are illustrated in the table. The same random seeds were used for corresponding iterations of the two systems. Note that the delay time for transit vehicles did not include dwell times at transit stops. However, the acceleration and deceleration delays at a stop remained part of the delay time. From this table, we can see that significant improvements were achieved in terms of the average transit vehicle delays and numbers of transit stops at an intersection. The average transit delay decreased by 15 seconds, and the number of transit stops decreased from 3.74 to

3.53 at the test intersections. The significant test was conducted also at the p=0.05 level. The results indicate that TSP functions apparently reduced transit delays and stops at signalized intersections.

Table 10-1 Simulation Results of Delays and Stops for Transits along the Corridor for Test Scenario 1 from Ten Simulation Iterations

Test Period 3 Hours	AVD[1]		ANS[2]	
Simulation Iterations	TSP On	TSP Off	TSP On	TSP Off
1	473.7	494.2	3.86	4.14
2	462.9	472.7	3.36	3.14
3	474.2	491.2	3.64	3.91
4	454.8	465.2	3.27	3.45
5	482.5	498.4	3.36	3.68
6	478.6	493.7	3.45	3.82
7	468.5	498.8	3.82	4.55
8	482.4	488.4	3.68	3.59
9	462.8	474.9	3.45	3.82
10	462.5	473.8	3.45	3.27
Average	470.3	485.1	3.53	3.74
Significance Test at the p=0.05 level	Y		Y	

[1] denotes average vehicle delay; [2] denotes average number of stops

To quantify the possible negative impacts on local traffic due to TSP operations, further analysis was conducted. Several MOEs were adopted to measure the system performance, including average vehicle delay (AVD); number of stops (NS); vehicle number (VN); average person delay (APD); and person number (PN). Table 10-2 illustrates the comparison results from ten simulation runs. It shows that, at different intersections, each MOE varied a little with and without TSP functions. The slightly longer average vehicle delay for the local traffic was observed when the TSP system functioned. The average vehicle delay increased from 24.2 seconds to 24.4 seconds. The average number of stops and the average person delay each kept the same values. The through-traffic and person number varied slightly by less than 0.02 percent. To further verify the difference between TSP system on and off, the MOEs were calculated for all 13 intersections. Table 10-3 illustrates the compared results for the entire corridor.

Although the average vehicle delay and the number of stops fluctuated slightly, they remained at the same level statistically, and there were no significant impacts on local traffic from the TSP system. Paired t-tests were also conducted to examine the MOE variations, and the results supported our conclusions: the TSP system does not have significant impacts on local traffic at the p=0.05 level.

Table 10-2 Simulation Results for General Traffic at Thirteen Intersections along the Corridor for Test Scenario 1 from Ten Simulation Iterations

Test Period 3 Hours	TSP On					TSP Off				
Intersections	AVD[1]	ANS[2]	VN[3]	APD[4].	PN[5]	AVD	ANS	VN	APD.	PN
164th ST.	18.5	0.72	7156	18.5	7391	18.4	0.73	7156	18.4	7391
168th ST.	28.0	0.65	9267	27.6	9502	27.9	0.65	9269	27.5	9504
174th ST.	12.1	0.41	8209	12.1	8444	12.1	0.41	8210	12.1	8445
176th ST.	16.7	0.38	9340	16.7	9575	16.8	0.38	9342	16.8	9577
188th ST.	28.8	0.91	9412	28.2	9647	28.5	0.92	9412	28.1	9647
196th ST.	29.8	0.63	11688	29.7	11929	29.8	0.62	11693	29.8	11934
200th ST.	33.0	1.01	10033	32.4	10278	32.1	0.94	10040	31.6	10285
208th ST.	29.3	0.88	9855	29.0	10090	29.6	0.92	9853	29.2	10088
212th ST.	24.8	0.78	10080	24.4	10315	24.5	0.75	10080	24.1	10315
216th ST.	20.9	0.65	9609	20.6	9844	20.7	0.63	9607	20.4	9842
220th ST.	34.7	0.90	11942	34.4	12177	34.2	0.88	11940	34.0	12175
224th ST.	13.7	0.55	8775	13.8	9010	13.8	0.57	8777	13.9	9012
238th ST.	17.8	0.54	8805	17.8	9040	17.7	0.52	8804	17.7	9039
Average	24.4	0.70	9551	24.1	9787	24.2	0.70	9553	24.0	9789

[1] Denotes average vehicle delay; [2] denotes average number of stops; [3] denotes vehicle number; [4] denotes average person delay; [5] denotes person number

Table 10-3 Compared Results for General Traffic along the Entire Corridor for Test Scenario 1 from Ten Simulation Iterations

Test Period 3 Hours	AVD[1]		ANS[2]		VN[3]		APD[4].		PN[5]	
Simulation Scenario	TSP On	TSP Off	TSP On	TSP Off	TSP On	TSP Off	TSP On	TSP Off	TSP On	TSP Off
1	24.5	24.3	0.70	0.69	123725	123697	24.3	24.1	126785	126757
2	24.3	24.0	0.69	0.69	123719	123756	24.0	23.8	126789	126826
3	24.5	24.2	0.71	0.70	124547	124568	24.3	24.0	127617	127638
4	24.4	24.3	0.70	0.70	124983	125070	24.1	24.0	128053	128140
5	24.3	24.2	0.69	0.70	123649	123634	24.1	24.0	126719	126704
6	24.6	24.4	0.71	0.69	123432	123445	24.4	24.2	126492	126505
7	24.3	24.2	0.70	0.70	124451	124462	24.1	24.0	127511	127522
8	24.2	24.1	0.70	0.70	124619	124603	24.0	23.9	127679	127663
9	24.4	24.3	0.70	0.70	123931	123934	24.2	24.1	127001	127004
10	24.1	24.1	0.69	0.69	124638	124656	23.9	23.9	127708	127726
Average	24.4	24.2	0.70	0.70	124169	124183	24.1	24.0	127235	127249
Significance Test at the p=0.05 level	N		N		N		N		N	

[1] Denotes average vehicle delay; [2] denotes average number of stops; [3] denotes vehicle number; [4] denotes average person delay; [5] denotes person number

10.2.2 Simulation Test under Scenario 2

Analogously, simulation tests were conducted for Scenario 2. The 130-second-cycle signal plan was used, with early green and green extension time intervals fixed at 15 seconds for TSP system operations. The average delays and stops for transit along the corridor are illustrated in Table 10-4. However, simulation results showed that the TSP system introduced considerable negative impacts on transit operations under this test scenario. Transit vehicles with priority green time allocation experienced much longer delays than those operating under the regular signal control scheme when traveling along the entire corridor. Such data were observed from multiple simulation iterations, as shown in Table 10-4, indicating that the problem was less likely a result of the randomness of the simulation process.

Table 10-4 Simulation Results of Delays and Stops for Transits along the Corridor for Test Scenario 2 from Ten Simulation Iterations

Test Period 3 Hours	AVD[1]		ANS[2]	
Simulation Iterations	TSP On	TSP Off	TSP On	TSP Off
1	484.4	474.7	4.48	3.77
2	455.8	455.2	3.32	3.00
3	484.9	480.3	3.82	3.32
4	455.8	448.6	3.32	3.00
5	484.8	461.2	3.82	2.82
6	469.8	468.5	4.00	3.32
7	482.5	441.8	3.50	2.77
8	469.4	460.6	3.59	2.59
9	458.7	487.2	3.41	3.64
10	489.3	478.6	3.73	3.45
Average	473.5	465.7	3.70	3.17
Significance Test at the p=0.05 level	Y		Y	

[1] Denotes average vehicle delay; [2] denotes average number of stops;

By decomposing transit operations at each intersection, further research was conducted. Detailed analysis demonstrated that although the TSP control scheme could reduce transit travel delays at isolated intersections, it could also lengthen transit travel times along a corridor under certain signal control conditions because of interrupted progression of traffic flow. For the entire corridor, signal control plans could be coordinated at each intersection, and disruption to traffic flow progression could be minimized by setting up a proper offset for each signalized intersection. However, the TSP system could potentially disrupt signal control coordination by allocating more green time to transit at upstream intersections, resulting in longer travel delays at downstream intersections.

Three consecutive intersections were selected to further clarify this issue. Simulation data including average travel delays and stops for transit were collected from ten simulation runs, as shown in Table 10-5. Further observations of simulation operations were included for verification. At the upstream intersection of SR 99 and 196th Street, the early green strategy was executed, and transit vehicles experienced less delay by starting earlier when the TSP system was on. When the TSP system was on, the average transit delay was 43.4 seconds, less than the 49.5 seconds of delay without the TSP system. Because of signal coordination, however, transit arriving during a red signal would have to wait at the next intersection of SR 99 and 200th Street. Conversely, a transit vehicle operating without the TSP system could pass through this intersection smoothly by using the green band provided by coordinated signal settings. Thus, longer delays were observed for transit vehicles when TSP was enabled. Simulation data showed that the transit delay increased from 19.2 seconds to 22.1 seconds. A similar analysis was conducted for the next intersection at SR 99 and 208th Street. Severe delays were observed for transit when the TSP system was on. Although the TSP system could allocate more green time to transit at some intersections, such time savings might not be sufficient to offset the delay introduced by disrupting signal coordination along the entire corridor. The overall performance of transit operations would degrade significantly under this coordinated signal plan.

Table 10-5 Simulation Results of Delays and Stops for Transits at Three Consecutive Intersections for Test Scenario 2 from Ten Simulation Iterations

Test Period 3 Hours	AVD[1]		ANS[2]	
Intersection	TSP On	TSP Off	TSP On	TSP Off
196th ST.	43.4	49.5	0.94	0.98
200th ST.	22.1	19.2	0.47	0.36
208th ST.	27.1	13.8	0.67	0.23
Average	30.9	27.5	0.7	0.5

[1] denotes average vehicle delay; [2] denotes average number of stops;

To measure the TSP system impacts on local traffic under this 130-second-cycle signal plan, the MOEs were collected for the entire corridor. As shown in Table 10-6, the output data indicate that longer average vehicle delays and average person delays could result from the TSP system. However, statistical tests verified that the difference was not remarkably significant at the p=0.05 significance level.

Table 10-6 Compared Results for General Traffic along the Entire Corridor for Test Scenario 1 from Ten Simulation Iterations

Test Period 3 Hours	AVD[1]		ANS[2]		VN[3]		APD[4].		PN[5]	
Simulation Scenario	TSP on	TSP off	TSP on	TSP off	TSP on	TSP off	TSP-on	TSP off	TSP on	TSP off
1	24.8	24.0	0.63	0.62	108773	108785	24.5	23.8	111833	111855
2	25.0	24.2	0.65	0.63	108877	109074	24.7	24.0	111937	112134
3	24.5	24.0	0.63	0.62	109202	109272	24.2	23.8	112262	112332
4	24.3	24.2	0.63	0.63	109741	109816	24.1	23.9	112801	112886
5	24.5	23.9	0.62	0.61	108568	108710	24.2	23.7	111628	111770
6	24.7	24.3	0.63	0.62	108152	108133	24.4	24.0	111222	111193
7	24.4	24.1	0.62	0.62	109144	109198	24.1	23.8	112204	112258
8	24.5	24.0	0.62	0.61	109280	109298	24.2	23.8	112340	112358
9	25.4	23.9	0.68	0.61	108635	108882	25.1	23.7	111695	111952
10	24.4	24.3	0.62	0.63	108895	108907	24.2	24.1	111965	111967
Average	24.7	24.1	0.63	0.62	108927	109008	24.4	23.9	111989	112071
Significance Test at the p=0.05 level	N		N		N		N		N	

[1] Denotes average vehicle delay; [2] denotes average number of stops; [3] denotes vehicle number; [4] denotes average person delay; [5] denotes person number

10.2.3 Simulation Test under Scenario 3

The 150-second-cycle signal timing plan was also evaluated, and simulation tests were conducted for Scenario 3. Tables 10-7 and 10-8 show simulation results for both transit and local vehicles. From these two tables, we can see that the TSP system functioned reasonably well under this control strategy. The transit delay time decreased from 452.2 seconds to 434.1 seconds for both the northbound and southbound directions along the corridor when the TSP system was on. The number of stops also decreased from 2.61 to 2.45, and a t-test verified that these improvements were significant at the p=0.05 level. Further studies were conducted to analyze local traffic operations based on Table 10-8. There were no significant negative impacts from the TSP system on local traffic.

Table 10-7 Simulation Results of Delays and Stops for Transit Vehicles along the Corridor for Test Scenario 3 from Ten Simulation Iterations

Test Period 3 Hours	AVD[1]		ANS[2]	
Simulation Iterations	TSP On	TSP Off	TSP On	TSP Off
1	432.9	463.1	2.68	2.95
2	431.8	443.8	2.59	2.45
3	433.5	463.0	2.23	2.77
4	423.8	460.3	2.23	2.68
5	440.9	470.9	2.36	3.00
6	431.8	446.7	2.27	2.36
7	431.7	443.9	2.59	2.55
8	434.2	448.3	2.45	2.59
9	441.9	451.5	2.55	2.55
10	438.2	433.5	2.50	2.23
Average	434.1	452.5	2.45	2.61
Significance Test at the p=0.05 level	Y		Y	

[1] Denotes average vehicle delay; [2] denotes average number of stops

In short, under the 150-second-cycle signal plan, significant improvements were observed for transit vehicles traveling along the corridor because of the TSP system in terms of average delays and stops. Meanwhile, there were no significant negative impacts on local traffic resulting from the TSP system under this test scenario.

10.2.4 Simulation Test under Scenarios 4, 5, and 6

To quantify the impacts of early green and green extension times on transit and local traffic operations, simulation experiments were conducted for test scenarios 4, 5, and 6. Various early green and green extension times were applied to indicate the extent of priority treatment given to transit vehicles and to further investigate their impacts on the entire system's operation. Because a standard NEMA control logic consisting of two rings and two barriers was used for most signalized intersections along the corridor, and each ring had four sequential phases, an increment of 3 seconds was specified for both early green and green extension time changes in this simulation test. The increment time of 3 seconds could be evenly distributed among the other three phases. Consequently, a wide range of early green and green extension times could be chosen, from 6 seconds to 30 seconds. By combining these diverse times with the three typical signal plan groups studied in the previous tests, new simulation tests were conducted.

Tables 10-9, 10-10, and 10-11 show the delays for both transit and general traffic when the TSP system operated with various early green and green extension times under different control plans. From Table 10-9 we can see that when more early green and green extension times were allocated to transit under the 120-second-cycle signal plan, transit vehicles received obvious benefits. The transit delays were reduced from 480.7 seconds to 448.2 seconds. Meanwhile, no significantly longer delays were observed for minor street traffic. However, under the 130-second-cycle signal plan, the transit delays fluctuated in a certain range when more early green and green extension times were allocated to transit. No consistent patterns were observed. Also, there were no considerable negative impacts on minor street traffic, although more time was assigned to the major street directions. Similar results were recorded for the 150-second-cycle signal plan.

To facilitate such comparisons, Figure 10-1 illustrates the delay curves for transit vehicles under different signal control plans. This visualized curve supports the above analysis that although more early green time and green extension times were allocated to transit, the time savings that transit vehicles received were closely associated with the specific signal timing plan. For example, under the 130-second-cycle and the 150-second-cycle signal control plans, transit delays fluctuated when early green and green extension times increased. Although more green time was arranged for transit vehicles, disruptions to flow progression introduced remarkable delays for transit traveling along the corridor under such coordinated signal plans.

Table 10-8 Compared Results for General Traffic along the Entire Corridor for Test Scenario 3 from Ten Simulation Iterations

Test Period 3 Hours	AVD[1]		ANS[2]		VN[3]		APD[4].		PN[5]	
Simulation Scenario	TSP on	TSP off	TSP on	TSP off	TSP on	TSP off	TSP on	TSP off	TSP on	TSP off
1	24.6	24.2	0.55	0.54	97734	97811	24.3	23.9	100804	100871
2	24.5	24.3	0.55	0.55	97311	97340	24.1	24.0	100381	100410
3	24.3	24.1	0.54	0.54	98150	98156	24.0	23.8	101220	101236
4	24.2	24.0	0.55	0.54	98418	98453	23.9	23.7	101498	101533
5	24.6	24.3	0.56	0.55	96636	96663	24.2	24.0	99716	99743
6	24.6	24.4	0.55	0.54	96791	96777	24.2	24.0	99861	99847
7	24.3	24.2	0.55	0.54	97640	97634	23.9	23.9	100710	100704
8	24.5	24.3	0.55	0.54	97946	97998	24.1	23.9	101016	101068
9	24.2	24.0	0.54	0.53	97277	97266	23.8	23.6	100357	100346
10	24.5	24.2	0.55	0.54	97852	97849	24.1	23.9	100932	100929
Total	24.4	24.2	0.55	0.54	97576	97595	24.1	23.9	100650	100669
Significance Test at 95% Confidence	N		N		N		N		N	

[1] Denotes average vehicle delay; [2] denotes average number of stops; [3] denotes vehicle number; [4] denotes average person delay; [5] denotes person number

Table 10-9 Simulation Results of Delays for Transit and General Traffic with Various Early Green and Green Extension Times under 120-Sec-Cycle Signal Plan from Ten Simulation Iterations

Test Period 3 Hours	Transit (Average Corridor Delay)		General Traffic (Average Intersection Delay)			
			Minor Street		Major Street	
Early Green and Green Extension (Second)	TSP On	TSP Off	TSP On	TSP Off	TSP On	TSP Off
6	480.7	485.1	47.8	47.4	17.3	17.4
9	477.8	485.1	48.1	47.4	17.2	17.4
12	472.9	485.1	48.2	47.4	17.2	17.4
15	470.3	485.1	48.3	47.4	17.3	17.4
18	469.8	485.1	48.6	47.4	17.2	17.4
21	464.5	485.1	48.9	47.4	17.3	17.4
24	460.0	485.1	49.0	47.4	17.3	17.4
27	453.7	485.1	49.2	47.4	17.3	17.4
30	448.2	485.1	49.4	47.4	17.4	17.4

Table 10-10 Simulation Results of Delays for Transit and General Traffic with Various Early Green and Green Extension Times under 130-Sec-Cycle Signal Plan from Ten Simulation Iterations

Test Period 3 Hours	Transit (Average Corridor Delay)		General Traffic (Average Intersection Delay)			
			Minor Street		Major Street	
Early Green and Green Extension (Second)	TSP On	TSP Off	TSP On	TSP Off	TSP On	TSP Off
6	462.8	465.7	53.1	52.2	15.7	15.7
9	462.4	465.7	53.6	52.2	15.6	15.7
12	451.5	465.7	53.8	52.2	15.6	15.7
15	473.5	465.7	54.4	52.2	15.8	15.7
18	439.7	465.7	54.5	52.2	15.6	15.7
21	428.3	465.7	54.7	52.2	15.6	15.7
24	435.8	465.7	54.7	52.2	15.8	15.7
27	438.3	465.7	54.8	52.2	15.8	15.7
30	438.7	465.7	54.6	52.2	15.8	15.7

Table 10-11 Simulation Results of Delays for Transit and General Traffic with Various Early Green and Green Extension Times under 150-Sec-Cycle Signal Plan from Ten Simulation Iterations

Test Period 3 Hours	Transit (Average Corridor Delay)		General Traffic (Average Intersection Delay)			
			Minor Street		Major Street	
Early Green and Green Extension (Second)	TSP On	TSP Off	TSP On	TSP Off	TSP On	TSP Off
6	443.3	452.5	59.6	59.4	14.5	14.6
9	440.8	452.5	59.7	59.4	14.5	14.6
12	436.9	452.5	59.8	59.4	14.5	14.6
15	434.1	452.5	59.9	59.4	14.7	14.6
18	421.8	452.5	60.0	59.4	14.6	14.6
21	428.3	452.5	60.1	59.4	14.7	14.6
24	417.5	452.5	60.3	59.4	14.8	14.6
27	420.1	452.5	60.3	59.4	14.9	14.6
30	422.1	452.5	60.5	59.4	15.0	14.6

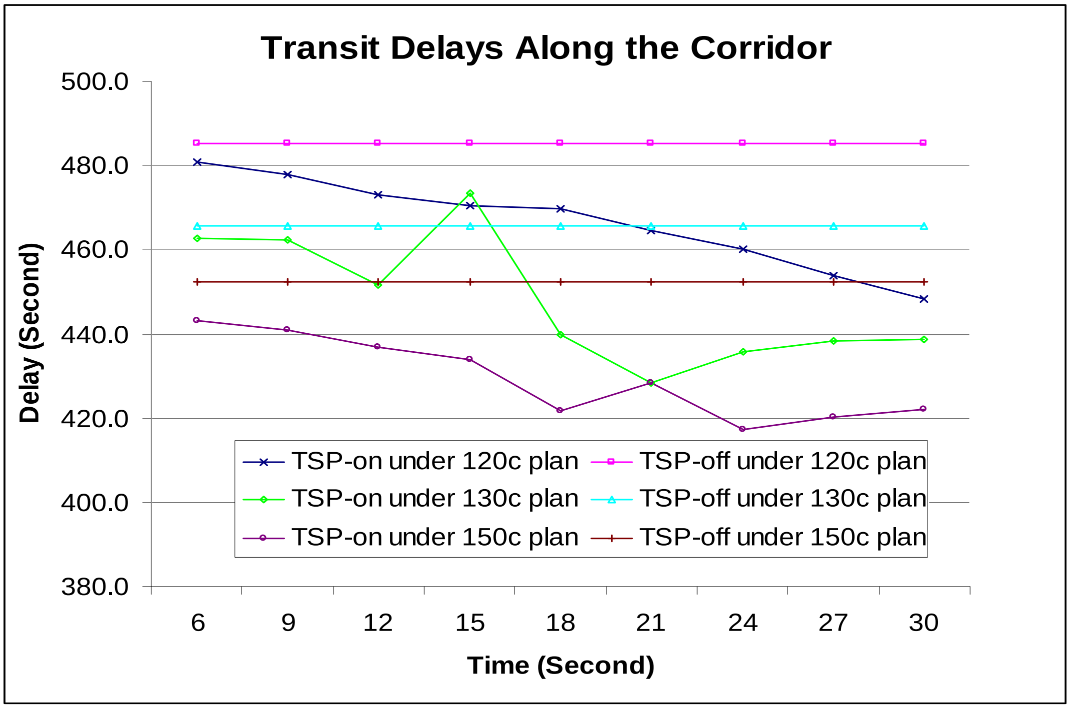

Figure 10-1 Transit Delay Comparisons with Various Early Green and Green Extension Times under Different Signal Plans

10.3 SIMULATION-BASED RESEARCH FINDINGS

In conclusion, to investigate TSP operations under different signal control plans and diverse priority settings, multiple simulation tests were conducted on the basis of three real signal plans provided by the City of Lynnwood, including the 120-second-cycle, 130-second-cycle, and 150-second-cycle signal timing plans. Under the 120-second-cycle and 150-second-cycle signal plans, remarkable time savings were observed for transit vehicles traveling along the corridor when the TSP control strategy was implemented with early green and green extension times of 15 seconds. Meanwhile, negative impacts on general traffic resulting from the TSP control scheme were not statistically significant at the p=0.05 level.

However, TSP system operations were not beneficial for both transit and general traffic under the 130-second-cycle signal plan. Although more green time was allocated to transit, longer travel time was observed for transit traveling along the entire corridor because of severe disruption of traffic progression. Negative impacts of the TSP system on local traffic were also observed, although they were not statistically significant. Therefore, we can conclude that the TSP system can shorten transit's travel time at some isolated intersections, but it may introduce interruptions to flow progression and hence cause longer travel time for a corridor with coordinated signal control. In-depth research is needed to investigate the compatibility between TSP control strategies and coordinated signal plans prior to implementation.

Further studies were conducted to investigate the impacts of two important parameters, early green and green extension times, on TSP system operations. A broad range of early green and green extension times, distributed from 6 seconds to 30 seconds, were tested under these three typical signal plans. Simulation results indicated that under the 120-second-cycle signal plan transit achieved noticeable benefits in terms of travel delay and stops with increasing early green and green extension times. However, under the 130-second-cycle and the 150-second-cycle signal timing plans, transit delays fluctuated to some extent when early green and green extension times increased, and there was no consistent pattern indicating transit travel time changes. These data further clarified that the TSP system control scheme must be tuned in relation to the coordinated signal control plan to maximize overall system performance. Although the negative impacts of the TSP system on general traffic increased when more early green and green extension times were used, they were not statistically significant because a larger number of general vehicles on major streets could benefit from the longer green times allocated for TSP system operations than vehicles on minor streets.

CHAPTER 11 CONCLUSIONS AND RECOMMENDATIONS

11.1 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 produced remarkable benefits for transit vehicles, with insignificant negative impacts to local traffic on cross-streets. The overall impact of the SS-RTSP system on the local traffic of an entire intersection was a minor net benefit, though it was not statistically significant.

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 seconds, or about 6 percent, 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. In the Phase Two test, the average saved transit corridor travel time was 54 seconds, or 4.93 percent. Because of the saved transit travel time, the SS-RTSP system decreased overall person delay. 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 0.02 second in the Phase Two test. For Phase One and Phase Two together, the overall saved personal delay was 56,227 person-hours per year, for peak-hour travel only.

The impact of the SS-RTSP system on local traffic for an entire intersection was to sometimes increase and sometimes decrease delay, 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. 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 also not significant at the p=0.05 level after SS-RTSP implementation.

11.2 RECOMMENDATIONS

To improve the performance of the current SS-RTSP system, more transit vehicles could 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. Given that the negative impact of the SS-RTSP on local traffic was not significant, more transit trips could be granted with TSP treatment, and the frequency of TSP requests could be increased to generate more benefits from the SS-RTSP system.

Simulation-based investigations of TSP system operations and optimization were conducted. Different coordinated signal control plans were utilized to examine TSP system performance. The simulation results indicated that under particular coordinated signal control plans, longer transit travel time along a corridor could be produced by the TSP treatment as a result of severe disruption of traffic progression. Therefore, for new applications, TSP systems should be fully evaluated to minimize the potential inconsistency between the TSP control strategies and the existing signal control coordination along the corridor.

ACKNOWLEDGMENTS

The authors are grateful for the financial support to this project from Transportation Northwest (TransNow), the USDOT University Transportation Center for Federal Region 10, and the Washington State Department of Transportation (WSDOT). The authors also appreciate help from Larry Senn from WSDOT; Zohreh Zandi, Marjean Penny, and Connie Allen from Community Transit (CT); Kevin Tucker and John Tatum from Snohomish County; and Paul Coffelt and Dick Adams from the City of Lynnwood. Students from the Smart Transportation Applications and Research Laboratory (STAR Lab) at the University of Washington also contributed considerably to the data collection, analysis, and report editing tasks for this research project.

REFERENCES

Abdulhai, B., A. Shalaby, and J. Lee, and A. Georgi. 'Microsimulation modeling and impact assessment of streetcar transit priority options: the Toronto experience'. Pre-print CD-Rom for the 81st Annual Meeting of the Transportation Research Board, Washington D.C. 2002

Al-Sahili, K.A., and Taylor, W.C. 'Evaluation of bus priority signal strategies in Ann Arbor, Michigan'. Transportation Research Record 1554, Transportation Research Board, Washington, D.C., 74-49. 1996

Baker, R.J., Collura, J., Dale, J.J., Head, L., Hemily, B., Ivanovic, M., Jarzab, J.T., McCormick, D., Obenberger, J., Smith, L., and Stoppenhagen, G.R. 'An overview of transit signal priority'. Intelligent Transportation Society of America, Washington, D.C., 2002.

Casey F. R. 'Advanced Public Transportation Systems Deployment in the United States - Year 2000 Update'. Report FTA-MA-26-7007-02.1, DOT-VNTSC-FTA-02-06, Federal Transit Administration, U.S. Department of Transportation. 2002

Chada, S., and Newland, R. 'Effectiveness of bus signal priority – final report'. Report NCTR-416-04, National Center for Transit Research, University of South Florida, FL. 2002

Chang, E., and A. Ziliaskopoulos. 'Data challenges in the development of a regional assignment-simulation model to evaluate transit signal priority in Chicago'. Pre-print CD-Rom for the 82nd Annual Meeting of the Transportation Research Board, Washington D.C. 2003

Chang, G.-L., Vasudevan, M., and Su, C.C. 'Bus preemption under adaptive control environments'. Transportation Research Record 1494, Transportation Research Board, Washington, D.C., 146-154. 1995

Collura, J., Rakha, H., and Guifford, J. 'Guidelines for the planning and deployment of emergency vehicle preemption and transit priority strategies'. Research Report, Virginia Tech Transportation Institute. 2003

Community Transit. 'Addendum to Results of Service Quality Monitor On-Board Survey Data: September 2004 – February 2005'. 2005

Dion, F., Rakha, H., and Zhang, Y. 'Evaluation of potential transit signal priority benefits along a fixed-time signalized arterial'. Preprint CD-ROM, 81st Transportation Research Board Annual Meeting, Washington, D.C. 2002

Garcia-Molina, H., J.D. Ullman, and J. Widom. *Database Systems: The Complete Book*. Prentice-Hall, Inc. Upper Saddle River, New Jersey, 2002

Garrow, M., and Machemehl, R. 'Development and evaluation of transit signal priority strategies.' Research Report SWUTC/97/472840-00068-1, Southwest Region University Transportation Center, Center for Transportation Research, University of Texas, Austin, Texas. 1997

King County Department of Transportation. ‘An evaluation of transit signal priority on Aurora Avenue north’. King County Department of Transportation, Transit Speed and Reliability Program. 2002

Ludwick, John S. ‘Simulation of an unconditional preemption bus priority system.’ Transportation Research Record 536. Washington, D.C. 1975

McCain Traffic Supply. AVITSP System Operations Manual – Including System Enhancements. 2004

National Transit Database. 2003. ‘Transit profiles all reporting agencies’. Federal Transit Administration. 2004

Ngan, Vikki. ‘A comprehensive strategy for transit signal priority’. Institute of Transportation Engineers, ITE Journal, 73(11), pp. 28~32, 2003

Rakha, Hesham and Yihua Zhang. ‘Sensitivity analysis of transit signal priority impacts on operation of a signalized intersection’. Journal of Transportation Engineering. Vol. 130, no. 6, pp. 796~804, 2004

Snohomish County. 164th Street S.W. Phase 2, Spruce Wang to Ash Way. CRP# RC-1068. Snohomish County. 2003

Sunkari, Srinivasa R. Beasley, Phillip S. Urbanik II, Thomas, and Fambro, Daniel B. ‘Model to evaluate the impacts of bus priority on signalized intersections’. Transportation Research Record 1494. Washington, D.C. 1995

Transportation Research Board. Highway Capacity Manual. National Research Council, Washington D.C., 2000

Transportation Research Board. Transit Capacity and Quality of Serivce Manual (TCRP Report 100). In Transit Cooperative Research Program. Washington, D.C. 2003

VISSIM User’s Manual. Version 4.00. PTV Planung Transport Verkehr AG., Karlsruhe, Germany, June 2004

Yand, M.C. ‘Effective transit signal priority’. Proceedings of 2004 Annual Meeting and Exhibit, Institute of Transportation Engineers. 2004

Zheng, Jianyang, Yinhai Wang, Hongchao Liu, and Mark E. Hallenbeck. (submitted) ‘Modeling the Impact of Near-Side Bus Stop on Transit Delays at Transit Signal Priority Enabled Intersections’, Transportation Research Record. 2006