FINAL CONTRACT REPORT

TRANSIT SIGNAL PRIORITY PROJECT PHASE II: FIELD AND SIMULATION EVALUATION RESULTS

Hesham Rakha, Ph.D., P.Eng.
Associate Professor, Civil & Environmental Engineering
Virginia Polytechnic Institute & State University
and
Director, Center for Sustainable Mobility
Virginia Tech Transportation Institute

Kyoungho Ahn, Ph.D.
Senior Research Associate
Virginia Tech Transportation Institute

Project Managers
Michael A. Perfater, Virginia Transportation Research Council
Catherine C. McGhee, Virginia Transportation Research Council

Contract Research Sponsored by
Virginia Transportation Research Council

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

February 2006
VTRC 06-CR

NOTICE

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

Transit Signal Priority (TSP) is recognized as an emerging technology that is capable of enhancing traditional transit services. Basic green-extension TSP was implemented on U.S. Route 1 in the Northern Virginia Area (or Washington, DC metropolitan area). This study quantifies the impact of TSP technology on transit-vehicle performance using field-collected Global Positioning System (GPS) data and evaluates the system-wide benefits of TSP operations using computer simulations to expand on the field evaluation study.

The field study demonstrated that overall travel-time improvements in the order of 3% to 6% were observed for TSP-operated buses. However, the results also demonstrated that green-extension TSP can increase transit-vehicle travel times by approximately 2.5% during congested morning peak periods. In addition, the study demonstrated that TSP strategies reduce transit-vehicle intersection delay by as much as 23%. The field study demonstrated that the benefits associated with TSP were highly dependent on the roadway level of congestion and were maximized under moderate to low levels of congestion.

However, the simulation results indicated that TSP did not result in statistically significant changes in auto or system-wide travel times (differences less than 1%). Furthermore, a paired t-test concluded that basic green-extension TSP did not increase side-street queue lengths. An increase in the traffic demand along Route 1 resulted in increased system-wide detriments; however, these detriments were minimal (less than 1.37%). The study demonstrated that an increase in side-street demand did not result in any statistically significant system-wide detriments. Increasing the frequency of transit vehicles resulted in additional benefits to transit vehicles (savings in transit vehicle travel times by up to 3.42%), but no system-wide benefits were observed. Finally, TSP operations at near-side bus stops (within the detection zone) resulted in increased delays in the range of 2.85%, while TSP operations at mid-block and far-side bus stops resulted in network-wide savings in delay in the range of 1.62%. Consequently, we recommend not implementing TSP in the vicinity of near-side stops that are located within the TSP detection zone.

The simulation results indicated that a TSP system generally benefits transit vehicles, but does not guarantee system-wide benefits. In this study, a maximum transit vehicle travel-time savings of 3% to 6% was observed with the provision of green-extension TSP from both the field and simulation evaluation studies. However, the green-extension TSP operation did not benefit nor damage the non-transit vehicles in most cases. Also, it should be noted that the results of the study may be specific to Route 1 corridor because of the unique characteristics of the study corridor, the specific traffic demand, and TSP logic implemented.

Finally, the study recommends the calibration of current TSP settings to improve the effectiveness of TSP operation. Also, different transit priority strategies or a combination of other TSP strategies should be investigated to increase the benefits of TSP operations. A conditional TSP system that only provides priority to transit vehicles behind schedule and an intelligent transit monitoring system are also recommended to improve the TSP system on the Route 1 corridor.

FINAL CONTRACT REPORT

TRANSIT SIGNAL PRIORITY PROJECT
PHASE II: FIELD AND SIMULATION EVALUATION RESULTS

Hesham Rakha, Ph.D., P.Eng.
Associate Professor, Civil & Environmental Engineering
Virginia Polytechnic Institute & State University
and
Director, Center for Sustainable Mobility
Virginia Tech Transportation Institute

Kyoungho Ahn, Ph.D.
Senior Research Associate
Virginia Tech Transportation Institute

INTRODUCTION

Transit Signal Priority (TSP) is recognized as an emerging technology that is capable of enhancing traditional transit services. According to a recent study (Baker et al., 2002), TSP is defined as "*an operational strategy that facilitates the movement of in-service transit vehicles, either buses or streetcars, through traffic-signal controlled intersections*." TSP is deployed to improve transit operations and service quality and eventually promote more ridership, improve person mobility, reduce traffic congestion, and reduce mobile-source emissions and fuel consumption rates.

In recent years, TSP has been widely implemented by transportation agencies in North America and worldwide. The growing deployments of TSP across the nation require extensive evaluation studies. A number of studies have attempted to evaluate TSP using either empirical, analytical, and/or simulation tools (Ngan, 2003; Dion et al., 2004; Kimpel et al., 2004; Bertini et al., 2005; Dion and Rakha, 2005). Analytical studies typically utilize mathematical formulations to quantify the impact of TSP operations, while simulation studies investigate the effectiveness of TSP strategies using simulation software. Alternatively, empirical studies quantify the impact of TSP on a number of measures of effectiveness (MOEs) by gathering field data. While analytical and simulation studies are widely used for the evaluation TSP projects, relatively few empirical studies have been conducted because of the high cost and manpower required to conduct such studies, the potential for errors, and unpredictable transit-vehicle schedules. This study quantifies the impact of TSP technology on transit-vehicle performance using field collected Global Positioning Systems (GPS) data and evaluates the system-wide benefits of TSP operations using computer simulations to expand on the field evaluation study.

GPS technology offers a cost-effective means to conduct such field evaluation studies. GPS technology is increasingly being employed for intelligent transportation system (ITS) applications. This study utilizes portable GPS units to gather transit vehicle second-by-second trajectories to quantify the impact of TSP technology on transit-vehicle performance.

U.S. Route 1, also known as the Richmond Highway, is one of the most heavily congested arterials in the Northern Virginia Area (or Washington, DC metropolitan area). The corridor connects two highly congested interstate highway interchanges on I-495 and I-95 and serves a closely located metro station, Huntington Station. On typical weekdays morning traffic congestion continues until noon on I-95. The study corridor is frequently used as an alternative route to I-95. The corridor also serves one of the busiest fire stations in the Northern Virginia Area and provides frequent preemptions requested by emergency vehicles in order to provide safer and faster service. Thus, the impacts of TSP on the Route 1 corridor are a matter of common interest to local government, traffic signal operators, transit bus operators/riders, and local road users.

This study quantifies the impact of various transit parameters on the effectiveness of TSP using the 171 line along the Route 1 corridor. In particular, this study describes the findings of a field evaluation and a simulation study of TSP operations on transit-vehicle travel time and intersection delay, and system-wide benefit.

PURPOSE AND STUDY SCOPE

The purpose of this project is to quantify the impact of TSP operations on transit vehicle and system-wide performance based on a field and simulation study evaluation. The scope of this study is limited to the morning peak period.

The objectives of this study are summarized as follows:

- To evaluate the benefits of TSP on transit vehicles in terms of travel time and intersection delay savings using field-collected GPS data.
- To investigate the feasibility and applicability of GPS technology for such evaluation applications.
- To develop and calibrate a simulation model to realistically model the Route 1 traffic demand using field-observed data.
- To investigate the system-wide benefits of a TSP system.
- To attempt to identify the impacts of TSP for various congestion levels on Route 1.
- To investigate the impacts of TSP for increased side-street demands.
- To conduct a sensitivity analysis of TSP operations for different transit vehicle frequencies and bus stop locations.

BACKGROUND

This section describes the study corridor characteristics, the transit signal priority logic, and green-extension algorithm embedded within the INTEGRATION software.

Study Corridor Characteristics

Prior to describing the study method, a brief overview of the study corridor is presented. As shown in Figure 1, the study corridor extends over 12.9 km (8.06 mi) and covers 27 signalized intersections. The northern part of the study section has three lanes per direction of travel while the southern part has two lanes per direction of travel. The study section starts at Fairfax County Parkway to the south and extends to North King/Shields intersection to the north. The North King/Shields intersection is located within 2.5 km (1.56 mi) from one of the busiest interstate highway interchanges in the area (the interchange between I-95 and I-495).

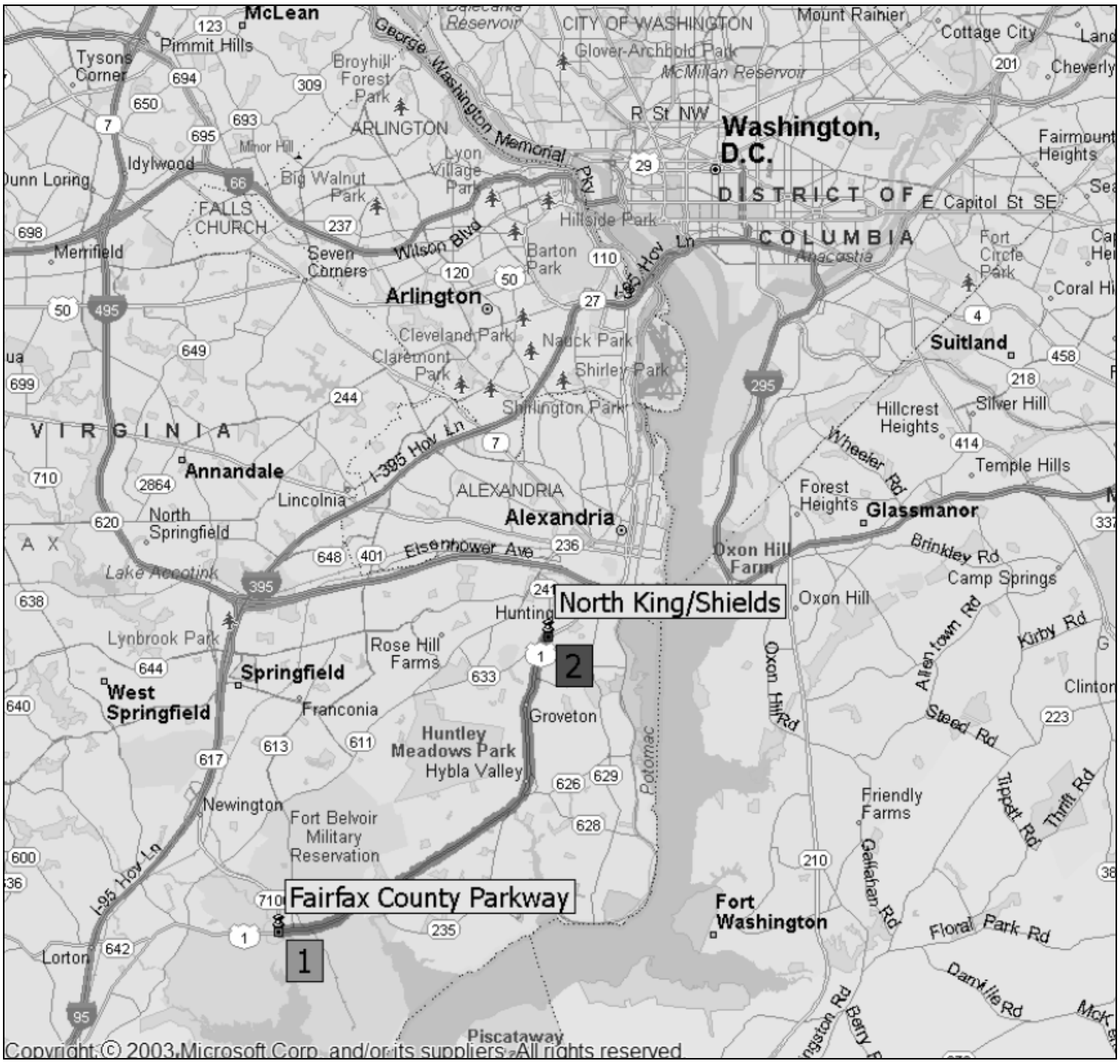

Figure 1. Route 1 Study Corridor

The traffic volume in the typical morning peak hour (6:30 – 9:30 a.m.) is around 3,300 veh/h in the northbound direction, with a total demand of approximately 16,000 vehicles over the 3-hour morning peak period. Traffic flows along the corridor are typically directional, however, the morning peak period also carries a significant traffic demand in the southbound direction. During the morning peak hours, traffic along the study corridor generally moves northbound, towards downtown Washington, DC and Alexandria, VA. It should be noted that the northern portion of the study section, which has closely spaced signalized intersections, is typically more congested than other portions of the study section. Of the 27 signalized intersections, those with S. Kings, Sherwood, Mt. Vernon, Old Mill, and the Fairfax County Parkway carry significant traffic demand from side streets.

The study corridor is controlled by a coordinated-actuated signal mode with an optimized cycle length of 180 s. Most of the signal cycle time is assigned to Route 1. The directional distribution of signal timing varies according to the time of the day. The average traffic signal spacing is 480 m with a minimum spacing of 51 m and a maximum spacing of 1,400 m.

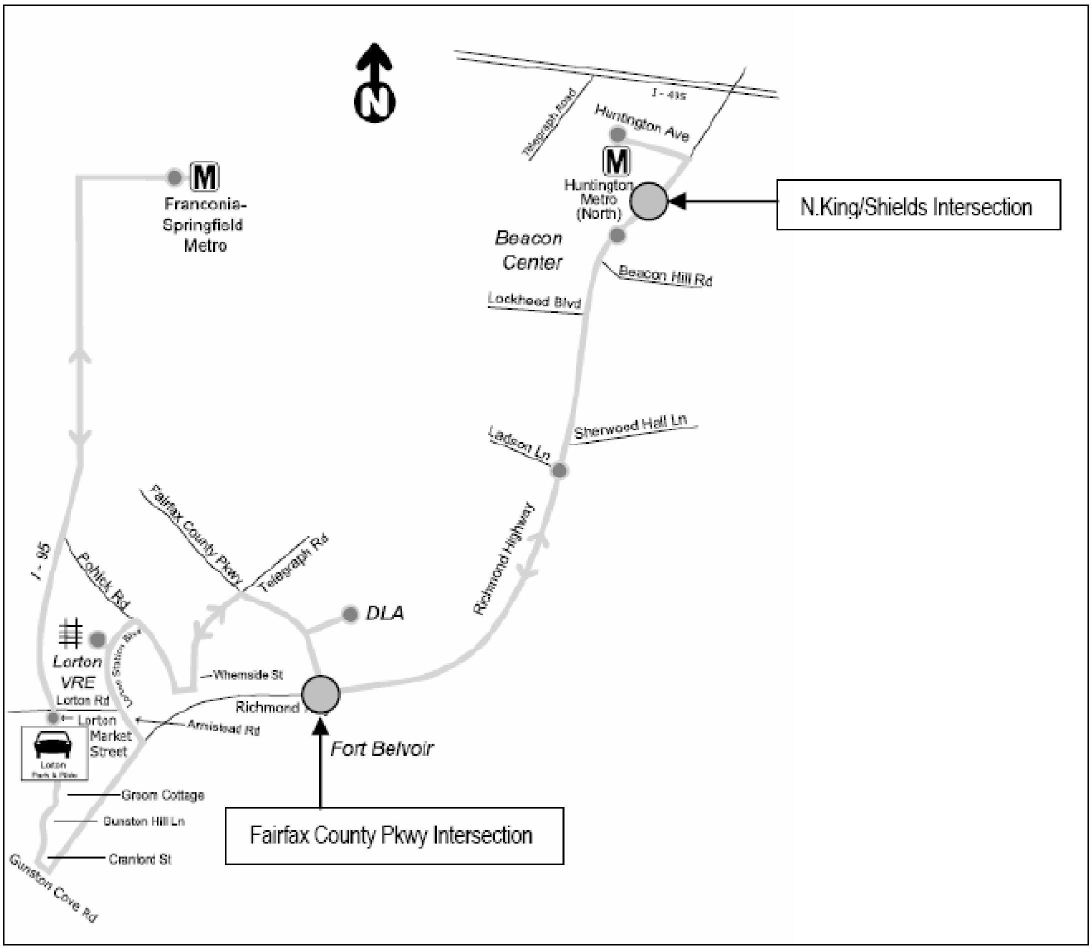

Figure 2. Bust 171 Route and Study Corridor 1

Three different bus routes (route numbers 151, 161, and 171) are operated by the Fairfax Connector along the study corridor. All three routes connect Huntington Metro Station, which is located in proximity to the North King/Shields intersection, and serves the residential areas south of the study corridor. For purposes of this study, only the Bus 171 route was equipped with GPS technology since this bus line is the only route that extends over the entire study corridor. As illustrated in Figure 2, bus route 171 departs from Franconia-Springfield Metro Station and connects to Huntington Metro Station providing access to the Washington Metrorail Service. It should be noted that the large circles indicate the northern end and southern end of the study corridor. There are a total of 63 bus stops located along the study corridor including 14 near-side, 15 far-side, and 24 mid-block stops. A total of 30 bus trips (bus routes 151, 161, and 171) are made during the morning peak period that is equally distributed between northbound and southbound trips. The transit route for Bus 171 operates at a 30-minute headway during the morning peak period.

TSP Logic

The priority logic that was implemented along the study corridor involved a simple green-extension logic. Green extension was granted when a transit vehicle was detected or expected to arrive at a traffic signal a few seconds after the end of the green indication. Consequently, the transit vehicle utilized additional green time to allow it to clear the intersection before the traffic signal indication changed. This strategy was only provided when the signal was in a green indication and the approaching vehicle was equipped with a transit priority device; thus if the TSP-equipped vehicle arrived during a red indication, signal priority was not granted. The green-extension strategy is known to be one of the most effective approaches in granting priority to transit vehicles. The method allows a transit vehicle to be served and significantly reduces the delay to that vehicle relative to waiting for an early green or special transit phase. Also, green extension does not require additional clearance intervals (Baker et al., 2002).

The green-extension strategy for the study corridor utilized a constant green extension of 10 s because of the high traffic demand and long cycle length (180 s) along the corridor. A 3M Opticom emitter was utilized as part of system. The system consisted of emitters on the transit vehicles and optical detectors located at the traffic signals. The emitter was typically installed on the roof of transit vehicles while an optical detector and a confirmation light were set up on the traffic signal head. The TSP system was processed when the optical detector received a request from a transit vehicle during a green indication if there was no ongoing pedestrian phase at the time and no emergency vehicle preemption call was being made simultaneously.

Green-Extension Algorithm Embedded within INTEGRATION

A green-extension algorithm was implemented into the INTEGRATION model (version 2.30g). A detailed description of the TSP logic is provided in the literature (Dion and Rakha, 2005; M. Van Aerde and Associates, 2005) and summarized as follows. If the system detects that a transit vehicle will arrive at a traffic signal a few seconds after the end of the green indication, the green indication is extended n seconds. In this study, the extension time was set to 5 s. The duration of the extended green indication cannot exceed the maximum green. The extended time is subtracted from the next phases in the same cycle ensuring that it does not go less than its minimum allowed duration. Thus, the cycle length is not affected by green extension. The detection range was set to 60 m (200 ft) from the upstream of the intersection, which is consistent with the detection range setting of the 3M Opticom system installed on the Route 1 study corridor. While a pedestrian phase is not modeled in this study, the minimum green time of a phase can be considered to be the pedestrian crossing phase. Finally, it should be noted that preemptions of emergency vehicles were not considered in this study.

METHODS

In order to meet the objectives of this study, the following seven tasks were performed.

1. Collect GPS data for transit vehicles with and without TSP along the Route 1 corridor study section.
2. Extract the GPS relevant data for the study section and estimate various measures of effectiveness from the collected GPS data.
3. Conduct a field evaluation of TSP impacts on bus performance in terms of travel time and delays at critical intersections.
4. Construct a simulation model of the study corridor.
5. Collect sample probe-vehicle travel time and queue length data at representative traffic signals for use in validating the simulation results.
6. Calibrate and validate the simulation results against the probe-vehicle travel time and queue length data.
7. Conduct an analysis of TSP simulation runs of the selected scenarios.

The following section describes the GPS data collection procedures, the simulation model construction, and simulation scenarios.

GPS Data Collection Procedures

GPS technology is increasingly being used for transportation-related applications. The study utilized portable Wide-Area Augmented System (WAAS)-enabled GPS receivers to gather second-by-second transit vehicle trajectories along the Route 1 study section. WAAS-enabled GPS receivers provide longitude and latitude data to an accuracy of 2 m, altitude data to an accuracy of 3 m, and speed measurements to an accuracy of 0.1 m/s. This section describes the experimental design for the study.

Transportation Data Collection using GPS

Reliable and accurate travel behavior are difficult to obtain because traditional data collection is typically expensive, labor intensive, inflexible, time consuming, and error prone. Alternatively, laboratory simulation offers an economic means to gather data; however, minor behavioral differences can cause significant discrepancies between actual and measured behavior (Marca et al., 2001; Belliss, 2004). To address these problems, GPS technology integrated with in-vehicle data collection systems has emerged as a cost-effective data-gathering technology. GPS data collection systems provide a flexible data recording platform supporting a variety of in-vehicle data recording applications; GPS tracking of vehicle trajectories; real-time transmission of vehicle position and performance variables; tracking trip-making behavior (generation and routing) as a function of levels of congestion, anticipated travel time, and other route information (Marca et al., 2001).

A variety of studies have utilized GPS technology to evaluate transportation operational projects. For example, Rakha et al. demonstrated how GPS data can be utilized to evaluate the energy and environmental impacts of transportation operational projects (Rakha et al., 2001). The study demonstrated that appropriate data-smoothing techniques efficiently improved the speed profiles generated by GPS speed measurements. In addition, Marca et al., developed an extensible data collection unit (EDCU) which combines a standard GPS unit, a cellular data modem, and an embedded processor to serve the in-vehicle data collection needs of Intelligent Transportation System (ITS) researchers (Marca et al., 2001). Belliss utilized low-cost GPS equipment to measure detailed speed and travel-time data using commercial buses. The study shows that the collected GPS data allow valid calculations of speed, delay, and acceleration without the need for costly instrumentation and constant recalibration (Belliss, 2004). The GPS data collection is accurate, consistent, reliable, and automated. Because of these advantages, numerous publications have documented the use of GPS technology in transportation studies (Quiroga and Bullock, 1997; Lin and Zeng, 1999; Oloufa et al., 2003; Oloufa, 2003; Jeong and Rilett, 2004).

Experimental Design and Bus Travel Data Collection

A portable GPS unit, GD30L, manufactured by LAIPAC Technology Inc. was utilized in the study. The GPS unit is designed to record the date, time, vehicle longitude, vehicle latitude, vehicle speed, vehicle heading, and the number of tracking satellites. The GD30L unit (94.5 mm (width)×136.0 mm (depth)×45.0 mm (height)) is small enough to be installed inside a glove compartment in any vehicle and powered by the cigarette-lighter power adapter. The system is completely configurable and the user can change the setup of the DIP switches to select the recording interval from 1 s to 30 min, as well as the data recording format. The logged GPS data are recorded in a removable MultiMedia Flash Memory Card (MMC) and the 32MB MMC card easily holds 10 days of bus operational data at a 1-second intervals. A flash memory card reader is used to transfer the GPS data to a PC. The device is operated as a stand alone unit without the need for a PC or other equipment. Once the GD30L is powered-up, the GPS unit collects the data automatically.

The GPS bus data were collected on weekdays (Monday through Friday) between March and May of 2005. Five GPS units were installed on five buses which were also equipped with the 3M emitter system for transit priority detection. The five test buses were operated along Bus 171's route. The bus travel data were recorded at a 1-second resolution and downloaded to a personal computer on Sunday nights. After the data were downloaded, the files on the MMC card were deleted for the following week's data collection effort and the emitter on the bus was activated (or deactivated) to evaluate the impact of TSP. Thus typically the emitters of two to three buses were ON and the other emitters were OFF.

Table 1 shows the required sample sizes for the evaluation of TSP and the number of valid GPS bus trip data. The minimum sample size (N) was calculated to satisfy the 95% and

90% confidence limits (Z value, 1.96 or 1.645) using the standard deviation (σ) value and travel time error (δ). In order to estimate the sample size, the GPS travel time data that were collected between June and July of 2004 were utilized. The GPS data were originally collected for the analysis but the data were excluded from the analysis due to the bus schedule change. The values of standard deviation were ranged from 2:31 to 3:06 while the travel time errors were between 7% and 13%. As shown in the table, the GPS data that were gathered exceeded the required minimum sample size. In total 256 bus trips were recorded, of which 147 traveled in the northbound and 109 traveled in the southbound direction.

$$N = \left(\frac{1.96}{\delta}\right)^2 \sigma^2 \qquad [1]$$

Table 1. Sample Size Requirements

			Required Sample Size		Valid Bus Trips
			90% Confidence Limit	95% Confidence Limit	
NB	TSP On	Total	33	47	79
		AM Peak	9	13	18
	TSP Off	Total	27	39	68
		AM Peak	10	14	18
	NB Total				147
SB	TSP On	Total	25	36	60
		AM Peak	10	15	28
	TSP Off	Total	20	28	49
		AM Peak	13	19	23
	SB Total				109

GPS Data Reduction and Management

The GPS data were gathered using the RMC format which includes essential, as follows:

*$GPRMC,123519,A,4807.038,N,01131.000,E,022.4,084.4,230304,003.1,W*6A*

Where:

RMC	Recommended minimum sentence C,
123519	Fix taken at 12:35:19 UTC,
A	Status A=active or V=Void,
4807.038,N	Latitude 48 deg 07.038' N,
01131.000,E	Longitude 11 deg 31.000' E,
022.4	Speed over the ground in knots,
084.4	Track angle in degrees,
230094	Date - 23rd of March 2004,
003.1,W	Magnetic Variation, and
*6A	The checksum data, always begins with *

GPS data were continuously recorded and saved in an ASCII file. Each unit produced a single file for each day from 00:00:00 to 23:59:59. It should be noted that for purposes of data analysis, the original GPS time was converted to the local time. Test buses that operated along

Bus 171's route typically departed the Fairfax Connector parking garage between 3:30 and 5:00 a.m. and returned to the garage between 10:30 a.m. to 2:00 p.m. All trips departing after 6:30 a.m. and arriving before 2:00 p.m. were considered in the analysis. The analysis was divided into three periods, namely: a.m. peak from 6:30 to 9:30, a.m. off-peak 9:30 to 11:00, and midday peak from 11:00 a.m. to 2:00 p.m. Each transit vehicle typically had four trips (2 northbound and 2 southbound trips) during the a.m. period. The portion of the trips that covered the study section was extracted from the entire trip for analysis purposes using a MATLAB code that was developed for this purpose. The software automatically identified the first and last GPS points within the study corridor using the coordinates of the boundary intersections. Following the data reduction, a unique trip number was assigned to each trip.

A sample trip time-space diagram is illustrated in Figure 3. The figure illustrates the free-speed vehicle trajectory super-imposed on the sample trip trajectory. In addition, the figure illustrates the locations of various intersections. It should be noted that if the slope of the sample trip profile is steeper than the slope of free-speed trajectory, the speed of vehicle exceeds the free-speed. However, if the slope is less than the free-speed trajectory, the transit vehicle incurs delay.

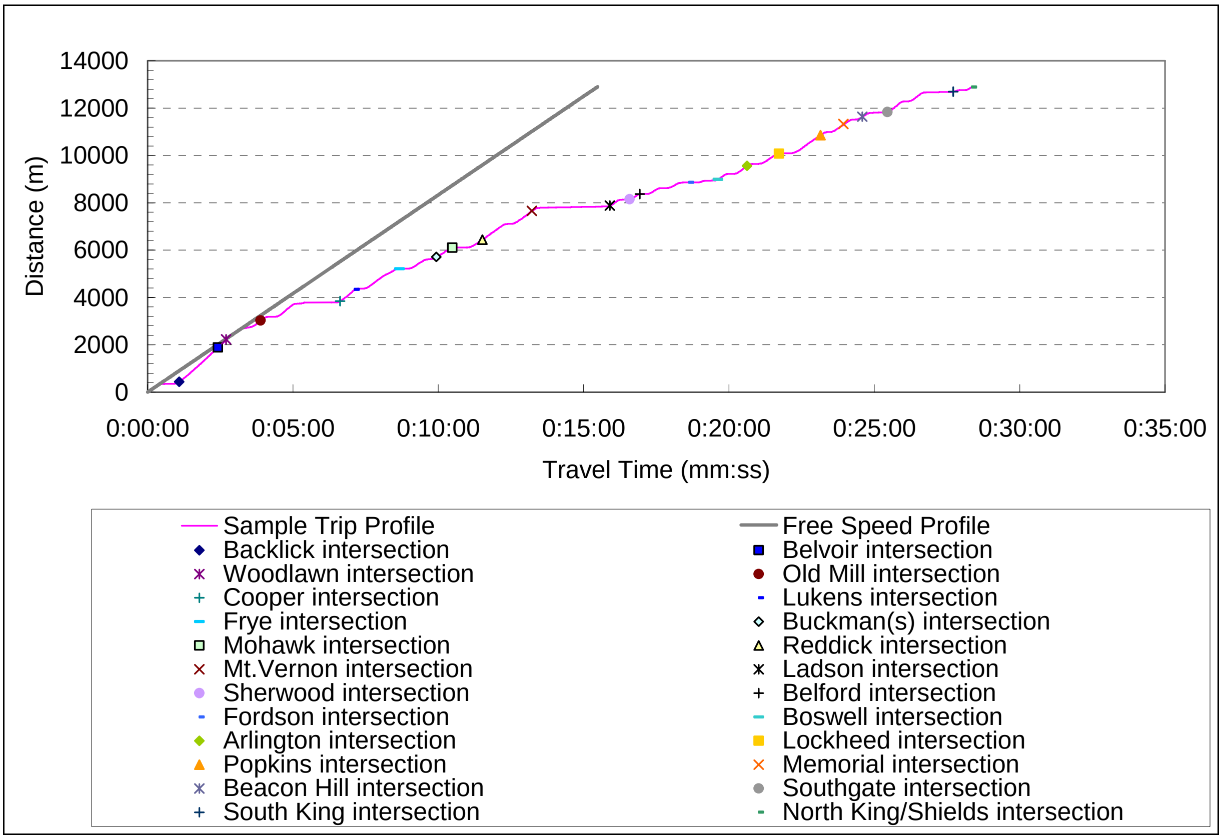

Figure 3. Time-Space Trajectory for Sample Transit Vehicle

In Figure 3, the transit vehicle travels at a speed higher than the free-speed between the Backlick and Belvoir intersections (00:01:05 to 00:02:30). Multiple stops are observed reflecting stops at signalized intersections and bus stops. Typical intersection delays are found at the

Cooper, Ladson, and South King intersections. Figure 3 also illustrates that the test bus stopped at near-side bus stops before the Lukens, Frye, and Mohawk intersections. The time difference between the sample trip and the free-speed trajectory at any specific location reflects the delay at that location. For example, the total delay was 13 min when the bus arrived at the North King/Shields intersection. This delay includes intersection delay, running delay, and stopped delay including dwelling time at bus stops.

Simulation Model Construction

The INTEGRATION microscopic traffic simulation software was used to evaluate the system-wide benefits of TSP operations. While a detailed description of INTEGRATION is provided in the literature (M. Van Aerde and Associates, 2005; Rakha and Ahn, 2004), it should be noted that a number of TSP evaluation studies have been successfully performed by the software (e.g., Dion and Rakha, 2005; Dion et al., 2004; Rakha and Zhang, 2004).

The traffic demand utilized for the simulation study was estimated based on observed traffic flow and the turning movement count data that were provided by the Virginia Department of Transportation (VDOT). The traffic data collected during 1 hr of the morning peak period were available in SYNCHRO file format, a software package for modeling and optimizing traffic signal timings. Later, the SYNCHRO input files were used for the traffic signal timing and optimization on the Route 1 corridor.

QUEENSOD, a maximum likelihood O-D estimation software, was used to estimate the O-D demand tables (M. Van Aerde and Associates, 2002; Van Aerde et al., 2003). QUEENSOD estimates O-D demands based on observed link flow and turning movement counts, link travel times, and, potentially, additional information on drivers' route choices. The estimated O-D demand table showed a high level of consistency between estimated and field-observed link flow counts with a coefficient of determination in excess of 0.99, as illustrated in Figure 4. The figure demonstrates that the estimated flows of the generated O-D table generally matched the observed flows.

The simulation model was constructed using information derived from field data. The field-collected information included number of lanes, lane striping, free-flow speed, saturation flow rate, jam density, and bus stop locations. The free-flow speed was measured from "Floating Car" studies. A Floating Car is a method that collects and records traffic data using a small number of vehicles that "float" with the traffic as measuring stations. The probe vehicle is equipped with special devices such as GPS units and records variables such as time, speed, position, and direction of travel for a particular trip. The saturation flow rate, which was 2,200 veh/h, was measured at major intersections and the jam density, 140 veh/km, was also observed from the study corridor during the a.m. peak period. Node location information was derived from commercially available mapping software.

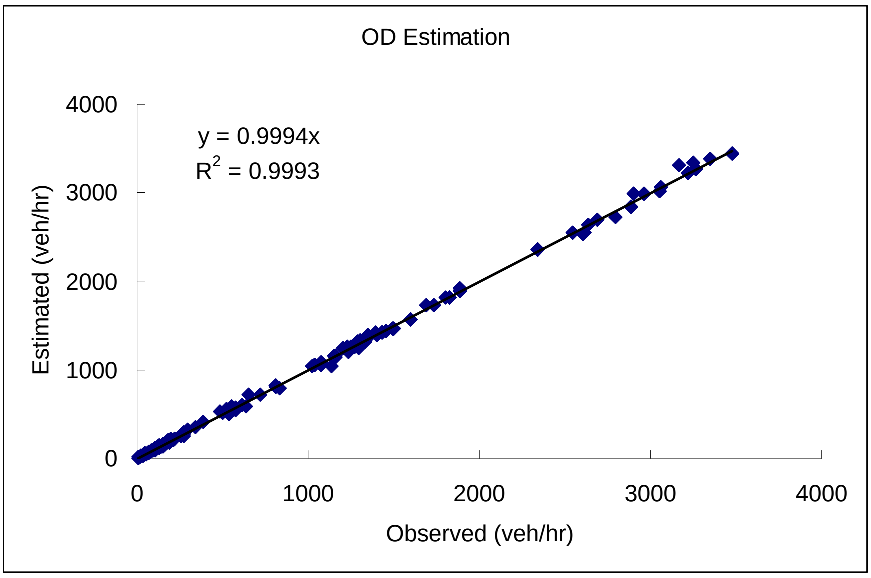

Figure 4. Validation of O-D Matrix Estimation

The simulation model was calibrated using field data and validated against independent GPS-measured probe-vehicle travel time and side-street queue length data. Table 2 demonstrates that the simulation results were in very good agreement with observed travel times for both transit vehicles and passenger cars. In particular, it was observed that the travel times of simulation results were within the error range of 1 min compared to the travel times of the GPS Floating Car, except for one southbound trip of a passenger car.

Table 2. Validation of Travel Times (Simulation vs. GPS Floating Car)

	GPS bus data		Simulation (bus)	
	NB	SB	NB	SB
No. of observations	18	28	15	15
Average travel time	0:30:08	0:28:23	0:31:00	0:27:28
Maximum travel time	0:34:51	0:32:29	0:34:35	0:29:21
Minimum travel time	0:24:39	0:23:17	0:27:25	0:25:35
	GPS floating car		Simulation (car)	
	NB	SB	NB	SB
No. of observations	3	4	15	15
Average travel time	0:17:13	0:16:28	0:16:49	0:15:19
Maximum travel time	0:19:35	0:19:21	0:20:22	0:18:02
Minimum travel time	0:15:55	0:13:37	0:13:09	0:13:03

Table 3 compares the field-observed side-street queue lengths to the simulated queue lengths. As listed in the table, the queue size generated from the simulation shows good agreement with the field-observed queue length data, indicating that the simulation model reasonably modeled the morning peak traffic condition on the study corridor. Table 3 demonstrates that most of the queue lengths generated by the simulation model were greater than the minimum field observed queue size and less than the maximum field observed queue size.

Table 3. Comparison of Queue Length (Simulation vs. Observation)

Side-Street	Average Max. Queue from Simulation	Min. Queue Observed	Max. Queue Observed
Shields	3.1	0	2
N. King	9.3	1	10
Beacon Hill E.	9.1	6	13
Beacon Hill W.	4.9	2	12
Collard W.	3.5	0	3
Popkins	8.5	3	13
Lockheed	27.6	12	28
Dart	4.5	0	3
Sherwood Hall E.	24.1	15	26
Sherwood Hall W.	3.7	1	5
Sacramento S.	18.0	13	17
Mt. Vernon S.	25.2	16	31
Old Mill	18.1	9	22
Backlick S.	10.4	1	10
Fairfax County	35.9	30	50

Simulation Scenarios

Five simulation scenarios were tested to quantify the system-wide impacts of green-extension TSP operations on Route 1. Each simulation was repeated 15 times with a different random seed in order to consider the stochastic properties of the INTEGRATION software. The number of required iterations was estimated to satisfy the 95% and 90% confidence limits (Z value of 1.96 or 1.645) using field-observed standard deviation (σ) and travel time error (δ) values, as shown in Equation 1.

The five scenarios utilized for this study are summarized as follows:

- Base scenario: No Priority vs. Priority based on Route 1 field data collection.
- Scenario 1: No Priority vs. Priority for various congestion levels on Route 1.
- Scenario 2: No Priority vs. Priority for increased demands on side-streets.
- Scenario 3: No Priority vs. Priority for the sensitivity analysis of the frequency of transit vehicles.
- Scenario 4: No Priority vs. Priority for modifications of bus stop locations.

RESULTS

Field Evaluation Results

The travel time frequency plots for transit vehicles are illustrated in Figure 5. The figure demonstrates that in the case of transit priority, the trip duration mode falls in the range of 25 to 30 min for both directions of travel. However, when transit priority is not activated, the mode of the distribution falls in the 30- to 35-minute range. The overall travel time results demonstrate that green extension TSP results in savings in the range of 3% and 4% for the northbound and southbound directions, respectively, as summarized in Table 4. In order to confirm the results, t-tests were performed at a 5% significance level assuming identical mean travel times for both cases. The t-test for the northbound trips produced a p-value of 0.31, which indicates that there is insufficient evidence to reject the null hypothesis of equal travel times. Thus we conclude that the green-extension TSP does not result in any changes in the transit vehicle travel times for the northbound trips. On the other hand, the southbound t-test yields a p-value of 0.03, which is statistically significant.

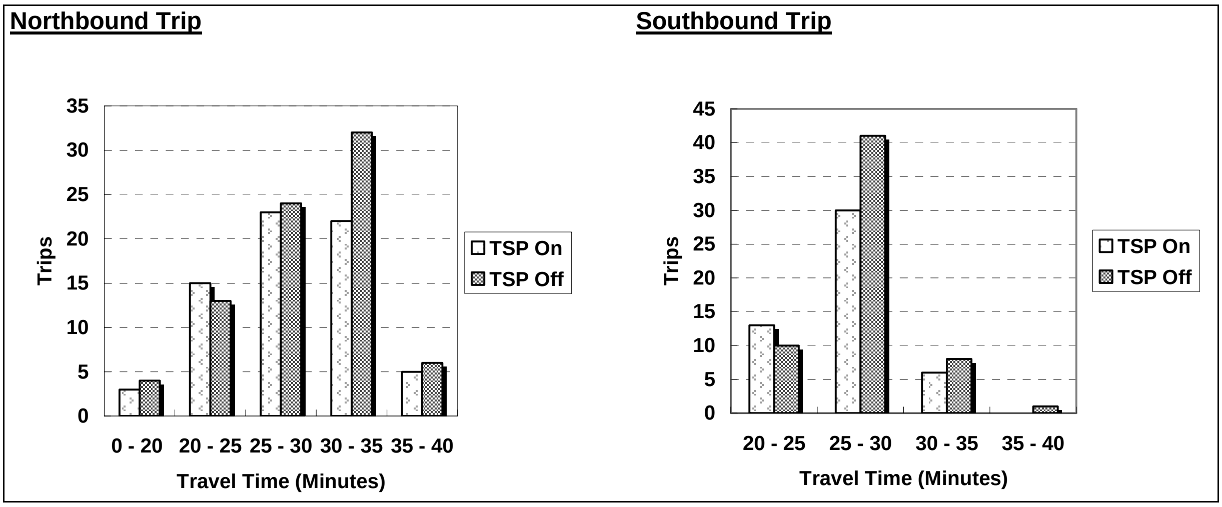

Figure 5. Transit Vehicle Travel Time Distribution

Similarly, Table 5 summarizes the impact of TSP on transit vehicle travel times for the morning peak, midday peak, and non-peak periods. Table 5 demonstrates that green-extension TSP can produce savings in transit vehicle travel times in the range of 3% to 6% when summarized for each peak period. The results also demonstrate that in some cases green-extension TSP can increase transit-vehicle travel times, as is the case for the northbound direction for the morning peak period (-2.54%) and the southbound direction for the midday peak (-2.27%). Interestingly, the results demonstrate a higher average travel time for the midday peak period in comparison to the morning peak period for both directions of travel. The findings typically demonstrate that the travel-time savings increase as the average travel time decreases. Consequently, it appears that green-extension TSP performs better on less congested roads than highly congested roads. Statistical analysis was also performed on the travel-time data for each peak period. However the t-test results concluded that only the southbound morning peak period trips reduced transit vehicle travel time significantly with a p-value of 0.01.

Table 4. Total Travel Time Results

		TSP ON	TSP Off	Benefit
NB trips	Average Speed (kph)	27.89	27.08	3.01%
	Average Travel Time	0:28:13	0:29:04	2.90%
	Number of Trip	68	79	
SB trips	Average Speed (kph)	28.65	27.52	4.13%
	Average Travel Time	0:26:39	0:27:48	4.17%
	Number of Trip	49	60	

Table 5. Detailed Travel Time Results

			TSP On	TSP Off	Benefit
NB Trips	AM Peak (6:30 AM - 9:30 AM)	Average Travel Time	0:30:54	0:30:08	-2.54%
		Number of Trip	18	18	
	Mid Peak (11 AM - 2 PM)	Average Travel Time	0:30:47	0:31:48	3.20%
		Number of Trip	16	20	
	Non Peak	Average Travel Time	0:25:36	0:27:15	6.07%
		Number of Trip	34	41	
SB Trips	AM Peak (6:30 AM - 9:30 AM)	Average Travel Time	0:26:45	0:28:23	5.75%
		Number of Trip	23	28	
	Mid Peak (11 AM - 2 PM)	Average Travel Time	0:29:47	0:29:08	-2.27%
		Number of Trip	7	10	
	Non Peak	Average Travel Time	0:25:22	0:26:28	4.17%
		Number of Trip	19	22	

In transit operation, dwelling times are an important factor that affect the total travel time. Table 6 demonstrates the bus-dwelling-time behavior for the study corridor using the data that were collected on Route 1 between the section of Lockheed intersection and Shields intersection in June 2003. As shown in Table 6, the dwelling time behavior is not affected by TSP operation. Specifically, TSP-on buses have an average dwelling time of 15 s and a total dwelling time of 71 s for the entire trip compared to an average dwelling time of 16 s and total dwelling time of 73 s for TSP-off buses. Also, the table shows that the average transit bus makes a stop at 6 bus stops from the 10 bus stops (57% to 59% of total bus stops) on the Route 1 study area, according to the collected data.

Table 6. Transit Vehicle Dwelling Time Behavior

		TSP OFF	TSP ON
No. of Trip		35 trip	7 trip
Stop % at Bus Stop		57 %	59 %
Individual Bus Stop (when a stop was made)	Average Dwelling Time	16 s	15 s
	Standard Deviation of Dwelling Time	11 s	8 s
Single Trip	Average Dwelling Time	73 s	71 s
	Standard Deviation of Dwelling Time	31 s	37 s

Figure 6 illustrates a plot of travel time vs. traveled distance as was illustrated in Figure 3. The figure illustrates midday peak trips of Test Bus 7859, which are the most observed trips in same time of departure. The figure clearly demonstrates the variability in travel times along the study corridor for an identical trip. In general, the figure shows that the TSP activated trips (eight trips) have shorter travel times than the trips (seven trips) without TSP. However, it is noted that one TSP operated trip takes 39 min to pass through the study area, while two trips without TSP complete the trip within 30 min.

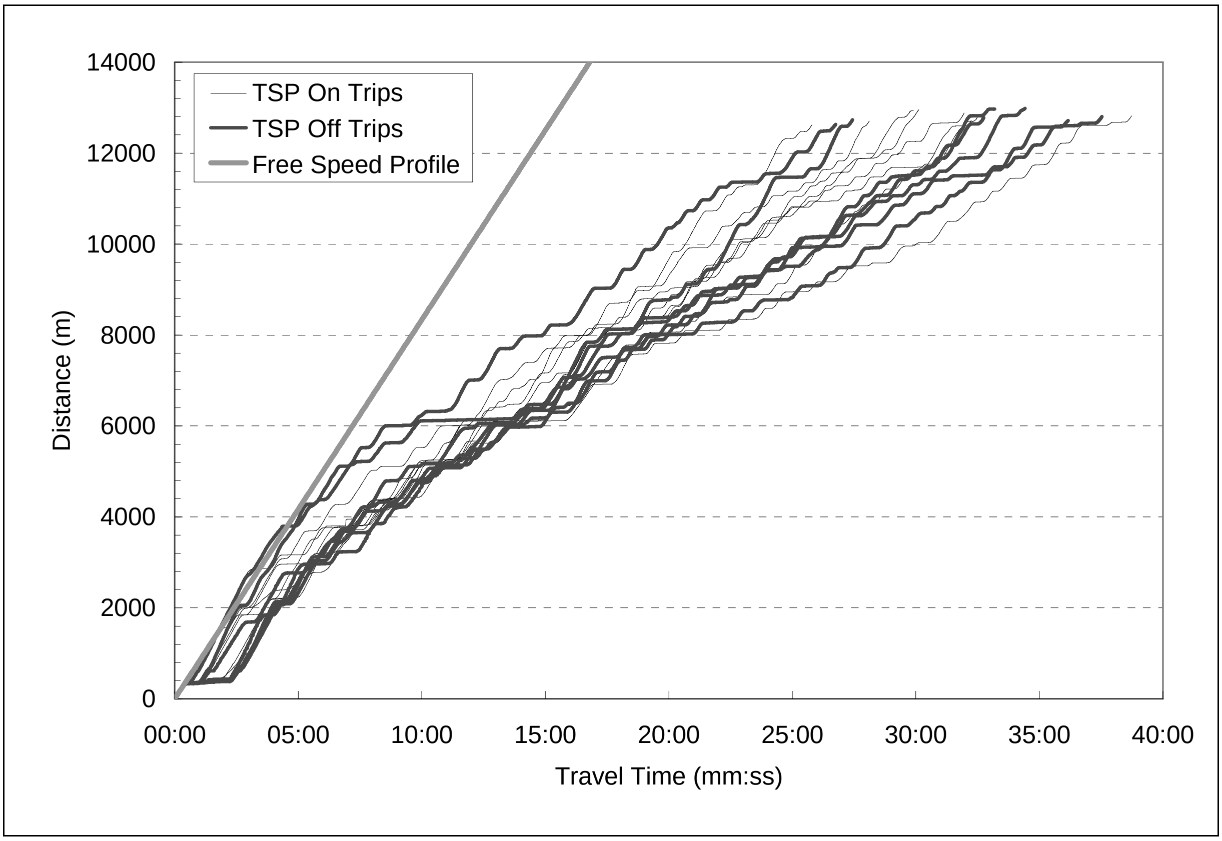

Figure 6. Time-Space Trajectory for Bus 7859 Midday Peak Trips

The two detailed distance-time diagrams of Figure 6 are illustrated in Figure 7. The TSP-on trip was recorded between 11:20:00 a.m. and 11:51:57 a.m. and has a total travel time of 31:57 (min:sec), which is the fifth travel time of eight TSP-on trips. The TSP-off trip was recorded between 11:24:31 a.m. and 11:58:57 a.m. and has a total travel time of 34:26 (min:sec), which is also the fifth travel time of seven TSP-off trips. The figure demonstrates the TSP-on trip saves about 2:30 (min:sec) of travel time compared to the TSP-off trip. During the early stage of the trip, the speed of the TSP-off bus was similar to the TSP-on bus. However the TSP-off bus was delayed about 90 s at Old Mill and Popkins intersections and further delays were discovered at several intersections resulting in a longer travel time when compared to the TSP-on bus. It should be noted that the intersection delays cannot be considered as dwelling time delay since there are not any near-side and far-side bus stops at both intersections. The long delays at both intersections are attributed to the TSP logic. Since a green extension is only granted when a transit vehicle is expected to arrive at a signalized intersection a few seconds after the end of the green indication, such long delays experienced by the TSP-off bus are generally not experienced on the TSP-on bus.

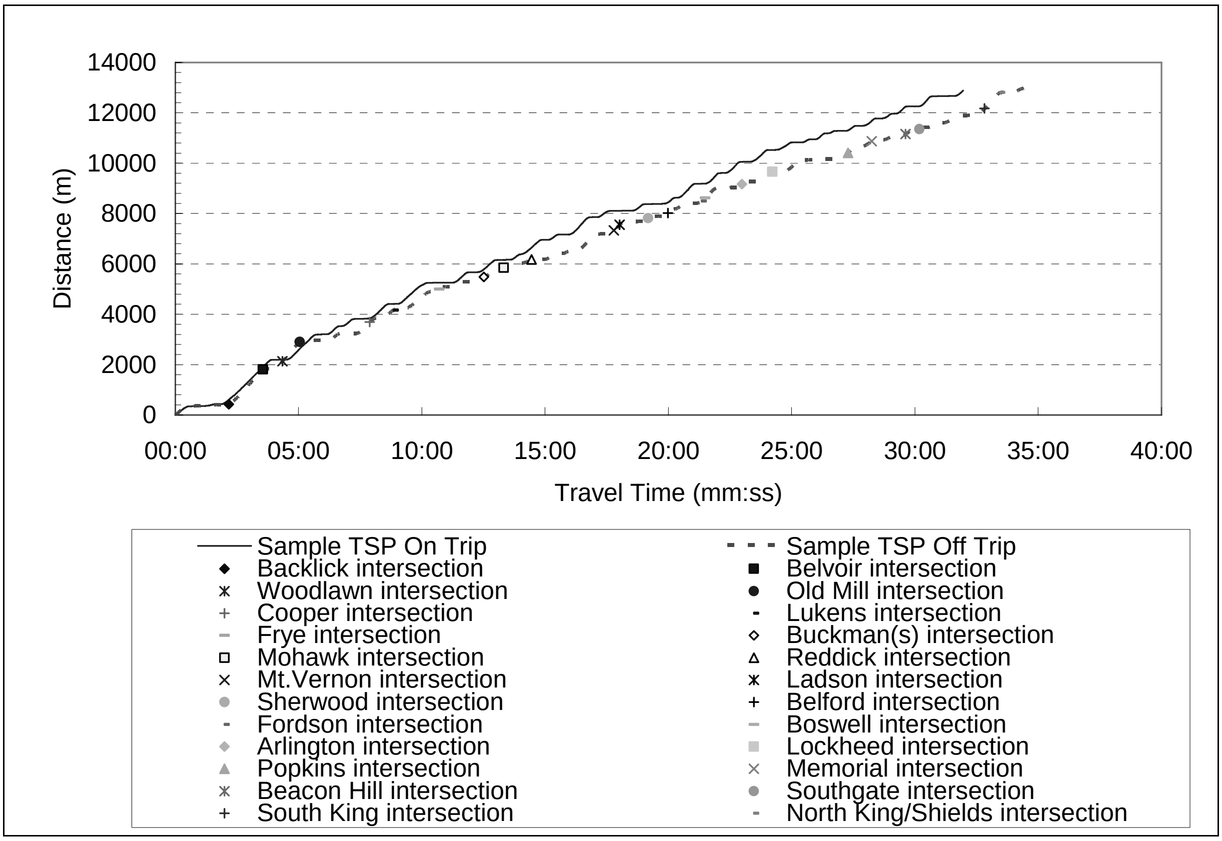

Figure 7. Impact of TSP Operation

Travel time is typically used as a MOE in the evaluation of operational-level transportation projects. However, several factors affect travel time within the context of TSP, such as bus-stop locations, number of passengers entering and exiting transit vehicles, the frequency of bus stops, and the potential speeding of transit-vehicle drivers to make up for any delay incurred. Consequently, an additional MOE was considered in the analysis, namely intersection delay. It should be noted that if the priority is effectively operated, the intersection delay should be reduced since the green-extension TSP is designed to reduce transit-vehicle delays at signalized intersections dependent on the bus-arrival timing and a green-extension priority setting. In conducting the analysis, a MATLAB code (programming software) was designed to compute the intersection delay incurred by transit vehicles. Intersection delay was estimated as the difference in travel time between the transit-vehicle speeds versus free-flow speed starting from 100 m upstream of the intersection stop bar. As was mentioned earlier, the free-flow speed was set at 50 km/h based on an analysis of the transit-vehicle trajectories.

The intersection delay is computed as:

$$d_k = \int_{\alpha}^{\beta} \left[1 - \frac{\min(v_f, v_i)}{v_f} \right] \Delta t \qquad [2]$$

where d_k is the delay incurred at intersection k (s), Δt is the duration of the time interval (s), α is the time interval when transit vehicle is 100 m upstream of intersection, β is the time interval when transit vehicle passes the approach stop bar, v_f is the free-speed (m/s), and v_i is the vehicle speed at instant i. This delay formulation has been described in the literature and validated against the Highway Capacity Manual (HCM) and queuing theory delay estimates (Dion et al., 2004). Approach delays were only computed at approaches that did not have near-side bus stops within 100 m of the intersection. Consequently, only 12 and 11 of the 27 intersections were identified for analysis purposes in the northbound and southbound directions, respectively. It should be noted that the 100-meter stop bar was chosen to increase the number of intersections to measure the delays since the GPS data analysis could not differentiate between intersection delays and dwelling times at near-side bus stops.

The results demonstrate that for intersections that are not influenced by near-side bus stops green-extension TSP tends to reduce the approach delay, as illustrated in Figure 8. For example, the average delay for the entire a.m. analysis period at the 12 northbound intersections is decreased from 8.62 s to 7.47 s, which represents a 13.3% reduction. Similarly, the green-extension TSP significantly reduces the intersection delay by 23% in the midday peak period (11:00 a.m. to 2:00 p.m.), from an average delay of 11.66 s to 8.94 s. Similarly, reductions in delay of 9.26 s and 10.17% are observed for the morning peak and non-peak periods. Interestingly, Figure 8 clearly demonstrates that the Mt. Vernon/Old Mill intersection produces significant delays for all analysis periods in comparison to the other intersections. Paired t-tests were performed on the average intersection delays considering a 5% significance level assuming equal means. The results demonstrate that for the entire analysis period, the hypothesis of unequal means is statistically significant with 0.005 and 0.01 p-values. However, the morning-peak and off-peak period results were not statistically significant.

The approach delays for travel in the southbound direction demonstrate no clear benefit for TSP, as illustrated in Figure 9. Instead, increases in approach delays are observed at the S. King, Memorial, Beacon Hill, and Woodlawn intersections during the midday peak period with delay increases as high as 20 s at the Memorial intersection. Equal mean t-tests demonstrated that only non-peak hour approach delays were significantly reduced by green-extension TSP (p-value of 0.036), while during the other periods the findings were statistically insignificant. In addition, it should be noted that the average intersection delay of non-peak trips were reduced by 21.4% from 7.36 s to 5.79 s. Finally, it is interesting to note that the delay at the intersection with Lockheed Boulevard is less than 1 s in most cases.

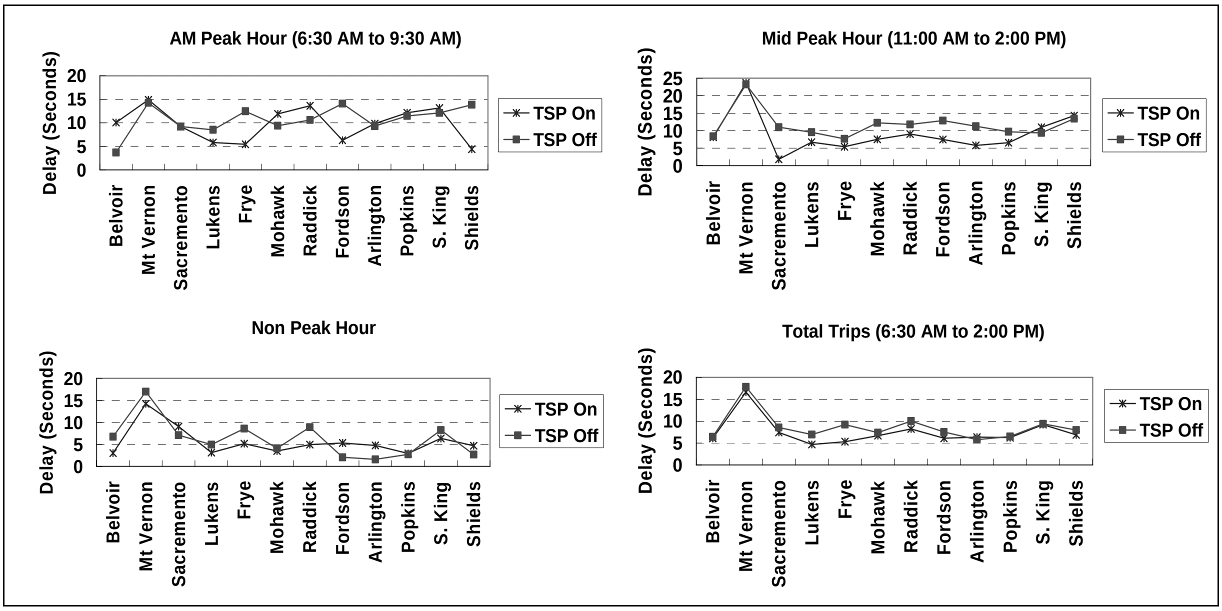

Figure 8. Intersection Delays for Northbound Trips

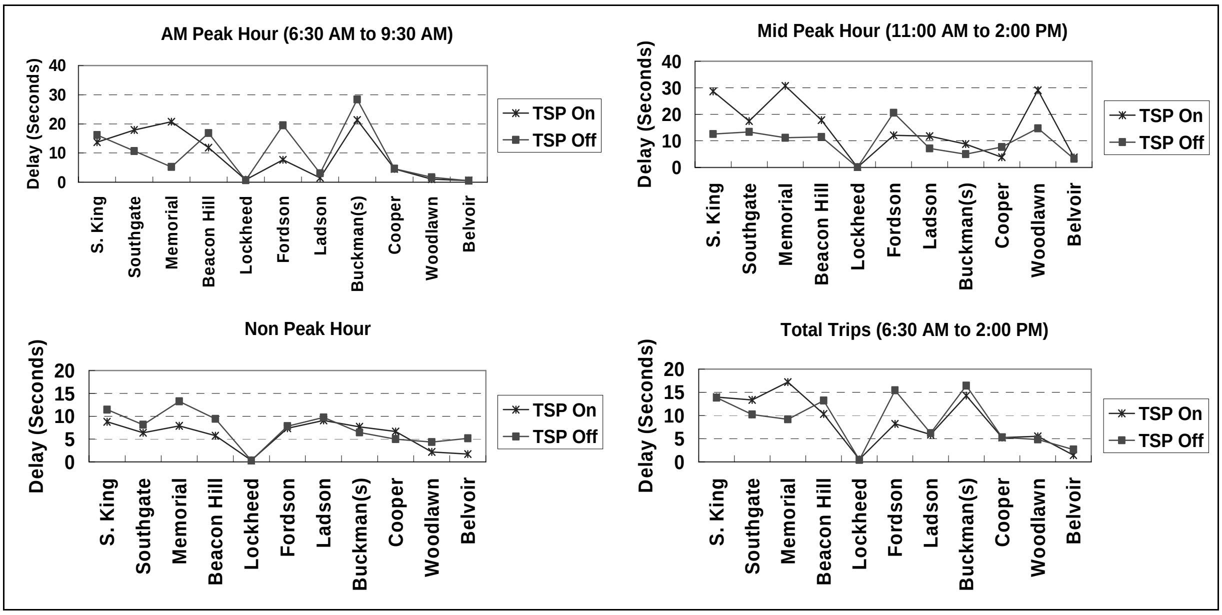

Figure 9. Intersection Delays for Southbound Trips

Simulation Results

Fifteen 1-hour simulation runs were executed for each scenario and the results were compared considering average measures of effectiveness (MOEs). The following section summarizes the simulation results for each scenario. Travel times of transit vehicles and passenger cars, total vehicle delay, vehicle stops, transit vehicle delay, fuel consumption, and emissions (HC, CO, and NOx) were extracted from output files and utilized as different MOEs.

Base Scenario

The base scenario case investigates the system-wide impact of TSP operation, which was not quantified in the earlier field study. Figure 10 compares the transit vehicle and passenger car travel times. As illustrated in Figure 10, no significant travel-time savings were found for passenger cars and transit vehicles with the provision of green-extension TSP. Interestingly, transit priority marginally increased the travel time for all four trips (less than 1%). T-tests were performed considering a 5% significance level assuming identical mean travel times for both cases using the 15 simulation replications. The t-tests produced *p*-values between 0.21 and 0.39, which indicate that there is insufficient evidence to reject the null hypothesis of equal travel times for both cars and transit vehicles. Therefore, we conclude that the green-extension TSP does not result in any travel time changes for both cars and transit vehicles.

These results are consistent with the field study findings, for the northbound direction a.m. peak commute. Figure 10 also illustrates the 95th percentile and 5th percentile travel times which are represented by the extents of the vertical lines. The figure demonstrates that TSP reduced the variability of transit-vehicle travel times for the northbound trips while no significant reduction in travel time variance was found in the case of the southbound trips. Also it should be noted that travel times of passenger cars were almost identical with and without green-extension TSP.

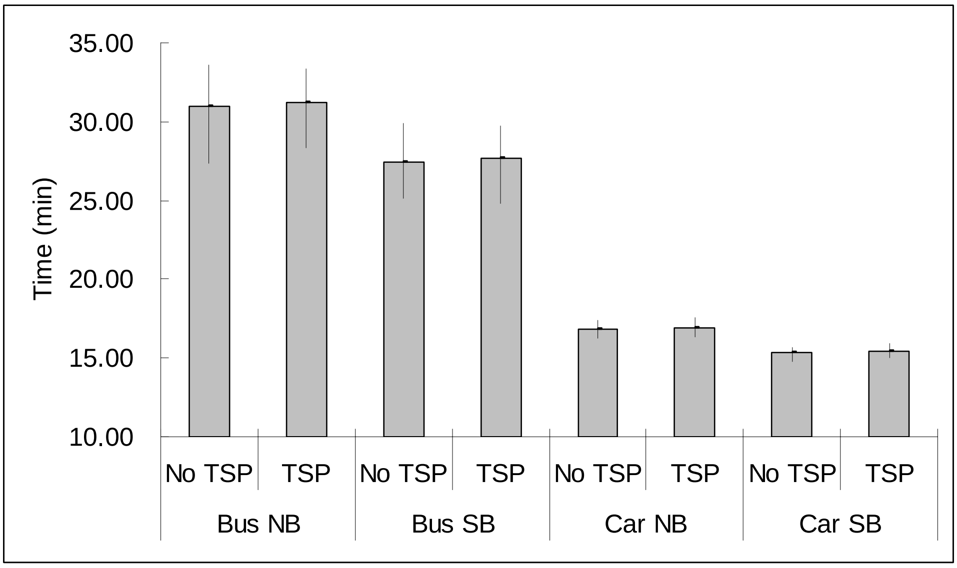

Figure 10. Travel Time Comparison for Base Scenario

The queue lengths along side-streets are typically used as an MOE in the evaluation of TSP operations. If transit priority is granted, the extended green time is taken out of the remaining phases, which are typically green times for side-streets; thus the traffic delay on side-streets is the most commonly cited negative impact of TSP system implementations.

Figure 11 illustrates the queue lengths of representative side-streets with and without transit priority. The selected intersections are the same intersections that were utilized in the validation of the simulation model. Figure 11 shows that there was no significant increase in the queue length of side streets when transit priority was implemented on the Route 1 corridor. It should be noted that the queue lengths were the average maximum queue of the 15 simulation runs. Paired t-tests were performed on the queue lengths considering a 5% significance level and assuming equal means. The results demonstrated that the hypothesis was not statistically significant with 0.09 *p*-values. Thus it is concluded that green-extension TSP for the current traffic demand along Route 1 does not increase the queue lengths of side streets.

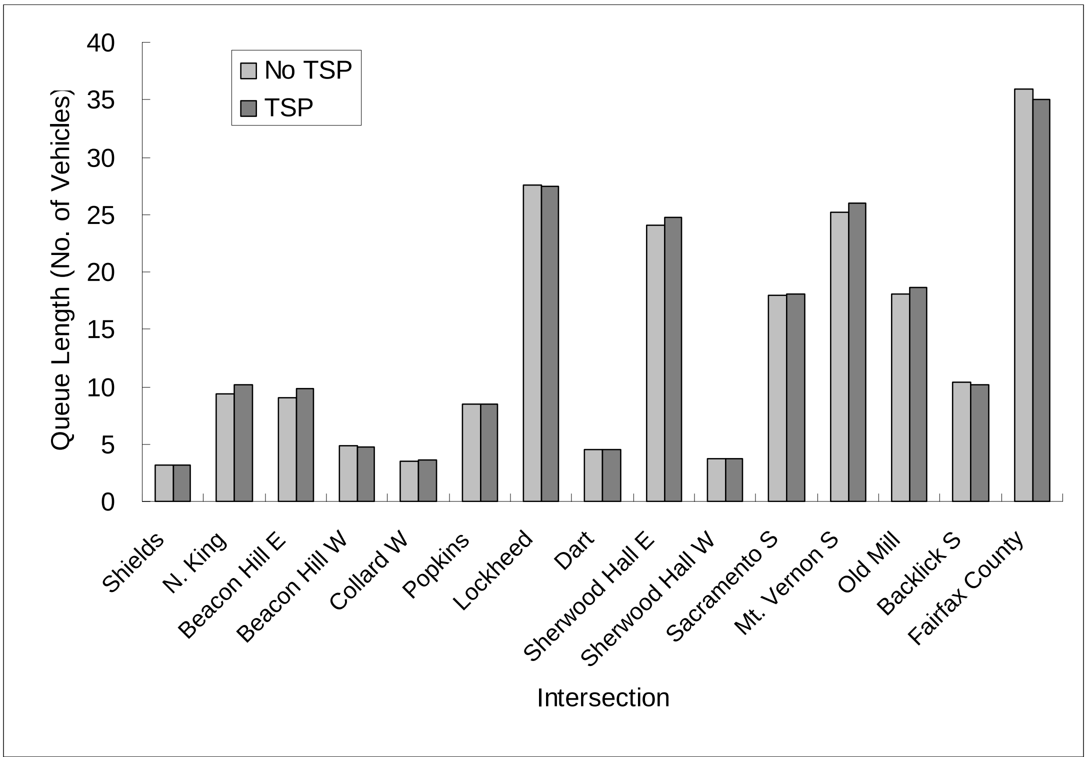

Figure 11. Side-Street Queue Length Comparison for Base Scenario

In terms of overall benefits of TSP operation on the study corridor, as shown in Table 7, transit priority did not improve the system-wide performance nor significantly downgrade the MOEs. In particular, the simulation results indicated that the provision of TSP caused little negative impacts for both the general traffic and transit vehicles. However, statistical tests confirmed with *p*-values of 0.11 and 0.41 that transit priority did not significantly increase or decrease the total delay and the other MOEs.

Table 7. Impacts of TSP for Base Scenario

MOEs	No TSP	TSP
Total Delay (veh-hr)	651.56	658.23
Average Delay (min/veh)	3.32	3.35
Average Stop per Veh	1.29	1.31
Average Bus Delay (min/veh)	19.22	19.37
Average fuel consumption (l/veh)	0.39	0.39
Average HC (g/veh)	0.12	0.12
Average CO (g/veh)	3.35	3.36
Average NOx (g/veh)	0.39	0.39

Scenario 1: Increased Mainline Traffic Demand

This section investigates the system-wide impact of TSP for various congestion levels. Varying the congestion level could produce different results and possibly identify the range of congestion levels for which green-extension TSP can be effectively operated. To quantify the impacts of TSP for various congestion levels, traffic demands in the simulation model were increased up to 1,000 veh/h in increments of 200 veh/h per direction. It should be noted that the increased demands were assigned for both northbound and southbound traffic flows from the northern (or southern) end to southern (or northern) end of the study corridor. Also, traffic signal timings were optimized for the corresponding increase in traffic demand. Figure 12 compares the travel times of transit vehicles and general traffic with and without TSP operation for the increased traffic demands. The simulation results indicate that no significant benefits or detriments in travel time are observed for increased traffic demands.

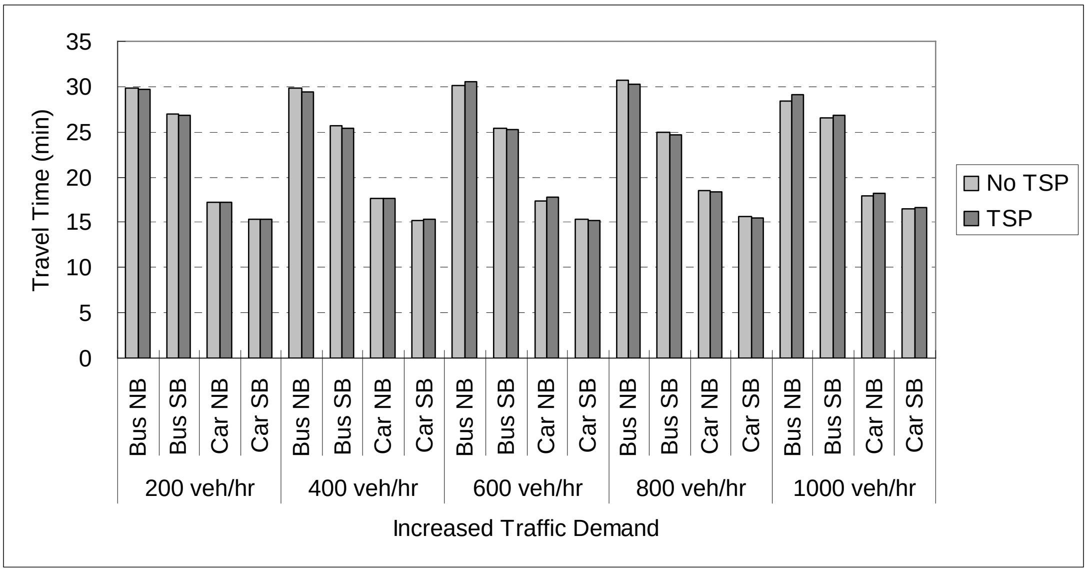

Figure 12. Travel Time Comparison of Increased Traffic Demands

Table 8 lists the performance measures under different congestion levels and indicates that vehicle delays, vehicle stops, fuel consumption, and emissions were increased as the traffic demands were increased. The table also shows that as the traffic demand on Route 1 increased, the delays to transit vehicles generally decreased. It is hypothesized that increasing the demand on the study corridor allocated more green time to the main corridor, and the increased green time reduced the intersection delays for transit vehicles. However, the reduced green on the side streets resulted in more delays and eventually increased the total delay, as shown in Table 8. Paired t-tests that were performed on side-street queue lengths indicated that the green-extension TSP under congested conditions did not increase the queue lengths of side streets.

Table 8. Impacts of TSP for Increased Traffic Demands

	200 veh/hr		400 veh/hr		600 veh/hr		800 veh/hr		1000 veh/hr	
MOEs	No TSP	TSP	No TSP	TSP	No TSP	TSP	No TSP	TSP	No TSP	TSP
Total Delay (veh-hr)	757	754	881	888	964	974	1079	1081	1147	1163
Average Delay (min/veh)	3.73	3.71	4.22	4.25	4.53	4.59	5.03	5.05	5.31	5.38
Average Stop per Veh	1.53	1.53	1.89	1.89	2.11	2.13	2.48	2.49	2.57	2.58
Average Bus Delay (min/veh)	18.34	18.26	17.76	17.42	17.77	17.93	17.80	17.47	17.45	17.97
Average fuel consumption (l/veh)	0.42	0.42	0.45	0.45	0.47	0.48	0.50	0.50	0.53	0.53
Average HC (g/veh)	0.13	0.13	0.13	0.13	0.14	0.14	0.15	0.15	0.16	0.16
Average CO (g/veh)	3.60	3.60	3.82	3.82	4.02	4.02	4.25	4.25	4.45	4.45
Average NOx (g/veh)	0.42	0.42	0.45	0.45	0.48	0.48	0.50	0.50	0.53	0.53

Scenario 2: Increased Side-Street Traffic Demand

Figure 13 illustrates the travel time of transit and non-transit vehicles when side-street demands were increased. The side-street demand was increased in increments of 25% of the original demand up to 100%. Also, traffic signal timings were optimized for the level of the traffic demand.

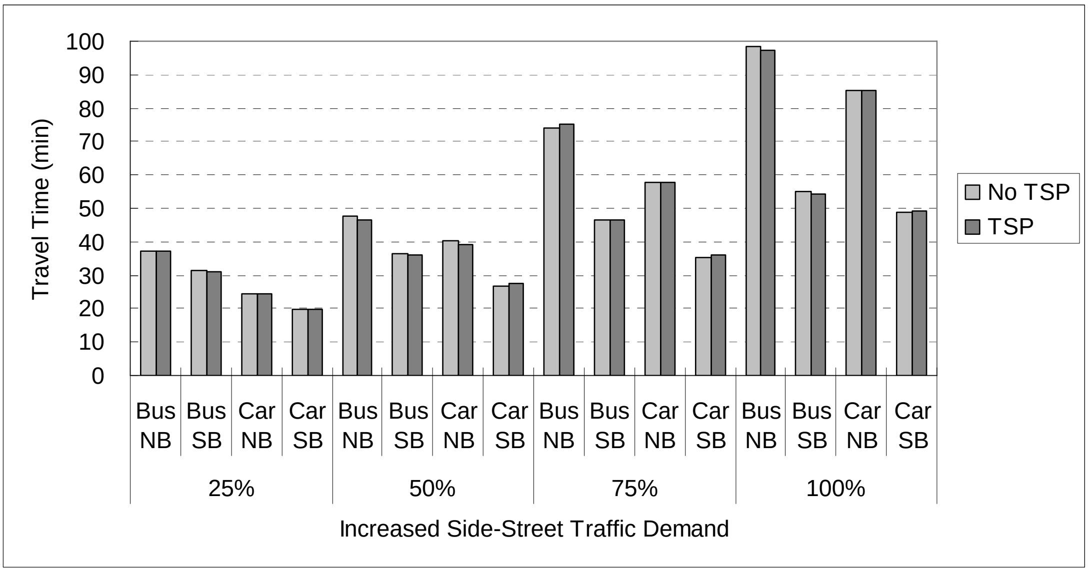

Figure 13. Travel Time Comparison of Increased Side-Street Demands

The figure demonstrates that an increase in the side-street demand did not result in any statistically significant system-wide benefits and/or detriments. However, significantly increased delays, travel times, number of stops, fuel consumption, and emissions were observed from the simulation results when the side-street demand was increased, as shown in Table 9. The increased delays and travel times were mostly incurred by the reduced green time on Route 1 approaches and signal timing adjustments due to increased side-street demand. It should be noted that the signal timing was optimized in proportion to the increased side-street demand.

Table 9. Impacts of TSP for Increased Side-Street Demands

	25% Side-St Demand Increase		50% Side-St Demand Increase		75% Side-St Demand Increase		100% Side-St Demand Increase	
MOEs	No TSP	TSP	No TSP	TSP	No TSP	TSP	No TSP	TSP
Total Delay (veh-hr)	1188	1179	2270	2247	3395	3447	6352	6354
Average Delay (min/veh)	5.20	5.16	8.82	8.70	12.45	12.60	19.68	19.58
Average Stop per Veh	1.99	1.98	3.53	3.48	5.51	5.58	10.11	9.99
Average Bus Delay (min/veh)	24.40	24.18	30.76	30.84	45.65	46.05	66.08	65.43
Average fuel consumption (l/veh)	0.43	0.43	0.51	0.51	0.58	0.58	0.75	0.75
Average HC (g/veh)	0.12	0.12	0.13	0.13	0.13	0.13	0.16	0.16
Average CO (g/veh)	3.49	3.49	3.63	3.63	3.63	3.63	4.09	4.09
Average Nox (g/veh)	0.39	0.39	0.39	0.40	0.39	0.39	0.43	0.43

Scenario 3: Transit Vehicle Service Frequency

Figure 14 illustrates the impact of TSP on travel times when the frequency of transit vehicles is increased and the vehicle headway is decreased to 15, 10, and 5 min. The simulation results demonstrated that green-extension TSP reduced the travel time of transit vehicles by up to 3.43% and 1.43% for the northbound and southbound directions. Similarly, a marginal reduction in travel time of 2.19% was observed for non-transit vehicles when a transit vehicle was dispatched every 15 min. However, t-test results indicated that the reductions of travel times were not statistically significant.

Paired t-tests were also performed to identify whether TSP operation increased the queue lengths on side streets at a 95% confidence level. The results demonstrated that for the 10-minute bus dispatch scenario, the hypothesis was statistically significant with 0.0038 *p*-values, indicating that the TSP operation created longer side-street queue lengths. However, the paired t-test results of the 5- and 15-minute dispatch cases showed that the side-street queue sizes did not increase when the green-extension TSP was operated.

The MOEs of simulation results are listed in Table 10. The results indicated that increasing the frequency of transit vehicles resulted in more benefits to the buses. However, no system-wide benefits were observed for non-transit vehicles from the simulation results. In particular, the frequent bus service marginally increased their total delays, stops, and fuel consumption.

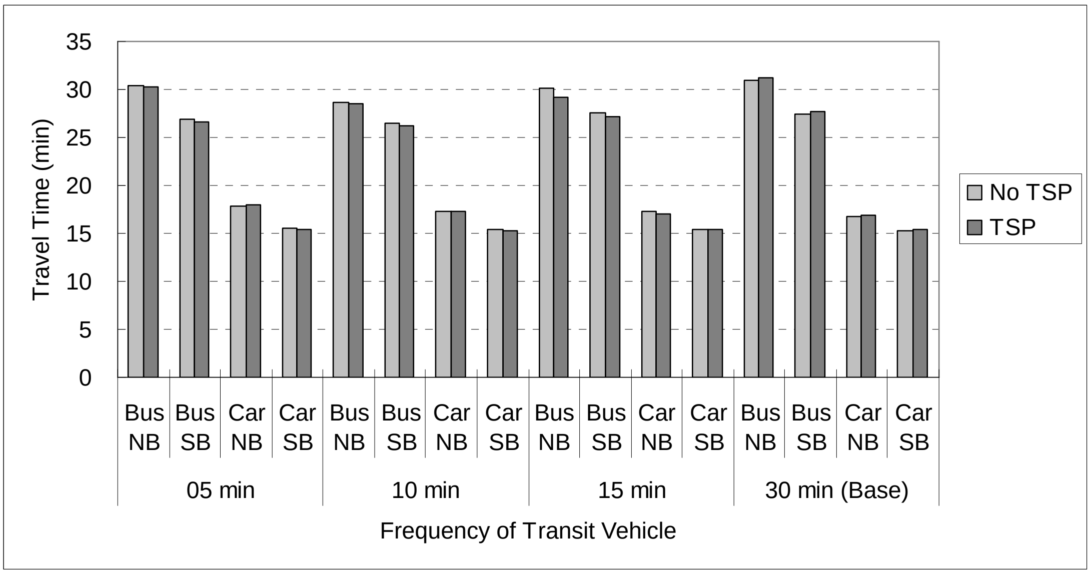

Figure 14. Travel Time Comparison of Increased Transit Vehicle Service Frequency

Table 10. Impacts of TSP for Increased Transit Vehicle Service Frequency

	5 min		10 min		15 min		30 min (Base)	
MOEs	No TSP	TSP	No TSP	TSP	No TSP	TSP	No TSP	TSP
Total Delay (veh-hr)	697	704	671	675	666	662	652	658
Average Delay (min/veh)	3.55	3.59	3.41	3.43	3.39	3.37	3.32	3.35
Average Stop per Veh	1.36	1.40	1.30	1.33	1.31	1.31	1.29	1.31
Average Bus Delay (min/veh)	18.53	18.38	17.52	17.40	18.75	18.15	19.22	19.37
Average fuel consumption (l/veh)	0.39	0.40	0.39	0.39	0.39	0.39	0.39	0.39
Average HC (g/veh)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Average CO (g/veh)	3.40	3.39	3.38	3.38	3.37	3.37	3.35	3.36
Average Nox (g/veh)	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39

Scenario 4: Bus Stop Location

This section describes the system-wide impact of TSP for various bus stop locations. To quantify the impacts of bus stop location, 14 far-side, 14 mid-block, and 14 near-side bus stops were selected and modeled. Small reductions (up to 1.15%) of bus travel times were observed, as illustrated Figure 15, when green-extension TSP was implemented at far-side and mid-block bus stops. The figure also shows that TSP operations at near-side bus stops (within the detection zone) increased the travel times of transit vehicles by up to 3.68%. However, the t-test results indicated that there was no significant benefit or detriment to travel time when TSP was operated. Also, paired t-test results showed that green-extension TSP did not increase the queue lengths of side streets for far-side, mid-block, and near-side bus stops.

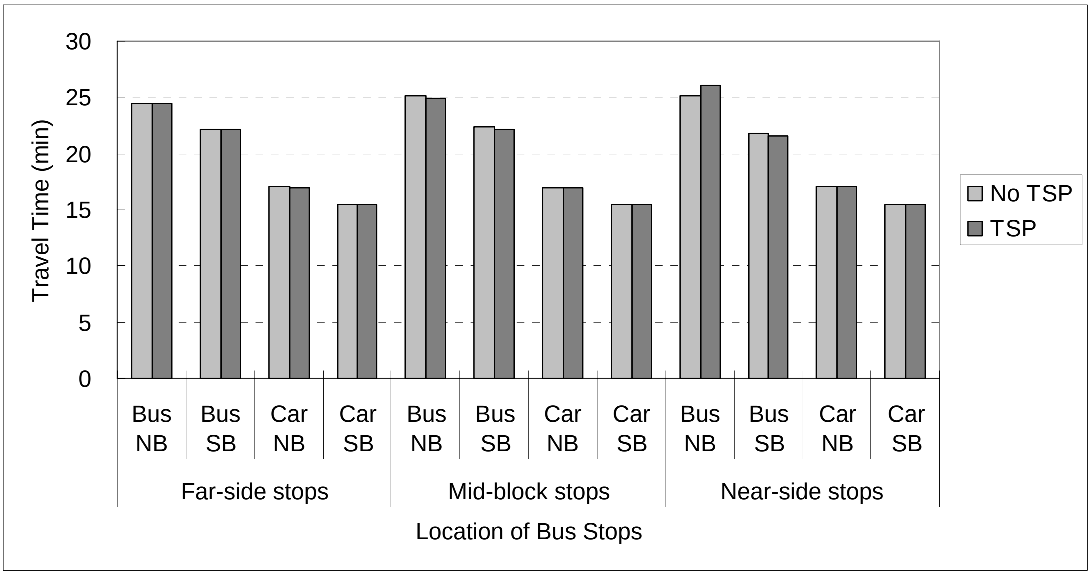

Figure 15. Travel Time Comparison of Modified Bus Stop Location

Table 11 indicates that TSP operations at near-side bus stops (within the detection zone) resulted in increased total delays (0.80%) and transit vehicle delays (2.85 %), while TSP operations at mid-block and far-side bus stops reduced the network-wide delays by up to 1.62%.

Table 11. Impacts of TSP for Modified Bus Stop Location

MOEs	Far-Side Stops		Mid-Block Stops		Near-Side Stops	
	No TSP	TSP	No TSP	TSP	No TSP	TSP
Total Delay (veh-hr)	658	652	653	651	654	660
Average Delay (min/veh)	3.35	3.32	3.32	3.32	3.33	3.36
Average Stop per Veh	1.29	1.29	1.28	1.29	1.29	1.30
Average Bus Delay (min/veh)	13.32	13.26	13.73	13.51	13.44	13.83
Average fuel consumption (l/veh)	0.39	0.39	0.39	0.39	0.39	0.39
Average HC (g/veh)	0.12	0.12	0.12	0.12	0.12	0.12
Average CO (g/veh)	3.35	3.35	3.35	3.35	3.35	3.35
Average Nox (g/veh)	0.39	0.39	0.39	0.39	0.39	0.39

FINDINGS AND CONCLUSIONS

This study reports the results of a case study field and a simulation evaluation of green-extension TSP on a highly congested urban arterial in Northern Virginia. The field evaluation study found that overall improvements of 3% to 6% were observed for transit vehicle travel times. However, the results also demonstrate that green-extension TSP can increase transit-vehicle travel times by 2.5% during congested morning peak periods. The time-space diagram

(Figure 7) of TSP-on and TSP-off trips clearly demonstrates the benefit of green-extension TSP showing that long intersection approach delays, which are experienced by TSP-off buses are generally not experienced by the TSP-on buses. The field evaluation study also demonstrated that green-extension TSP can reduce intersection approach delays by as much as 23%.

The findings of the field evaluation study are summarized as follows:

- The study demonstrated that the WAAS-enabled GPS receiver is an effective technology in the evaluation of TSP.
- The study found that the dwelling time behavior is not affected by TSP operation.
- As would be expected, green-extension TSP generally reduces delay to transit vehicles at intersections. However, the benefits provided by TSP are highly dependent on the level of congestion and can be maximized under moderate-to-low levels of congestion.

A simulation study was also conducted and quantified the system-wide benefits of green-extension TSP operation on the Route 1 corridor. An INTEGRATION microscopic simulation model was utilized to evaluate five scenarios: the base case, increased mainline traffic demand, increased side-street demand, increased transit vehicle service frequency, and modified bus stop locations. Overall, the simulation results indicate that transit vehicles generally benefit from a priority system, but this does not guarantee a system-wide benefit. In this study, marginal travel-time savings (up to 3.40%) are observed for transit vehicles when green-extension TSP is operated. Also, the study found that the green-extension TSP operation neither benefits nor damages non-transit vehicles. The conclusions of the simulation study of Route 1 can be summarized as follows:

- TSP has no impact on transit vehicle travel times, system-wide travel times, and side street queues. Consequently, we conclude that the use of basic green-extension TSP does not produce transit vehicle benefits, nor system-wide detriments for the Route 1 case study.
- As the traffic demand on Route 1 increases, the system-wide detriments of TSP generally increase. However, it should be noted that the maximum system-wide increase in delay is minimal (less than 1.37%). No changes are observed in transit-vehicle travel times when the TSP is implemented.
- An increase in the side-street demand does not result in any statistically significant system-wide detriments.
- Increasing the frequency of transit vehicles results in more benefits to the buses, reducing their delays by up to 3.20%. However, no system-wide benefits are observed when TSP is operated.
- TSP operations at near-side bus stops (within the detection zone) results in increased delays in the range of 2.85%, while TSP operations at mid-block and far-side bus stops results in network-wide savings in delay in the range of 1.62%.

A systematic sensitivity analysis evaluation of TSP on a signalized intersection within a coordinated arterial (Rakha and Zhang, 2004) concluded the following:

- Generally, TSP provides benefits to transit vehicles that receive priority. These benefits are highly dependent on the time of arrival of the transit vehicle within the cycle length and the phase of the traffic signal.
- TSP has a marginal system-wide impact for low traffic demands; however, as the demand increases, the system-wide detriments of TSP increase.
- The system-wide impact of TSP is dependent on the frequency of transit vehicles. As the transit vehicle frequency increases, larger system-wide detriments are observed.
- TSP impacts are sensitive to the demand distribution at a signalized intersection. Transit vehicle arrivals on heavily congested approaches may result in system-wide benefits if the conflicting approaches are not congested. Alternatively, transit vehicle arrivals on lightly congested approaches may produce significant system-wide detriments if the conflicting approaches are heavily congested.
- The system-wide benefits of TSP are dependent on the phase at which the transit vehicles arrive, especially if the cycle length is maintained within the priority logic. Transit vehicle arrivals during the early phases produce minimum disruptions to the general traffic while transit vehicle arrivals for the latter phases produce significant system-wide detriments.
- The system-wide benefits of TSP are highly dependent on the optimality of the base signal timings. Specifically, if the priority logic enhances the signal timings, system-wide benefits can be achieved by virtue of improving the signal timings.
- Transit vehicle dwell times at near-side bus stops can have significant system-wide impacts on the potential benefits of TSP. Specifically, the system-wide detriments increase with an increase in bus dwell times if the bus stop is located within the detection range of the traffic signal.

IMPLEMENTATION RECOMMENDATIONS

The following are recommendations for future TSP implementations:

- TSP impacts are highly dependent on the level of congestion and can be maximized under moderate-to-low levels of congestion. TSP should not be implemented when the approach volume-to-capacity ratios are greater than 80 %.
- Green-extension TSP should be carefully implemented under congested traffic conditions. The reason is that even when green extension is granted, the existence of queues on heavily congested signalized approaches can prevent the transit vehicle from reaching the intersection. An enhancement to the TSP logic to account for when a vehicle will actually clear the intersection could enhance the TSP logic.
- We recommend not implementing TSP in the vicinity of near-side stops that are located within the detection zone of a TSP system.

- Signal timings should be adjusted so that the roadway receiving priority actuation operates in earlier phases within a cycle. This ensures that priority can be granted with minimum impacts on the latter phases within the signal timing plan.
- Any agency contemplating the installation of a TSP system should invest resources in the calibration of TSP settings in order to maximize the potential benefits of such a system.

RECOMMENDATIONS FOR FURTHER STUDIES

Further research is recommended to enhance TSP operations as follows:

- The calibration of TSP settings is critical to effectively operate the TSP system. In this study corridor, all detection ranges of a transit vehicle were set to 60 m (200 ft) regardless of the bus stop location and the geometric design of the intersection. Thus it might be desirable to investigate the impact of individual TSP settings for each intersection to improve system-wide benefits of TSP.
- Different transit priority strategies or combinations of other strategies should be considered to increase the benefits of TSP operations. The study corridor has a long cycle length of 180 s, and most of the signal cycle time is assigned to Route 1. Thus the possibility of getting a green extension for transit vehicles is very limited because the green extension is granted only when a transit vehicle is expected to arrive at a traffic signal a few seconds after the end of the green indication. Even when a TSP-equipped vehicle arrives during a red indication, a stopped delay is relatively short because most of the cycle time is assigned to Route 1. Therefore, an optimum priority method should be investigated and tested.
- The green-extension TSP should be carefully implemented under congested traffic conditions because even when green extension is granted, the existence of queues on heavily congested signalized approaches can prevent the transit vehicle from reaching the intersection. An enhancement to the TSP logic to account for the time when a vehicle will actually clear the intersection could enhance the TSP logic.
- In order to improve the reliability of transit service, it is necessary to maintain the schedule of transit vehicles. Under the current TSP system on the study corridor, a green extension is granted to eligible transit vehicles regardless of the bus schedules, even when a transit vehicle is ahead of schedule. Thus, it might be desirable to investigate the possibility of an intelligent transit monitoring system and conditional TSP that can grant the priority to transit vehicles depending on their schedule adherence.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Virginia Transportation Research Council for providing the funding for this research effort. The authors also acknowledge the help of Jeffery

Cox and Aram A. Jones of Fairfax Connector for their help in conducting the GPS data collection. The authors gratefully acknowledge the assistance of several persons who contributed to this effort: John Collura from Univ. of Massachusetts, Amherst; Robert Owolabi; Jimmy Carrell; Doug Hansen from Fairfax County; Bob Sheehan and Nhan Vu from VDOT; and Pat Cosgrove from 3M. The authors offer special thanks to graduate students of Virginia Tech for their valuable help in collecting the data for this study.

REFERENCES

Ahn, K., Rakha, H., and Collura, J. (2006). Evaluation of Green Extension Transit Signal Priority Strategies using Portable GPS Receivers. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C.

Baker, R. J., J. Collura, J.J. Dale, L. Head, B. Hemily, M. Ivanovic, J.T. Jarzab, D. McCormick, J. Obenberger, L. Smith, and G.R. Stoppenhagen (2002). *An Overview of Transit Signal Priority*. Washington DC, ITS America.

Belliss, G. (2004). Detailed Speed and Travel Time Surveys Using Low-Cost GPS Equipment. *IPENZ*, Wellington, New Zealand.

Bertini, R.L., C. Glasgow, and J. Peters (2005). Evaluating Traffic Signal Improvements Using Archived Transit AVL Data. *ITS Journal on the Web* Vol. 75 (2).

Dion, F. and H. Rakha (2005). Integration of Transit Signal Priority within Adaptive Signal Control Systems. Presented at 84th Annual Meeting of the Transportation Research Board, Washington, D.C.

Dion, F., H. Rakha, and Y. Kang (2004). Comparison of delay estimates at under-saturated and over-saturated pre-timed signalized intersections. *Transportation research. Part B, Methodological* 38(2): 99-122.

Dion, F., H. Rakha, and Y. Zhang (2004). Evaluation of Potential Transit Signal Priority Benefits along a Fixed-Time Signalized Arterial. *Journal of transportation engineering* 130(3): 10.

Jeong, R. and L. R. Rilett (2004). Bus arrival time prediction using artificial neural network model. *Proceedings - 7th International IEEE Conference on Intelligent Transportation Systems, ITSC 2004*, Washington, DC, United States.

Kimpel, T.J., J. Strathman, R.L. Bertini, P. Bender, and S. Callas (2004). Analysis of Transit Signal Priority Using Archived TriMet Bus Dispatch System Data. Presented at 83rd Annual Meeting of the Transportation Research Board, Washington, D.C.

Lin, W.-H. and J. Zeng (1999). Experimental study of real-time bus arrival time prediction with GPS data. *Transportation Research Record*. n 1666 1999: 101-109.

Marca, J.E., C.R. Rindt, M.G. McNally, and S. Doherty (2001). A GPS Enhanced In-Vehicle Extensible Data Collection Unit. Presented at 80th Annual Meeting of the Transportation Research Board, Washington, D.C.

Ngan, V. (2003). A Comprehensive Strategy for Transit Signal Priority. *ITE Journal-Institute of Transportation Engineers* 73(11): 28-32.

Oloufa, A., M. Ikeda, and H. Oda (2003). GPS-Based Wireless Collision Detection of Construction Equipment. *NIST special publication*(989): 461-466.

Oloufa, A. A. (2003). Web-based Tracking of School Buses utilizing GPS & Voice Radios. Presented at 82nd Annual Meeting of the Transportation Research Board, Washington, D.C.

Quiroga, C. A. and D. Bullock (1997). Travel time studies on signalized highways using GPS. *Proceedings of the 1997 Conference on Traffic Congestion and Traffic Safety in the 21st Century*, Chicago, IL, USA.

Rakha, H., F. Dion, and H. Sin (2001). Using global positioning system data for field evaluation of energy and emission impact of traffic flow improvement projects: Issues and proposed solutions. *Transportation Research Record*. n 1768 2001: 210-223 01-2427.

Rakha, H. and Y. Zhang (2004). Sensitivity Analysis of Transit Signal Priority Impacts on Operation of a Signalized Intersection. *Journal of transportation engineering* 130(6): 9.

Rakha, H., and Ahn, K. (2004). Integration Modeling Framework for Estimating Mobile Source Emissions. *Journal of Transportation Engineering*, Volume 130, Issue 2, March/April 2004, pp. 183–193.

Van Aerde, M., and Associates (2002). *QUEENSOD Rel. 2.10 User's Guide: Estimating Origin Destination Traffic Demands from Link Flows.* Kingston, Canada, M.Van Aerde and Associates.

Van Aerde, M., and Associates (2005). *INTEGRATION Release 2.30 for Windows, User's Guides.* Kingston, Canada, M.Van Aerde and Associates.

Van Aerde, M., Rakha, H., and Paramahamsan, H. (2003). Estimation of O-D Matrices: The Relationship between Practical and Theoretical Considerations. Presented at 82nd Annual Meeting of the Transportation Research Board, Washington, DC.