FINAL CONTRACT REPORT

TRANSIT SIGNAL PRIORITY PROJECT– PHASE II – SIMULATION STUDY RESULTS

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ABSTRACT

This study investigated the system-wide benefits of green extension Transit Signal Priority (TSP) operation on the U.S. Route 1 corridor using the INTEGRATION microscopic traffic simulation software. Basic green extension Transit Signal Priority (TSP) was implemented on U.S. Route 1 in the Northern Virginia Area (or Washington, DC metropolitan area). The field evaluation study of TSP impacts on transit vehicles on U.S. Route 1 was conducted using global positioning system (GPS) units with and without TSP operation. The field evaluation study quantified the overall travel time improvements and intersection delays for TSP-operated buses. While the field evaluation study quantified the benefits of green extension TSP on travel time and intersection delay for transit vehicles, the system-wide impacts of TSP operation could not be performed because it would be practically infeasible to equip all vehicles with GPS units. Thus, in order to investigate the system-wide impacts of a green extension TSP, a simulation study was conducted and described in this report

The traffic demand was estimated by feeding observed link flow and turning movement counts to a synthetic Origin-Destination (O-D) estimator entitled QUEENSOD. These counts were provided by the Virginia Department of Transportation (VDOT). The O-D demand table was estimated using the QUEENSOD software, which utilizes a maximum likelihood synthetic O-D estimation procedure to estimate O-D tables and path flows. The calibration results showed a high level of consistency between estimated and field-observed link flow counts with a coefficient of determination in excess of 99%. Subsequently, a simulation model was constructed for the U.S. Route 1 network and validated against probe-vehicle travel time and queue length field measurements.

The simulation results indicated that transit signal priority did not result in statistically significant changes in transit vehicle, 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 disbenefits, however, these disbenefits 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 disbenefits. Increasing the frequency of transit vehicles resulted in more benefits to the buses, 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 detection zone.

The simulation results indicate that a priority system generally benefits transit vehicles, but does not guarantee system-wide benefits. In this study, a maximum travel-time saving of 3.40% was observed with the provision of green extension TSP. However, the green extension TSP operation did not benefit nor disbenefit the non-transit vehicles in most cases. Also, it should be noted that the results of the study were specific to the U.S. Route 1 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 the 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 U.S. Route 1 corridor.

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INTRODUCTION

Transit Signal Priority (TSP) is an emerging technology defined as an operational strategy that facilitates the movement of transit vehicles through traffic-signal controlled intersections (Baker et al. 2002). In recent years, TSP has been widely implemented by transportation agencies in North America and worldwide, and a large number of studies have evaluated the effectiveness of TSP systems. A green extension TSP system was implemented on U.S. Route 1, also known as the Richmond Highway, in the Northern Virginia area (or Washington, DC metropolitan area). The field evaluation of green extension TSP on transit vehicle performance was conducted using global positioning system (GPS) data that were collected with and without TSP operation along the U.S. 1 corridor during the morning peak period. The field evaluation study revealed overall travel time improvements in the order of 3 to 6% for TSP-operated buses. However, the results also showed that in some cases green-extension TSP could increase transit-vehicle travel times by 2.5% during congested periods (Ahn et al. 2006).

While the field evaluation study quantified the benefits of green extension TSP on travel time and intersection delay of transit vehicles, it was not possible to quantify the system-wide impacts of TSP operations. Consequently, a simulation study was conducted to expand on the field evaluation study.

This study presents the results of various simulation case studies that evaluated the effectiveness of the TSP system on the U.S. 1 corridor, where green extension TSP logic was deployed. In particular, this study quantifies the overall system-wide benefits of TSP green extension strategies using simulation.

PURPOSE AND SCOPE

The purpose of this project is to perform an evaluation of the system-wide impacts of TSP along the U.S. Route 1 study corridor using simulation. The scope of this study is limited to the evaluation of TSP impacts using the INTEGRATION traffic simulation software during the morning peak period.

The detailed objectives of this study are summarized as follows:

- To develop and calibrate the simulation model to realistically model the U.S. 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 U.S. 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.

METHODS

To meet the objectives of this study, the following four tasks were performed:

1. Constructed a simulation model of the study corridor.
2. Collected sample probe-vehicle travel time and queue length data at representative traffic signals for use in validating the simulation results.
3. Calibrated and validated the simulation results against the probe-vehicle travel time and queue length data.
4. Conducted an analysis of TSP simulation runs of the selected scenarios.

Overview of Study Corridor

The study section, U.S. Route 1, 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 the nearby Huntington metro station. On typical weekdays, morning traffic congestion on I-95 continues until noon. Drivers frequently use the study corridor as an alternative route to I-95. 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 the North King/Shields intersection to the north.

The traffic volume in the typical morning peak hour is around 3,300 veh/h in the northbound direction with a total demand of approximately 16,000 vehicles over the 3-hour morning 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 (6:30 to 9:30 a.m.), traffic along the study corridor generally moves northbound, toward 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 at 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 U.S. 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.

Three different bus routes (route numbers 151, 161, and 171) are operated by the Fairfax Connector along the study corridor. This study simulated bus route 171 and compared the simulation results with the route 171 field evaluation study. The route is the only one that extends over the entire study corridor. There are a total of 53 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, and they are equally distributed between northbound and southbound trips. Transit route 171 operates at a 30-minute headway during the morning peak period.

Simulation Model Construction

The INTEGRATION microscopic traffic simulation software was used to evaluate the system-wide benefits of TSP operations. While the 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).

The traffic demand utilized for the simulation study was estimated based on the observed traffic flows and the observed link turning movement count data that were provided by the Virginia Department of Transportation (VDOT). The traffic data collected during one hour of the morning peak period were available with the format of the input files of SYNCHRO, 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 U.S. 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 1. The figure demonstrates that the estimated flows of the generated O-D table were generally well matched with the observed flows.

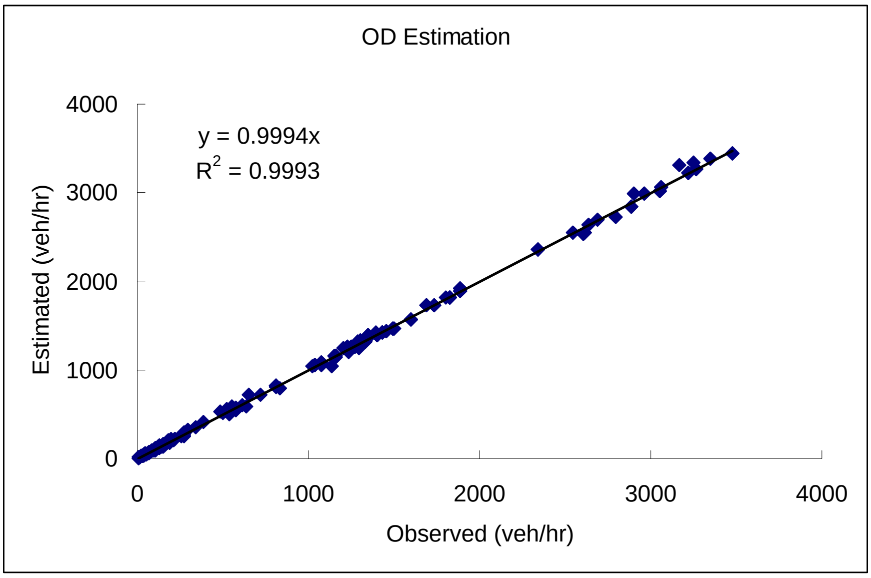

Figure 1. Validation of O-D Matrix Estimation

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. Node location information was derived from commercially available mapping software.

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 1 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 one minute compared to the travel times of the GPS floating car, except for one southbound trip of a passenger car.

Table 1. 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 2 compares the field-observed side-street queue length and the queue length extracted from simulation results. 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 duplicated the morning peak traffic condition on the study corridor. Table 2 demonstrates that most of the queue lengths generated by the simulation model were greater than the minimum queue size and less than the maximum queue size.

Table 2. 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

Green Extension Algorithm in INTEGRATION

Green extension is one of the available TSP strategies—which include passive priority, early green (red truncation), transit phase actuation, phase insertion, phase rotation, and/or adaptive/real-time signal control—to improve transit vehicle operations (Baker et al. 2002). Green extension is granted when a transit vehicle is detected or expected to arrive at a traffic signal a few seconds after the end of the green indication. The transit vehicle is then granted additional green time to allow it to clear the intersection before the traffic signal indication changes. This strategy is only provided when the signal is in a green indication and the approaching vehicle is equipped with a transit priority device; thus if the TSP-equipped vehicle arrives during a red indication, signal priority is not granted. The green extension strategy is known to be one of the most effective approaches in granting priority to transit vehicles. The method significantly reduces the delay and does not require additional clearance intervals (Baker et al. 2002).

A green extension algorithm was implemented into the INTEGRATION model (version 2.30g). The 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 seconds.

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 that has not been reduced to 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 U.S. 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.

Simulation Scenarios

Five simulation scenarios were evaluated to quantify the system-wide impacts of green extension TSP operations on U.S. 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.

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

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

- Base scenario: No Priority vs. Priority based on U.S. Route 1 field data collection.
- Scenario 1: No Priority vs. Priority for various congestion levels on U.S. 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

Fifteen 1-hour simulation runs were executed for each scenario and 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 2 compares the transit vehicle and passenger car travel times. As illustrated in Figure 2, no significant travel-time saving 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 the15 simulation replications. The t-tests produced *p*-values between 0.21 and 0.39, which indicated that there was insufficient evidence to reject the null hypothesis of equal travel times for both cars and transit vehicles. It should be noted that these results are consistent with the field study findings which concluded that transit vehicle travel times were identical with and without green extension TSP.

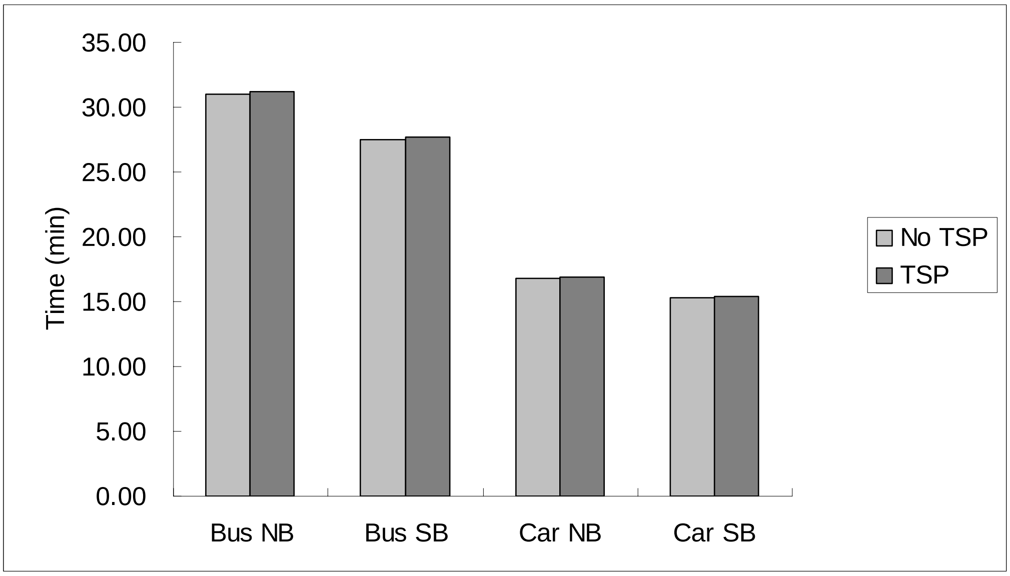

Figure 2. Travel Time Comparison for Base Scenario

The queue lengths of side-streets are typically used as an MOE in the evaluation of TSP projects. 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 the implementation of TSP systems. Figure 3 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 3 shows that there was no significant increase in the queue length of side-streets when transit priority was implemented on the U.S. 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 length 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 on the current traffic demand along U.S. Route 1 does not increase the queue lengths of side streets.

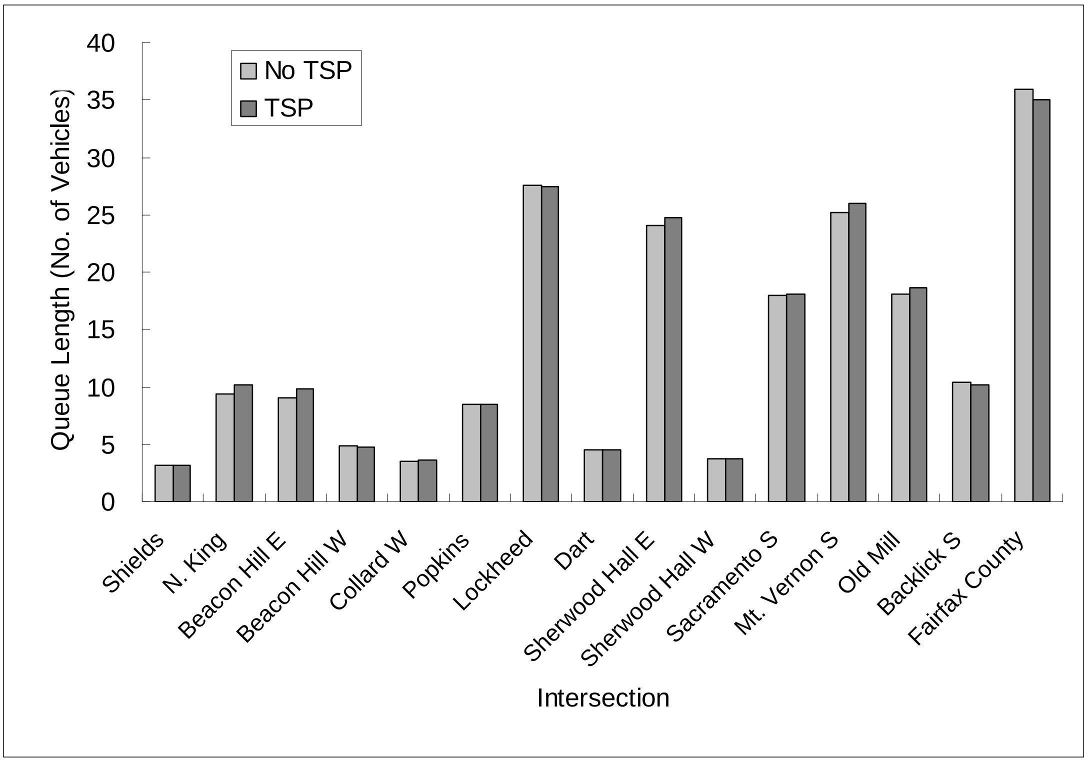

Figure 3. Side-Street Queue Length Comparison for Base Scenario

In terms of overall benefits of TSP operation on the study corridor, as shown in Table 3, 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 3. 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 impacts 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 vehicles per hour in increments of 200 vehicles per hour 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. Figure 4 compares the travel times of transit vehicles and general traffic with and without TSP operation for the increased traffic demands. The simulation results indicated that no significant benefits or disbenefits on travel time were found for increased traffic demands.

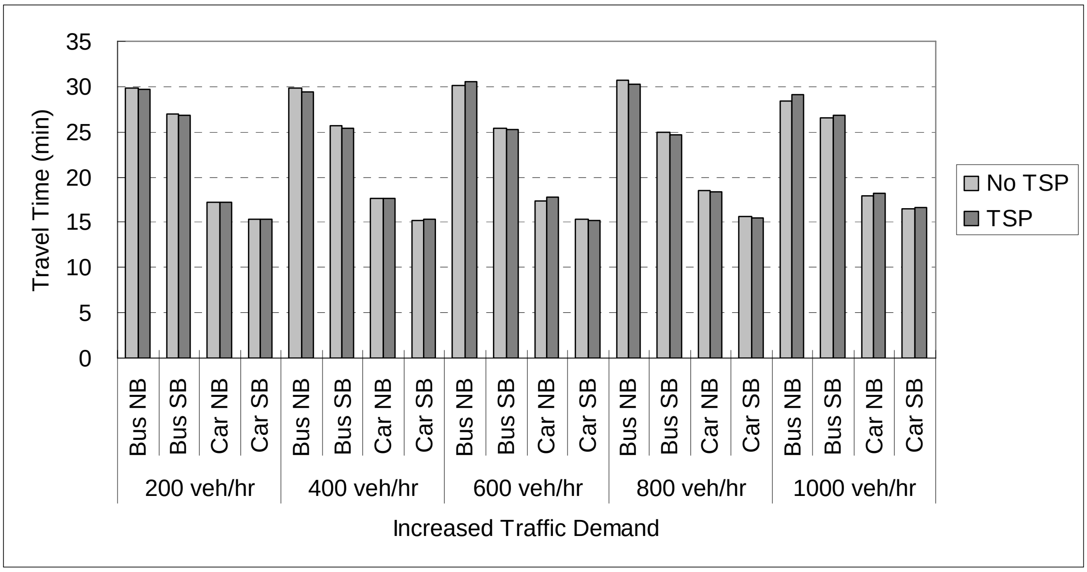

Figure 4. Travel Time Comparison of Increased Traffic Demands

Table 4 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 U.S. Route 1 increased, the delays to transit vehicles generally decreased. It is hypothsized 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 4. Also, 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 4. Impacts of TSP for Increased Traffic Demands

MOEs	200 veh/hr		400 veh/hr		600 veh/hr		800 veh/hr		1000 veh/hr	
	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 5 illustrates the travel time of transit and non-transit vehicles when side-street demands are increased. The side-street demand was increased in increments of 25% of the original demand up to 100%. The figure demonstrates that an increase in the side-street demand did not result in any statistically significant system-wide disbenefits. 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 5. The increased delays and travel times were mostly incurred by the reduced green time on U.S. Route 1 approaches and signal timing adjustments due to increased side-street demand. It is also notable that the travel time of the northbound bus trip at the 100% increased demand was not recorded because no bus completed a trip in the northbound direction due to the significant level of congestion on Route 1.

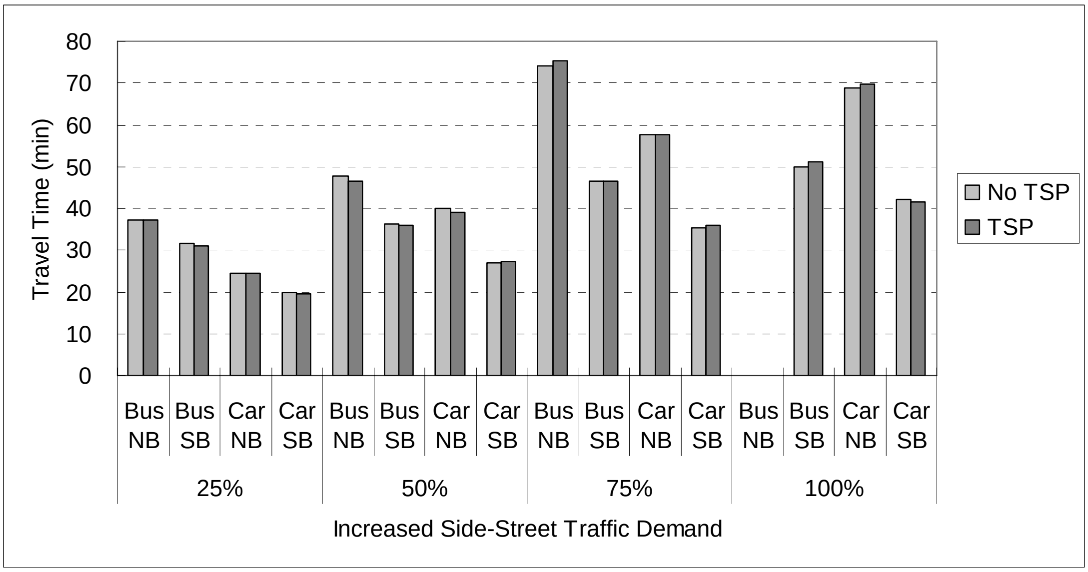

Figure 5. Travel Time Comparison of Increased Side-Street Demands

Table 5. 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	3815	3789
Average Delay (min/veh)	5.20	5.16	8.82	8.70	12.45	12.60	14.84	14.72
Average Stop per Veh	1.99	1.98	3.53	3.48	5.51	5.58	7.31	7.26
Average Bus Delay (min/veh)	24.40	24.18	30.76	30.84	45.65	46.05	40.00	41.23
Average fuel consumption (l/veh)	0.43	0.43	0.51	0.51	0.58	0.58	0.61	0.60
Average HC (g/veh)	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.13
Average CO (g/veh)	3.49	3.49	3.63	3.63	3.63	3.63	3.51	3.51
Average Nox (g/veh)	0.39	0.39	0.39	0.40	0.39	0.39	0.37	0.37

Scenario 3: Transit Vehicle Service Frequency

Figure 6 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 minutes. 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 minutes. 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 length of 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.

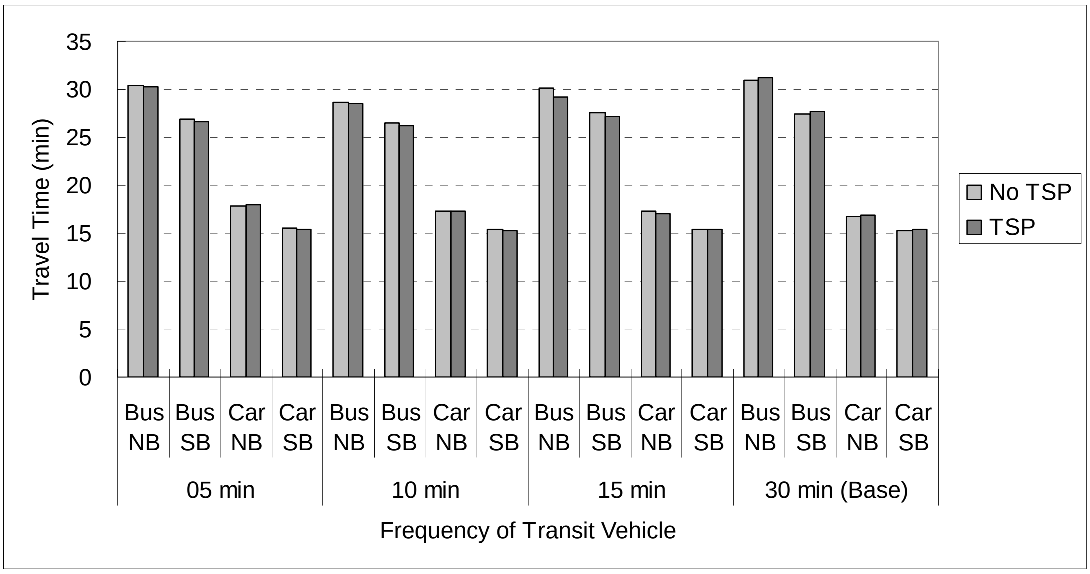

Figure 6. Travel Time Comparison of Increased Transit Vehicle Service Frequency

The MOEs of simulation results are listed in Table 6. 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.

Table 6. Impacts of TSP for Increased Transit Vehicle Service Frequency

	5-Minute		10-Minute		15-Minute		30-Minute (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 7, 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 disbenefit 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.

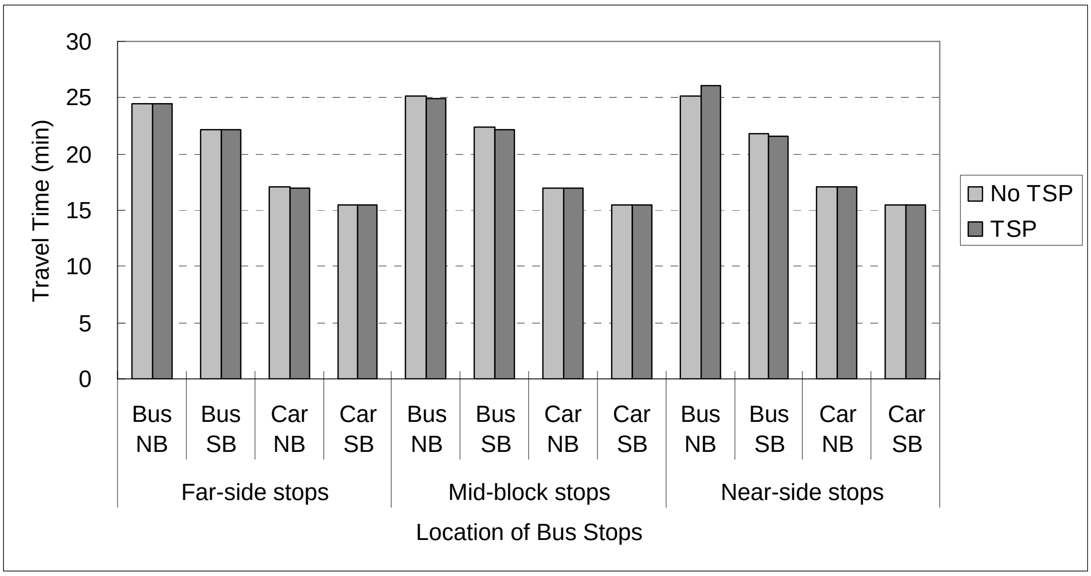

Figure 7. Travel Time Comparison of Modified Bus Stop Location

Table 7 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 7. 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

CONCLUSIONS

The study quantified the system-wide benefits of green extension TSP operation on the U.S. 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 location. Overall, the simulation results indicate that transit vehicles generally benefited 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 does not benefit nor disbenefit non-transit vehicles.

The conclusions of the simulation study of Route 1 can be summarized as follows:

- Transit signal priority had 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 disbenefits for the U.S. Route 1 case study.
- As the traffic demand on Route 1 increases, the system-wide disbenefits of transit signal priority 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 the 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 disbenefits.
- 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%. Consequently, we recommend not implementing TSP in the vicinity of near-side stops that are located within the detection zone.

A systematic sensitivity analysis evaluation of TSP on a signalized intersection within a coordinated arterial 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 disbenefits of TSP increases.
- The system-wide impact of TSP is dependent on the frequency of transit vehicles. As the transit vehicle frequency increases, larger system-wide disbenefits 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 disbenefits 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 disbenefits.
- 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 disbenefits increase with an increase in bus dwell times if the bus stop is located within the detection range of the traffic signal.

RECOMMENDATIONS

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 seconds, and most of the signal cycle time is assigned to U.S. 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 U.S. 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.

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