Final report of ITS Center project: Integrating Transit Signal Priority and Adaptive Traffic Signal Control

A Research Project Report

For the Center for ITS Implementation Research
A U.S. DOT University Transportation Center

INTEGRATING TRANSIT SIGNAL PRIORITY AND ADAPTIVE TRAFFIC SIGNAL CONTROL

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DISCLAIMER

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A final report for the National ITS Implementation Center

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INTRODUCTION

This study quantifies the impact of Transit Signal Priority (TSP) operations within the SCOOT (Split Cycle Offset Optimization Technique) adaptive traffic signal control system on transit and passenger vehicle operations using field-collected Global Positioning System (GPS) data. The SCOOT system optimizes the signal timing split, cycle, and offset in real-time to minimize vehicle stops and delays in response to fluctuations in traffic demand. The system is deployed and operated by transportation agencies in North America and worldwide.

TSP, which is defined as "an operational strategy that facilitates the movement of in-service transit vehicles, either buses or streetcars, through traffic-signal controlled intersections", is recognized as an emerging technology that is capable of enhancing traditional transit services. 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 (Baker et al., 2005).

The SCOOT version 3.1 and later versions contain TSP functionality as an option. Researchers have attempted to evaluate TSP within SCOOT using either analytical and/or simulation tools (Dion and Rakha, 2005; Feng et al., 2003; Hounsell and Landles, 1995).

However, there are very limited field studies that have been performed to demonstrate the benefits of integrating a TSP system within an adaptive traffic signal control system.

The Columbia Pike arterial, also known as VA 244, runs through the Arlington and Fairfax Counties in the Northern Virginia section of the Washington, D.C. metropolitan area. The section of the Columbia Pike (between Dinwiddie and Courthouse Rd.) is controlled by the SCOOT system, while other intersections are controlled using traditional time-of-day fixed-time control. This study quantifies the impact of integrating TSP operations within the SCOOT system on a number of measures of effectiveness (MOEs) using the 16G metro bus line along the Columbia Pike corridor by gathering field-collected GPS data. In particular, this study describes the findings of the field evaluation study of TSP operations on transit-vehicle travel time and intersection delay, fuel consumption, and emissions.

PURPOSE AND STUDY SCOPE

The purpose of this project is to quantify the impact of TSP operations within the SCOOT adaptive traffic signal control system on transit and passenger vehicles based on a field study evaluation. In particular, the objectives of this study are summarized as follows:

- To evaluate the benefits of TSP on transit and passenger vehicles in terms of travel time and intersection delay savings using field-collected GPS data.
- To evaluate the energy and environmental impact of TSP within a SCOOT system using a microscopic energy and emission model.

The scope of this study is limited to the field evaluation of TSP impacts using GPS data that are gathered with and without TSP operation along the Columbia Pike corridor during the morning, mid-day, and afternoon peak periods.

METHODS

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

1. Collect GPS data for transit vehicles with and without TSP along the Columbia Pike corridor study section.

2. Extract from the GPS data relevant data for the study section and estimate various measures of effectiveness from the GPS data.

3. Conduct a field evaluation of TSP impacts within the SCOOT system on transit and passenger car performances in terms of travel time and delays at critical intersections.

4. Investigate the energy and environmental impact of an integrated TSP and SCOOT adaptive traffic signal control system.

The following section describes the study corridor characteristics, the transit signal priority logic, and the GPS data collection procedures which include a description of the GPS equipment and experimental design of bus travel data collection. Finally, the GPS data reduction procedures and data analyses are discussed.

Study Corridor Characteristics

As shown in Figure 1, the study corridor, which is one of major urban arterials in the Northern Virginia section of the Washington, D.C. metropolitan area, extends over 3.4 mi (5.4 km) and covers 20 signalized intersections. Columbia Pike, which runs through Arlington County, VA, has two lanes per direction through the study section. The study section starts at Carlin Springs Rd. to the west and extends to the Joyce St. intersection to the east. The corridor serves residential and medium-density retail business neighborhoods as well as large federal agencies, such as the Pentagon and Navy Annex, at its eastern end. The corridor also connects congested interstate highway interchanges on I-395 and serves two closely located metro stations, Pentagon Station and Pentagon City Station.

Traffic flows along the corridor are typically directional. During the morning peak hours, traffic along the study corridor generally moves eastbound, towards downtown Washington, D.C. and the Pentagon City Station metro station. However, it should be noted that during the afternoon peak period the corridor also carries a significant traffic demand in the eastbound direction. The corridor serves approximately 26,000 vehicles per day. It should be noted that the western end of the study section, which has closely spaced signalized intersections, is typically more congested than other portions of the study section. Of the 20 signalized intersections, those with Carlin Springs, George Mason, Glebe, Walter Reed, and Washington Blvd. carry significant traffic demand from side streets.

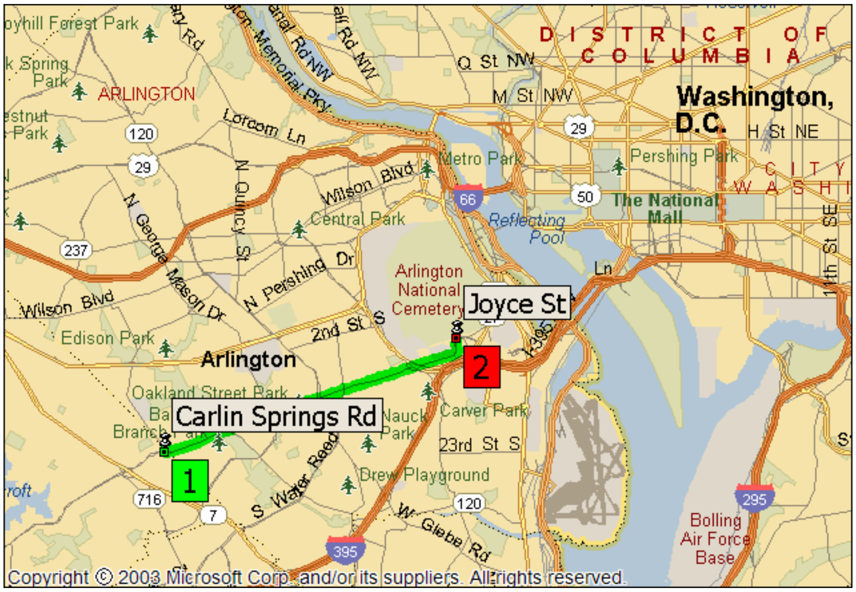

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Figure 1. Columbia Pike Study Corridor

The study corridor is controlled by the ACTRA traffic management system. Intersections between Dinwiddie and Quinn are controlled by the SCOOT system (16 intersections) and the other intersections are controlled by time-of-day fixed-time control. Among the 16 SCOOT controlled intersections, seven intersections were equipped with transit signal priority equipment and also three more intersections among the traditional time-of-day fixed-time controlled intersections were operated by the TSP system. Thus, a total of ten intersections are controlled by the TSP system, as demonstrated in Table 1. The average traffic signal spacing is 272 m (892 ft) and the section between Dinwiddie and George Mason, which is 990 m (3250 ft) in length, covers six signalized intersections with average traffic signal spacing of 165 m (541 ft). It should be noted that significant delay was caused due to these closely spaced traffic signals.

Table 1. Study Intersections in Columbia Pike

Intersection Name	Control	Purpose
Columbia Pike & Carlin Springs	ACTRA	TSP/EVP
Columbia Pike & Jefferson	ACTRA	TSP/EVP
Columbia Pike & Greenbrier	ACTRA	TSP/EVP
Columbia Pike & Dinwiddie	SCOOT	TSP/EVP
Columbia Pike & Four Mile Run	SCOOT	EVP
Columbia Pike & Buchanan	SCOOT	TSP/EVP
Columbia Pike & Wakefield	SCOOT	EVP
Columbia Pike & Thomas	SCOOT	EVP
Columbia Pike & Taylor	SCOOT	EVP
Columbia Pike & George Mason	SCOOT	EVP
Columbia Pike & Quincy	SCOOT	EVP
Columbia Pike & Monroe	SCOOT	EVP
Columbia Pike & Glebe	SCOOT	TSP/EVP
Columbia Pike & Highland	SCOOT	EVP
Columbia Pike & Walter Reed	SCOOT	TSP/EVP
Columbia Pike & Barton	SCOOT	TSP/EVP
Columbia Pike & Wayne	SCOOT	EVP
Columbia Pike & Court House	SCOOT	TSP/EVP
Columbia Pike & Quinn	SCOOT	TSP/EVP
Columbia Pike & Joyce	ACTRA	EVP

Ten different bus routes (16A, 16B, 16D, 16E, 16F, 16J, 16G, 16H, 16K, and 16W) operated by the Washington Metropolitan Area Transit Authority (WMATA) travel along the study corridor. All ten routes connect either Pentagon Station or Pentagon City Station, which is located in proximity to the Joyce St. intersection, and serves the residential areas east of the study corridor. It should be noted that the corridor serves 9,000 transit trips per day, which is the highest ridership of any bus corridor in Virginia. For purposes of this study, only the 16G route buses were utilized since this bus route extends over the entire study corridor.

As illustrated in Figure 2, bus route 16G departs from Pentagon City Metro Station and connects to Carlin Springs Rd. for westbound trips. For eastbound trips, the route departs from Dinwiddie St. to Pentagon City Metro Station, providing an access to the Washington Metro-rail Service. Thus, the trip distance (3.4 mi) of the westbound route is longer than the eastbound bus trips (2.87 mi). It should be noted that the large red circles indicate the eastern end and western end of the study corridor.

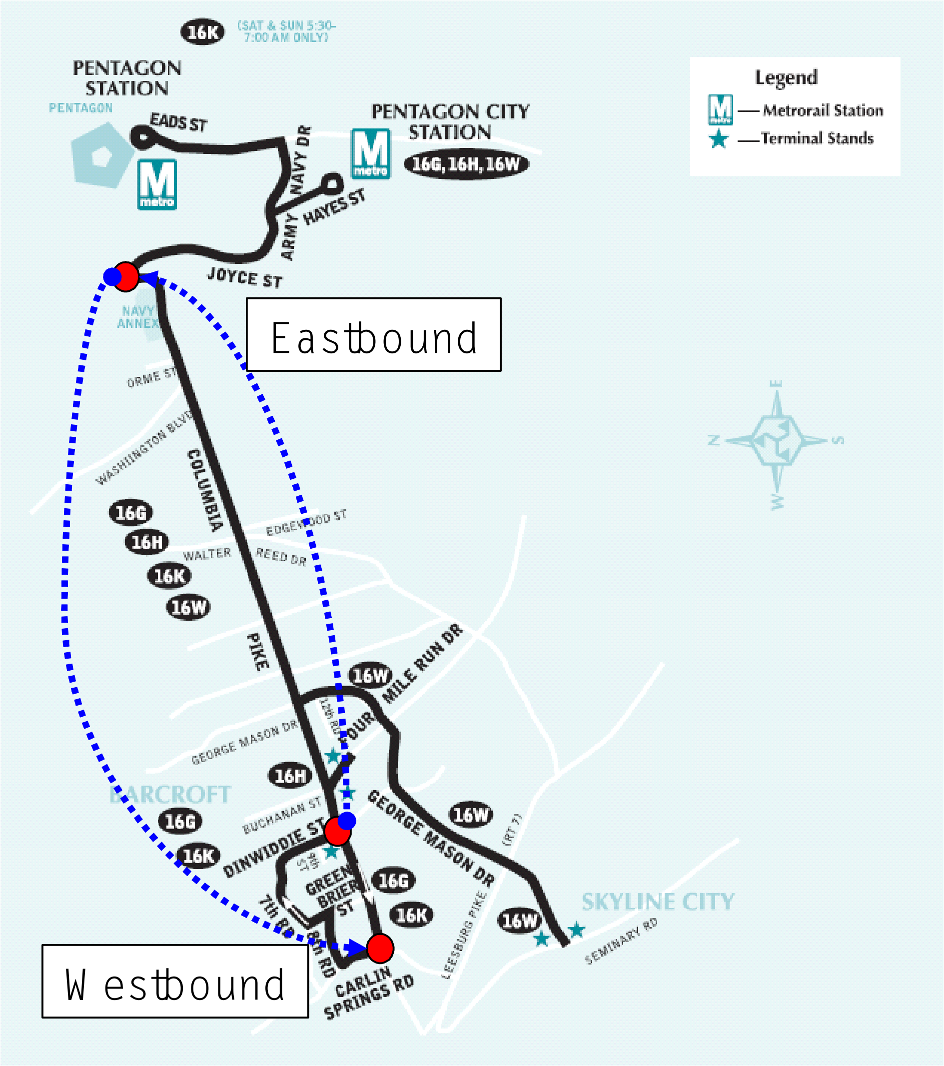

Figure 2. Metrobus 16G Route

TSP Logic

The priority logic that was implemented along the study corridor within the SCOOT system involved green-extension and early green activation. 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. An early green strategy was also utilized along Columbia Pike. The early green shortens the current green time and the succeeding phase is called to expedite the return to green to the transit vehicles (Baker et al., 2005).

The TSP system consists of emitters on the transit vehicles and optical detectors located at the traffic signals. The emitter is 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 emitter generates a series of pulses in the infrared and visible wavelengths. These pulses are sensed by the detector mounted at the intersection. The TSP system is processed when the optical detector receives a request from a transit vehicle if there is no ongoing pedestrian phase at the time and no emergency vehicle preemption call is being made simultaneously.

METHODS

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

1. Collect GPS data for transit and passenger vehicles with and without TSP along the study 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 performance in terms of travel time and delays at intersections.
4. Conduct an analysis of environmental and energy impacts on TSP operations

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 Columbia Pike 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 data 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 (Belliss, 2004; Marca et al., 2001). 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 (Jeong and Rilett, 2004; Lin and Zeng, 1999; Oloufa et al., 2003; Oloufa, 2003; Quiroga and Bullock, 1997).

Experimental Design and Bus Travel Data Collection

GPS technology offers a cost-effective means to conduct such field evaluation studies. GPS technology is increasingly being employed for 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.

Two portable GPS units were utilized in the study: GD30L manufactured by LAIPAC Technology Inc. and a Virginia Tech Transportation Institute (VTTI) custom-built GPS unit. Both GPS units are designed to record the date, time, vehicle longitude, vehicle latitude, vehicle speed, vehicle heading, and the number of tracking satellites. They are small enough to be installed inside a glove compartment in any vehicle and powered by the cigarette-lighter power adapter. Both units are operated as a stand alone unit without the need for a PC or other equipment. Once the units are powered-up, the GPS unit collects the data automatically.

Before condition GPS data were collected on weekdays (Tuesday through Thursday) in March 2006 while after condition GPS data were collected on weekdays between October and November 2006. Unfortunately, construction on the roadway resulted in a large temporal lag between the before and after data collection efforts. The data were collected for three periods: the a.m. peak (7:30 a.m. – 9:30 a.m.), the midday peak (12:00 p.m. – 1:00 p.m.), and the p.m. peak (4:30 p.m. to 6:30 p.m.). For bus data collection, four portable GPS units were utilized on the TSP-equipped buses for transit priority detection. The bus travel data were recorded at a 1 s resolution and downloaded to a personal computer every night. For car data collection, two probe vehicles equipped with GPS units were utilized. In order to reflect the aggregate characteristics of traffic flow, the probe vehicles maintained the average speed of the traffic stream. 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.

Tables 2 and 3 show the required sample sizes for the evaluation of TSP and the number of valid GPS 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). As shown in the table, the GPS data that were gathered exceeded the required minimum sample size for bus and car trips. In total, 336 valid bus trips and 380 valid car trips were recorded for this study.

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

Table 2. Bus Sample Size Requirements

Direction		Valid Trips		Required Sample Size	
		TSP Off	TSP On	95% Confidence	90% Confidence
EB	AM	36	31	32	23
	Mid	19	24	19	13
	PM	27	28	23	16
EB Total		82	83	72	57
WB	AM	33	35	27	19
	Mid	20	23	21	15
	PM	33	27	24	17
WB Total		86	85	72	51
Grand Total		168	168	144	108

Table 3. Car Sample Size Requirements

Direction		Valid Trips		Required Sample Size	
		TSP Off	TSP On	95 % Confidence	90% Confidence
EB	AM	41	35	23	16
	Mid	22	27	12	9
	PM	42	30	13	10
EB Total		105	92	49	34
WB	AM	40	32	15	10
	Mid	21	23	19	13
	PM	37	30	16	11
WB Total		98	85	50	35
Grand Total		203	177	99	69

RESULTS

The average travel time plots for transit vehicles are illustrated in Figure 3. The figure demonstrates that in the case of transit priority, the bus travel time increased by up to 12.63 % during the afternoon peak period traveling in the eastbound direction. Similarly, the figure illustrates the bus travel time increased for all periods for both directions. The average increase in travel time for both directions is 37 s (or 4.3 % relative to the TSP-off travel time scenario). The overall travel time results demonstrate that TSP operation increases in the range of 5.6% and 4.2% of total travel time for the eastbound and westbound directions, respectively. Statistical t-tests were performed at a 5% significance level assuming identical mean travel times for both cases. The t-test for the eastbound and westbound trips produced p-values of 0.27 and 0.16, which indicate that there is insufficient evidence to reject the null hypothesis of equal travel times. Thus, we conclude that the TSP does not result in any changes in the transit vehicle travel times for both the eastbound and westbound trips. It should be noted that possible changes in travel demand on Columbia Pike were not investigated in this study.

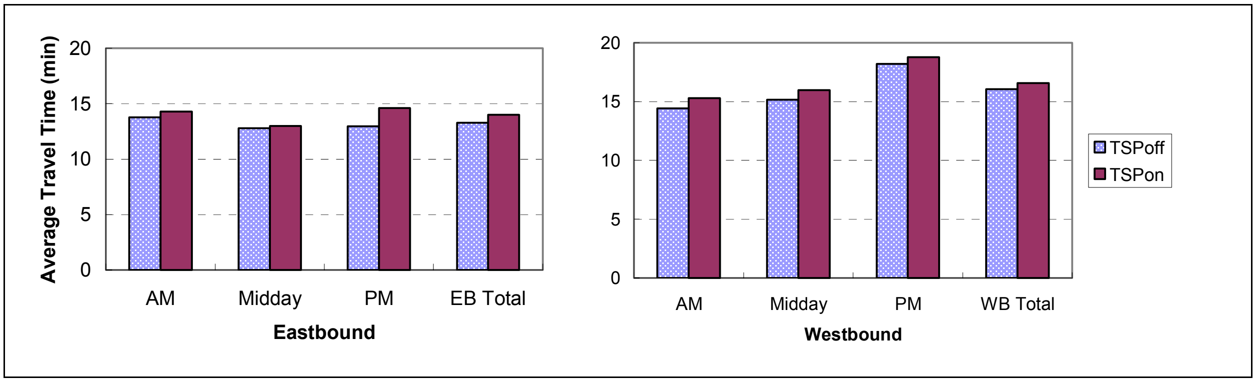

Figure 3. Transit Vehicle Travel Time

Table 4 summarizes the variation in the average stopped time at bus stops and the operational times (time spent traveling) for all trips. It should be noted that GPS data cannot differentiate between bus stop dwell times and delays when intersections are near-side and within the influence area of traffic signals. The table demonstrates that the average stop duration increased by approximately 9.7 % for both directions and increased by up to 38 % during the afternoon peak period for the eastbound direction when TSP was implemented. This increased stop time could be attributed to a higher transit vehicle ridership in the after data collection effort. The bus operational time, which is shown in Table 4, represents the difference between the trip travel time and the total time the bus is stopped at bus stops. Table 4 demonstrates that there is only a 1.6 percent (or 9.4 s) difference in the bus operational time between TSP-on and TSP-off operations, demonstrating that there is no significant increase in total delay. Furthermore, the t-test results concluded that TSP operations did not affect the total travel times with p-values of 0.11 and 0.14 in the eastbound and westbound directions, respectively.

Table 4. Stop Duration and Running Time of Transit Vehicles

	Peak	Stop Duration (min)		Operational time (min)	
		TSP off	TSP on	TSP off	TSP on
EB	AM	4.87	5.19	8.90	9.10
	Midday	4.00	4.00	8.79	8.99
	PM	4.11	5.66	8.85	8.94
EB Total		4.42	5.00	8.86	9.01
WB	AM	4.13	4.63	10.29	10.65
	Midday	4.49	5.18	10.66	10.79
	PM	6.55	6.88	11.66	11.90
WB Total		5.14	5.49	10.90	11.08
Total		4.79	5.25	9.90	10.06

Figure 4 shows the average travel time plots of passenger cars. The figure illustrates that TSP-on travel times were increased by approximately 5.2 percent (or 29 s) and up to 14 percent during the p.m. peak period of westbound traffic, which is similar to bus travel time results. T-tests and wilcoxon ranksum tests were performed at a 5% significance level assuming identical mean travel times for eastbound and westbound cases. Both tests confirm that TSP did not result in increased travel times for passenger cars, except for the eastbound trips using the t-test. The eastbound and westbound t-tests and the eastbound and westbound ranksum tests yield p-values of 0.10, 0.00, 0.01, and 0.02, respectively. It should be noted that the stop durations of car trips were also measured and the stop durations also increased with an average value of 13 s (or 8.7 percent) when compared with TSP-off conditions. Also, both t-tests and wilcoxon ranksum tests confirm that after data collection (TSP-on condition) increased, the stop durations producing p-values of 0.03, 0.02, 0.01, and 0.02, which are statistically significant. Similarly, Table 5 summarizes the average speeds of transit vehicles and passenger cars. The table demonstrates that the average speeds were decreased when TSP was operated similar to the travel time results.

The field study results found that the TSP operations generally increase the travel times of both transit and passenger vehicles and reduce average travel speeds. Travel time is typically used as an 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, the potential speeding of transit-vehicle drivers to make up for any delay incurred, and increased traffic demand. Thus, the increases of travel time don't necessarily confirm that TSP operation adversely affects the travel time and average travel speed. 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 TSP is designed to reduce transit-vehicle delays at signalized intersections dependent on the vehicle arrival timing and a priority setting.

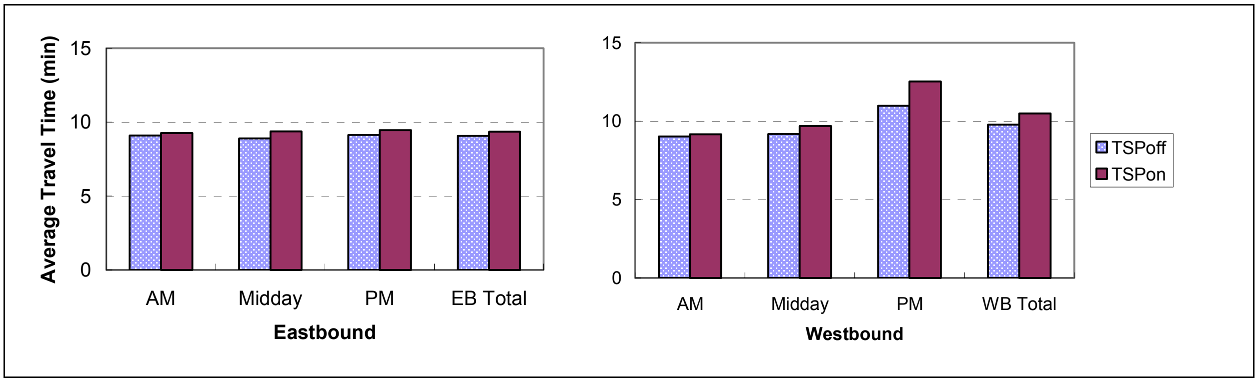

Figure 4. Passenger Car Vehicle Travel Time

Table 5. Average Speed of Buses and Cars

		Bus (mi/h)		Car (mi/h)	
	Peak	TSP-off	TSP-on	TSP-off	TSP-on
EB	AM	12.53	12.10	22.45	21.28
	Midday	13.30	13.34	23.11	21.57
	PM	14.32	13.89	21.71	21.60
EB Total		13.29	13.06	22.29	21.47
WB	AM	14.27	13.42	22.25	22.19
	Midday	13.64	12.93	21.80	20.70

	PM	11.41	11.33	18.34	16.13
WB Total		13.03	12.62	20.71	19.65
Total		13.16	12.84	21.52	20.60

In conducting the intersection delay 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 35 mi/h (or 56 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).

The results demonstrate that for both non near-side and near-side bus stops, TSP tends to reduce the approach delay, as illustrated in Table 6. For example, the average delay at non near-side bus stop intersections is decreased from 14.8 s to 14.3 s, which represents a 3.3 % reduction while the average delay at near-side bus stop intersections is decreased from 28.1 s to 27.8 s, which represents a 5.7 % reduction. It should be noted that the average delays of the intersections with near-side bus stops are significantly higher than the delays of the intersections without near-side bus stops due to dwelling time delays. The table also demonstrates that the average delay for eastbound intersections is decreased from 20.6 s to 18.93 s, which represents a 7.9 % reduction. Similarly, the TSP significantly reduces the intersection delay by 34.7 % in the midday peak period (12:00 p.m. to 1:00 p.m.) at eastbound intersections, from an average delay of 20.7 s to 13.5 s. However, the results demonstrate that TSP does not operate effectively for the westbound intersections during the midday peak period increasing the intersection delays from 7.6 s to 11.2 s, which is a 47 % increase. The results also demonstrate that in some cases TSP can increase intersection delays at non near-side intersections, as is the case for the westbound direction for the mid-day period (-3.7%). T-tests were also performed to identify whether TSP operation reduces the intersection delays at a 95% confidence level. The results demonstrated that for Glebe (EB) intersection, the hypothesis was statistically significant with 0.020 p-value, indicating that the TSP operation resulted in reductions in intersection delay. However, the t-test results of the other intersection cases showed that the intersection delays were not significantly reduced when the TSP was operated.

Table 6. Bus Intersection Delay with TSP

	Peak	Intersection Delay (Non-Nearside BS)		Intersection Delay (Nearside BS)	
		TSP-off	TSP-on	TSP-off	TSP-on
EB	AM	19.51	18.06	40.98	39.82
	Midday	20.72	13.52	22.64	23.48
	PM	21.82	19.73	25.87	23.39
EB Total		20.55	18.93	31.76	29.63
WB	AM	8.59	8.10	27.32	24.71
	Midday	7.63	11.22	28.29	27.74
	PM	10.31	10.53	27.98	28.09
WB Total		9.03	9.68	27.82	26.57
Total		14.79	14.30	29.79	28.10

Table 7 summarizes the approach delays at the intersections where the TSP system was not installed. The average delays were increased by 0.8 % and 11.8 % for non near-side bus stop and near-side bus stop intersections, respectively. Thus, tables 6 and 7 results confirm that the TSP operation reduces the intersection delays where the TSP system is implemented. Similar to Table 6 results, the average delays of the intersections with near-side bus stops is significantly higher than the delays of the intersections without near-side bus stops due to dwelling time delays. However, the t-tests produced p-values between 0.45 and 0.87, which indicate that there is insufficient evidence to reject the null hypothesis of equal intersection delays for transit vehicles. These results demonstrate that in terms of intersection delay the before and after traffic conditions were similar with no statistical evidence for differences.

Table 7. Delays at the Intersection without TSP System

	Peak	Intersection Delay (Non-Nearside BS)		Intersection Delay (Nearside BS)	
		Before	After	Before	After
EB	AM	16.39	16.73	18.80	22.31
	Midday	15.32	10.48	18.28	19.74
	PM	11.63	12.60	16.36	16.98
EB Total		14.61	14.07	17.89	19.79
WB	AM	3.63	4.21	14.82	18.71
	Midday	5.81	5.87	19.01	21.26
	PM	4.43	5.69	25.29	28.29
WB Total		4.45	5.13	19.85	22.41
Total		9.53	9.60	18.87	21.10

Individual intersection approach delays with and without TSP system are compared in Figure 5. In particular, the figure illustrates the benefits of TSP system within SCOOT showing that TSP operation reduces the delays of intersections with TSP system with an average delay saving of 4.2 percent and decreases the approach delays at 10 of 13 intersections where TSP is installed. Paired t-tests were performed on the average intersection delays considering a 5% significance level assuming equal means. However, the results demonstrate that the hypothesis of unequal means is not statistically significant with a p-value of 0.082 explaining that the intersection reduction is not statistically significant.

The figure also demonstrates that the most of intersections (13 of 17 intersections) without TSP system increase the delays with an average increase of 10.4 percent and up to 36 percent at Quincy of westbound. Paired t-tests were also performed to identify whether TSP operation increased the delays at intersections without TSP system at a 95% confidence level. The results demonstrated that the hypothesis was statistically significant with 0.014 p-values, indicating that the TSP operation created longer delays at intersections without TSP equipments.

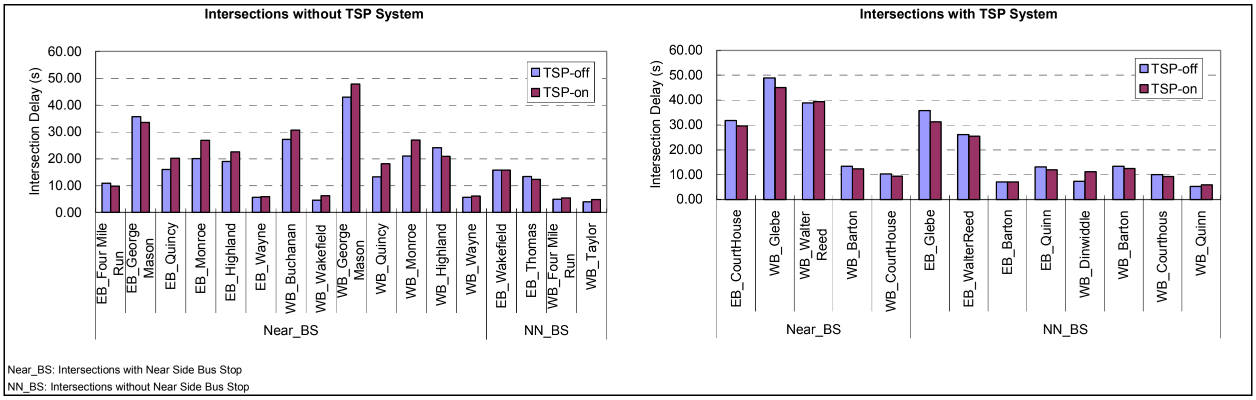

Figure 5. Intersection Delay Comparison of with and without TSP system for Buses

The impacts of TSP at traditional fixed-time control intersections are illustrated in Figure 6. Interestingly, the figure demonstrates that the intersection approach delays were increased by 2.6 %, 13.7 %, and 1.0 % for Carlin Springs, Jefferson, and Greenbrier intersections, respectively, when TSP was functional. It should be noted that Carlin Springs, Jefferson, and Greenbrier intersections were operated under a fixed-time control, as opposed to SCOOT control. The results demonstrate that TSP increases the delays for all cases except the cases for the p.m. peak period for Carlin Springs and Greenbrier. Statistical analysis was also performed on the intersection delay for each peak period. The t-test results concluded that only the Jefferson and Greenbrier a.m. peak period increase the delays significantly with p-values of 0.04 and 0.01.

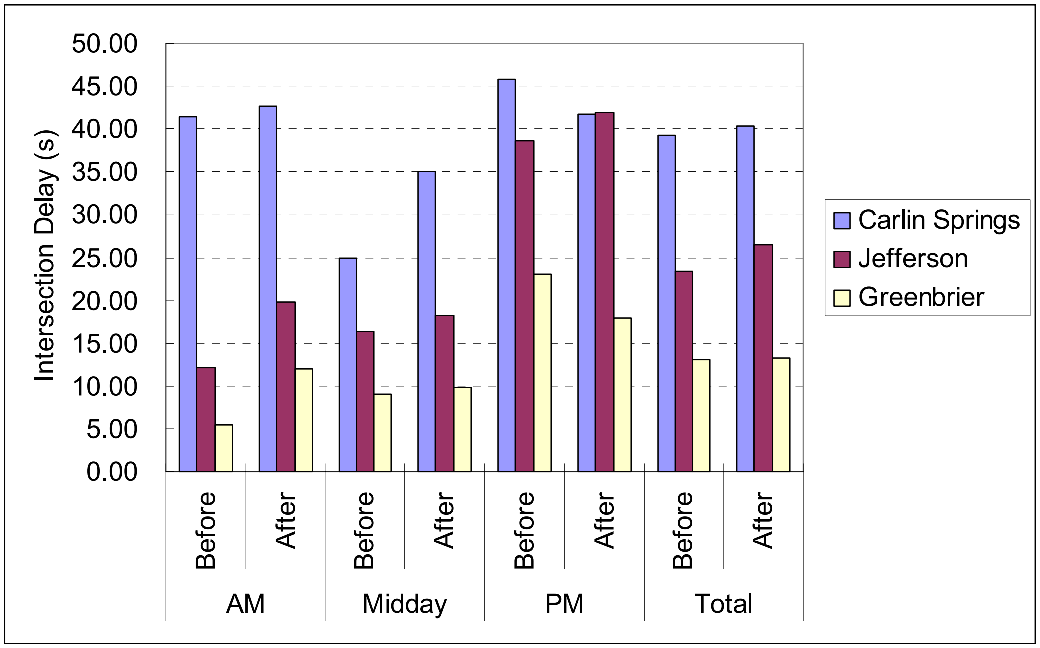

Figure 6. Delays at Fixed-Time Control Intersections with TSP for Buses

Figure 7 illustrates the intersection approach delays for passenger cars at both intersections with non near-side bus stops and near-side bus stops. The TSP can produce savings in passenger car intersection delays in the range of 2.2% to 5.3% except for the case of the westbound intersections with near-side bus stops, as illustrated in the figure.

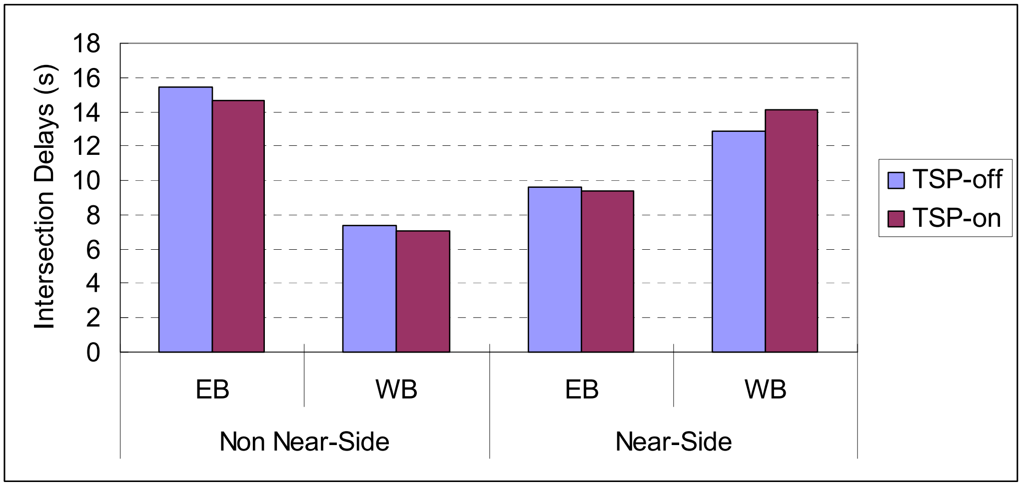

Figure 7. TSP impacts on Intersection Delays for Cars

Figure 8 illustrates the passenger car approach delays for the intersections which are controlled by fixed-time control. The figure demonstrates that the TSP system produces no clear benefits for these intersections. Instead, increases in approach delays are observed for both the eastbound and westbound trips regardless of the location of the bus stops. The after condition data significantly increased the intersection delay by 62% in the westbound direction at the intersections with near-side bus stops, from an average delay of 5.7 s to 9.3 s. Consequently, the results clearly demonstrate that the integration of TSP within the SCOOT adaptive traffic signal control system can produce reductions in transit vehicle delays and potentially system-wide intersection delays.

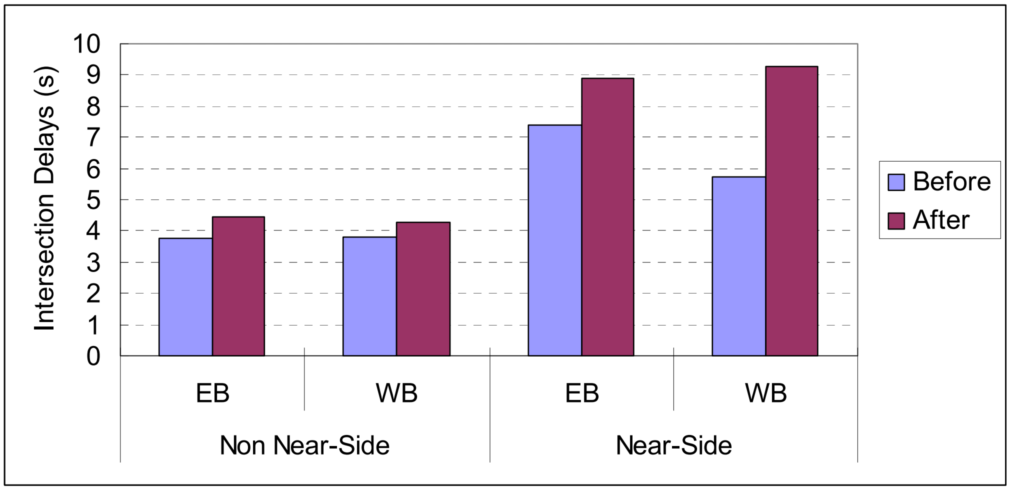

Figure 8. Car Delays at Intersections without TSP system

Figure 9 compares fuel consumption rates for passenger cars and bus as a function of the vehicle's average speed as estimated by the VT-Micro model. A more detailed description of the model derivation is provided in the literature (Ahn et al., 2004; Ahn et al., 2002; Rakha et al., 2004). According to the model estimates, fuel consumption rates are generally highest at low speeds and decrease with an increase in the vehicle speed up to some optimal speed beyond which the fuel consumption increases. In this case, best fuel economy is obtained at 40 mph with 9.3 mi/gal for buses and at 50 mph with a fuel consumption rate of 30.1 mi/gal for passenger cars. However, it should be noted that fuel consumption and emission rates are highly dependent on the speed and acceleration levels of the vehicle and the engine load. Thus, real-world fuel consumption can be significantly different from the estimates in Figure 9 due to the transient changes in a vehicle's speed and acceleration levels as it travels on a network. It should be noted that temperature, cold start, altitude, vehicle mileage, road grades, and vehicle distributions effects are not considered in this study. These are assumed to be identical for the before and after conditions.

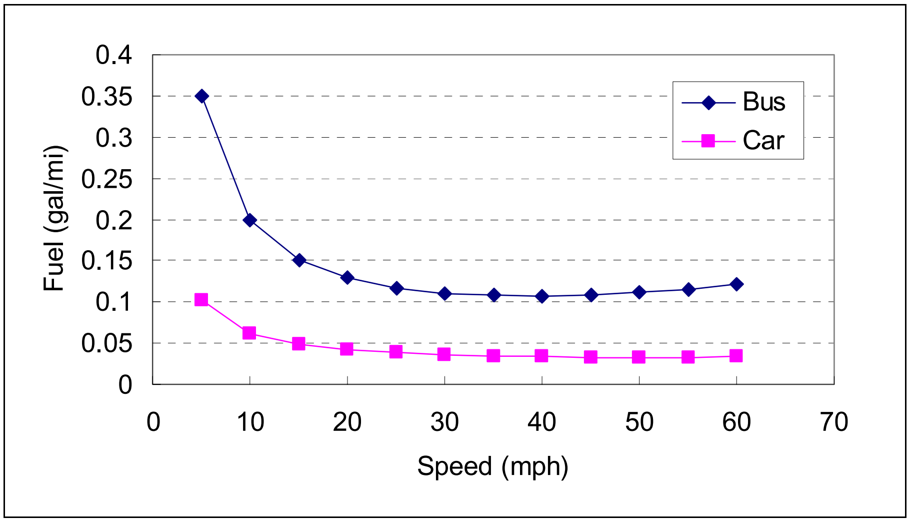

Figure 9. Fuel consumption for Car and Bus as a Function of Average Speed

Fuel consumption estimates of individual buses and cars are illustrated in Figure 10. The figure illustrates that the TSP (or after condition) did not produce any fuel savings, as illustrated in Figure 10. Considerable increases in fuel consumptions were observed in most of the cases with a 26 percent increase during the p.m. peak period for westbound travel for car trips. The average fuel consumption increases were 7.1 % and 13.4 % for bus and car trips, respectively. Statistical analysis also confirmed that the fuel consumption rates for both bus and car trips were significantly increased with p-values of 0.004 and 0.000.

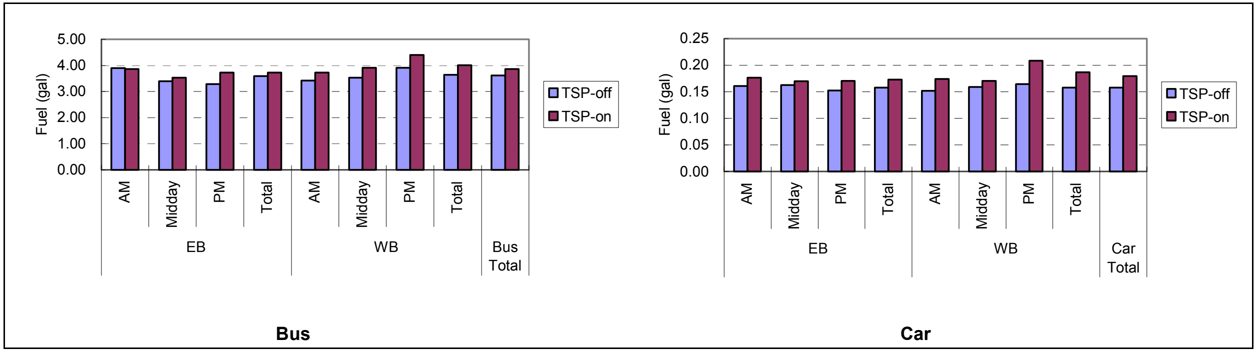

Figure 10. Fuel consumption Estimates for Car and Bus

Bus emission results were estimated in grams for hydrocarbon (HC), carbon monoxide (CO), nitrogen oxides (NOx), and carbon dioxide (CO_2) emissions, as illustrated in Figure 11. Similar to the fuel consumption results, after condition (TSP-on) data increased the emissions by 4.6 %, 2.0 %, 4.6 %, and 3.9 % for HC, CO, NOx, CO_2 emissions. Equal mean t-tests demonstrated that HC, NOx, CO_2 emissions were significantly increased (p-values of 0.036, 0.015, and 0.017), while CO emissions were statistically insignificant.

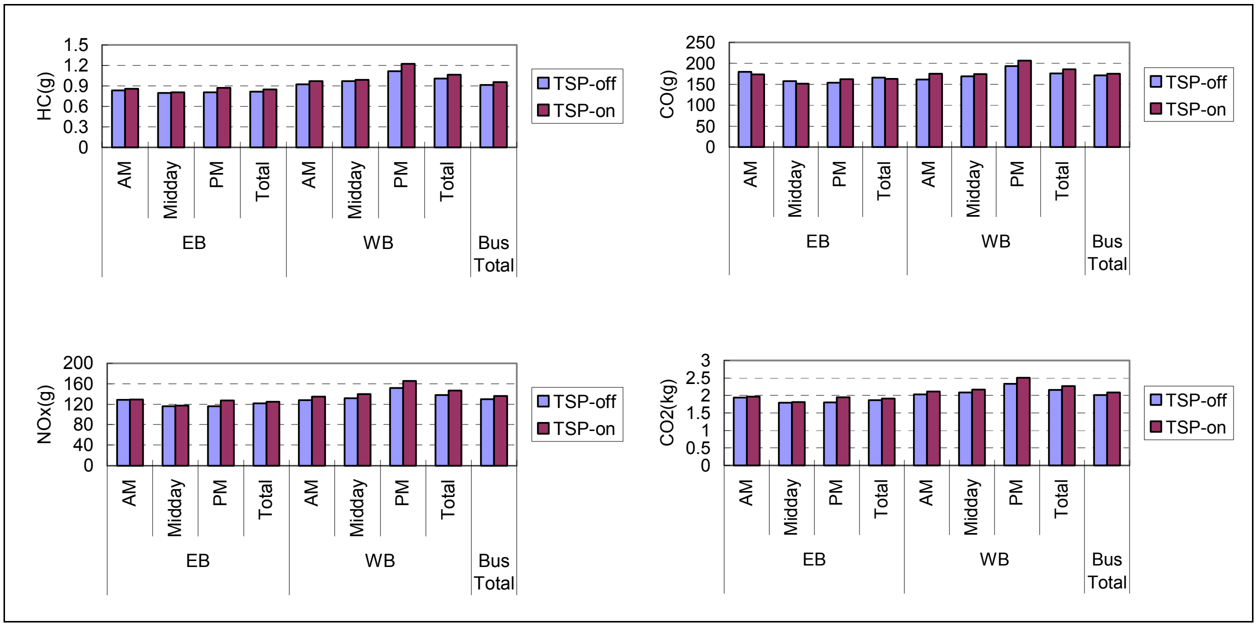

Figure 11. Bus Emissions Estimates

Passenger car emission results are illustrated in Figure 12. The figure shows the TSP produces improvements in air quality by as much as 20 % of CO emissions. Furthermore, 4.5 % and 0.4 % of HC and NOx emission are reduced when TSP is operated, while CO_2 emissions are increased by up to 14.2 %. T-tests were performed on each emission considering a 5 percent significance level assuming equal means. The results demonstrate that for HC, CO, and CO_2 emissions the hypothesis is statistically significant with 0.013, 0.001, and 0.001 p-values. However, NOx emission result was not statistically significant with a p-value of 0.367.

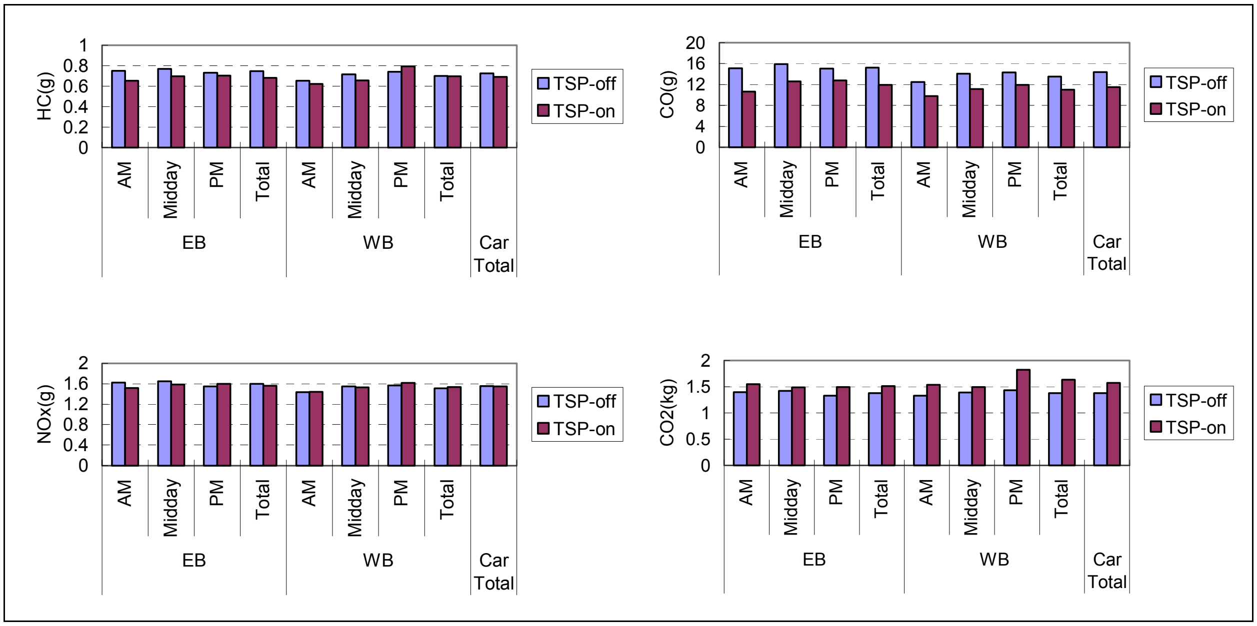

Figure 12. Car Emissions Estimates

FINDINGS AND CONCLUSIONS

The field results demonstrate that traffic conditions for the after scenario (TSP-on) were higher than for the before scenario with increases in transit-vehicle and passenger car travel times in the range of 3.1 to 5.6 %. Despite these higher levels of congestion the study demonstrates that by integrating TSP within the SCOOT adaptive traffic signal control system overall reductions in transit vehicle approach delays in the range of 3.3 % can be observed in the case of non near-side bus stops. Furthermore, the study demonstrates that TSP operations can reduce approach delays by 5.6 % for near-side bus stop intersections. The study also demonstrates that the integration of TSP and adaptive signal control benefits passenger vehicles with savings in intersection delay by up to 5.2 %.

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

- TSP within the SCOOT system generally reduces delay to both TSP-equipped buses and passenger cars at intersections with TSP detectors. These improvements are also observed at intersection approaches with near-side bus stops.
- TSP within a fixed-time signal control system generally increases intersection delay to both TSP equipped buses and cars at intersections with TSP detectors.
- The study found that TSP has no beneficial impacts on transit vehicle and passenger car travel times.
- TSP generally decreases the fuel economy for both transit vehicles and passenger cars.
- TSP also increases transit vehicle emissions while the emissions from passenger cars are generally reduced except for CO_2 emissions.

RECOMMENDATIONS FOR FURTHER STUDIES

Further research is recommended to evaluate the system-wide impacts of TSP and enhance TSP operations as follows:

- Compare the travel demand levels on the study corridor for the before and after scenarios.
- The system-wide impact of TSP for various congestion levels should be investigated. Varying the congestion level could result in different behavior and possibly identify the range of congestion levels for which TSP can be effectively operated.
- The study investigated the benefits of transit vehicles for TSP green extension and early green strategies. However, since the grant of green extension and early green shortens the green times of side-streets, the impact of TSP on the operation of side-streets should be analyzed for various levels of congestion. The research should attempt to identify the range of side-street demand that results in system-wide benefits of TSP.
- The calibration of TSP setting for individual intersections should be considered to effectively operate TSP for the intersection with fixed time control intersections. Each intersection has various characteristics and different congestion levels. Thus, it might be desirable to investigate the impact of individual TSP settings for each intersection to improve the system-wide benefits of TSP.
- In order to improve the reliability of transit service, it is necessary to maintain the schedule of transit vehicles. Thus, it might be desirable to investigate the possibility of an intelligent transit monitoring system that can transit vehicle schedule adherence. Conditional TSP may be granted to transit vehicles depending on their schedule adherence.

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