FINAL CONTRACT REPORT

TRANSIT SIGNAL PRIORITY PROJECT– PHASE II – FIELD EVALUATION RESULTS

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ABSTRACT

Transit Signal Priority (TSP) 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. 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. 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. Global Positioning Systems (GPSs) offer a cost-effective means to conduct such studies.

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. The purpose of this project is to conduct a field evaluation of TSP impacts on transit vehicle operations. The US 1 (Richmond Highway) in Northern Virginia, where “green extension” TSP logic is deployed, is used as the case-study network. The study corridor extends over 12.9 km (8.06 mi) and covers a total of 27 signalized intersections. The field evaluation is conducted using Global Positioning System (GPS) receivers that are Wide Area Augmented System (WAAS) enabled and installed on a sample of transit vehicles. The study demonstrates that WAAS-enabled GPS receivers provide accurate, reliable, and cost-effective data that are superior to traditional travel survey data because these data are output at a second-by-second level of resolution.

The study demonstrates that overall travel time improvements in the order of 3 to 6 percent are observed for TSP operated buses with occasional negative impacts during congested periods. In addition, the study demonstrates that TSP strategies can reduce transit-vehicle intersection delay by as much as 23 percent. Furthermore, the study demonstrates that the benefits associated with TSP are highly dependent on the roadway level of congestion and are maximized under moderate to low levels of congestion.

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INTRODUCTION

Traffic signals and traffic congestion are two major sources of delay for traditional bus service. 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; 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.

Global Positioning Systems (GPSs) offer a cost-effective means to conduct such 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 U.S. 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 U.S. 1 corridor. In particular, this study describes the findings of a field evaluation of TSP strategies on transit-vehicle travel time and intersection delay.

PURPOSE AND SCOPE

The purpose of this project is to perform a field evaluation of TSP impacts on transit vehicle performance. 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 US 1 corridor during the morning peak period.

The objectives of this study are twofold. First, the study presents a case-study evaluation of the benefits of TSP on transit vehicles in terms of travel time and intersection delay savings. Second, the study demonstrates the feasibility and applicability of GPS technology for such applications.

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 U.S. 1 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 on bus performance in terms of travel time and delays at critical intersections.

The GPS bus data were collected on weekdays (Monday through Friday) between March and May of 2005. 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 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).

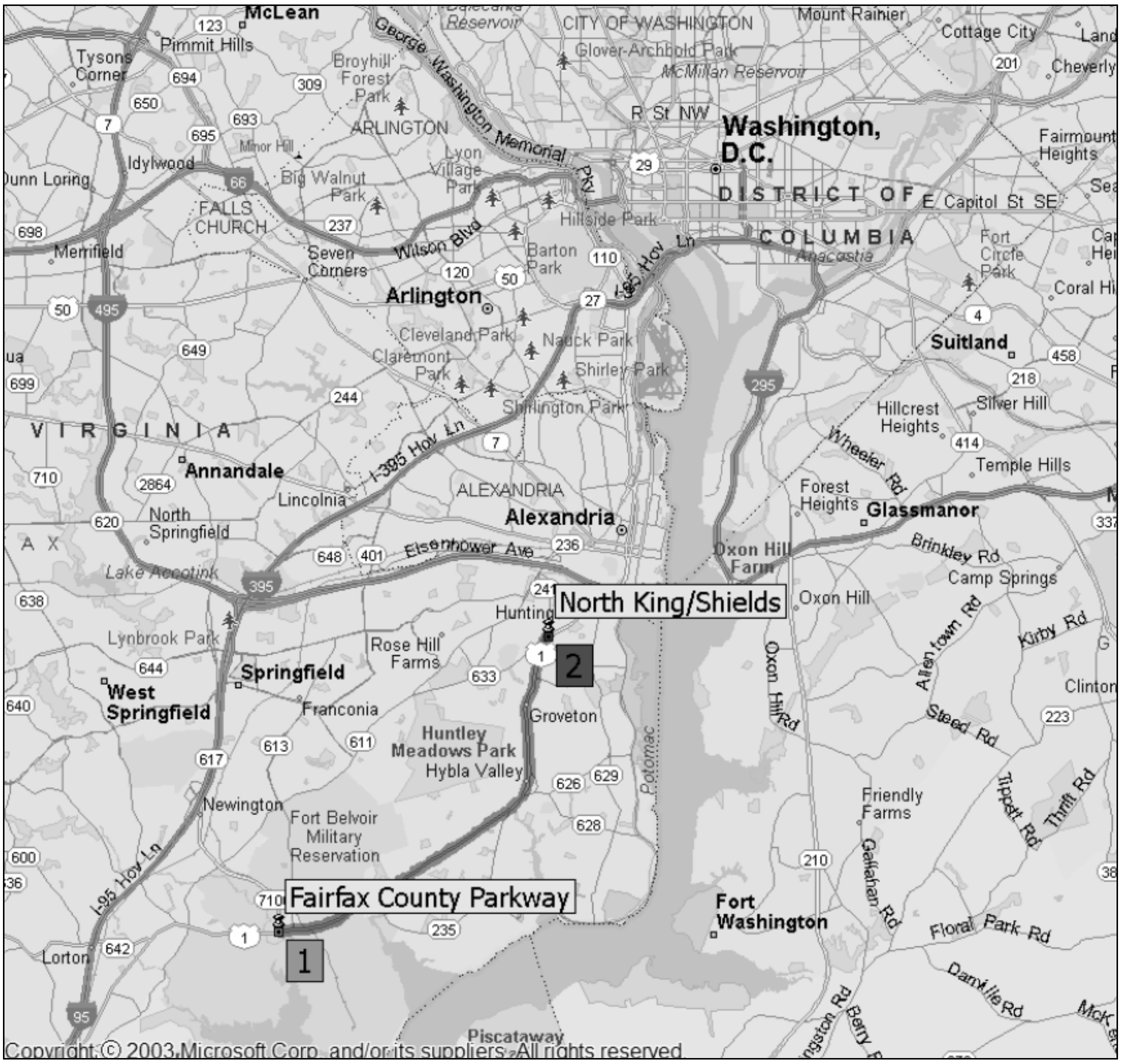

Figure 1. U.S. 1 Study Corridor

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 a.m. period. Traffic flows along the corridor are typically directional, however, the a.m. peak period also carries a significant traffic demand in the southbound direction. During the morning peak (6:30 – 9:30 a.m.), 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 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 1400 m.

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 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 an access to the Washington Metrorail Service. It should be noted that the large red 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 a.m. peak period that is equally distributed between northbound and southbound trips. Transit route 171 operated at a 30-minute headway during the a.m. peak period.

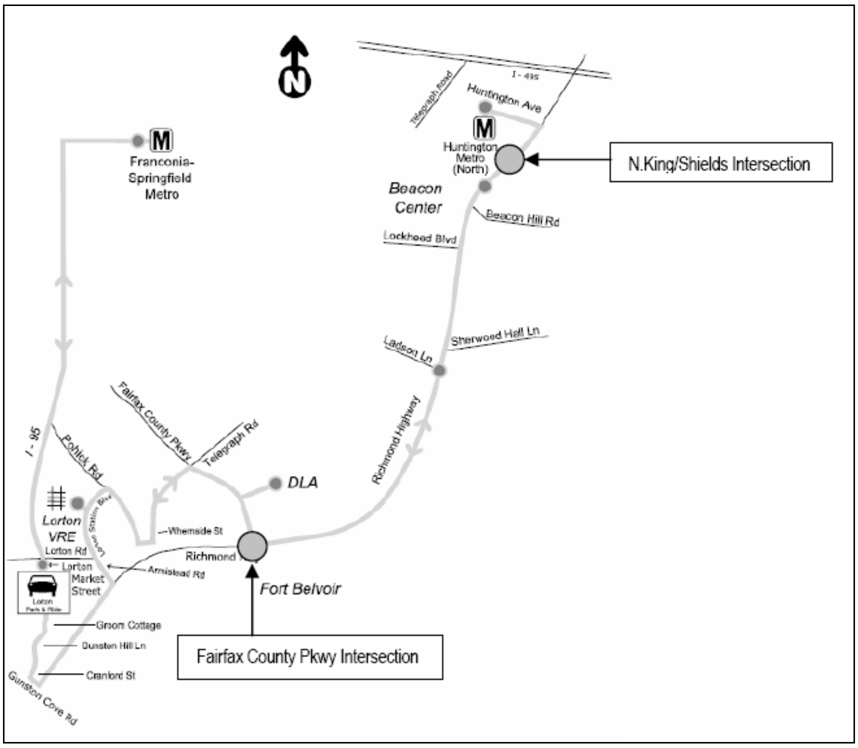

Figure 2. 171 Bus Route and Study Corridor 1

Transit Signal Priority Logic

TSP can improve transit vehicle operations through passive priority, early green (red truncation), green extension, transit phase actuation, phase insertion, phase rotation, and/or adaptive/real-time signal control (Baker et al. 2002). The priority logic that was implemented along the study corridor involved simple green extension and will be described in this section.

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. Consequently, the transit vehicle is 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 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 green extension of 10 s because of the high traffic demand and long cycle length (180 seconds) along the corridor. The 3M Opticom emitter system was utilized. The 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 is set up on the traffic signal head. The TSP system is processed when the optical detector receives a request from a transit vehicle during a green indication if there is no ongoing pedestrian phase at the time and no emergency vehicle preemption call is being made simultaneously.

GPS Data Collection Procedures

Global positioning system (GPS) technology is increasingly being used for transportation-related applications. The study utilizes portable WAAS-enabled GPS receivers to gather second-by-second transit vehicle trajectories along the U.S. 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 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 the bus route 171. 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 percent 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 values of standard deviation were ranged from 2:31 to 3:06 while the travel time errors were between 7 percent and 13 percent. 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 the 171 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. peak 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. 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 after 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.

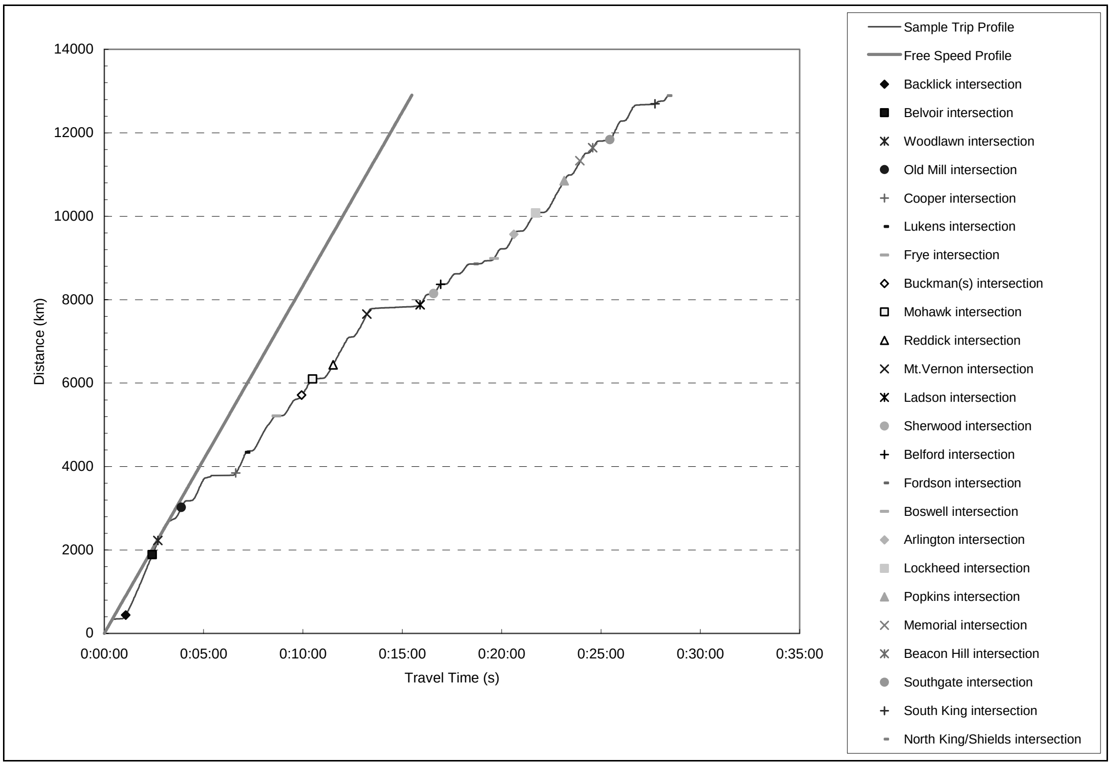

Figure 3. Time-Space Trajectory for Sample Transit Vehicle

RESULTS

The travel time frequency plots for transit vehicles are illustrated in Figure 4. 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 percent for the northbound and southbound directions, respectively, as summarized in Table 2. In order to confirm the results, t-tests were performed at a 5 percent significance level assuming identical mean travel times for both cases. The t-test for the northbound trips produces 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.

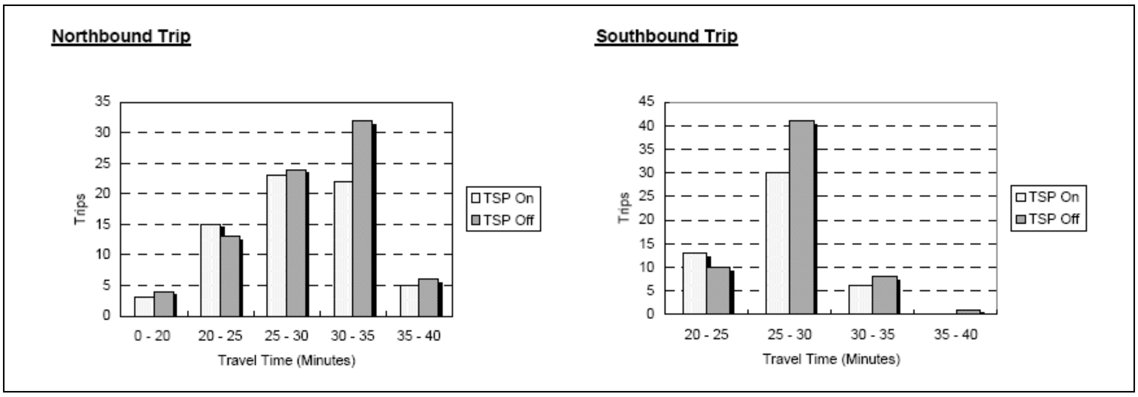

Figure 4. Transit Vehicle Travel Time Distribution

Table 2. 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	

Similarly, Table 3 summarizes the impact of TSP on transit vehicle travel times for the a.m. peak, midday peak, and non-peak periods, where the a.m. peak period is defined between 6:30 and 9:30 a.m., the midday peak is defined between 11:00 a.m. and 2:00 p.m., and the non-peak period is between 9:30 and 11:00 a.m. Table 3 demonstrates that green-extension TSP can produce savings in transit vehicle travel times in the range of 3 to 6 percent 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 a.m. peak period and the southbound direction for the midday peak. Interestingly, the results demonstrate a higher average travel time for the midday-peak period in comparison to the a.m. 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 a.m. peak period trips reduced the travel time significantly with a p-value of 0.01.

Table 3. 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 affects the total travel time. Table 4 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 4, 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 percent of total bus stops) on the U.S. 1 study area, according to the collected data.

Table 4. 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 second	15 second
	Standard Deviation of Dwelling Time	11 second	8 second
Single Trip	Average Dwelling Time	73 second	71 second
	Standard Deviation of Dwelling Time	31 second	37 second

Figure 5 illustrates a plot of travel time vs. traveled distance which is similar to 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 explains the variability in travel times along the study corridor in a same scheduled trip. In general, the figure shows that the TSP activated trips (eight trips) has shorter travel times than the trip (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 finish the trip within 30 min.

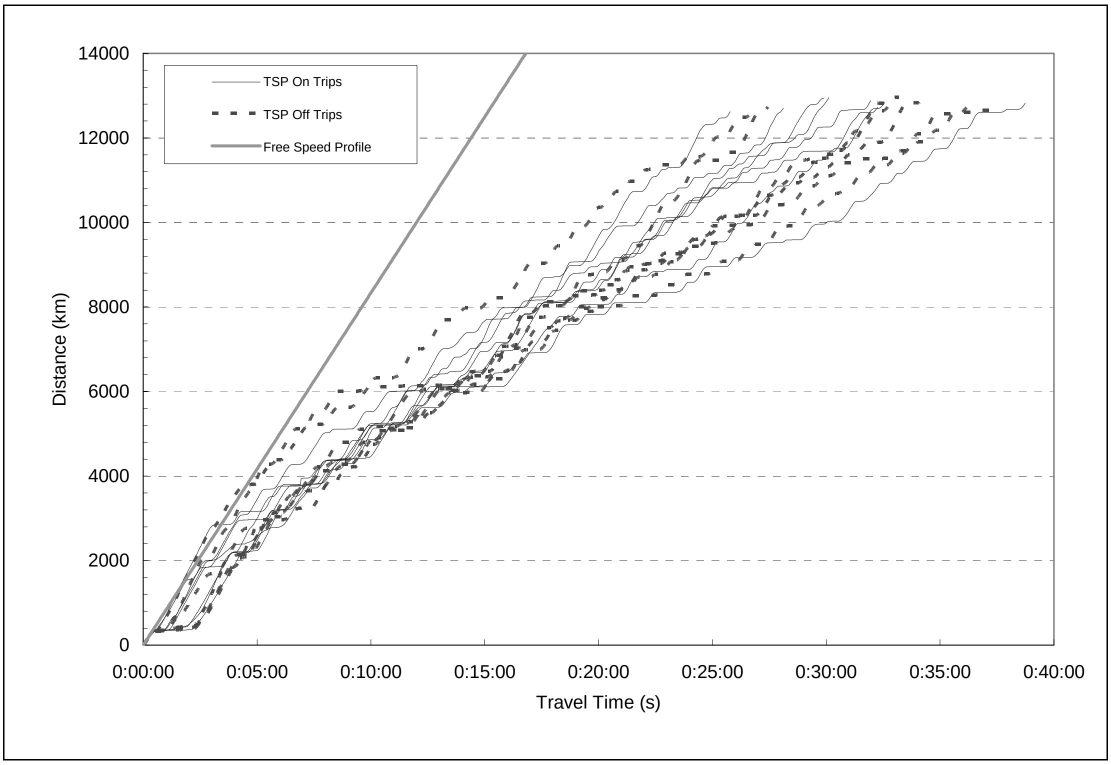

Figure 5. Time-Space Trajectory for Bus 7859 Midday Peak Trips

The detailed distance-time diagrams of the fifty percentile travel times (median travel times) of Figure 5 are illustrated in Figure 6. The figure demonstrates the TSP-on trip saves about 3 min of travel time compared to the TSP-off trip. During the early stage of the trip, the speed of the TSP-off bus was faster than the TSP-on bus. Specifically, the traditionally operated bus arrived at Reddick intersection 3 min earlier than the transit-priority-activated bus. However the TSP-off bus was delayed about 4 min at Reddick intersection and further delays were discovered at several intersections resulting the longer travel time than TSP bus. The long delay at Reddick intersection can explain the benefit of the green-time extension strategy. Since green extension is granted when a transit vehicle is expected to arrive at a traffic signal a few seconds after the end of the green indication, such a long delay which experienced at Reddick by the TSP-off bus is generally not experienced on the TPS-on bus.

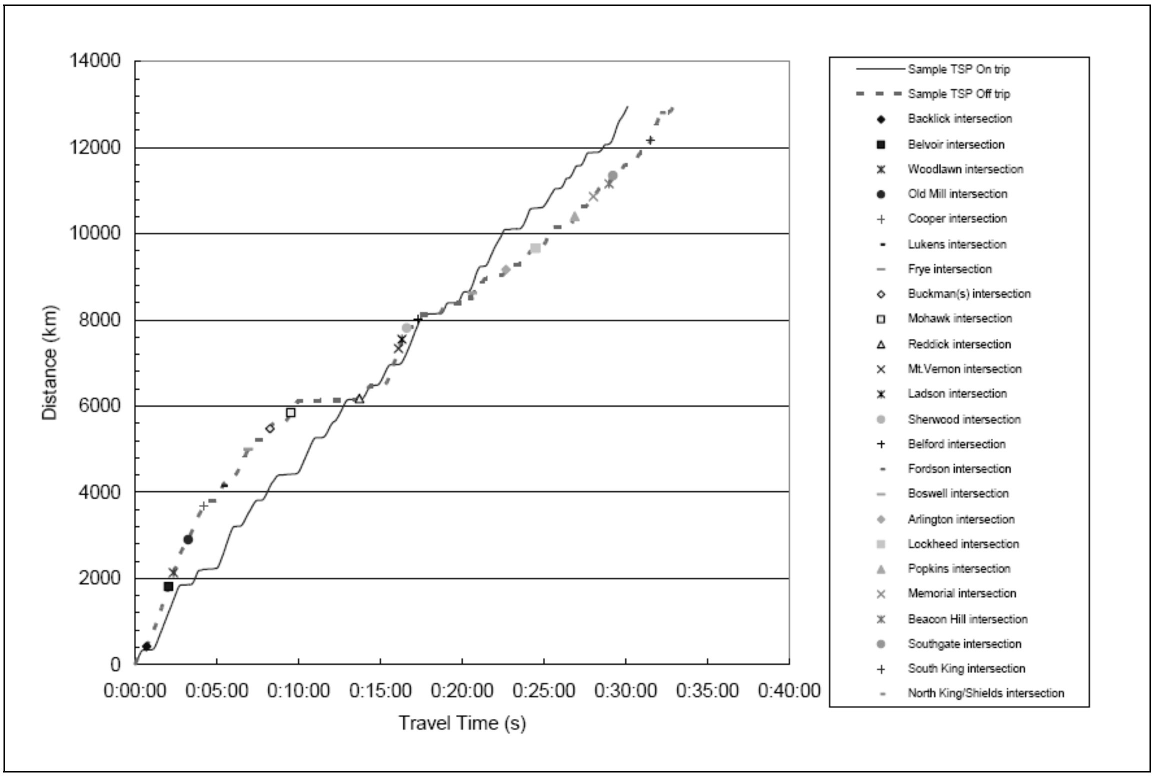

Figure 6. Impact of TSP Operation

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 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). It should be noted that 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 100-meter stop bar was chosen to increase the number of intersection to measure the delays since the GPS data analysis can't differentiate 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 7. For example, the average delay for the entire a.m. analysis period (6:30 a.m. to 2:00 p.m.) at the 12 northbound intersections is decreased from 8.62 s to 7.47 s, which represents a 13.3 percent reduction. Similarly, the green extension TSP significantly reduces the intersection delay by 23 percent 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 percent are observed for the a.m. peak and non-peak periods. Interestingly, Figure 7 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 percent significance level assuming equal means. The results demonstrate that for the entire analysis period (6:30 a.m. to 2:00 p.m.) and the midday peak period (11:00 a.m. to 2:00 p.m.) the hypothesis is statistically significant with 0.005 and 0.01 p-values. However, the a.m. peak and off-peak period results were not statistically significant.

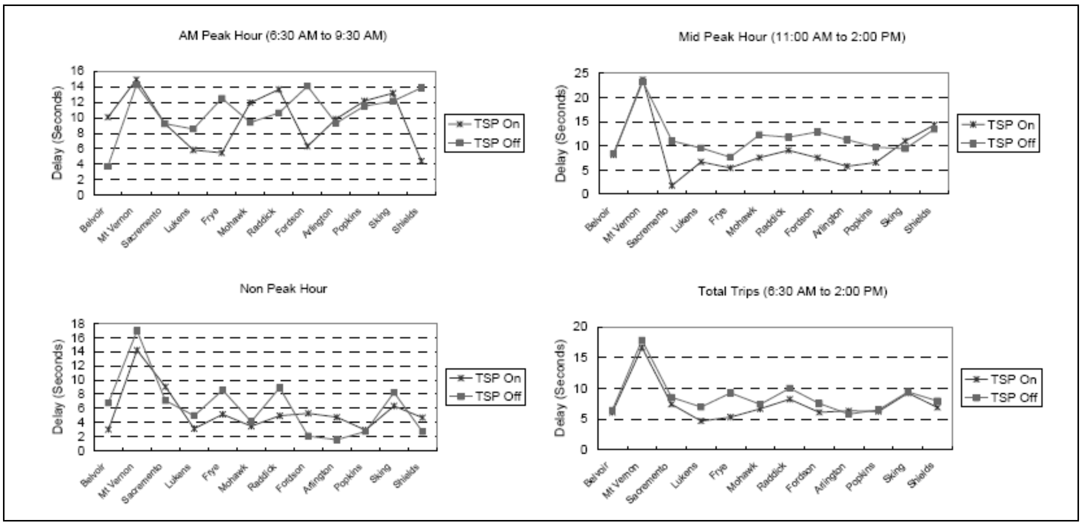

Figure 7. Intersection Delays for Northbound Trips

The approach delays for travel in the southbound direction demonstrate no clear benefit for TSP, as illustrated in Figure 8. Instead, increases in approach delays are observed at the Belvior, Mt. Vernon/Old Mill, Sacramento, and Popkins intersections during the midday peak period with delay increases as high as 20 s at the Sacramento 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 percent from 7.36 s to 5.79 s. Finally, it is interesting to note that the delay at the intersection with Frye St. is less than 1s in most cases.

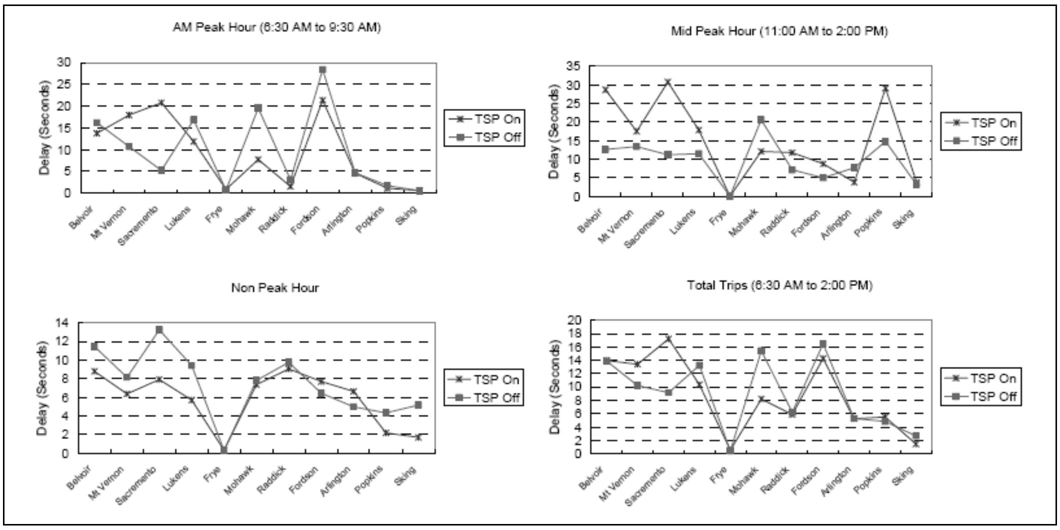

Figure 8. Intersection Delays for Southbound Trips

CONCLUSIONS

The findings are summarized as follows:

- The study demonstrated the effectiveness of WAAS-enabled GPS receiver technology in the evaluation of TSP.
- 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.
- The 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.
- The benefit of TSP can be improved when the green extension is utilized at roads where the cycle length is shorter.

RECOMMENDATIONS

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

- The system-wide impacts of TSP for various congestion levels should be investigated. Varying the congestion level could result in different results and possibly identify the range of congestion levels for which green-extension TSP can be effectively operated.
- 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 green-extension TSP. 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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