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Kun Zhou et al.

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Final Report

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16. ABSTRACT

This document reports the results of the evaluation of the Transit Signal Priority currently under operation at AC Transit. The paper discusses about the Measure of Effectiveness and a quantitative evaluation method for TSP. It reports the data collected and analysis conducted of the concerned TSP system and presented the evaluation results.

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Field Evaluation of San Pablo Corridor Transit Signal Priority (TSP) System

1 Overview of AC Transit Rapid 72R Corridor and TSP System

1.1 AC Transit Rapid 72R Corridor

The Alameda-Contra Costa Transit District (AC transit) began BRT (Bus Rapid Transit) service on its San Pablo Rapid line, Line 72R, on June 30, 2003. This rapid bus corridor is 13.5 miles long. The southern terminus is Jack London Square located in downtown Oakland, and the northern terminus is located at Contra Costa College in San Pablo. It runs through seven cities, Oakland, Emeryville, Berkeley, Albany, El Cerrito, Richmond, and San Pablo, and two counties, Alameda and Contra Costa, as illustrated in **Figure 1-1**. The Rapid operates every day from 6 am to 7 pm on a headway-based schedule of 12 minutes.

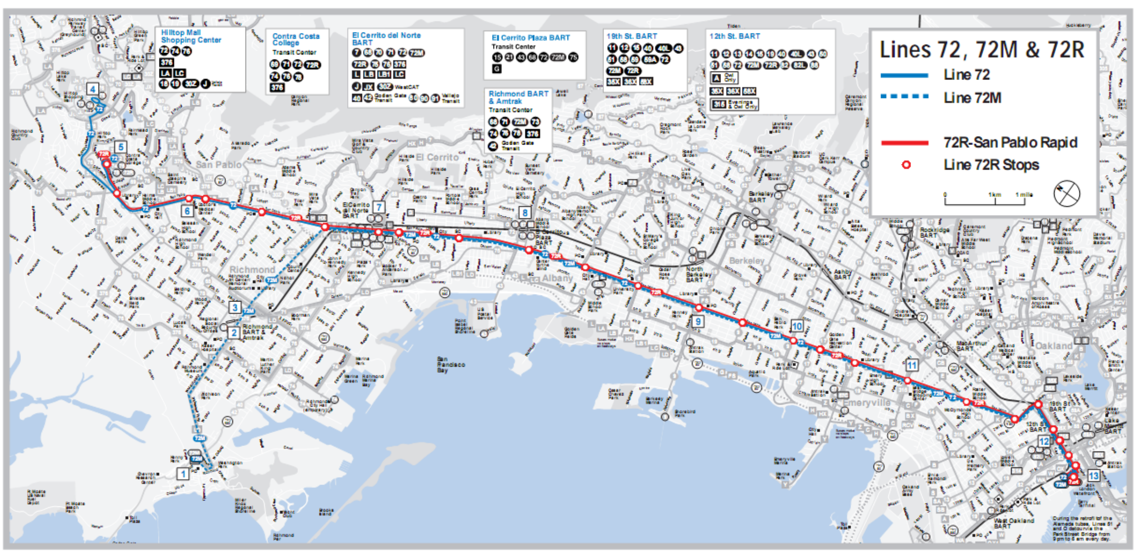

Figure 1-1 The AC Transit Rapid 72R Corridor[1]

1.2 Bus-Stops

This Rapid operates in mixed traffic and was developed with 27 stops located at major intersections. These stops are spaced 0.5 miles apart on average along the length of the corridor, with the minimum and the maximum distance between adjacent bus-stops at 63 meters and 1,505 meters, respectively. Most bus-stops are located at the far-side of intersections to decrease the overall travel time. Figure 1-2 illustrates the geographic layout of bus-stops along the Rapid line 72R.

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[1] Source: http://www.actransit.org

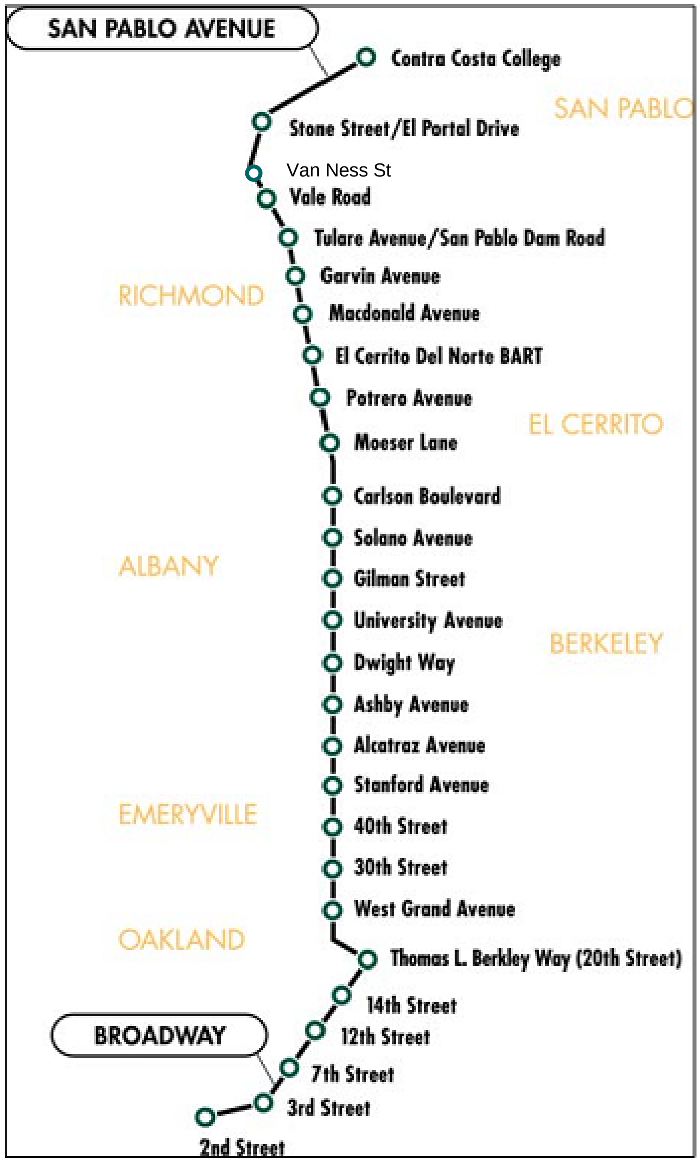

Figure 1-2 The AC Transit Rapid 72R Corridor[2]

1.3 Signalized Intersections

Rapid line 72R runs through 82 signalized intersections. The average distance between adjacent signalized intersections is 203 meters, with the minimum and maximum distance at 47 meter and 810 meters, respectively. Table 1-1 lists the locations of signalized intersections along the length of the corridor. GPS location of each signalized intersections is measured at the middle of the intersection box.

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[2] Source: The San Pablo Rapid BRT Project Evaluation, Final Report, Federal Transit Administration, June, 2006

Table 1-1 List of Signalized Intersections along Rapid Line 72R

INT ID	Cross Street	City	Latitude (degree)	Longitude (degree)	INT ID	Cross Street	City	Latitude (degree)	Longitude (degree)
1	3rd St	Oakland	37.7968	122.2759	42	W Addison St	Emeryville	37.8678	122.2917
2	5th St	Oakland	37.7981	122.2751	43	University Ave	Berkeley	37.8692	122.2921
3	6th St	Oakland	37.7988	122.2746	44	Delaware Ave	Berkeley	37.8717	122.2930
4	7th St	Oakland	37.7995	122.2742	45	Dedar Ave	Berkeley	37.8752	122.2941
5	8th St	Oakland	37.8002	122.2738	46	Gilman St	Berkeley	37.8805	122.2958
6	9th St	Oakland	37.8009	122.2733	47	Monroe St	Berkeley	37.8846	122.2971
7	10th St	Oakland	37.8016	122.2729	48	Marin Ave	Berkeley	37.8868	122.2978
8	11th St	Oakland	37.8022	122.2725	49	Bachnanan St	Berkeley	37.8878	122.2982
9	12th St	Oakland	37.8029	122.2720	50	Solano Ave	Albany	37.8903	122.2990
10	13th St	Oakland	37.8036	122.2716	51	Washington Ave	Albany	37.8923	122.2996
11	14th St	Oakland	37.8043	122.2712	52	Clay St	Albany	37.8961	122.3008
12	15th St	Oakland	37.8053	122.2706	53	Brighton Ave	Albany	37.8967	122.3010
13	16th St	Oakland	37.8058	122.2703	54	Carlson Blvd	El Cerrito	37.8990	122.3019
14	17th St	Oakland	37.8066	122.2697	55	Fairmount Ave	El Cerrito	37.9006	122.3026
15	19th St	Oakland	37.8078	122.2690	56	Central Ave	El Cerrito	37.9022	122.3034
16	20th St	Oakland	37.8091	122.2682	57	Stockton Ave	El Cerrito	37.9077	122.3062
17	20th Ave at Telegraph Ave.	Oakland	37.8095	122.2696	58	Moeser Ln	El Cerrito	37.9113	122.3086
18	20th Ave	Oakland	37.8102	122.2732	59	Schmidt Ln	El Cerrito	37.9141	122.3105
19	Castro Ave	Oakland	37.8115	122.2737	60	Manila Ave	El Cerrito	37.9157	122.3116
20	W Grand Ave	Oakland	37.8127	122.2740	61	Potrero Ave	El Cerrito	37.9207	122.3151
21	Brush Ave	Oakland	37.8135	122.2743	62	Hill St	El Cerrito	37.9236	122.3172
22	25th Ave	Oakland	37.8154	122.2748	63	Cutting Blvd	El Cerrito	37.9254	122.3185
23	27th Ave	Oakland	37.8178	122.2756	64	Knott Ave	El Cerrito	37.9266	122.3193
24	Market St	Oakland	37.8202	122.2764	65	Conlon Ave	El Cerrito	37.9296	122.3214
25	31st Ave	Oakland	37.8215	122.2768	66	Macdonald Ave	El Cerrito	37.9323	122.3234
26	35th Ave	Oakland	37.8264	122.2784	67	Barrett Ave	Richmond	37.9353	122.3251
27	36th Ave	Oakland	37.8270	122.2786	68	Roosevelt Ave	Richmond	37.9370	122.3258
28	Adeline St	Oakland	37.8287	122.2792	69	?	Richmond	37.9387	122.3266
29	40th Ave	Oakland	37.8310	122.2799	70	Clinton Ave	Richmond	37.9404	122.3275
30	Park Ave	Oakland	37.8324	122.2802	71	Solano Ave	Richmond	37.9421	122.3283
31	45th Ave	Oakland	37.8342	122.2809	72	Garvin Ave	Richmond	37.9437	122.3291
32	47th Ave	Oakland	37.8356	122.2814	73	Esmond Ave	Richmond	37.9452	122.3298
33	53rd Ave	Oakland	37.8372	122.2818	74	McBryde Ave	Richmond	37.9473	122.3308
34	Stanford Ave	Oakland	37.8409	122.2831	75	Rheem Ave	Richmond	37.9498	122.3320
35	E 63rd Ave	Oakland	37.8457	122.2846	76	FoodMax Plz	Richmond	37.9518	122.3329
36	W 63rd Ave	Oakland	37.8461	122.2847	77	San Pablo Dam Rd	Richmond	37.9533	122.3336
37	Alcatraz Ave	Oakland	37.8470	122.2850	78	Vale Rd	Richmond	37.9556	122.3357
38	Ashby Ave	Emeryville	37.8521	122.2867	79	Van Ness St	Richmond	37.9605	122.3426
39	Grayson St	Emeryville	37.8562	122.2880	80	23rd Ave	San Pablo	37.9627	122.3454
40	Dwight Way	Emeryville	37.8611	122.2896	81	International Market Plz	San Pablo	37.9650	122.3451
41	Allston Way	Emeryville	37.8664	122.2913	82	El Portal Dr	San Pablo	37.9674	122.3442

1.4 San Pablo Corridor TSP System

The Rapid employs several forms of Intelligent Transportation Systems (ITS) to help in the operations, including the use of Transit Signal Priority (TSP), the Automated Vehicle Locator (AVL), Automated Passenger Counters (APC), and real-time bus arrival information displays that are located inside the shelters at most bus-stops.

The San Pablo corridor TSP system utilizes 3M's Opticom TSP system to detect the presence of transit buses, to generate TSP calls and uses enhanced traffic signal control software developed by Caltrans to control TSP operations.

The Opticom system uses infrared based communications between the buses and the signalized intersections to detect the approach of a transit bus. The primary components of the system are emitters mounted on the front of buses, an optical detector mounted on the signal head, and a phase selectors installed in the roadside controller cabinet. When activated, the bus emitter sends a frequency coded optical message that identifies the bus to the detector. The detector then sends a signal to the signal controller via the phase selector to request TSP operations. The signal is dropped when the bus has cleared the intersection, and a check-out call is placed to terminate an on-going TSP execution.

The signal control system in place along San Pablo corridor is a closed-loop distributed control system with Model 170E controllers operating Caltrans C-8 local traffic signal controller software. The enhancements for TSP have been incorporated by updating the C-8 software to provide two types of TSP operations, Early Green which returns green earlier to the bus approach, and Green Extension which hold the green longer to allow the bus clear the intersection before the signal indication changes. Upon receiving a TSP call via the phase selector, the TSP control logic is as follows:

- If the green on the bus approach is on, the green is extended until either the maximum allowable green extension time (ten seconds) is reached or a check-out call is received;
- If the green is off, force-off points for all minor phases are moved forward by 20% until the signal returns green to the bus approach.

Optical detectors have been installed on the worst congested roadway segment along line 72R corridor to provide TSP operations. The 7.5 mile long TSP segment consists of 37 signalized intersections between 35th Ave in Oakland and Hill St in El Cerrito.

2 Measures of Effectiveness

Measures of effectiveness (MOEs) provide the basis for any TSP evaluation study. The California PATH program has developed a set of comprehensive MOEs that can be used for site-to-site comparison of TSP systems. These MOEs are classified into the following three categories to quantify the impacts of TSP operations on different stakeholders.

2.1 TSP System Performance

Any benefits of TSP operations depend on whether the TSP system fulfills its designed functionality. The MOEs that fall into this category capture the performance of the TSP system itself, identify operations problems and provide suggestions for improvement.

<u>Intersection-based MOEs</u>

- Transit vehicle detection rate at TSP enabled intersections
- Successful priority execution rate at TSP enabled intersections

<u>Trip-based MOEs</u>

- Number of detections per bus per one-way trip
- Number of successful executions per bus per one-way trip

2.2 Benefits of TSP Operations on Transit Vehicles

The MOEs that fall into this category quantify the benefits of TSP operations to the quality of transit service.

<u>Intersection-based MOEs</u>

- Transit vehicle stop rate due to red signal phase
- Transit vehicle stopped time due to red signal phase

<u>Trip-based MOEs</u>

- Trip travel time, in terms of dwell time, stopped time due to red signal phases and running time

2.3 Impacts of TSP Operations to Traffic

MOEs in this category quantify the impact of TSP operations on non-transit traffic. In particular, these measures describe impacts on cross-street and mainline left-turn traffic (i.e., minor-phase traffic).

Traffic Impacts of TSP Operations

- Traffic delay at prioritized intersections.

3 Field Data Collection

3.1 Architecture of Data Collection System

Three types of field data need to be collected to evaluate TSP system performance: transit operations data, traffic operations data and TSP operations data. Figure 3-1 illustrates the physical architecture of the data collection system used for this study.

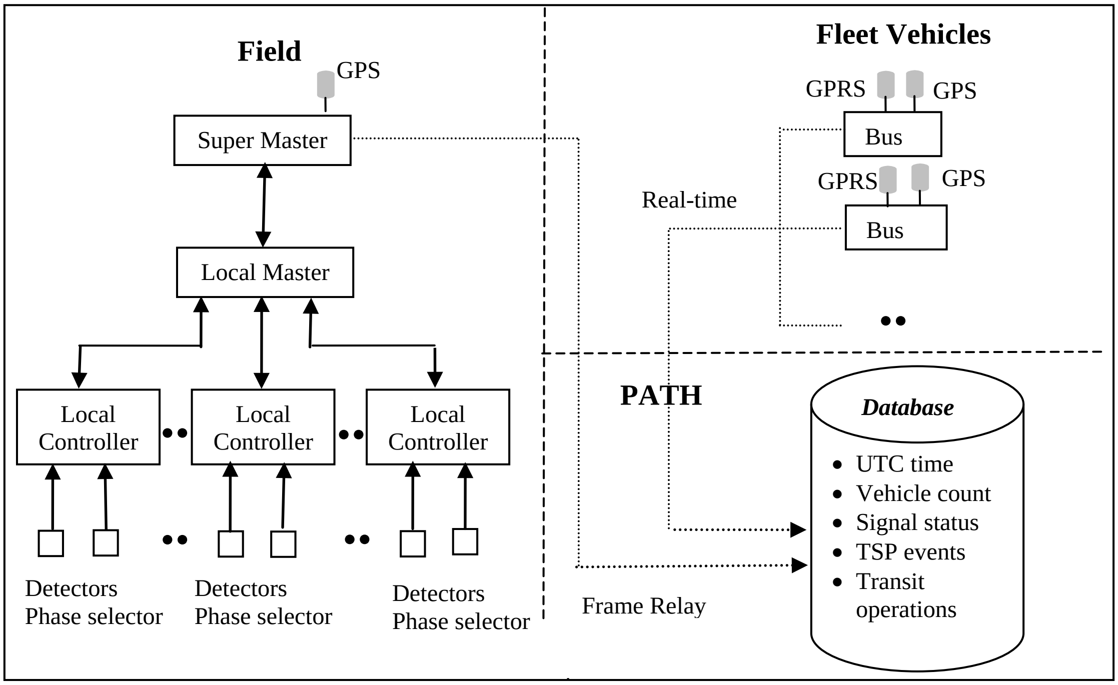

Figure 3-1Physical Architecture of Data Collection System

The signal control system in place is a closed-loop system with control logic distributed among three levels: the local controller, the on-street master and the super master. Typically, the local controller receives information from loop detectors and Opticom phase selectors, the local master controller receives information from the local controller, and the super master enables the system operator to monitor and control the system's operation based on data collected from the field. The data available from the signal control system include time-of-day timing plans, traffic counts, occupancy, and signal status. The resolution is every one to two seconds. The database also logs every TSP event data, including the type of request (early green/green extension), requested time and execution condition. The data are polled and stored in super-master computers that are located inside traffic cabinets together with field masters. The data are retrieved regularly from the field via a frame relay connection.

Cell phone based GPS/GPRS communication devices have been installed on 12 buses serving Line 72R for the purpose of collecting transit operations data. The wireless devices automatically forward bus GPS data (UTC time, latitude, longitude, and speed over ground) to the computer located at PATH's traffic lab. The sampling rate of GPS data updates is 1 second.

3.2 Description of Data Collection Procedures

The data used in this report were collected from March 5, 2007 to May 25, 2007. Data collection was conducted in the following two periods:

- Period 1 (03/05/2007 to 04/27/2007): “after” (with TSP scenario) data collection with the emitters activated for the 12 buses, so they could request priority, and
- Period 2 (05/02/2007 to 05/25/2007): “before” (without TSP scenario) data collection, with the emitters being deactivated for the 12 buses, so they could not request priority.

Within each period, data were collected at the following three different times of day:

- Morning Peak (AM): 7 am to 11 am;
- Mid-day Peak (MD): 11 am to 3 pm; and
- Afternoon Peak (PM): 3 pm to 7 pm

The peaks were selected based on the traffic profiles along the corridor, and are consistent with the signal timing plans in use. The traffic, signal status, and TSP event data were independently collected from transit operations data but within the same time periods, thus both types of data can be synchronized.

3.3 Summary of Collected Bus One-Way Trips

Table 3-1 summarizes the collected effective bus one-way trips for the “before” scenario and “after” scenario, in terms of time-of-day and travel direction. A total of 375 and 774 bus one-way trips were collected for the “before” and “after” scenario, respectively. Note that there are more bus trips being collected during the 3-month data collection period. However, some of the trip data have large GPS data noise and blockages. Those data are excluded from this study.

Table 3-1 Number of Collected Effective Bus One-Way Trips

	Northbound		Southbound	
	“Before” Scenario	“After” Scenario	“Before” Scenario	“After” Scenario
Morning Peak	56	104	99	137
Mid-day Peak	49	123	71	155
Afternoon Peak	30	119	70	136
Total	135	346	240	428

3.4 Summary of Collected TSP Event Log Data

Although the 37 signalized intersections, between 35th Ave in Oakland and Hill St in El Cerrito, all have TSP functionality enabled, TSP event log data were only available at 16 intersections. The reason for missing TSP event log data is that either the intersection belongs to a local city that does not record TSP events or there were communication issues between the local controller and the master controller. Table 3-2 lists the 16 intersections that have TSP event log data available for this study.

Table 3-2 List of Intersections with TSP Event Log Data Available

Intersection ID	Cross Street	City
28	Adeline St	Oakland
29	40th Ave	Oakland
30	Park Ave	Oakland
31	45th Ave	Oakland
32	47th Ave	Oakland
33	53rd Ave	Oakland
48	Marin Ave	Berkeley
49	Bachnanan St	Berkeley
50	Solano Ave	Albany
51	Washington Ave	Albany
52	Clay St	Albany
53	Brighton Ave	Albany
56	Central Ave	El Cerrito
58	Moeser Ln	El Cerrito
59	Schmidt Ln	El Cerrito
61	Potrero Ave	El Cerrito

4 Data Analysis

The goal of this evaluation study was to assess the effectiveness of the San Pablo corridor TSP system. The study aims to provide AC Transit and Caltrans with a quantitative description of the benefits and impacts, if any, associated with implementing signal priority technology on transit and non-transit vehicle traffic. Data analysis was carried out to quantify the MOEs described in section 2 of this report.

4.1 TSP System Performance

Collected bus one-way trip data and TSP event log data at the 16 intersections listed in Table 3-2 were used to evaluate the functionalities of the TSP system.

4.1.1 The Need for Priority

Prior to evaluating the performance of the TSP system itself, it is necessarily to understand the need for TSP operations. The need for priority varies from intersection to intersection, because the characteristics (e. g., traffic volume, signal timing, and bus arrival time) are intersection specific. At the intersection level, two questions need to be answered: how frequently a bus would stop due to a red signal phase, i.e. the intersection stop rate and how long it would remain stationary, i.e. the average actual stopped time. At each intersection, the product of intersection stop rate and the average actual stopped time, i.e. the average stopped time due to the signal, provides a measure of the need for priority. The greater the average stopped time, the greater the need for priority. In this study, a speed threshold of 5 MPH was used to differentiate a stopped status from a moving status. This threshold was selected based on the histogram of bus speed as recorded by GPS.

Figure 4-1 and Figure 4-2 illustrate the average intersection stopped time for northbound and southbound trips, respectively.

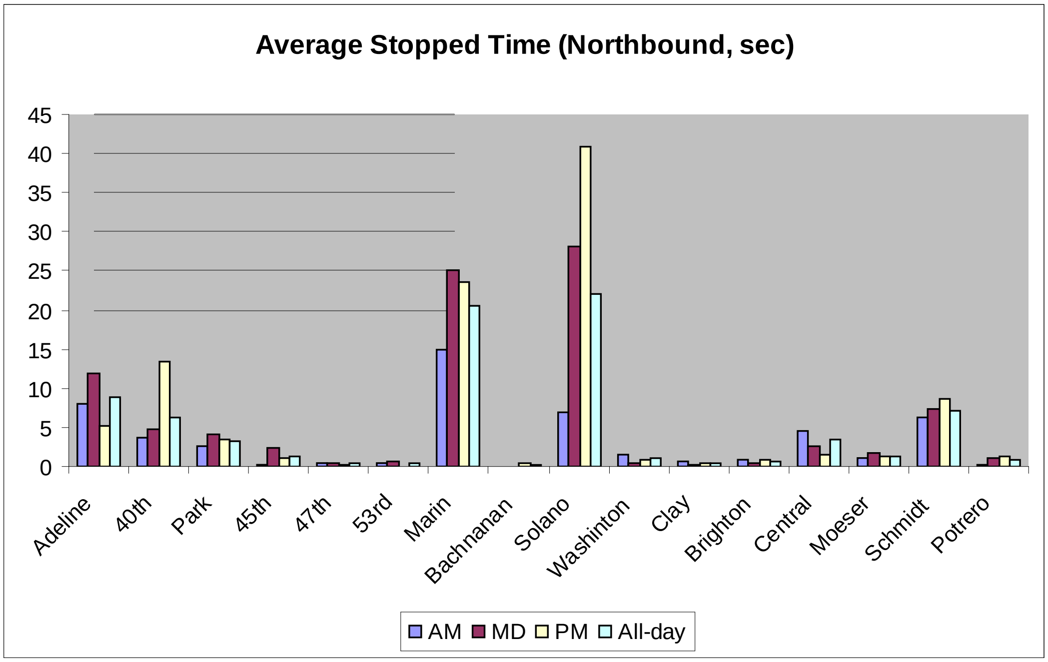

Figure 4-1 Average Intersection Stopped Time (Northbound, without TSP)

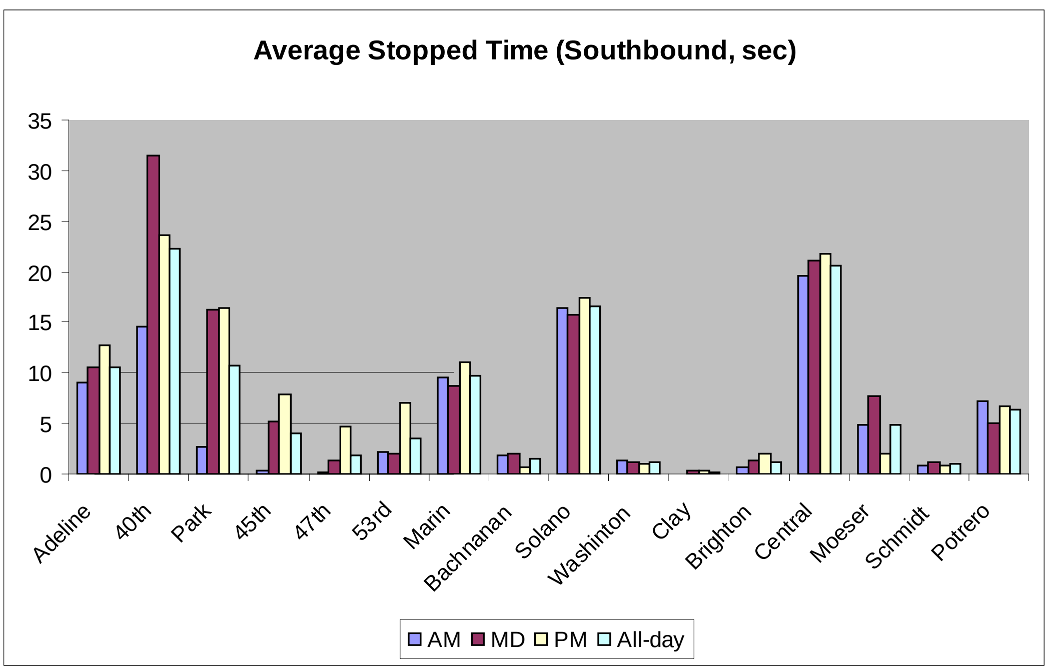

Figure 4-2 Average Intersection Stopped Time (Southbound, without TSP)

The top five intersections that need priority in the northbound direction are Solano Ave, Marin Ave, Adeline St, Schmidt Lane, and 40th Ave. The top five on southbound are 40th Ave, Central Ave, Solano Ave, Park Ave, and Adeline St, followed closely by Marin Ave. Based on the recorded stopped time, TSP should perform well at these intersections.

4.1.2 Transit Vehicle Detection Rate

In order to obtain priority, a transit vehicle needs to be detected first by the Opticom system and be registered to the signal controller to request TSP operations. Ideally, the detection rate should be 100 percent, as whenever a bus is within the field of view of the detector it should be detected. In reality, the detection rate is always lower than the ideal rate due to a number of reasons such as the line-of-sight between the emitter and the detector being blocked, a dirty lens on the emitter and/or receiver or communication errors.

Figure 4-3 and Figure 4-4 illustrate the bus detection rate at northbound and southbound intersections, respectively. At each intersection, the detection rates are very consistent in terms of time-of-day. Among the top intersections that need priority, several intersections have detection rates lower than 50 percent. Two intersections, northbound at Solano Ave and southbound at Park Ave, have extremely low detection rates (less than 5%). The causes of the failure in detecting transit vehicles at these intersections need to be identified and resolved to further improve the TSP system performance.

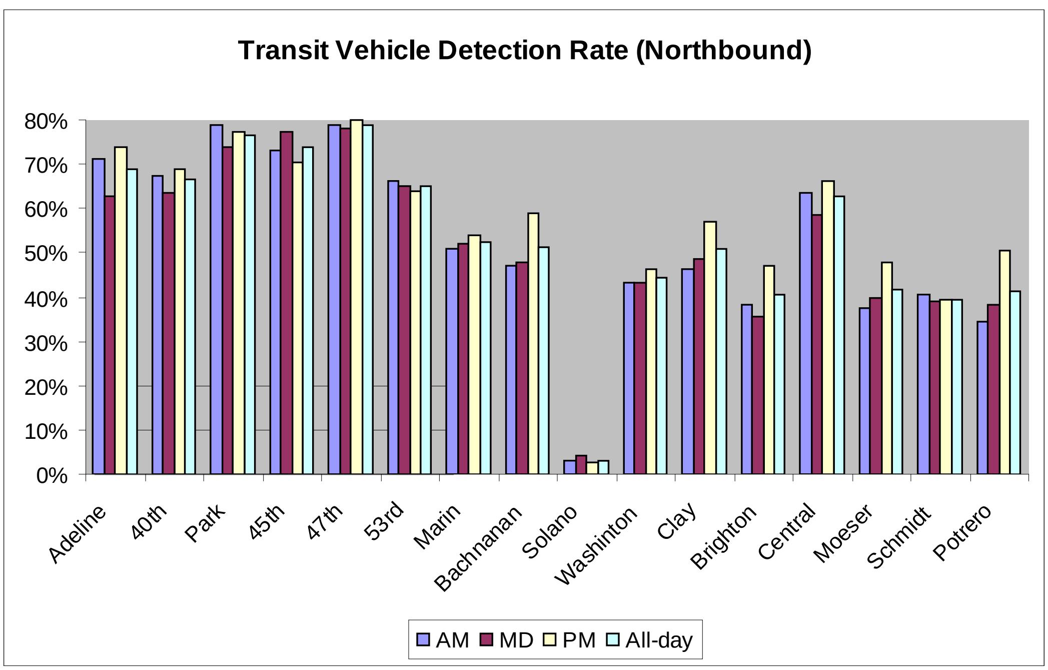

Figure 4-3 Transit Vehicle Detection Rate on Northbound

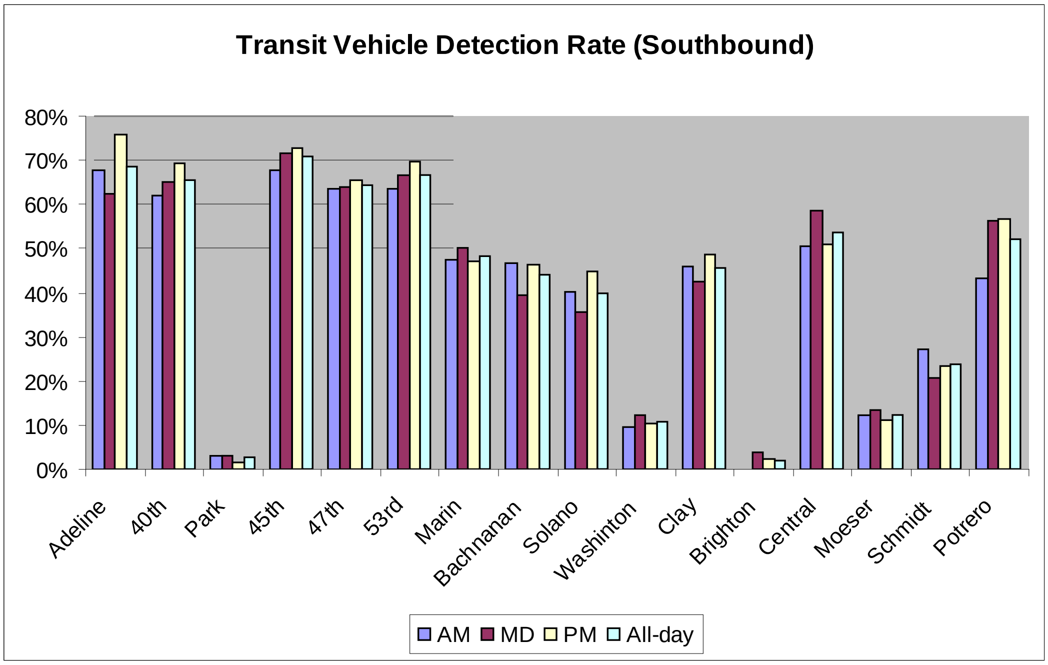

Figure 4-4 Transit Vehicle Detection Rate on Southbound

4.1.3 TSP Execution Rate

When a local controller receives a priority request, it grants the priority based on pre-determined criteria. Not all executions can benefit a bus. For example, if an Early Green call was placed during the yellow or all-red interval of the phase just prior to the bus phase, the bus gains no benefit from the execution as the yellow and all-red interval can not be reduced. Another example is if a Green Extension call was placed, but the bus passes the intersection during the normal green interval. Therefore, we defined the execution rate as the rate of successful executions. The result is presented in Table 4-1. Priority execution rates are also consistent in terms of time-of-day. Among the top intersections that need priority, most intersections have higher priority execution rates. The exceptions are northbound at Solano Ave and southbound at Park Ave and Central Ave.

Table 4-1 Priority Execution Rate (%)

INT ID	Cross St	Direction	Morning Peak			Mid-day Peak			Afternoon Peak		
			EG	GE	Total	EG	GE	Total	EG	GE	Total
28	Adeline St	Northbound	19.2	6.7	26.0	19.5	7.3	26.8	26.1	5.9	31.9
		Southbound	29.2	16.8	46.0	35.5	7.7	43.2	38.2	11.8	50.0
29	40th Ave	Northbound	19.2	5.8	25.0	13.0	9.8	22.8	9.2	8.4	17.6
		Southbound	12.4	16.1	28.5	11.0	18.1	29.0	24.3	11.8	36.0
30	Park Ave	Northbound	2.9	46.2	49.0	10.6	37.4	48.0	12.6	46.2	58.8
		Southbound	0.0	0.0	0.0	1.3	0.0	1.3	0.0	0.0	0.0
31	45th Ave	Northbound	4.8	4.8	9.6	18.7	4.1	22.8	20.2	3.4	23.5
		Southbound	5.1	13.1	18.2	8.4	9.0	17.4	10.3	12.5	22.8
32	47th Ave	Northbound	9.6	4.8	14.4	9.8	4.1	13.8	16.8	3.4	20.2
		Southbound	1.5	8.0	9.5	7.1	5.8	12.9	0.7	5.1	5.9
33	53rd Ave	Northbound	2.9	6.7	9.6	2.4	2.4	4.9	5.0	2.5	7.6
		Southbound	10.9	19.7	30.7	13.5	21.3	34.8	10.3	19.1	29.4
48	Marin Ave	Northbound	26.0	5.8	31.7	22.8	4.9	27.6	20.2	8.4	28.6
		Southbound	27.7	1.5	29.2	27.1	7.1	34.2	30.9	1.5	32.4
49	Bachnanan St	Northbound	0.0	0.0	0.0	0.0	0.8	0.8	5.0	8.4	13.4
		Southbound	11.7	0.7	12.4	5.8	0.0	5.8	5.9	3.7	9.6
50	Solano Ave	Northbound	1.0	1.9	2.9	1.6	1.6	3.3	1.7	0.0	1.7
		Southbound	14.6	8.0	22.6	14.8	3.2	18.1	16.9	2.9	19.9
51	Washington Ave	Northbound	5.8	0.0	5.8	4.9	3.3	8.1	8.4	4.2	12.6
		Southbound	0.7	0.0	0.7	2.6	0.6	3.2	2.2	0.0	2.2
52	Clay St	Northbound	0.0	1.0	1.0	0.8	0.0	0.8	1.7	0.8	2.5
		Southbound	1.5	0.7	2.2	2.6	1.9	4.5	6.6	1.5	8.1
53	Brighton Ave	Northbound	0.0	0.0	0.0	0.8	0.8	1.6	0.8	1.7	2.5
		Southbound	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0
56	Central Ave	Northbound	0.0	0.0	0.0	0.8	0.0	0.8	0.8	0.0	0.8
		Southbound	0.7	0.0	0.7	0.6	0.6	1.3	0.7	0.7	1.5
58	Moeser Ln	Northbound	7.7	1.0	8.7	2.4	2.4	4.9	4.2	0.0	4.2
		Southbound	5.8	0.0	5.8	3.9	0.0	3.9	2.9	0.7	3.7
59	Schmidt Ln	Northbound	13.5	1.9	15.4	10.6	3.3	13.8	9.2	2.5	11.8
		Southbound	5.1	0.7	5.8	2.6	1.9	4.5	2.9	2.9	5.9
61	Potrero Ave	Northbound	7.7	1.0	8.7	4.1	3.3	7.3	6.7	4.2	10.9
		Southbound	11.7	2.9	14.6	20.6	2.6	23.2	15.4	3.7	19.1

EG: successful Early Green execution
GE: successful Green Extension execution

4.1.4 Number of Detections and Number of Executions per Bus One-Way Trip

Figure 4-5 and Figure 4-6 illustrate the number of detections and number of successful executions per bus one-way trip. For the purpose of comparison, the number of stops at the 16 signalized intersections is also included. On average, when traveling northbound, the bus stopped at 3 intersections and the system generated 9 priority requests. Of those, two were successfully executed. The numbers are 4, 7 and two, respectively, for southbound trips.

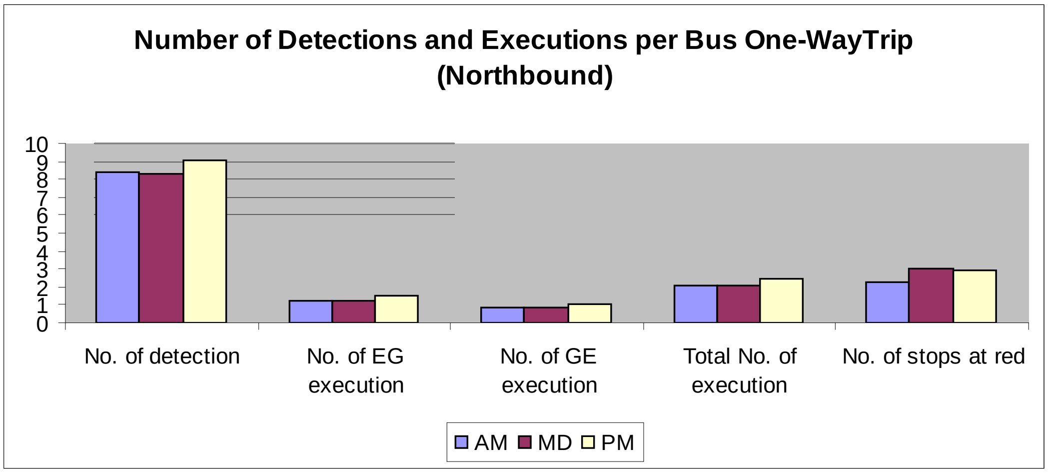

Figure 4-5 Number of Detections and Executions per Trip on Northbound

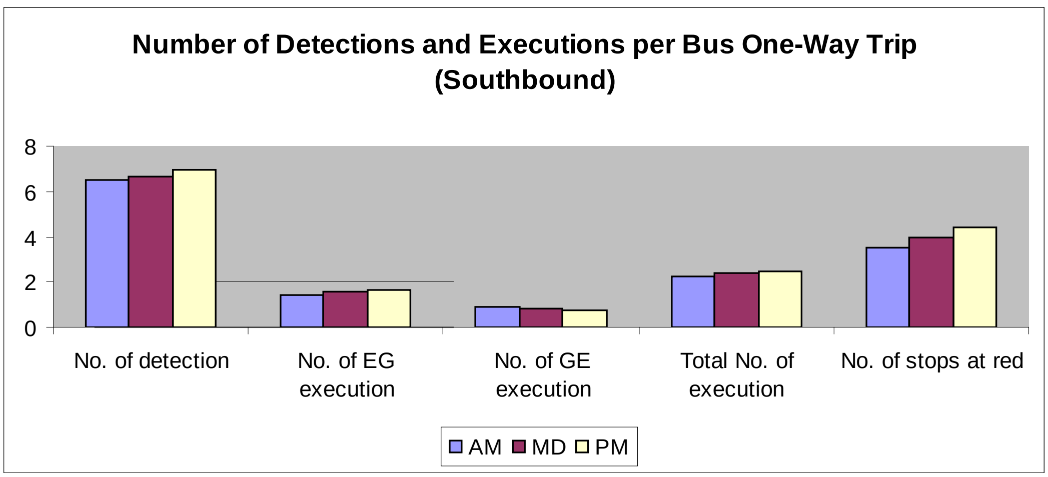

Figure 4-6 Number of Detections and Executions per Trip on Southbound

4.2 Benefits of TSP Operations on Transit Vehicles

Synchronized bus location data and signal status data make it possible to quantify bus intersection delay. Bus travel time can be broken down into three components as shown:

Travel time = Dwell time (at bus stops) + Stopped time (at signals) + Running time

Benefits of TSP operations on transit vehicles can be represented at the intersection level, in terms of changes in intersection stop rates and average stopped time, and at the trip level, in terms of total trip travel time, running time and stopped time at signals.

4.2.1 Intersection Stop Rate

Figure 4-7 and Figure 4-8 compare bus stop rates at the 16 intersections for the scenarios of “with TSP” and “without TSP.”.

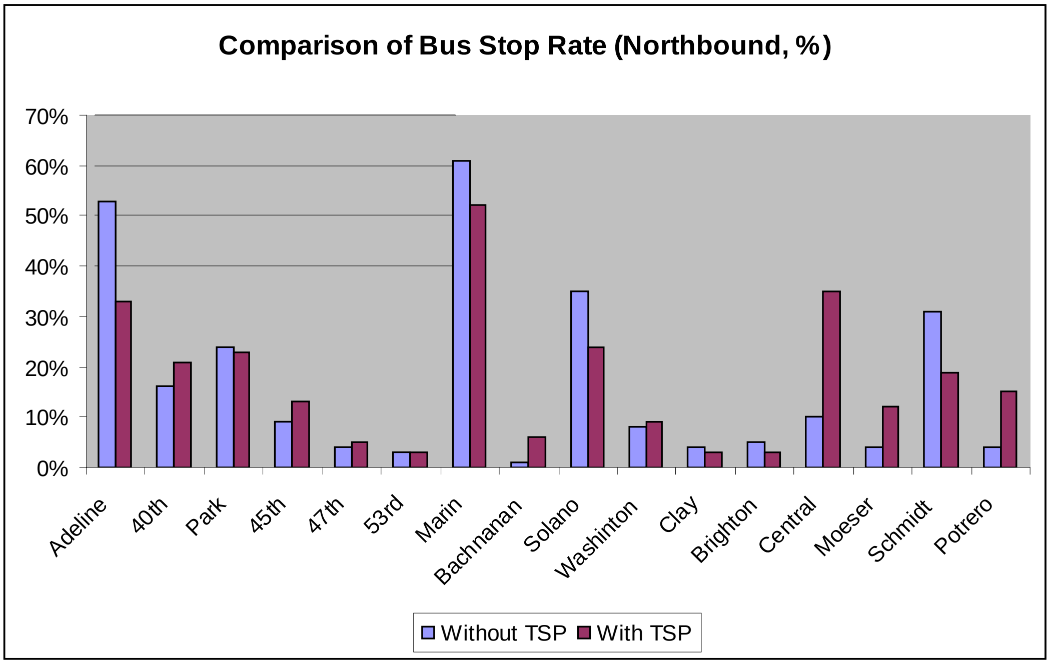

Figure 4-7 Comparison of Intersection Stop Rates on Northbound

At the top five northbound intersections that were determined to need priority the most, TSP operations significantly reduced stop rate at Solano Ave (-11%), Marin Ave (-9%), Adeline St (-22%) and Schmidt Lane (-12%). However, TSP slightly increased the stop rate at 40th Ave (+5%).

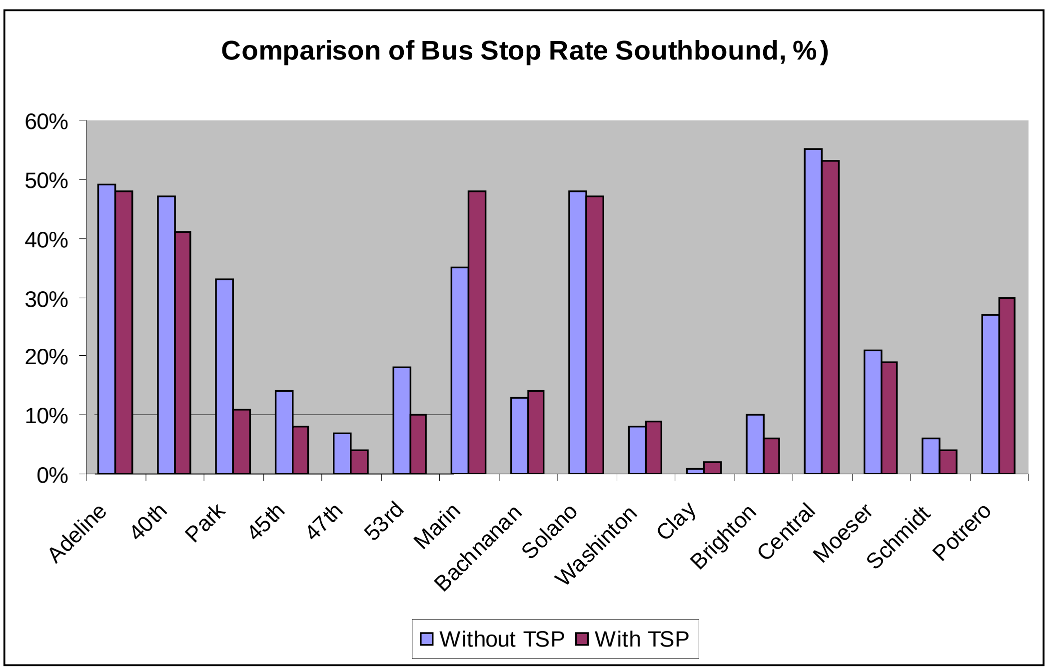

Figure 4-8 Comparison of Intersection Stop Rates on Southbound

At the top five southbound intersections that were determined to need priority the most, TSP operations reduced stop rates at all of the intersections, more specifically, a 6% reduction at 40th Ave, 2% at Central Ave, 1% at Solano Ave, 22% at Park Ave, and 1% at Adeline St.

4.2.2 Average Intersection Stopped Time

Figure 4-9 and Figure 4-10 compare the average intersection stopped time at the 16 intersections for the scenarios of “with TSP” and “without TSP.” The changes at the intersections marked with a yellow dot are statistically significant at the 5% level.

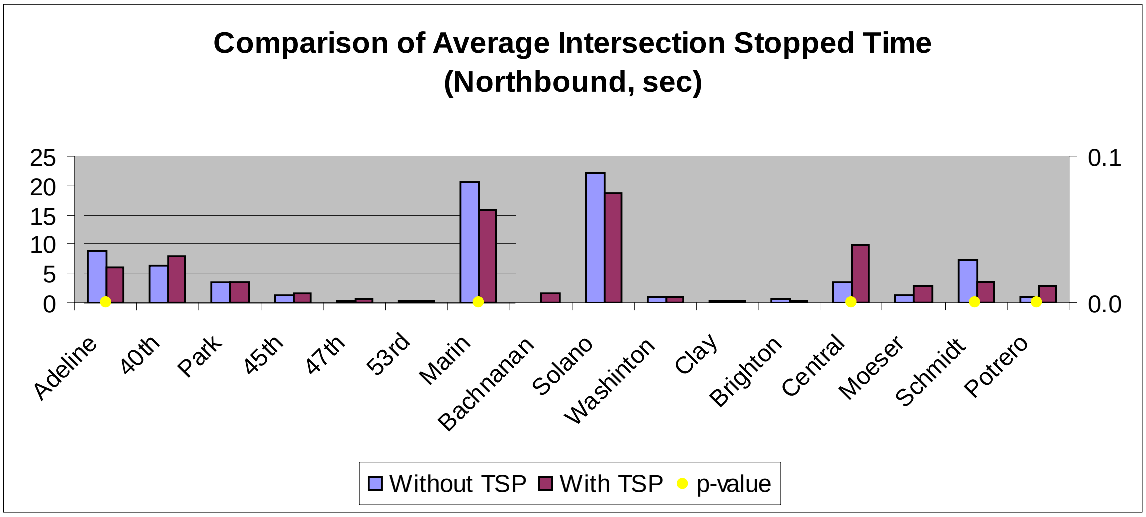

Figure 4-9 Comparison of Average Intersection Stopped Time on Northbound

On northbound trips, the significant changes occurred at Adeline St (reduced 3 seconds), Marin Ave (reduced 5 seconds), Central Ave (increased 6 seconds), Schmidt St (reduced 4 seconds), and Potrero Ave (increased 2 seconds).

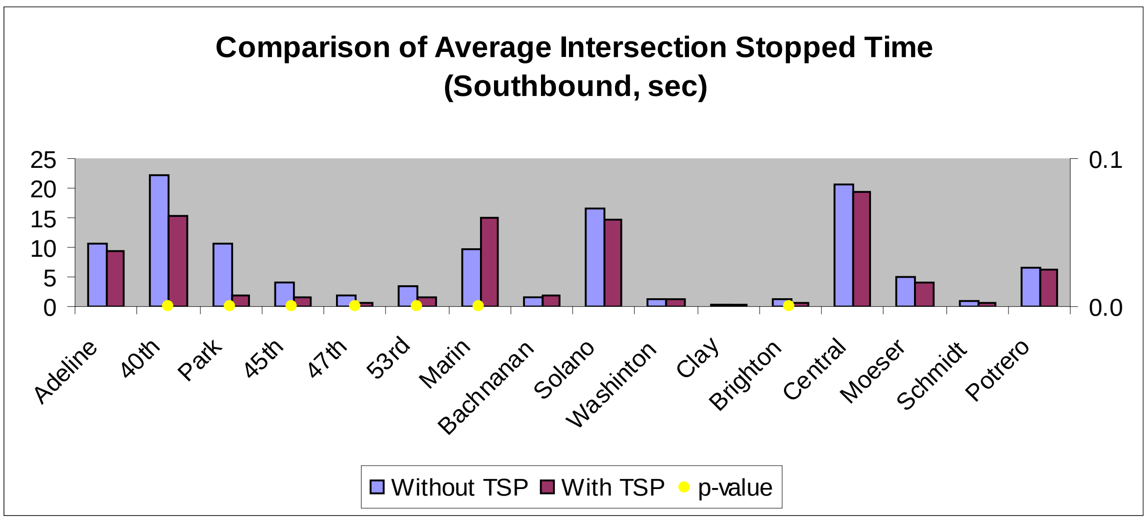

Figure 4-10 Comparison of Average Intersection Stopped Time on Southbound

On southbound trips, the significant changes occurred at 40th Ave (reduced 7 seconds), Park Ave (reduced 9 seconds), 45th Ave (reduced 3 seconds), 47th Ave (reduced 1 second), 53rd Ave (reduced 2 seconds), Marin Ave (increased 5 seconds), and Brighton Ave (reduced 1 second).

4.2.3 Actual Stopped Time per Prioritized Intersection

At isolated intersections, TSP operations can reduce bus intersection delay. On the Rapid bus lines, there are normally several intersections between two consecutive bus-stops. The amount of delay savings at a prioritized intersection is affected by the TSP execution at a particular intersection as well as priority executions at upstream intersections. Upstream executions can change the chance of stopping and the actual stopped time at downstream intersections. This explains the situation that TSP operations can increase the bus stop rate and the average stopped time at some intersections, as described in the previous two sections. The actual stopped time per prioritized intersection per bus trip is used to quantify the TSP impacts on bus intersection delay. The comparison results are presented in Table 4-2. In this comparison, all of the 37 prioritized intersections are considered. On average, TSP operations reduced the actual stopped time per prioritized intersection by 8.2% (or 2.4 seconds) on northbound trips and by 10.1% (or 3.1 seconds) on southbound trips.

Table 4-2 Actual Stopped Time per Prioritized Intersection per Bus Trip

	Without TSP (second)	With TSP (second)	Change		t-test (p-value)
			Value	Percentage	
Northbound	29.1	26.7	-2.4	-8.2%	0.0053
Southbound	30.4	27.3	-3.1	-10.1%	0.0000

4.2.4 Trip Travel Time, Dwell Time, Running Time and Stopped Time

Table 4-3 compares the trip-based MOEs for the scenarios of “without TSP” and “with TSP”. In most cases, TSP operations reduced bus travel time, total intersection delay and running time. TSP impacts on bus travel time have a strong relationship with the changes in the number of stops at red signals. In cases where the number of stops at red was reduced, transit vehicles gained benefits from TSP operations. The changes in travel time, total intersection delay and running time for these cases are statistically significant at 5% level of significance. For example, for the mid-day southbound bus trips, bus travel time was reduced by 7% (221 seconds), total intersection delay was reduced by 16% (104 seconds), total running time was reduced by 5% (118 seconds). Therefore bus average traveling speed was increased by 5%. In cases that the number of stops at red was increased, such as afternoon-peak northbound bus trips, the impacts are statistically insignificant.

Table 4-3 Comparison of Trip Time / Total Intersection Delay

Direction	MOE	Time-of-Day	Without TSP	With TSP	Change		t-test (p-value)
					Value	%	
Northbound	Travel Time (minutes)	Morning Peak	45.5	44.1	-1.4*	-3.1%*	0.0162*
		Mid-Day Peak	50.2	48.9	-1.3	-2.5%	0.0570
		Afternoon Peak	53.5	54.0	0.5	1.0%	0.6739
	Running Time (minutes)	Morning Peak	38.4	37.5	-0.8*	-2.2%*	0.0244*
		Mid-Day Peak	40.6	40.0	-0.6	-1.6%	0.1103
		Afternoon Peak	41.7	42.7	1.1	2.5%	0.0984
	Total Intersection Stopped Time (minutes)	Morning Peak	7.1	6.5	-0.6	-8.2%	0.0822
		Mid-Day Peak	9.6	9.0	-0.7	-6.8%	0.1120
		Afternoon Peak	11.8	11.3	-0.5	-4.4%	0.4853
	Dwell Time (minutes)	Morning Peak	4.9	5.7	0.8*	17.1%*	0.0224*
		Mid-Day Peak	5.5	6.5	1.0*	18.1%*	0.0234*
		Afternoon Peak	7.6	8.0	0.4	5.5%	0.5571
	Number of Stops at Red Signal	Morning Peak	17.4	16.7	-0.7	-4.0%	0.2196
		Mid-Day Peak	20.6	20.5	-0.1	-0.5%	0.8699
		Afternoon Peak	22.7	23.6	0.9	4.0%	0.3231
Southbound	Travel Time (minutes)	Morning Peak	48.6	47.3	-1.3*	-2.6%*	0.0138*
		Mid-Day Peak	53.3	49.6	-3.7*	-6.9%*	0.0000*
		Afternoon Peak	53.6	52.4	-1.2	-2.3%	0.1244
	Running Time (minutes)	Morning Peak	39.8	39.4	-0.4	-1.0%	0.2186
		Mid-Day Peak	42.3	40.3	-2.0*	-4.6%*	0.0000*
		Afternoon Peak	42.6	42.1	-0.4	-1.0%	0.3832
	Total Intersection Stopped Time (minutes)	Morning Peak	8.7	7.8	-0.9*	-9.9%*	0.0036*
		Mid-Day Peak	11.0	9.3	-1.7*	-15.7%*	0.0001*
		Afternoon Peak	11.1	10.3	-0.8	-7.1%	0.0839
	Dwell Time (minutes)	Morning Peak	7.7	7.3	-0.4	-5.4%	0.3406
		Mid-Day Peak	7.3	7.0	-0.3	-4.2%	0.4797
		Afternoon Peak	7.2	7.2	0.1	1.1%	0.8757
	Number of Stops at Red Signal	Morning Peak	18.7	18.3	-0.4	-2.1%	0.3462
		Mid-Day Peak	21.0	19.6	-1.4*	-6.7%*	0.0064*
		Afternoon Peak	20.9	21.0	0.1	0.5%	0.9690

* Significant at 5% level of significance

4.3 Impacts of TSP Operations on Traffic

Traffic delay at prioritized intersection is the major measure of TSP impacts to traffic. To make a meaningful comparison, the delays of "without TSP" are averaged across multiple cycles, corresponding to, in terms of time-of-day, the cases of "with TSP". The delays of "with TSP" are averaged across only three cycles, including the cycle of TSP execution and the immediately preceding and following cycles. Note that the definition of average delay "with TSP" here is different from the one used in many previous evaluations, such as the evaluation of LADOT/LAMTA's signal priority system. There, delay is averaged across a certain period of time encapsulating all cycles, whether impacted by TSP operation or not. With such a definition, if TSP operation is infrequent, the calculated average delay would not change when compared with the scenario of "without TSP".

The prioritized intersection at Potrero Ave was selected for the evaluation of the TSP impacts on traffic. For each early green execution the average green time stolen from the minor phase traffic was 6 seconds; and that for each green extension execution was 5 seconds. Table 4-4 compares the traffic delays for the scenario of "without TSP" and "with TSP", in terms of the types of granted priority. TSP operations reduced major phase traffic delay as that traffic shares the right-of-way with the transit vehicles. The negative impacts on minor phase (or cross street) traffic were minor, within 2 seconds per vehicle.

Table 4-4 Comparison of Traffic Delays

	Early Green Execution		Green Extension Execution	
	Major phase delay	Minor phase delay	Major phase delay	Minor phase delay
Without TSP (sec/veh)	17.5	36.3	17.2	38.1
With TSP (sec/veh)	16.3	38.1	16.4	38.2
Changes (sec/veh)	-1.2	1.8	-0.8	0.0
Changes in %	-7.0%	5.0%	-4.8%	0.1%

5 Summary and Recommendations for Further System Improvement

AC Transit began its BRT service, the Rapid 72R line, on June 30, 2003. This 13.5 mile long bus corridor, the San Pablo corridor, covers a total of 82 signalized intersections as well as 27 bus-stops. 37 out of the 82 intersections are TSP enabled to reduce the transit travel time along the corridor. The TSP system utilizes 3M's Opticom TSP system to detect the presence of transit vehicles and to request TSP operations to the signal controller. The enhancements for TSP operations developed by Caltrans have been incorporated by updating the C-8 software to provide early green and green extension treatments.

The goal of this study was to assess the effectiveness of the San Pablo corridor TSP system. A data collection system was set up to collect synchronized traffic and transit operations data. The traffic data were collected through the signal control system and include traffic counts, occupancy, and signal status. The data resolution was every two seconds. TSP event log data such as priority requests, requested times and execution conditions were also collected. In addition, locations of transit vehicles were recorded second by second via a portable GPS/GPRS device installed on 12 Rapid 72R buses operating in the corridor. Data were transmitted via those devices to a data server computer located at PATH traffic lab.

Field operations data used in this study were collected from March 5, 2007 and May 25, 2007. The collections of "after" survey data ("with TSP") and "before" survey data ("without TSP") were conducted in sequence: from March 5, 2007 to April 27, 2007 for "after" survey with emitters active on the 12 buses, and from May 2, 2007 to May 25, 2007 for "before" survey, with the 23 buses having de-activated emitters.

The collected data were then analyzed to evaluate the performance of the TSP system, the main concerns being fulfillment of system functionality and TSP impacts on transit vehicles and on traffic.

TSP System Performance

On average, the transit vehicle's detection rate at prioritized intersection is about 50%. The detection rates at intersections that buses made most frequent stops were within a reasonable range. However, the detection rates at Solano Ave northbound and Park Ave southbound were extremely low, while transit bus stop rate at those locations is relatively high.

Along the 16 sampling prioritized intersections, the bus stopped at 3 intersections when traveling on northbound and 4 while southbound. The TSP system generated 9 northbound priority requestsand 7 southbound requests. Of those requests, two northbound and two southbound requests were successfully executed.

TSP Impacts on Transit Vehicles

At intersections that transit vehicles made the most frequent stops, TSP operations were likely to reduce bus intersection stop rate and stopped time. The actual stopped time per prioritized intersection per trip was reduced by 8.2% (2.4 seconds) on northbound and reduced by 10.1% (3.1 seconds) on southbound trips. The reductions are statistically significant at the 5% level of significance.

In most cases, TSP operations reduced bus travel time, total intersection delay and running time. It was found that TSP impacts on bus travel time have a strong relationship with the changes in number of stops at red signals. In cases where the number of stops at red was reduced, transit vehicles gained benefits from TSP operations. The changes in travel time, total intersection delay and running time are statistically significant at 5% level of significance for those cases. For example, on the mid-day southbound bus trips, bus travel time was reduced by 7% (221 seconds), total intersection delay was reduced by 16% (104 seconds), total running time was reduced by 5% (118 seconds), and therefore bus average traveling speed was increased by 5%. In cases that the number of stops at red was increased, such as afternoon-peak northbound bus trips, the impacts are statistically insignificant.

TSP Impacts on Traffic

When granting priority to transit vehicles the signal controller managed to steal green time from the minor phase (or cross street) traffic. The average time stolen from the minor phase was 6 seconds for an early green execution and 5 seconds for a green extension.

Intersection delays were calculated for both the major phase traffic and the minor phase traffic to quantify the TSP impacts on traffic. For the case of "with TSP", the delay was averaged across three signal cycles, including the cycle of TSP execution and the immediately preceding and following cycles. With such a delay definition, the impacts are independent with the TSP execution rate.

TSP operations reduced major phase traffic delay, as that traffic shares the right-of-way with the transit vehicles, and increased the minor phase traffic delay. The changes in traffic delay were minor, all within 2 seconds per vehicle.

Recommendations for Further System Improvements

- Resolve the low detection rates at some intersections
- Enable TSP functionality at selected intersections that currently do not provide TSP
- Intelligently grant TSP taking into consideration the affects of the initial priority execution on the downstream intersections.