Sacramento-Watt Avenue Transit Priority and Mobility Enhancement Demonstration Project

Phase III Evaluation Report

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16. Abstract

This report presents the results of the national evaluation of the Sacramento-Watt Avenue Transit Signal Priority Project, a cooperative project between Sacramento County and the Sacramento Regional Transit District (RT) to deploy transit signal priority along a highly congested section of Watt Avenue just east of downtown Sacramento. The evaluation approach was to collect data to assess the impact of the transit signal priority on transit travel times and travel time reliability, and to determine if the addition of the system had an impact on traffic on either Watt Avenue or its cross-streets. Bus travel time data was manually collected on-board buses operating on the corridor before and after deployment of TSP, data from automated vehicle location devices on buses operating with and without TSP emitters was obtained, and travel time runs were conducted on Watt Avenue and its cross-streets before and after deployment of TSP. Data were compared to determine the impact of TSP. The results of the transit mobility and performance analysis showed that the average travel time for TSP equipped buses was between 14 and 71 seconds less than for non-TSP buses traveling over the same segments. For the control intersections (i.e., those without TSP), the travel times for TSP and non-TSP buses were similar, indicating that this difference can be attributed to the TSP. The results of the travel time reliability analysis showed that TSP did not significantly improve travel time reliability. For the segments of the corridor with TSP, TSP buses experienced better travel time reliability than non-TSP buses in two of the six time periods (as compared to one out of the six time periods when looking at non-TSP intersections. The results of the traveler mobility analysis was inconclusive. Although difficult to state with much certainty, the results indicated that the addition of TSP on Watt Avenue had somewhat of a positive impact on Watt Avenue traffic and somewhat of a negative impact on cross-street traffic.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AVL	Automated Vehicle Location
Caltrans	California Department of Transportation
CCTV	Closed Circuit Television
GPS	Global Positioning System
ITS	Intelligent Transportation Systems
LRT	Light Rail Transit
MOE	Measure of Effectiveness
RT	Sacramento Regional Transit District
TOC	Traffic Operations Center
TSP	Transit Signal Priority
USDOT	United States Department of Transportation

EXECUTIVE SUMMARY

This document presents the evaluation strategies and objectives, the data collection methodologies, and the results of the national evaluation of the Transit Signal Priority and Mobility Enhancement Demonstration Project in Sacramento, California.

PROJECT DESCRIPTION

Watt Avenue, a major north-south thoroughfare in suburban Sacramento County, is one of the major traffic crossings of the American River in Sacramento. Although there are three other river crossings within three miles to the west of Watt Avenue, there is an eight-mile gap between Watt Avenue and the next river crossing to the east. This channels a large volume of traffic to the American River Bridge at Watt Avenue. Traffic volumes on Watt Avenue in the vicinity of the bridge can exceed 100,000 vehicles per day, and congestion is a significant problem during peak periods.

One result of this congestion is that transit buses providing service along the six-mile stretch of Watt Avenue between Interstate 80 and Highway 50 are often significantly delayed. The two impacted bus routes are Sacramento Regional Transit District (RT) Routes 80 and 84. On weekdays and Saturdays, five buses provide service on these routes, operating on headways of approximately 30 minutes. On Sundays, two buses provide service, operating on headways of approximately 60 minutes. Travel time variability along these routes makes schedule adherence challenging during certain times of the day (travel time along the corridor by bus can take as few as 27 minutes, or as long as 51 minutes). To address these problems, Sacramento County and RT proposed deployment of TSP along this stretch of Watt Avenue.

TSP was implemented at 15 intersections along a 9.8-mile section of Watt Avenue (along Routes 80 and 84) from the Watt/I-80 light rail transit (LRT) station to the Watt/Manlove LRT station. Routes 80/84 follow Watt Avenue for most of this section with a brief detour to the west between Arden Way and Butano Drive. This portion of the routes includes a total of 37 bus stops in each direction and 30 signalized intersections.

The system provides "active priority" to buses, meaning that priority treatment is only provided when the signal controller detects a bus. The system provides priority in two ways:

- A "green extension" is provided when a bus approaches an intersection during the green phase without enough time to clear the intersection before the yellow phase. The signal maintains the green for up to ten additional seconds to give the bus an opportunity to clear the intersection. As the bus may be able to clear the intersection before the 10-second extension ends, the system halts the extension once the bus has cleared the intersection so as not to provide an excessive extension. The subsequent red phase is then reduced by the length of the extension in order to return the signal to its previous cycle.
- An "early green" (also referred to as a "red truncation") is provided when a bus approaches an intersection on the red phase. The signal returns to green ten seconds earlier than it would have otherwise (resulting in a 10-second truncation on the green phase of the cross-street). The total green phase is extended by 10 seconds, and the signal returns to its normal phasing at the conclusion of that cycle.

The system provides "unconditional priority", meaning that a bus is granted priority whenever it approaches the intersection, regardless of whether the bus is ahead of or behind schedule (some TSP systems use "conditional priority", meaning that the bus is only granted priority when certain requirements are met, such as that the bus is behind schedule by a certain number of minutes).

EVALUATION OVERVIEW

The primary goal of the national evaluation of the Sacramento-Watt Avenue Transit Signal Priority (TSP) project was to determine the impact of transit signal priority on transit operations. The other goal of the evaluation was to determine if the addition of transit signal priority would have an impact on traffic operations. Additionally, the evaluation aimed to gather and document the experiences and lessons learned of the stakeholders in deploying and operating the system so that other transit agencies might benefit from the experiences in Sacramento.

The evaluation studied the following hypotheses:

- TSP will improve transit mobility and performance by reducing travel times through the study area and by minimizing signal delay.
- TSP will improve travel time reliability and schedule reliability.
- TSP will improve traveler mobility in the corridor by reducing vehicle delay and travel times.

The evaluation involved three data collection and analysis components: (1) collecting and analyzing transit travel time data while on-board Route 80 and 84 buses before and after deployment of TSP; (2) obtaining and analyzing GPS data from the project stakeholders for buses operating on the corridor both with and without TSP; and (3) conducting and analyzing floating car run data on Watt Avenue and Watt Avenue's cross-streets before and after deployment of TSP. It should be noted that Sacramento County did not make any changes to signal timings along Watt Avenue during the course of the evaluation.

SUMMARY OF SYSTEM IMPACT STUDY FINDINGS

The findings of this evaluation are summarized here according to the two evaluation objectives:

- Assess the impacts of TSP on bus travel times and travel time reliability.
- Assess the impacts of TSP on traffic mobility.

Assess the Impacts of TSP on Bus Travel Times and Travel Time Reliability

In order to assess the impacts of TSP on transit travel times, the evaluation team conducted on-board observations of buses traveling along the corridor before and after deployment of transit signal priority. The evaluation team also obtained automated GPS data for buses operating on the corridor with and without TSP emitters.

From analysis of the manual data collection[1] it was found that, in most cases, TSP equipped buses experienced fewer red lights at TSP intersections than non-TSP equipped buses. It was also found that, on average, TSP equipped buses experienced less time waiting for green lights than non-TSP equipped buses (the difference in average time to wait for a green light was approximately 20 seconds less for TSP equipped buses). Similarly, TSP equipped buses experienced less signal delay at TSP intersections than non-TSP equipped buses (while the total signal delay experienced at non-TSP intersections was similar for all buses).

[1] Note that the results of the manual data collection were not found to be statistically significant.

From the GPS data analysis[2] (note that these results *were* found to be statistically signification) it was found that the average travel time for TSP equipped buses was between 14 and 71 seconds less than for non-TSP buses traveling over the same segments. For the control intersections (i.e., those without TSP), the travel times for TSP and non-TSP buses were similar, indicating that this difference can be attributed to the TSP.

Because the overall travel time savings due to TSP (less than 1 minute per run on average), was small compared to the total travel time (about 40 minutes), the operational impacts of the Sacramento TSP deployment were minimal. These small time savings were not enough to allow RT to modify their schedules or otherwise change their operations.

Among other factors, this limited benefit may be due in part to the low density of the TSP intersections in the study corridor. The study area includes only 15 TSP equipped intersections out of a total of 29 intersections over a route nearly 5 miles in length. The route also includes 38 bus stops, which means that the bus spends a good deal of time loading and unloading passengers. Over the course of an average run, it was found that each bus spent approximately 25 minutes of each run traveling, 5 minutes loading and unloading passengers, and 10 minutes waiting at traffic signals. Of the time spent at traffic signals, about 4 minutes were spent waiting for green lights, with the remainder spent waiting for the queue to begin moving and reaching the intersection. Since the TSP on Watt Avenue only has the potential to reduce the “waiting time” (4 minutes per intersection, on average), the potential for an operational impact of TSP in Sacramento was small. The addition of queue jumps[3] at select intersections could eliminate much of the time spent waiting for the queue to dissipate after the light turns green (6 minutes per intersection, on average).

The results do not indicate that the addition of TSP improved travel time reliability. For the segments with TSP, TSP buses experienced better travel time reliability than non-TSP buses in two of the six time periods (as compared to one out of the six time periods when looking at non-TSP intersections).

Assess the Impacts of TSP on Traffic Mobility

In order to assess the impacts of TSP on traffic mobility, the evaluation team conducted floating car runs along a portion of Watt Avenue and on sections of five of Watt Avenue’s cross-streets. The team collected these data both before and after TSP was deployed along the corridor, and then compared the data to determine if the addition of TSP had an impact on traffic mobility along the corridor. The evaluation team looked at both travel time and travel time reliability.

While the system was intended to improve transit on-time performance and reliability,[4] it seems that it may have also produced the residual benefit of travel time improvements of approximately 10 percent to the overall traffic. Travel time reliability on Watt Avenue also improved during this timeframe; in the absence of other factors, presumably due to the implementation of transit signal priority.

Travel times on Watt Avenue cross-streets increased in three-quarters of the cases, indicating that TSP may have had a negative impact on the cross-streets. Travel time reliability on the

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[2] Note that the results of the GPS data analysis were found to be statistically significant.

[3] The bus approaches queue jump intersections in the right-turn lane, and a separate signal head provides an advance green to the bus so that they can “jump the queue.”

[4] Note that the results of the floating car run analysis were not found to be statistically significant.

cross-streets showed mixed results; travel time reliability improvements were observed in approximately 50 percent of the cases.

CONCLUSIONS

Based on the results of this evaluation and the conclusions drawn, the hypotheses stated up front have either been supported by the results of the evaluation, have not been supported by the results of the evaluation, or are inconclusive at this time. The conclusions for each of the hypotheses are as follows.

- Hypothesis: TSP will improve transit mobility and performance by reducing travel times through the study area and by minimizing signal delay. *This hypothesis is supported by the analysis performed of GPS data for buses operating along Watt Avenue with and without TSP.* From the GPS data analysis it was found that the average travel time for TSP equipped buses was between 14 and 71 seconds less than for non-TSP buses traveling over the same segments. For the control intersections (i.e., those without TSP), the travel times for TSP and non-TSP buses were similar, indicating that this difference can be attributed to the TSP.
- Hypothesis: TSP will improve travel time reliability and schedule reliability. *This hypothesis is not supported.* For the segments with TSP, TSP buses experienced better travel time reliability in two of the six time periods (as compared to one out of the six time periods when looking at non-TSP intersections).
- Hypothesis: TSP will improve traveler mobility in the corridor by reducing vehicle delay and travel times. *This hypothesis is inconclusive.* Although difficult to state with much certainty, the results indicate that the addition of TSP on Watt Avenue had somewhat of a positive impact on Watt Avenue traffic and somewhat of a negative impact on cross-street traffic.

1. INTRODUCTION

1.1 PROGRAM OVERVIEW

In 2001, the U.S. Congress earmarked funds for selected projects that were assessed as supporting improvements in transportation efficiency, promoting safety, increasing traffic flow, reducing emissions, improving traveler information, enhancing alternative transportation modes, building on existing intelligent transportation systems (ITS), enhancing integration, and promoting tourism. One such project was the Sacramento - Watt Avenue Transit Signal Priority project, which involved deployment of transit signal priority (TSP) along a portion of Watt Avenue in Sacramento, California. The primary goal of the project was to improve bus service along Watt Avenue in an effort to reduce traffic congestion along the corridor.

Each year a small number of these projects are selected for national evaluation as part of the United States Department of Transportation (USDOT) ITS Integration Program. The purpose of the national ITS evaluation program is to investigate the impacts of ITS across the country and to provide insights into the potential strengths and weaknesses of the overall national integration program. Each evaluation is intended to provide information on the benefits and lessons learned of the project to potentially assist other agencies across the nation who may be considering similar deployments. The Sacramento–Watt Avenue TSP project was among the projects selected for national evaluation.

The USDOT selected an independent evaluation team to carry out an evaluation of the impacts of the system. As the primary goal of the project was to improve transit operations on the Watt Avenue corridor, the evaluation focused on measuring the impacts of the deployment on transit mobility and reliability. The evaluation also studied traffic mobility along the corridor to determine if traffic was impacted by the addition of TSP. This final evaluation report presents the findings of the assessment.

1.2 PROJECT DESCRIPTION

1.2.1 Background

Watt Avenue, a major north-south thoroughfare in suburban Sacramento County, is one of the major traffic crossings of the American River in Sacramento. Although there are three other river crossings within three miles to the west of Watt Avenue (see Figure 1-1), there is an eight-mile gap between Watt Avenue and the next river crossing to the east. This channels a large volume of traffic to the American River Bridge at Watt Avenue. Traffic volumes on Watt Avenue in the vicinity of the bridge can exceed 100,000 vehicles per day, and congestion is a significant problem during peak periods. Watt Avenue traffic moves as fast as 50 mph at times, although the speed limit along the corridor is 40 mph. Taking into account stops at signalized intersections, the overall average speed on Watt Avenue is about 25 mph.

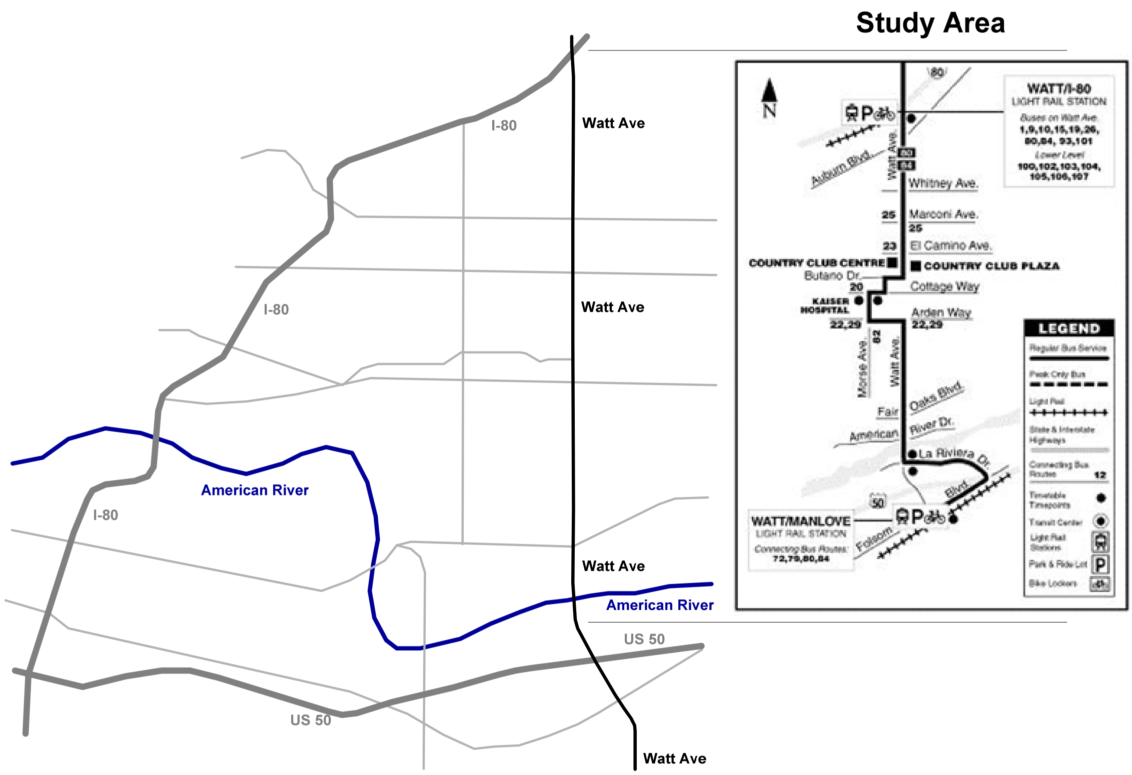


Figure 1-1. Watt Avenue and Watt Avenue Bus Routes

To help relieve some of this congestion, Sacramento County has made several upgrades to the Watt Avenue corridor over the past several years. Intersection improvement projects totaling to $2.2 million were completed in recent years, and the American River Bridge was widened in September 2002. Sacramento County also completed the integration of their Traffic Operations Center (TOC) around this time. Their TOC, shown in Figure 1-2, includes closed circuit television surveillance cameras, changeable message signs, highway advisory radio, and a fiber optics communications trunkline.

Figure 1-2. Sacramento County Traffic Operations Center

Despite these improvements, congestion remains a significant problem during peak periods as shown in Figure 1-3, which illustrates the typical level of peak-period congestion along Watt Avenue.

Figure 1-3. Congestion on Watt Avenue

One result of this congestion is that transit buses providing service along the six-mile stretch of Watt Avenue between Interstate 80 and Highway 50 are often significantly delayed. The two impacted bus routes are Sacramento Regional Transit District (RT) Routes 80 and 84. On weekdays and Saturdays, five buses provide service on these routes, operating on headways of approximately 30 minutes. On Sundays, two buses provide service, operating on headways of approximately 60 minutes. Travel time variability along these routes makes schedule adherence challenging during certain times of the day (travel time along the corridor by bus can take as few as 27 minutes, or as long as 51 minutes). To address these problems, Sacramento County and RT proposed deployment of TSP along this stretch of Watt Avenue.

1.2.2 Watt Avenue Bus Routes

TSP was implemented at 15 intersections along a 9.8-mile section of Routes 80 and 84 from the Watt/I-80 light rail transit (LRT) station to the Watt/Manlove LRT station. As shown in the route map in Figure 1-4, Routes 80/84 follow Watt Avenue for most of this section with a brief detour to the west between Arden Way and Butano Drive. This portion of the routes includes a total of 37 bus stops in each direction and 30 signalized intersections (note that while Watt Avenue intersects many other cross-streets, only the signalized intersections are shown in this schematic).

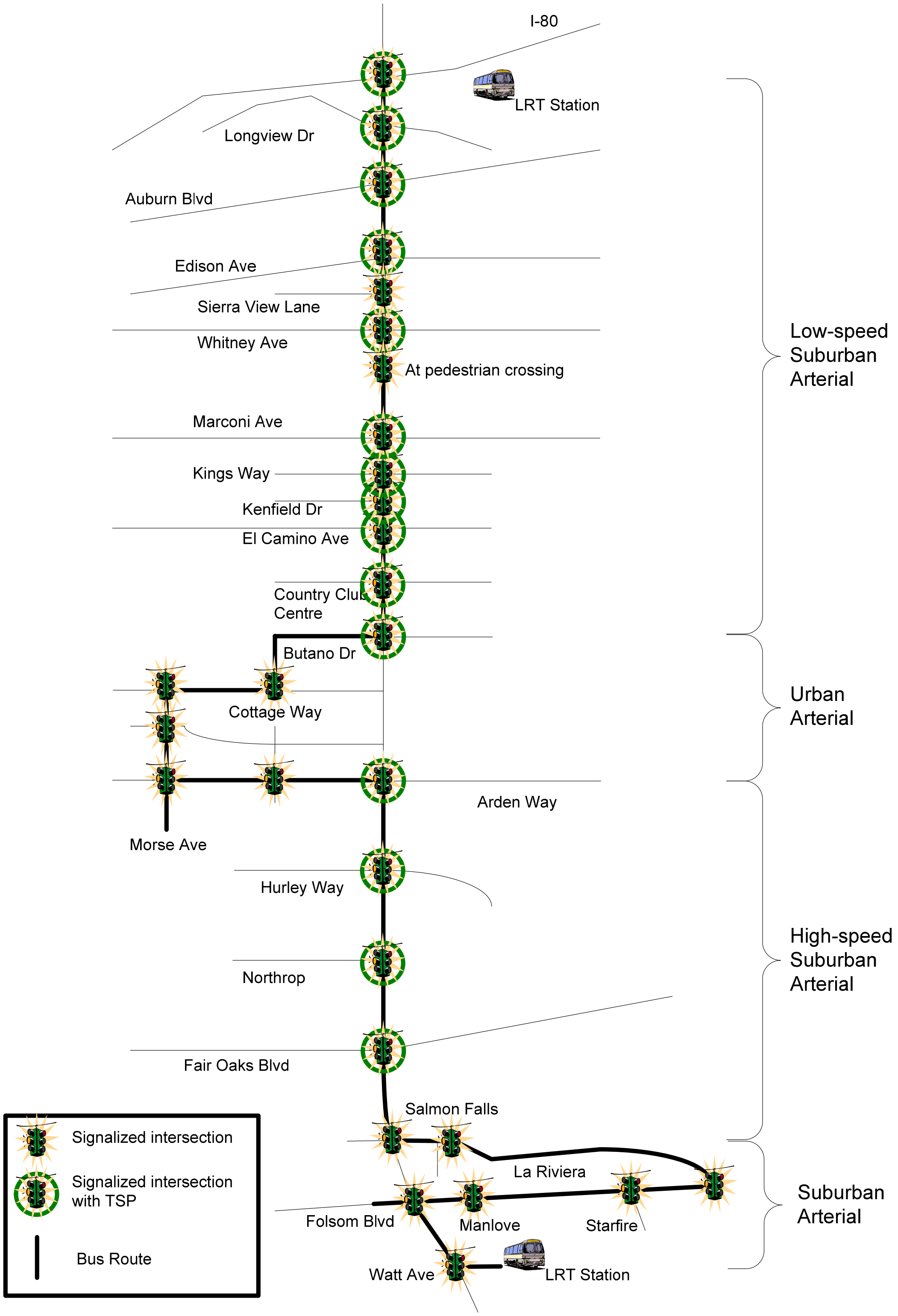


Figure 1-4. Map of Study Corridor Showing Signalized Intersections

The portion of Routes 80 and 84 between the two light rail stations can be characterized by the following four sub-segments (as labeled in Figure 1-4):

- The northernmost segment is a 2.7-mile segment of Watt Avenue extending from Butano Drive at the south to the I-80 LRT Station at the north. This segment is a low-speed suburban arterial with commercial and high-density residential development. Traffic tends to be congested on this section due to the heavy commercial development with many entrances and exits. This segment includes 12 signalized intersections (10 of which are equipped with TSP) and 10 bus stops.
- The next segment runs between Arden Way and Butano Drive. In this section the bus route detours off of Watt Avenue and passes over roads that can be classified as urban arterial. This segment, which is about 1.7 miles long, includes 6 signalized intersections (1 of which is equipped with TSP) and 10 bus stops.
- The next segment extends about 2.3 miles along Watt Avenue from the intersection with La Riviera to the intersection with Arden Way. Watt Avenue is a high-speed arterial through this section and traffic volumes tend to be particularly heavy since this section includes the river crossing. This segment includes 4 signalized intersections (all of which are equipped with TSP) and 6 bus stops.
- The southernmost segment of the routes runs from the Manlove LRT Station to the intersection of La Riviera and Watt Avenue. The route follows suburban arterials for this 2.8-mile segment and traffic along this section of Watt Avenue tends to be lighter than the northern sections. The segment includes 7 signalized intersections (none of which are equipped with TSP) and 11 bus stops.

1.2.3 Description of the Watt Avenue TSP System

As noted in the previous section, Sacramento County has deployed TSP receivers at 15 signals along Watt Avenue (note that all of the signals have 2070N controllers). The Sacramento system uses a transmitter in the bus to send a line-of-sight priority request to a receiver at the intersection. The transmitters (also called emitters) have an “on/off” switch. The unit must be turned on and in “priority” mode for the bus to receive priority (the other setting, “probe” mode, is generally used for testing purposes – in this setting the signal controllers receive a request and are aware of the presence of the bus, but no priority is granted).

The receiver can be adjusted to respond only to requests that are above a specified signal strength. This feature is used to create “detection zones,” so that a bus will only trigger a request for signal priority when it is within a certain distance of an intersection. The system also detects when a bus clears the intersection so that the minimum green extension needed for the bus to clear the intersection can be applied.

The system provides “active priority” to buses, meaning that priority treatment is only provided when the signal controller detects a bus. The system provides priority in two ways:

- A “green extension” is provided when a bus approaches an intersection during the green phase without enough time to clear the intersection before the yellow phase. The signal maintains the green for up to ten additional seconds to give the bus an opportunity to clear the intersection. As the bus may be able to clear the intersection before the 10-second extension ends, the system halts the extension once the bus has cleared the intersection so as not to provide an excessive extension. The subsequent red phase is then reduced by the length of the extension in order to return the signal to its previous cycle.

- An “early green” (also referred to as a “red truncation”) is provided when a bus approaches an intersection on the red phase. The signal returns to green ten seconds earlier than it would have otherwise (resulting in a 10-second truncation on the green phase of the cross-street). The total green phase is extended by 10 seconds, and the signal returns to its normal phasing at the conclusion of that cycle.

The system provides “unconditional priority”, meaning that a bus is granted priority whenever it approaches the intersection, regardless of whether the bus is ahead of or behind schedule (some TSP systems use “conditional priority”, meaning that the bus is only granted priority when certain requirements are met, such as that the bus is behind schedule by a certain number of minutes). There are only two exceptions to the unconditional priority for buses on Watt Avenue, both for safety purposes. One is in the event that an emergency vehicle approaches the intersection at the same time as a bus. In this case, the emergency vehicle overrides the bus. The other exception is when a pedestrian request occurs during the same signal cycle as a bus priority request. In this case, the signal controller will only provide a “green extension” or “red truncation” if it can do this while providing the minimum time required for pedestrian crossing at that particular intersection.

1.2.4 Expected Benefits

The Sacramento TSP system is expected to decrease bus travel times on Watt Avenue and improve travel time reliability without significantly impacting traffic mobility on the cross-streets when buses are given priority.

1.2.5 Project Stakeholders

The project stakeholders and partners involved in the Sacramento Transit Signal Priority project are listed in Table 1-1 below along with their corresponding roles.

Table 1-1. Project Stakeholders

Stakeholder	Role
U.S. Department of Transportation	Project Sponsor. USDOT provided Federal funding for the project and funded an evaluation of the project.
CalTrans	Project Sponsor. CalTrans provided matching funds for the project.
Sacramento Regional Transit District	Project Management. RT manages the transit system and was responsible for installing the priority request transmitters on the RT buses. RT also trained bus drivers in the use of the system and managed the effort of ensuring that transmitter-equipped buses were assigned to the Watt Avenue routes.
County of Sacramento	Project Management. The County of Sacramento manages the signal system on Watt Avenue and provided support needed for the receivers at the intersections to respond to the bus priority request transmissions.

1.3 EVALUATION OVERVIEW

The primary goal of the national evaluation was to determine the impact of transit signal priority on transit operations. The other goal of the evaluation was to determine if the addition of transit signal priority would have an impact on traffic operations. Additionally, the evaluation aimed to gather and document the experiences and lessons learned of the stakeholders in deploying and operating the system so that other transit agencies might benefit from the experiences in Sacramento.

It should be noted that the original evaluation plan included other hypotheses that were dropped over the course of the evaluation for various reasons. One hypothesis was that the addition of TSP would result in a reduction in the number of buses running red lights. This was not able to be measured as no archived data exists; the only way to gather information on red light running was through observational data. The evaluation team took note of driver behavior during the data collection, but did not observe any instances of red light running. Consequently this hypothesis was dropped from consideration.

Similarly, all hypotheses based on the assumption that TSP would be "fully" deployed on Routes 80 and 84 (i.e., that only TSP equipped buses would operate on these routes) were dropped from the evaluation as TSP buses are not exclusively used on Watt Avenue (this is further explained in Section 2). The hypotheses that were dropped included:

- TSP will result in a reduction in the number of buses required to operate the service due to improved schedule reliability and reduced transit travel times.
- TSP will allow for the transit agency to develop improved schedules.
- TSP will increase transit customer satisfaction by improving transit schedule reliability and reducing transit travel times.
- Corridor efficiency will be improved as transit ridership increases due to improved schedule reliability and reduced transit travel times.

Table 1-2 shows the overall evaluation approach including the key hypotheses as well as the associated measures of effectiveness (MOEs) and data sources.

Table 1-2. Overall Evaluation Approach

Goals	Key Hypotheses	MOEs	Data Sources
Improve transit mobility and performance.	TSP will improve transit mobility and performance by reducing travel times through the study area and by minimizing signal delay.	Average travel time through the study area.	On-board data collection / GPS data obtained from RT.
		Average signal delay (i.e., the time it takes a bus to traverse from the back of the queue at an intersection to the intersection itself).	On-board data collection.
		Average number of stops at red lights (i.e., average number of red lights that the bus encounters when traveling through the study area).	On-board data collection.
		Average number of occurrences of cycle failure (i.e., when the queue at an intersection queue is so long that the bus is not able to clear the intersection during the first available green phase).	On-board data collection.
Improve transit reliability.	TSP will improve travel time reliability and schedule reliability.	Travel time variability.	On-board data collection / GPS data obtained from RT.
		Schedule adherence at various bus stops.	On-board data collection / GPS data obtained from RT.
Improve traveler mobility in the corridor.	TSP will improve traveler mobility in the corridor by reducing vehicle delay and travel times.	Corridor and signal delay. Cross street delay. Vehicle average operating speeds. Overall corridor travel time.	Floating car runs on Watt Avenue and cross-streets. Traffic volumes on Watt Avenue and cross-streets.

1.3.1 The Evaluation Process

The evaluation process consisted of three phases. The first phase involved selection of this site for national evaluation and identification of the hypotheses that the evaluation would set out to measure.

Phase II of the evaluation involved creating an evaluation plan, collecting baseline data, and documenting the results of this baseline data collection in a final report. The Evaluation Plan presented detailed objectives, hypotheses, and data needs for each evaluation goal area (as was highlighted in the previous section).[5] This plan was submitted to USDOT for review and approval prior to the start of any data collection activities. The evaluation team then collected data before the TSP system was deployed in order to document baseline operations. Bus travel time data were collected by stationing evaluators on the buses to record timestamps as the bus

[5] Sacramento-Watt Avenue Transit Priority and Mobility Enhancement Demonstration: Final Evaluation Plan, November 25, 2002.

passed intersections and bus stops. Data on cross-street traffic mobility were collected by conducting travel time runs on Watt Avenue and the cross-streets. The data collected during Phase II of the evaluation were summarized and presented in the Phase II Evaluation Report.[6]

Phase III of the evaluation involved collecting data after TSP deployment. The data collection procedures essentially mirrored the Phase II data collection procedures. Following collection of the Phase III data, the before and after data were analyzed and compared. The results of this analysis are presented in this Phase III Evaluation Report.

1.3.2 The Evaluation Report

This document presents the results of the Sacramento – Watt Avenue Transit Signal Priority (TSP) evaluation. This report includes before-and-after analyses of the projects' impacts on system performance by comparing the data collected during Phases II and III of the evaluation. The remainder of the document is structured in the following format:

Section 2 – Institutional Issues and Lessons Learned. This section describes the experiences in deploying and using the TSP system that result in lessons learned that should benefit other transit agencies.

Section 3 – Impacts on Bus Travel Time and Travel Time Reliability. This section describes the impact of the TSP system on bus travel times and travel time reliability.

Section 4 – Impacts on Traffic Mobility. This section describes the impacts of the TSP system on traffic mobility, concentrating on the impact of the system on cross-street traffic.

Section 5 – Summary and Conclusions. This section provides a summary of the conclusions of the evaluation.

The results of the evaluation are summarized in the Executive Summary, and the more detailed analysis results that are not presented in the main body of the report are documented in the report's Appendices.

[6] Sacramento-Watt Avenue Transit Priority and Mobility Enhancement Demonstration Project Phase II Evaluation Report, September 26, 2003.

2. INSTITUTIONAL ISSUES AND LESSONS LEARNED

The evaluation team documented experiences and lessons learned of the stakeholders through informal discussions with the stakeholders throughout the course of the deployment and evaluation. There were several key issues that made deployment and operation of transit signal priority a challenge.

2.1 ALLOCATE SUFFICIENT TIME TO CALIBRATE TSP EMITTERS

Sacramento County found that it was quite time intensive to manually determine the detection distance[7] for each intersection. They did this through a trial-and-error process to ensure that the detectors would “pick up” the buses at the proper distance at each intersection (for example, if a bus is detected when it is too far away from the signal, it will not be able to reach the intersection in time to pass through within the 10-second time window of the green extension). They outfitted a county vehicle with an emitter and performed a minimum of three test runs at each intersection by driving the vehicle through the intersection and determining the signal strength at various distances from the intersection. They found it important to perform more than one test run at each intersection due to various factors that affected the signal strength or detection distance on each run. While the horizontal alignment of the roadway leading up to the intersection clearly affected the detection distance, other factors were also found to affect the signal strength (e.g., trucks and other large objects, light reflecting off of other nearby objects, the amount of dirt on the emitter lens). By conducting several runs at each intersection they were able to determine the best “average” detection distance for the range setting for that intersection. Although the default value is 300 feet, they found that 600 feet was a good starting point for the testing.

One specific challenge that the stakeholders encountered was related to near-side bus stops. Whenever they encountered a near-side bus stop located within 300 feet of a TSP-equipped intersection, they specified the range setting to be less than 300 feet so that the signal controller would not detect the bus while it is at the bus stop loading and unloading passengers.

2.2 INSTALL TSP EMITTERS THAT REQUIRE MINIMAL OPERATOR INTERFACE

Most TSP emitters operate automatically whenever the bus is moving and the door is closed. However, the units deployed as part of this project are the type that must be activated by an operator switch in the vehicle (the switch is shown in Figure 2-1). This resulted in an additional level of complexity when ensuring that the units were working properly. The operator switch has three modes: *off, probe, and priority.* When the emitter is in *priority mode*, detectors recognize the bus and grant priority; when the emitter is in *probe mode*, detectors recognize the bus but do not grant priority (this is used for testing purposes). Whenever on a non-TSP route, the emitters are left in the *off* position so as to prolong the life of the units.

Although RT had undertaken an initial training effort to ensure that bus operators were aware of the system and that they would place the emitters in priority mode at the start of each Watt Avenue run, operator turnover and rotation in assignments led to confusion among many of the operators. In talking with bus operators during the data collection, the evaluation team heard a

[7] The distance at which the signal controller becomes aware of the presence of an emitter-equipped bus.

range of responses about the system. Some believed that they were not supposed to turn the units on as they interfere with emergency vehicles. Others seemed to think that they were only supposed to turn the units on when stopped at a red light. Others seemed discouraged about the units in general and indicated that they never put them in the *on* position as they do not think there is a benefit in doing so. It is likely that many of these misconceptions could have been avoided through additional efforts to educate drivers about how the system works and what sort of benefit it is capable of providing. One element contributing to this was that drivers rotate routes each quarter, and drivers are able to select their routes based on seniority. According to RT, Routes 80 and 84 are not popular routes among drivers due to the problems with schedule adherence. Therefore, having the least senior drivers handling the units may have contributed to the problem.

As a result of this operator confusion, the evaluation team found many TSP equipped buses operating on Routes 80 and 84 while their emitters were left in the *off* position. To combat this problem, the transit agency considered installing a signal at the exit to the shop that would display a green light to drivers upon exit only if their emitter was in the *on* position (described more in the following section). It was decided that additional driver outreach would be sufficient, and when additional units were later purchased, it was arranged for the "on" switch to be hard-wired to the door mechanism to eliminate the operator interface.

Figure 2-1. TSP Emitter with Switch

2.3 USE A "TEST SIGNAL" TO VERIFY THAT TSP EMITTERS ARE FUNCTIONING PROPERLY

Installing a "test signal" can help an agency more promptly identify faulty emitters. RT has another TSP route in Sacramento that is a bus rapid transit (BRT) route, so labeled as it has tighter headways and some queue jumps (the bus approaches queue jump intersections in the right-turn lane and a separate signal head provides an advance green to the bus so that they can "jump the queue"). The transit operator has noted that an added benefit of queue jump intersections is that they are able to more quickly identify emitters that are not functioning properly. As soon as an emitter stops working, the operator becomes aware of it when they next approach a queue jump intersection (i.e., they will not be granted the advance green signal as usual), and notifies dispatch immediately. If an emitter fails on one of their other TSP equipped buses, it may be some time before the problem is identified. RT's experience on these two routes leads them to recommend that other agencies who do not have queue jumps seriously consider placing a "test signal" at the exit to their shop so that operators will immediately be aware of any functionality problems with their emitters.

2.4 REALIZE THAT SCHEDULING VEHICLES ON TSP ROUTES MAY BE DIFFICULT

RT found it difficult to ensure that emitter-equipped buses were consistently assigned to Routes 80 and 84. The primary reason for this was that vehicle assignments are actually made by maintenance staff who decide which buses to put on the road on a particular day. A scheduler can put in a request that only emitter-equipped buses be assigned to a particular route, but the request will not always be met depending on the number of buses that are out of service that day. An interesting note is that RT does not have this problem with their BRT route previously mentioned. The reason for this is that the BRT route has a separate fleet of buses that have been branded differently from the rest of the fleet. As there is a limited set of buses operating on this route, maintenance staff do not face the same challenge in consistently assigning TSP equipped buses to the route.

As a result of this breakdown in communication, many buses operating on Routes 80 and 84 are not equipped with TSP emitters. The most significant implication of this is that no "bigger picture" benefits of TSP can be realized. Without consistent use of equipped buses, there is no benefit beyond sporadic time savings. Consistent use could lead to benefits such as better overall schedule adherence and improved customer satisfaction.

3. IMPACTS ON BUS TRAVEL TIME AND TRAVEL TIME RELIABILITY

3.1 OVERVIEW OF APPROACH

The primary objective of a TSP system is to decrease bus travel times and increase travel time reliability by reducing the time a bus spends stopped at traffic signals. As such, the primary goal of the Watt Avenue TSP deployment was to improve transit mobility and efficiency throughout the study corridor. Project partners expected that reductions in transit travel times and signal delay would improve transit mobility and travel time reliability. This section focuses on the performance evaluation of transit service in the study area.

3.2 HOW TSP CAN IMPACT BUS TRAVEL TIMES AND RELIABILITY

Before jumping into the data analysis, it is important to understand the potential benefit that might be expected based on the operating environment and the type of system deployed in Sacramento. The Sacramento TSP system decreases bus travel times by extending the green time at a signal if the system detects that a bus is approaching when the signal is about to turn yellow, and by decreasing the red time if the system detects that a bus is stopped at the signal or if the bus is approaching the signal during the red phase. One can characterize the travel time savings of a bus approaching a TSP equipped intersection according to the arrival scenarios pictured in Figure 3-1.

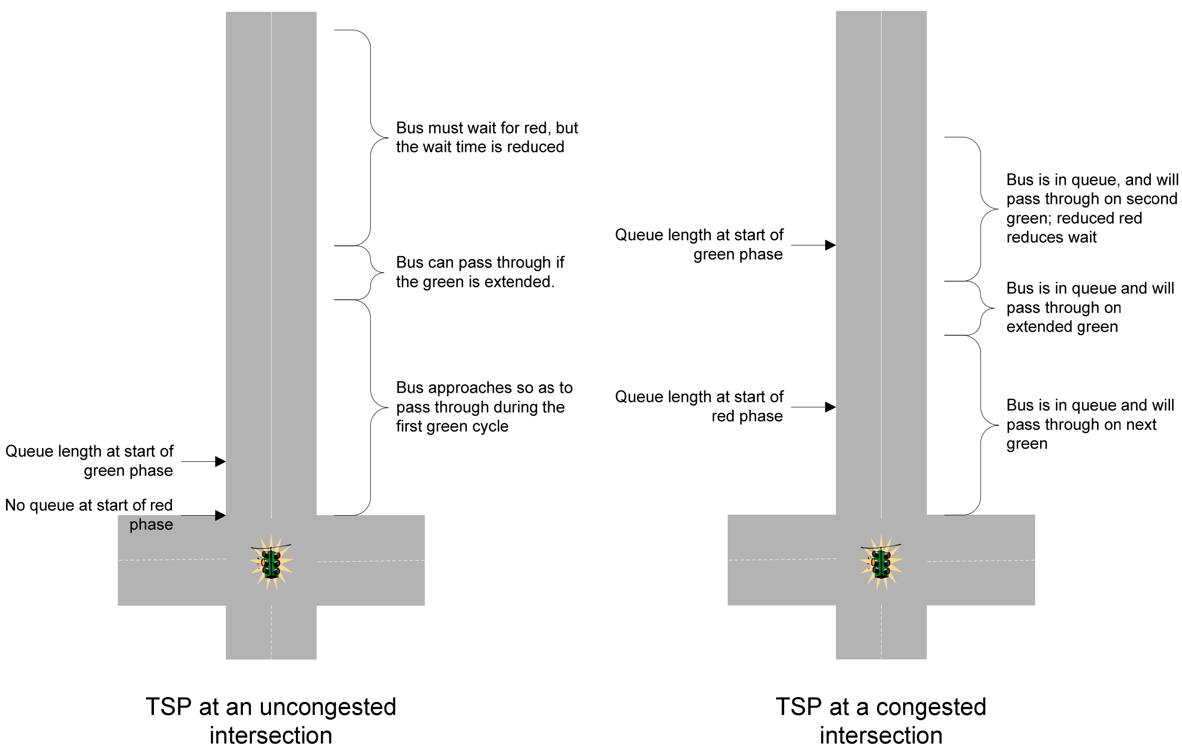


Figure 3-1. Effect of TSP on Signal Delay

In these diagrams, the notation on the right refers to the position of the bus at the time the light turns green. The resulting signal delay at an uncongested intersection is depicted in Figure 3-2.

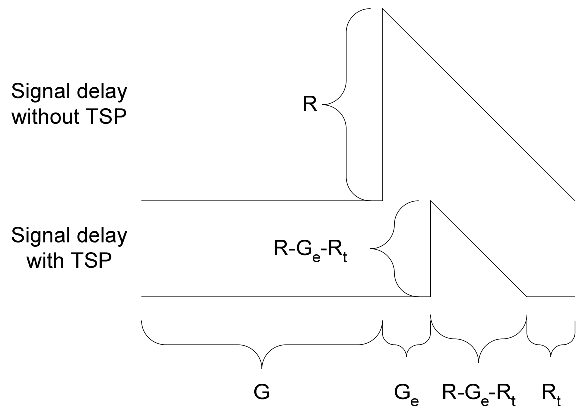


Figure 3-2. Signal Delay at an Uncongested Intersection, With and Without TSP

In these figures, G is the green time in the direction of travel for the bus, R is the combined red and yellow time, G_e is the green time extension, and R_t is the red time truncation.

Table 3-1. Equations for Signal Delay at an Uncongested Intersection

Type of Signal	Fraction of Time With No Delay	Average Delay	Standard Deviation of Delay
Without TSP	$\frac{G}{G+R}$	$\frac{R^2}{2(G+R)}$	$\left(\frac{R^3(R+4G)}{12(G+R)^2}\right)^{1/2}$
With TSP	$\frac{G+G_e+R_t}{G+R}$	$\frac{(R-G_e-R_t)^2}{G+R}$	$\left(\frac{(R-G_e-R_t)^3(R+4G-3G_e-3R_t)}{12(G+R)^2}\right)^{1/2}$

In Sacramento, the maximum green extension / red truncation that Sacramento allows along Watt Avenue is ten seconds. The following table indicates the improvements in travel time and travel time reliability at a TSP equipped signal with a cycle length of 120 seconds, a green time of 70 seconds, a red time of 40 seconds, and yellow times of 5 seconds.

Table 3-2. Effects of TSP at a Typical, Uncongested Intersection

Type of Signal	Fraction of Time With No Delay	Average Delay	Standard Deviation of Delay
Without TSP	58%	10.4 sec	15.5 sec
With TSP	42%	7.5 sec	6.5 sec

In other words, one would expect the average travel time for a bus equipped with TSP to be reduced by about 3 seconds (10.4 seconds minus 7.5 seconds) at TSP-equipped intersections, as compared to a bus not equipped with TSP.

3.3 DATA COLLECTION

The initial data collection plan called for the evaluation team to manually collect bus travel time data while on-board Route 80 and 84 buses. However, during the "after" data collection, it was discovered that not all Route 80 and 84 buses were being granted priority for a number of reasons (as mentioned in Section 2, both operator training and vehicle scheduling contributed to this problem). As data collection funds had already been expended to collect "after" data, the evaluation team worked with the project stakeholders to determine if there were any alternate options for obtaining data. The evaluation team learned that much of RT's fleet had recently been equipped with automated vehicle location (AVL) devices. This presented an opportunity to gather automated location/time data in a cost-effective manner. The only challenge was that none of the buses equipped with AVL were equipped with TSP emitters. RT agreed to procure TSP units for some of their AVL-equipped buses to support the evaluation efforts. The evaluation team then obtained global-positioning system (GPS) data for buses operating on Routes 80 and 84 – some operating with TSP emitters and some operating without TSP emitters.

The following sections provide details on the format, assumptions, and collection methods used in gathering these two types of data associated with transit operations.

3.3.1 Data Collection Procedures

Two approaches were used to collect bus travel time information for this study. The first approach was to position observers on buses to record travel time information. This was done using laptop computers running a Microsoft Excel/Visual Basic application developed by Sacramento County. A detailed description of the software is provided in Appendix E, and a more detailed description of the data collection procedures can be found in the Phase II Evaluation Report[8]. The software was designed to provide a sequential event list for each bus stop and intersection, which allowed the evaluation team to capture timestamps as each event occurred. Each observer would ride the bus as it traversed the route, and record the timestamps and other data at key events that occurred along the route. The advantage of this approach was that the on-board observer was able to record timestamps for a number of different events, including when the bus entered a queue at a signalized intersection.

The second approach involved obtaining data from buses on the routes of interest that were equipped with GPS receivers and on-board hardware that archived timestamp information when a bus arrived at a stop and periodically archived timestamp information while between stops. This approach had the advantages that (a) it was relatively inexpensive to gather the data, so data for a large number of runs was obtained, and (b) the data was not subjective. The main disadvantage to this data was that timestamps were only recorded every 500 ft, so it was not possible to accurately determine when a bus entered the back of a queue at a signalized intersection. Appendix A provides more details about the analysis approach undertaken by the evaluation team for these two sets of data.

[8] Sacramento-Watt Avenue Transit Priority and Mobility Enhancement Demonstration Project Phase II Evaluation Report, September 26, 2003.

3.3.2 Data Elements Collected

For each manually-collected run, the data collection team collected the data shown in Table 3-3. For comparison purposes, the team recorded intersection-related data at all intersections in the study corridor regardless of whether or not TSP was deployed at that intersection.

Table 3-3. Data Elements Collected On-Board Watt Avenue Buses

Event Type	Data Collected
Standard information recorded for each trip	Trip direction (northbound or southbound)
	Day of week
	Data collection period
	Anything noted to be out of the ordinary (e.g., rainy weather conditions)
Events recorded at each signalized intersection	The time the bus arrived at the back of the queue at the intersection
	The time the signal turned green
	The time the bus began moving (denoting start-up delay)
	The time the bus crossed the intersection stop bar
Events recorded at each bus stop location	The time the bus arrived at the bus stop
	The time when all passengers had boarded and paid
	The time the bus re-entered the traffic stream (denoting dwell time at the bus stop not attributed to passenger boarding and alighting)
Passenger counts recorded at each stop	The number of passengers who got off the bus
	The number of passengers who got on the bus and used a prepaid card
	The number of passengers who got on the bus and paid with cash
Other relevant information recorded	When the wheelchair lift was used at a bus stop
	When the bike rack was used at a bus stop
	Instances of the bus running a red light at an intersection (not actual crashes or citations, but rather observations of the research team)
	Occurrences of cycle failure (when the bus is required to wait through more than one red phase at a particular intersection)

For the GPS data, the GPS devices on the buses automatically recorded timestamps at bus stops and at regular intervals between stops. The devices also recorded the dwell time at each stop (i.e., the amount of time during which the door was open), the odometer reading, the GPS coordinates, and other values. Each record included the following information:

- The route number.
- The stop number.
- The time.
- An odometer reading (the number of feet traveled since the bus began service that day).
- The “stop dwell time” (the number of seconds the bus was stopped with the door open).
- The latitude and longitude of the bus location.

- An “event type” code (a number that indicates the purpose of the record – i.e., stopped at a bus stop, drove past a bus stop, stopped for passengers at a location other than a bus stop, assigned a new route to the operator, and ended the route).

3.3.3 Data Collection Periods

For the manually-collected data, the evaluation team collected *baseline* data for a two-week period from March 10th to March 21st of 2003 and *post-deployment* data for a one-week period from April 26th to April 30th of 2004. Data were collected Monday through Friday, primarily during the three periods of peak traffic flow: AM, mid-day, and PM peak. In order to investigate the impact of TSP on buses during off-peak hours, a limited number of runs were also collected outside of these peak periods.

The evaluation team aimed to collect two weeks’ worth of data both “before” and “after” deployment of the system to capture enough data to draw meaningful results from a comparison of the two time periods. The evaluation team arrived at a data collection period of two weeks after performing a statistical power analysis to determine the sample size needed to show significant and/or meaningful results. These power analyses are provided in Appendices B and C for reference. The power analysis was performed using a two-sided test since the direction of expected change could not be specified with certainty. In performing the analysis it was assumed that $\alpha = 0.05$ (i.e., a change in transit travel times as small as 5 percent would be able to be detected), and $\beta = 0.8$ (i.e., there would be an 80 percent probability of detecting a difference between the mean transit travel time before and after deployment of TSP).

As discussed in the introduction to this section, the evaluation team was unable to obtain two full weeks of “after” data as TSP equipped buses were not exclusively run on Watt Avenue during the study period. Table 3-4 summarizes the data collection runs that were conducted by the evaluation team.

Table 3-4. Number of On-Bus Observations

	2003: Pre-TSP	2004: No TSP	2004: TSP
NB, Peak	32	7	6
NB, Off Peak	84	19	20
SB, Peak	69	9	10
SB, Off Peak	48	10	14
Total	**233**	**45**	**50**

In this table, the “2003: Pre-TSP” column indicates the number of runs conducted in 2003, before TSP was deployed. The “2004: No TSP” column indicates the number of runs conducted in 2004 on buses that were not using a TSP transponder. The “2004: TSP” column indicates the number of runs conducted in 2004 on buses that were using a TSP transponder. The “NB, Peak” row refers to runs whose scheduled start times occurred between 3:10 pm and 5:40 pm, and “SB, Peak” runs had scheduled start times that occured at 7:24 am, 7:54 am, or between 5:21 pm and 5:27 pm. These same categories are used in the tables throughout this section of the report.

For the GPS data, the evaluation team obtained two weeks worth of data for buses operating on Routes 80 and 84 during May 2005 – some operating with TSP emitters and some operating without TSP emitters. The number of runs obtained are shown in Table 3-5 below.

Table 3-5. Number of Runs of GPS Data (May 2005)

	With TSP	Without TSP
NB, Peak	26	24
NB, Off Peak	84	41
NB, Weekend	39	26
SB, Peak	26	25
SB, Off Peak	92	45
SB, Weekend	42	28
Total	**309**	**189**

3.4 RESULTS

The primary goal in deploying a transit signal priority system is to reduce signal delay for buses with a consequent reduction in bus travel time and a related reduction in travel time variability. If these effects are large, they can lead to larger operational impacts. For example, a significant decrease in travel times on the route could allow bus schedules to be modified to provide more frequent service with the same number of buses. A reduction in travel time variability could increase rider satisfaction, which could result in an increase in ridership over time. However, as mentioned earlier, sporadic use of the emitters does not allow for these "bigger picture" benefits.

This section of the report describes the observed effects of the TSP deployment in Sacramento and examines the likelihood that those effects could result in operational improvements.

3.4.1 Manually Collected Data: Reduction in Signal Delay

TSP can reduce signal delay in four different ways:

(1) Increasing the frequency with which a vehicle passes through a signal without experiencing a red light.

(2) Decreasing the delay experienced when a vehicle experiences a single red light.

(3) Decreasing the frequency with which a vehicle experiences multiple red lights at a particular intersection (cycle failure).

(4) Decreasing the delay experienced when a vehicle experiences multiple red lights.

This section examines each of these factors separately by analyzing signal delay data collected by on-bus observers during 2003, before TSP was deployed, and during 2004, after it was deployed.

Table 3-6 considers two ways that TSP could decrease signal delay: by increasing the frequency with which a vehicle passes through a signal without stopping, and by decreasing the frequency with which a vehicle experiences cycle failure at a signal. The "No Red" column refers to the number of times a vehicle passed through a signal without stopping, the "One Red" column refers to the number of times a vehicle was stopped by a signal and passed through during the first green phase, and the "Multi Red" column refers to the number of times a vehicle did not make it through the light during the first green phase.

Table 3-6. Average Number of Red Lights Encountered by TSP and Non-TSP Buses

Number of Red Lights	No Red			One Red			Multi Red		
	2003: Pre-TSP	2004: No TSP	2004: TSP	2003: Pre-TSP	2004: No TSP	2004: TSP	2003: Pre-TSP	2004: No TSP	2004: TSP
TSP Intersections									
NB, Peak	5.1	5.0	7.2	7.4	7.6	5.7	0.5	0.4	0.2
NB, Off Peak	6.7	6.0	5.6	6.0	6.6	7.2	0.3	0.4	0.2
SB, Peak	6.7	8.2	7.8	6.3	4.8	5.2	0.0	0.0	0.0
SB, Off Peak	7.8	7.9	8.4	5.2	5.1	4.6	0.0	0.0	0.0
Non-TSP Intersections									
NB, Peak	6.6	5.8	5.4	6.3	7.2	7.6	0.1	0.0	0.0
NB, Off Peak	6.8	6.4	6.0	6.1	6.5	7.0	0.1	0.1	0.1
SB, Peak	6.2	6.0	5.6	6.4	6.4	7.3	0.4	0.6	0.1
SB, Off Peak	6.8	6.2	7.1	6.0	6.5	5.5	0.2	0.3	0.4

Note that the TSP equipped buses did, in most cases, experience fewer red lights at TSP intersections than the non-TSP buses. The only case where the value for the TSP buses was significantly different from the values for the *2003 without TSP* buses and the *2004 without TSP* buses was for northbound runs during peak hours.[9] At non-TSP intersections, the TSP equipped buses experienced the same or more red lights as the buses that were not equipped with GPS. This suggests that TSP reduced the signal delays experienced by the TSP equipped buses.

Another way in which TSP can improve bus travel times is by decreasing the time spent waiting for a green light. Table 3-7 lists the average time a bus spent waiting for a green light during a typical run. Note that these values only include the time spent waiting for the first green light, and exclude any additional waiting time that could have resulted from cycle failure.

[9] Because of the small number of observations in 2004, few of the differences observed will be statistically significant. This does not mean that the observed differences are not "real." It simply means that too few on-bus observations were made in 2004 to provide statistically meaningful results. (See Appendix A for more information on the 2004 observations.) For this reason, the statistical significance of differences will not be discussed in the remainder of this section.

Table 3-7. Observed Time Spent Waiting for a Green Light for TSP and Non-TSP Buses

Signal Delay	2003: Pre TSP		2004: No TSP		2004: TSP	
	μ	σ	μ	σ	μ	σ
TSP Intersections						
NB, Peak	280.5	82.4	214.0	59.2	196.8	60.8
NB, Off Peak	228.5	83.3	230.4	52.8	192.3	79.4
SB, Peak	169.8	65.6	133.1	57.9	143.3	62.0
SB, Off Peak	132.0	59.7	125.4	60.2	99.9	34.9
Non-TSP Intersections						
NB, Peak	148.6	58.0	158.3	56.8	180.0	39.1
NB, Off Peak	123.4	61.2	113.3	53.8	121.0	55.8
SB, Peak	186.8	64.5	166.6	55.0	159.3	35.1
SB, Off Peak	126.9	54.2	146.0	56.6	104.2	51.7

In most cases, the green light waiting time for TSP equipped buses at TSP intersections is lower than for buses without TSP, a relationship that does not hold true for non-TSP intersections. The observations in this table suggest that TSP did reduce green light waiting time at TSP intersections. It is interesting to note that the observed difference in green light waiting time between TSP and non-TSP buses in 2004, about 20 seconds, is similar in size to that expected from the theoretical estimates of Section 3.2. The theoretical estimates indicate that green light waiting time should decrease by about 3 seconds per intersection, or by about 45 seconds for the entire run that includes 15 TSP equipped intersections.

The next table, Table 3-8, shows the total signal delay experienced by TSP and non-TSP equipped buses during the manual observations.

Table 3-8. Total Signal Delay for TSP and Non-TSP Buses

Total Signal Delay	2003: Pre TSP		2004: No TSP		2004: TSP	
	μ	σ	μ	σ	μ	σ
TSP Intersections						
NB, Peak	419.3	112.3	382.0	109.6	329.0	137.9
NB, Off Peak	316.3	104.2	364.5	99.5	313.2	88.7
SB, Peak	239.4	79.6	195.8	66.6	203.4	59.5
SB, Off Peak	177.5	69.8	173.1	67.0	146.5	48.2
Non-TSP Intersections						
NB, Peak	205.2	79.2	222.5	89.7	251.6	76.8
NB, Off Peak	167.1	63.3	178.3	64.9	185.5	65.0
SB, Peak	229.3	70.3	239.1	72.6	213.1	53.3
SB, Off Peak	154.9	61.5	189.3	69.6	142.5	68.9

As with the previous signal delay results, the TSP equipped buses show generally better performance at TSP equipped intersections than non-TSP equipped buses, and do not show better performance at non-TSP equipped intersections.

The effects of TSP can also be examined on an intersection-by-intersection basis, as in Tables 3-9 through 3-12. In these tables, the “No Wait” column indicates the percentage of time a bus passed through an intersection without stopping for a red light, the “Avg Wait” column indicates the average time waiting for the first green light when a bus was stopped (in seconds), and the “Max Wait” column indicates the maximum time spent waiting for the first green light (in seconds).

Table 3-9. Effect of TSP for TSP equipped Intersections, Northbound Runs, Peak

Red Light Wait Time	2003: Pre TSP			2004: No TSP			2004: TSP		
	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait
Watt at Fair Oaks	22%	42	98	22%	59	330	13%	75	180
Watt at Northrop	72%	10	27	78%	14	28	88%	1	1
Watt at Hurley	47%	31	62	22%	14	39	75%	3	5
Watt at Arden	3%	58	154	13%	47	115	0%	38	88
Butano at Watt	13%	52	137	0%	60	118	25%	38	69
Watt at Country Club	25%	26	46	78%	6	11	100%	0	0
Watt at El Camino	34%	25	71	67%	0	1	86%	21	21
Watt at Kenfield	81%	23	46	67%	18	28	63%	18	21
Watt at Kings	41%	30	54	44%	16	31	50%	33	38
Watt at Marconi	22%	33	85	0%	25	69	25%	37	74
Watt at Whitney	50%	26	71	38%	11	22	25%	23	54
Watt at Edison	34%	43	85	56%	35	50	75%	37	43
Watt at Auburn	22%	39	87	11%	43	72	0%	29	49
Watt at Longview	66%	14	66	56%	10	22	88%	32	32
Watt at Off Ramp	56%	47	80	89%	24	24	63%	33	57

Table 3-10. Effect of TSP for TSP equipped Intersections, Northbound Runs, Off Peak

Red Light Wait Time	2003: Pre TSP			2004: No TSP			2004: TSP		
	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait
Watt at Fair Oaks	43%	35	90	27%	35	110	27%	35	83
Watt at Northrop	88%	4	11	82%	1	3	83%	6	13
Watt at Hurley	58%	15	63	36%	12	37	43%	12	47
Watt at Arden	6%	58	129	10%	66	132	4%	35	101
Butano at Watt	8%	59	128	9%	55	106	4%	49	101
Watt at Country Club	81%	28	61	91%	1	1	96%	0	0
Watt at El Camino	74%	40	145	55%	13	69	54%	5	21
Watt at Kenfield	75%	20	43	50%	25	39	50%	20	39
Watt at Kings	57%	26	58	45%	16	42	38%	21	42
Watt at Marconi	37%	40	90	9%	38	66	17%	35	65
Watt at Whitney	70%	21	68	52%	28	60	58%	22	67
Watt at Edison	26%	25	79	67%	28	51	40%	23	44
Watt at Auburn	14%	33	82	19%	42	70	20%	34	82
Watt at Longview	76%	11	33	59%	13	32	56%	11	29
Watt at Off Ramp	70%	51	96	91%	47	57	67%	31	82

Table 3-11. Effect of TSP for TSP equipped Intersections, Southbound Runs, Peak

Number of Red Lights	2003: Pre TSP			2004: No TSP			2004: TSP		
	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait
Watt at I-80 Off Ramp	79%	24	39	33%	21	54	50%	15	24
Watt at Longview	85%	31	64	86%	31	31	100%	0	0
Watt at Auburn	12%	40	74	13%	33	61	43%	42	69
Watt at Edison	82%	44	66	50%	28	38	63%	27	52
Watt at Whitney	32%	26	60	63%	37	47	63%	5	13
Watt at Marconi	38%	26	81	50%	18	72	75%	19	35
Watt at Kings Way	38%	15	43	88%	0	0	75%	14	26
Watt at Kenfield	88%	10	21	100%	0	0	100%	0	0
Watt at El Camino	79%	64	82	29%	55	70	38%	44	59
Watt at Country Club	41%	20	60	88%	2	2	88%	4	4
Watt at Butano	68%	22	56	75%	12	24	63%	19	53
Arden at Watt	35%	26	74	38%	29	58	25%	28	46
Watt at Hurley	35%	24	63	75%	30	59	50%	15	42
Watt at Northrop	56%	20	40	86%	31	31	63%	25	43
Watt at Fair Oaks	35%	52	94	29%	73	92	29%	74	97

Table 3-12. Effect of TSP for TSP equipped Intersections, Southbound Runs, Off Peak

Number of Red Lights	2003: Pre TSP			2004: No TSP			2004: TSP		
	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait	No Wait	Avg Wait	Max Wait
Watt at I-80 Off Ramp	51%	20	62	53%	14	33	59%	18	56
Watt at Longview	80%	25	44	80%	14	22	82%	19	26
Watt at Auburn	25%	35	83	25%	35	72	17%	32	73
Watt at Edison	67%	23	69	86%	33	52	71%	14	33
Watt at Whitney	61%	29	57	65%	13	29	76%	10	41
Watt at Marconi	39%	35	79	48%	32	72	52%	28	83
Watt at Kings Way	67%	9	37	73%	7	18	80%	11	24
Watt at Kenfield	86%	8	41	82%	18	33	76%	12	28
Watt at El Camino	59%	52	77	45%	41	74	28%	27	63
Watt at Country Club	64%	16	53	95%	5	5	96%	8	8
Watt at Butano	45%	16	64	55%	21	51	70%	20	58
Arden at Watt	25%	29	88	22%	26	58	20%	29	77
Watt at Hurley	42%	22	47	29%	26	59	44%	20	47
Watt at Northrop	61%	12	42	78%	3	8	71%	11	35
Watt at Fair Oaks	46%	43	108	32%	52	108	36%	45	84

In the northbound direction, the average wait time decreased for 11 out of the 15 intersections when comparing *2003 with TSP* buses and *2004 with TSP* buses, and for 10 out of 15 intersections when comparing *2004 without TSP* and *2004 with TSP*. For the southbound direction, the average wait time decreased for 9 and 7 of the 15 intersections, respectively.

3.4.2 GPS Data: Reduction in Travel Time and Travel Time Variability

Because of the nature of the GPS data, signal delay was not measured directly. Instead, the travel times between adjacent bus stops was available and used to infer information about signal delay by identifying the between-stop segments that contained one or more TSP equipped intersections. Table 3-13 shows travel times for buses equipped with TSP and for those not equipped with TSP.

Table 3-13. Travel Times for TSP and Non-TSP Buses, All Segments

Route	TSP	Travel Times (sec)		Count
		Avg	Stnd Dev	
NB, Weekday, Peak *	TSP	2248	229	26
	No TSP	2265	203	24
NB, Weekday, Off Peak	TSP	1787	189	84
	No TSP	1858	175	41
NB, Weekend *	TSP	1630	175	39
	No TSP	1678	166	26
SB, Weekday, Peak *	TSP	1854	186	26
	No TSP	1917	158	25
SB, Weekday, Off Peak *	TSP	1696	189	92
	No TSP	1710	187	45
SB, Weekend	TSP	1576	143	42
	No TSP	1637	156	28

*Results are not statistically significant at the 5 percent confidence level.

This table indicates that TSP reduced average travel times by between 14 seconds (for weekday southbound trips during off peak traffic periods) and 71 seconds (for weekday northbound trips during off peak traffic periods). Table 3-14 lists results restricted to segments that include a TSP-equipped intersection.

Table 3-14. Travel Times for TSP and Non-TSP Buses, Segments with TSP

Route	TSP	Travel Times (sec)		Count
		Avg	Stnd Dev	
NB, Weekday, Peak *	TSP	1405	164	26
	No TSP	1421	164	25
NB, Weekday, Off Peak	TSP	1025	150	85
	No TSP	1099	124	41
NB, Weekend	TSP	919	132	42
	No TSP	1003	127	27
SB, Weekday, Peak	TSP	1054	120	28
	No TSP	1106	116	28
SB, Weekday, Off Peak	TSP	959	131	92
	No TSP	948	146	45
SB, Weekend	TSP	896	95	45
	No TSP	955	110	29

*Results are not statistically significant at the 5 percent confidence level.

In this case, the *southbound, weekday, off peak* runs actually show an increase in travel times between buses equipped and not equipped with TSP. All the other groups show a statistically significant decrease in travel times, except for the *northbound, weekday, peak* runs, where the difference is not statistically significant.

Despite the fact that many of these differences are statistically significant, the differences could have resulted from something other than the presence of TSP. To test for this possibility, travel time statistics were determined for those portions of the route that did not include TSP equipped intersections. Because other factors that could affect travel time, such as the driver and the level of congestion, were the same for the portions of the same trip through TSP and non-TSP intersections, this approach controls for these other factors. Table 3-15 provides statistics about the travel times for the segments in the study area that do not include TSP intersections and for buses equipped or not equipped with TSP transponders, as indicated in the "TSP" column.

Table 3-15. Travel Times for TSP and Non-TSP Buses, Segments without TSP

Route	TSP	Travel Times (sec)		Count
		Avg	Stnd Dev	
NB, Weekday, Peak *	TSP	842	94	26
	No TSP	852	80	24
NB, Weekday, Off Peak *	TSP	758	82	85
	No TSP	759	84	41
NB, Weekend *	TSP	702	80	39
	No TSP	676	59	26
SB, Weekday, Peak *	TSP	810	103	26
	No TSP	826	96	25
SB, Weekday, Off Peak	TSP	737	83	93
	No TSP	763	75	46
SB, Weekend *	TSP	685	80	42
	No TSP	689	78	28

*Results are not statistically significant at the 5 percent confidence level.

While the travel times were often smaller for the TSP equipped buses than for those not equipped, this differences were much smaller than for the TSP segments, and were only statistically significant for the *southbound, weekday, off peak* segments. This supports the claim that the travel time reductions are due to TSP.

These results shown in Tables 3-14 and 3-15 do not indicate that the addition of TSP improved travel time reliability. For the segments with TSP, TSP buses experienced better travel time reliability than non-TSP buses in two of the six time periods (as compared to one out of the six time periods when looking at non-TSP intersections).

3.4.3 GPS Data: Operational Impacts of Reduced Travel Time / Travel Time Variability

Because the overall travel time savings due to TSP, averaging less than 1 minute per run, were small compared to the total travel time (about 40 minutes), the operational impacts of the Sacramento TSP deployment were minimal. These small time savings were not enough to allow RT to modify their schedules or otherwise change their operations.

Among other factors, this limited benefit may be due in part to the low density of the TSP intersections in the study corridor. The study area includes only 15 TSP equipped intersections out of a total of 29 intersections over a route nearly 5 miles in length. The route also includes 38 bus stops, which means that the bus spends a good deal of time loading and unloading passengers. Over the course of an average run, it was found that each bus spent approximately 25 minutes of each run traveling, 5 minutes loading and unloading passengers, and 10 minutes waiting at traffic signals. Of the time spent at traffic signals, about 4 minutes were spent waiting for green lights, with the remainder spent waiting for the queue to begin moving and reaching the intersection. Since the TSP on Watt Avenue only has the potential to reduce the "waiting time" (4 minutes per intersection, on average), the potential for an operational impact of TSP in Sacramento was small. The addition of queue jumps[10] at select intersections could eliminate much of the time spent waiting for the queue to dissipate after the light turns green (6 minutes per intersection, on average).

[10] The bus approaches queue jump intersections in the right-turn lane, and a separate signal head provides an advance green to the bus so that they can "jump the queue."

4. IMPACTS ON TRAFFIC MOBILITY

4.1 OVERVIEW OF APPROACH

For the traffic mobility portion of the evaluation, it was hypothesized that providing additional green time for buses on Watt Avenue would lead to an overall improvement in arterial traffic conditions on the mainline. Similarly it was thought that the addition of transit signal priority might negatively affect mobility on Watt Avenue's cross-streets. Therefore, the purpose of the traffic mobility portion of the evaluation was to measure traffic mobility on Watt Avenue and on Watt Avenue's cross-streets both before and after the addition of TSP, and to determine if there were any impacts resulting from the addition of the system.

4.2 DATA COLLECTION

The evaluation team performed floating car runs in the study area to provide data necessary to assess the overall traffic performance of Watt Avenue and its cross-streets during peak periods with and without the addition of TSP on the corridor. The evaluation team also obtained traffic volume counts from Sacramento County both before and after the addition of TSP to determine if volumes changed during this timeframe. The following section provides details on the format, assumptions, and collection methods used in gathering traffic data for the evaluation.

4.2.1 Data Collection Procedures

The evaluation team collected travel time data using floating cars outfitted with GPS-based GeoLogger™ devices mounted on evaluation team vehicles. The GPS logger is a small device that requires no human interaction during the drive other than that it alerts the user when the battery is low or the memory is full. The device collects data in five-second intervals, and aggregates traffic volume data into 15-minute periods.

The evaluation team collected data using two vehicles: one traveling northbound and southbound on Watt Avenue, and one traveling on a "serpentine" route covering five of Watt Avenue's cross-streets: Arden Way, El Camino Avenue, Marconi Avenue, Edison Avenue, and Auburn Boulevard. Figures 4-1 and 4-2 show the vehicle routes as recorded by the GPS loggers. In the interest of maximizing the number of runs collected, the evaluation team limited the boundaries of the travel time runs to the northern portion of the project area, between Arden Way and Auburn Boulevard. This portion was chosen as it includes 10 of the 15 intersections where TSP was deployed, and therefore it was expected that greater impact would be observed in this section of the study area. The Watt Avenue project segments included in the traffic portion of the study area are as follows:

- Segment II – Arden Way (throughput analysis of this intersection)
- Segment III – Alta Arden Way to Butano Drive
- Segment IV – Country Club Center to Auburn Boulevard

The "serpentine" route (shown in Figure 4-2) was a continuous route selected to maximize the amount of cross-street data collected and to minimize the number of U-turn maneuvers. The two streets parallel to Watt Avenue that were used to complete the route were Eastern Avenue and Fulton Avenue. During the post-processing of the data, entries from these streets were discarded, leaving only the Watt Avenue data and the cross-street data.

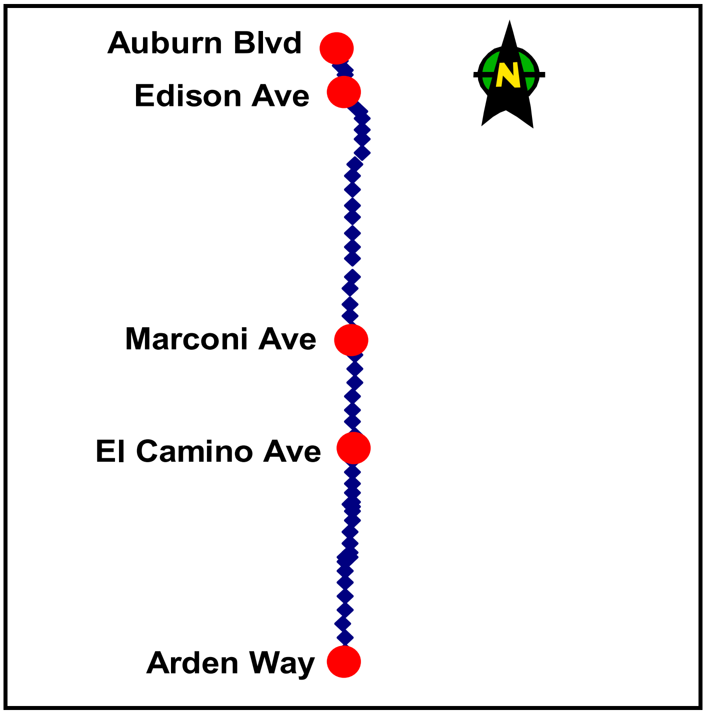


Figure 4-1. Watt Avenue Route

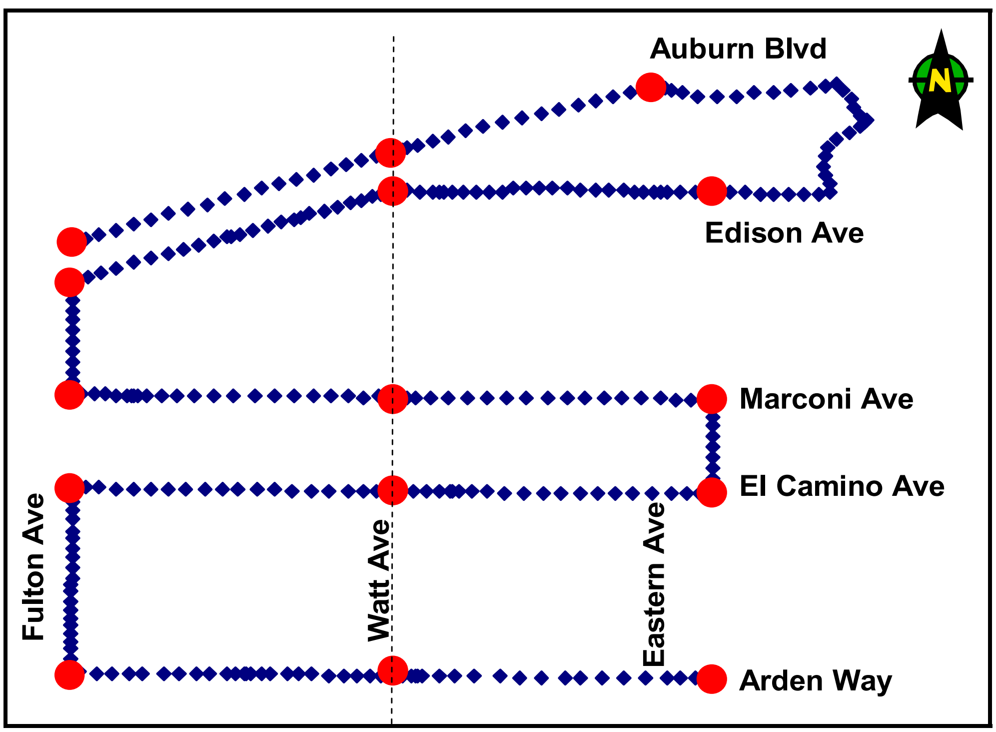


Figure 4-2. Cross Street "Serpentine" Route

4.2.2 Data Elements Collected

The data from the GPS loggers contained the following identifiers:

- GPS coordinates (longitude/latitude)
- Heading
- Date (Greenwich Mean Time [GMT])
- Time (GMT)
- Point speed

The evaluation team derived the total travel time from the recorded timestamps at the beginning and end of each run. Point speed data were not used for this analysis.

4.2.3 Other Traffic Data Collected

The evaluation team also gathered the following traffic volume data:

- Main arterial traffic volume data from the advance loop detectors on Watt Avenue northbound and southbound between Arden Way and Auburn Boulevard.
- Cross-street traffic volumes from the advance loop detectors and/or hose counters approaching Watt Avenue at Arden Way, El Camino Avenue, Marconi Avenue, Edison Avenue, and Auburn Boulevard.

4.2.4 Data Collection Periods

Baseline traffic data were collected from March 9 to March 14, 2003, and on March 20, 2003. Post-deployment data were collected from April 26 to April 30, 2004. Data were collected during the morning (7:00-9:00 am), mid-day (11:00 am-1:00 pm), and evening (4:00-6:00 pm) peak periods. Table 4-1 summarizes the sample size of traffic data collected during each of the two evaluation phases.

As with the transit data collection, not all buses operating on Routes 80 and 84 during the course of the "after" data collection were receiving priority as expected for a number of reasons mentioned previously in Section 2. As a result, all of the Phase III runs cannot all be classified as "with TSP" runs, and unlike the transit analysis already presented, it is impossible to identify which runs should be considered "with TSP" and which should be considered "without." For analysis purposes, all Phase III data has been considered "after" data and is compared to the Phase II or "before" data.

Table 4-1. Summary of Data Collection Sample Size

	Number of Runs Collected Before / After TSP Deployment					
	AM (7-9am)		Midday (11am-1pm)		PM (4-6pm)	
Corridor / Direction	**Phase II**	**Phase III**	**Phase II**	**Phase III**	**Phase II**	**Phase III**
Watt Avenue						
NB	29	31	29	32	22	28
SB	33	30	30	31	24	27
Arden Way						
EB	3	4	5	4	5	4
WB	3	6	5	7	6	6
El Camino Avenue						
EB	9	12	10	12	11	11
WB	8	7	9	8	8	6
Marconi Avenue						
EB	8	8	9	8	8	6
WB	8	12	10	12	7	11
Edison Avenue						
EB	8	12	10	12	7	12
WB	8	8	9	8	8	6
Auburn Boulevard						
EB	5	4	5	4	5	4
WB	3	6	4	6	5	6

4.3 RESULTS

The following sections present the results of the analysis of the traffic volume data and the travel time data.

4.3.1 Traffic Analysis

Traffic signals on Watt Avenue are actuated and coordinated for the Watt Avenue through-movements, with cycle lengths ranging from 110 seconds (1:50 minutes) to 150 seconds (2:30 minutes). Depending on traffic demand, the traffic signal controllers increase or decrease the cycle lengths and green times for each movement. Sacramento County did not make any changes to signal timings along Watt Avenue during the course of the evaluation. It should, however, be noted that many of the storefronts along this section of Watt Avenue were undergoing renovation during the Phase II data collection, and as a result some stores that were closed during Phase II were open during Phase III. Driveway traffic seemed busier near this area during the Phase III data collection, but no counts were performed to support this observation.

In order to verify that traffic volumes on Watt Avenue and its cross-streets had not changed significantly between the "before" and "after" data collection efforts, the evaluation team obtained traffic volume data for locations within the study area both before and after the addition of TSP, and compared these data to determine if there was a change. Data were obtained from advance loop detectors at intersections within the study area with detection coverage (many intersections do not have coverage). For intersections without complete detection coverage (e.g., a turn lane is not covered), volumes were estimated based on traffic patterns at nearby intersections with complete detection coverage. These volume data are presented in Table 4-2, and the percent changes between "before" and "after" are presented in Table 4-3.

Table 4-2. Traffic Volumes within Study Area Before and After TSP

	AM (7-9am)		Midday (11am-1pm)		PM (4-6pm)	
Corridor / Direction	**Phase II**	**Phase III**	**Phase II**	**Phase III**	**Phase II**	**Phase III**
Intersection of Arden Way and Watt Avenue (Segment II)						
NB	6,208	6,108	5,715	5,633	7,353	6,939
SB	6,302	5,984	6,651	6,313	7,269	6,722
WB	2,761	2,611	1,649	1,688	1,611	1,538
EB	1,225	1,204	2,479	2,294	2,957	2,970
Average of Watt Avenue Intersections within Segment IV						
NB	4,613	5,063	5,672	5,715	6,081	6,897
SB	5,981	6,312	5,222	5,320	5,460	5,666
WB	2,951	2,718	2,529	2,595	2,802	2,747
EB	2,162	2,117	2,685	2,597	2,928	2,804

Table 4-3. Traffic Volume Differences within Study Area Before and After TSP (percent)

Corridor / Direction	AM (7-9am)	Midday (11am-1pm)	PM (4-6pm)
Intersection of Arden Way and Watt Avenue (Segment II)			
NB	-2%	-1%	-6%
SB	-5%	-5%	-8%
WB	-6%	2%	-5%
EB	-2%	-8%	0%
Average of Watt Avenue Intersections within Segment IV			
NB	9%	1%	12%
SB	5%	2%	4%
WB	-9%	3%	-2%
EB	-2%	-3%	-4%

Overall, traffic volumes on Watt Avenue did not change significantly between the two evaluation periods. There was a slight decrease in volume at the intersection of Watt Avenue and Arden Way, located in Segment II, which was offset by approximately the same volume increases at intersections in Segment IV. For example, southbound Watt Avenue in Segment II, where Arden Way is located, experienced a volume drop of 8 percent, while northbound Watt Avenue in Segment IV experienced a volume increase of 12 percent. It is possible that this shift is due to new commercial developments in Segment IV drawing customers away from the developments near Arden Way. Overall, these data indicate that traffic within the study area did not change significantly during the course of the evaluation.

4.3.2 Traffic Mobility Analysis

The evaluation focused on two measures related to traffic mobility: *travel time* and *travel time reliability*, defined as the variability of the travel time runs one standard deviation away from the average. Larger values for travel time reliability indicate that travel times along the corridor are less consistent, while smaller values indicate that travel times along the corridor are more consistent. Table 4-4 presents the measured changes in travel time and travel time reliability when comparing the “before” and “after” data, while Figures 4-4 through 4-7 illustrate these changes graphically. Note that detailed data for travel time averages and travel time reliability are provided in Appendix B.

As shown in Figure 4-3, when comparing the “before” and “after” travel times along Watt Avenue, it was found that, on average, travel times decreased by 9 and 13 percent for the northbound and southbound directions, respectively. When isolating the data by direction and time of day, travel times decreased in all cases except for two: Segment III experienced a travel time increase of 1 percent during the PM peak in the southbound direction, and Segment IV experienced a travel time increase of 14 percent during the PM peak in the northbound direction.

As shown in Figure 4-4, the cross-streets experienced higher travel times in the “after” case in general. On average, the cross-streets experienced an increase in travel time of five percent. When isolating the data by direction and time of day, there were seven cases in which the travel time decreased. Of these, 3 experienced a decrease of 3 percent or less, while the other 4 experienced significant decreases: eastbound Arden during the AM peak (9 percent decrease), eastbound Auburn during the PM peak (30 percent decrease), and westbound Auburn during the midday and PM peak (23 and 7 percent decreases, respectively).

The evaluation team noted that during the Phase II data collection, westbound AM and eastbound PM travel times on Auburn Boulevard were especially high due to additional delays and travel time unreliability incurred from the heavy traffic movements from nearby I-80 Business Loop ramps. During the Phase III data collection, however, much of this delay was gone, resulting in a considerable improvement in travel times. This improvement could have been the result of the construction project near the Watt Avenue and Auburn Boulevard intersection in mid-2003, or due to changes in volumes at the Auburn Boulevard ramps. However, there is no conclusive evidence for either hypothesis, since no volume counts from the on-ramp or Auburn Boulevard were available.

Table 4-4. Before-After Travel Time and Travel Time Reliability Comparisons (percent change)

Corridor / Direction	AM (7-9am)	Midday (11am-1pm)	PM (4-6pm)
Watt Avenue Segment III			
NB	-3 (-28)	-36 (57)	-8 (51)
SB	-27 (33)	-17 (32)	1 (-24)
Watt Avenue Segment IV			
NB	-6 (52)	-14 (30)	14 (32)
SB	-18 (43)	-12 (50)	-7 (23)
Arden Way			
EB	-9 (25)*	19 (-156)*	13 (-179)*
WB	2 (51)*	7 (-16)	8 (48)
El Camino Avenue			
EB	-1 (8)	10 (-58)	4 (-3)
WB	1 (-240)	13 (-81)	17 (-57)
Marconi Avenue			
EB	20 (13)	4 (3)	7 (-138)
WB	-1 (3)	14 (-49)	19 (-20)
Edison Avenue			
EB	4 (-4)	7 (-49)	3 (12)
WB	1 (38)	-3 (51)	1 (-34)
Auburn Boulevard			
EB	20 (20)	1 (12)	-30 (40)
WB	-23 (73)*	-7 (-68)*	20 (-21)*

* The sample size for these runs was less than five.

Note: The first number shown indicates change in travel time. The following number (in parentheses) indicates the change in travel time reliability.

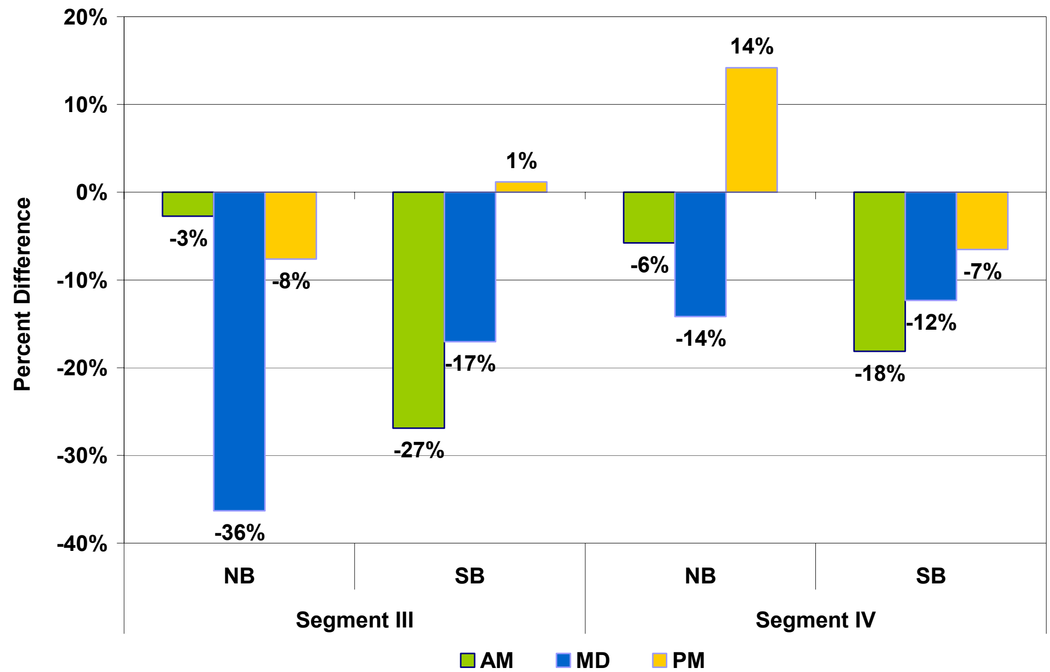


Figure 4-3. Comparison of Watt Avenue Travel Times Before and After TSP

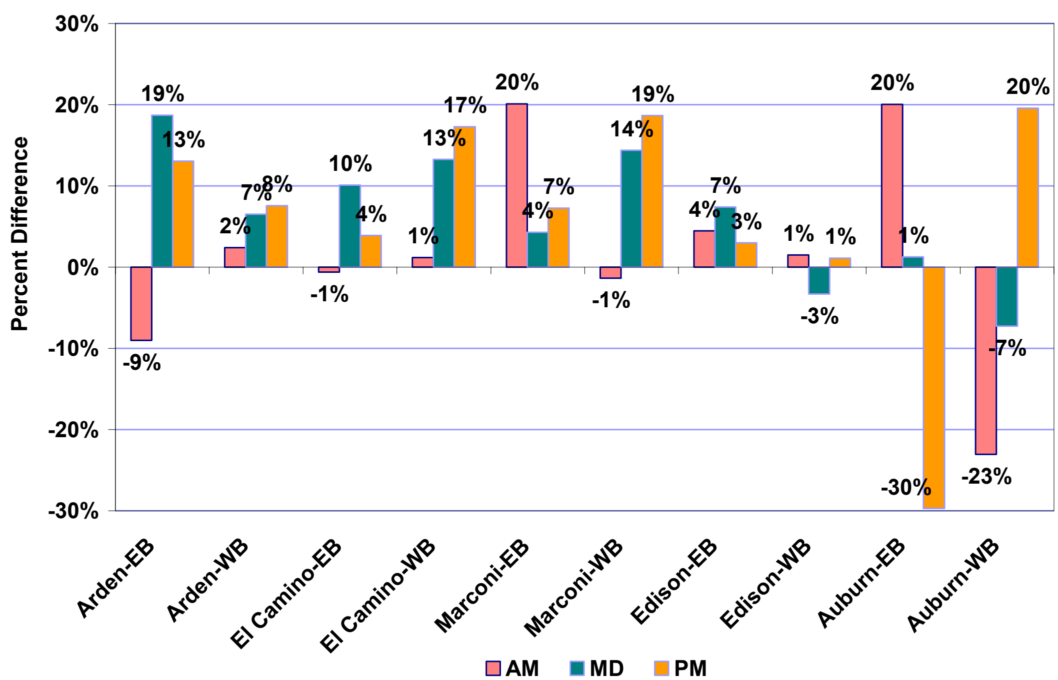


Figure 4-4. Comparison of Cross Street Travel Times Before and After TSP

As shown in Figure 4-5, travel time reliability on Watt Avenue increased significantly between the "before" and "after" cases, with improvements ranging from 23 to 57 percent. The only exceptions to this are that Segment III experienced a 28 percent decrease in travel time reliability during the AM peak, and a 24 percent decrease during the PM peak.

However, the improvement in travel time reliability on Watt Avenue was offset by a decrease in travel time reliability on most of the cross-streets. El Camino experienced the worst change with a 240 percent decrease in travel time reliability in the westbound direction during the AM peak. Eastbound Arden also experienced significantly less reliable travel times with 156 and 179 percent reductions during the midday and PM peaks, respectively.

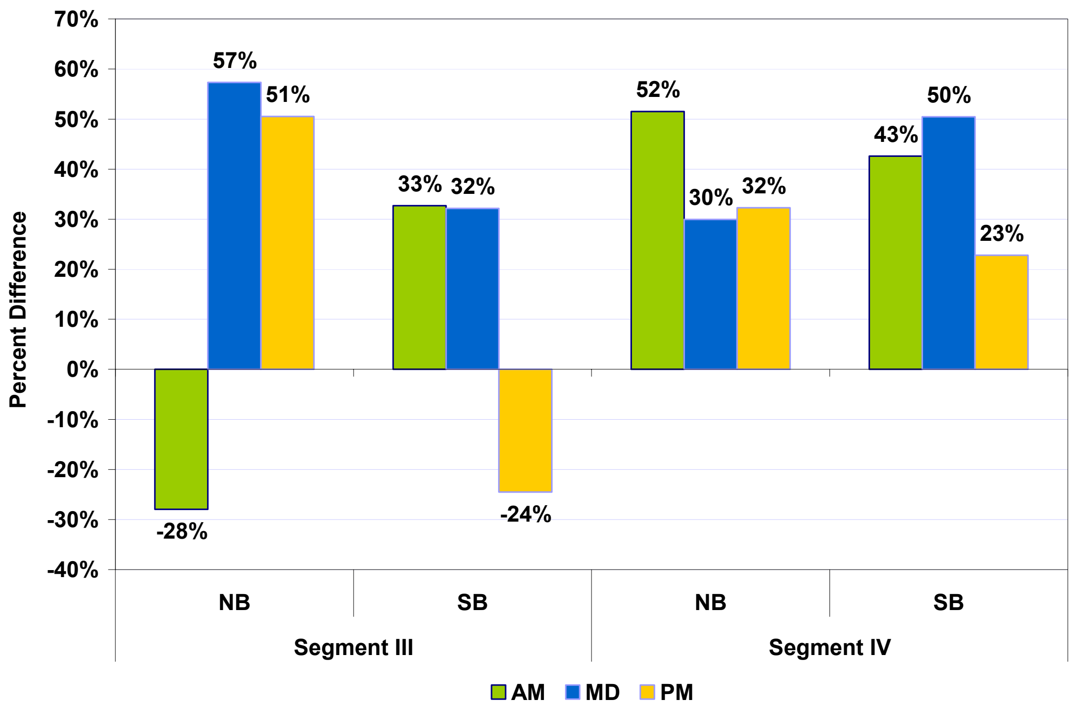


Figure 4-5. Comparison of Watt Avenue Travel Time Reliability Before and After TSP

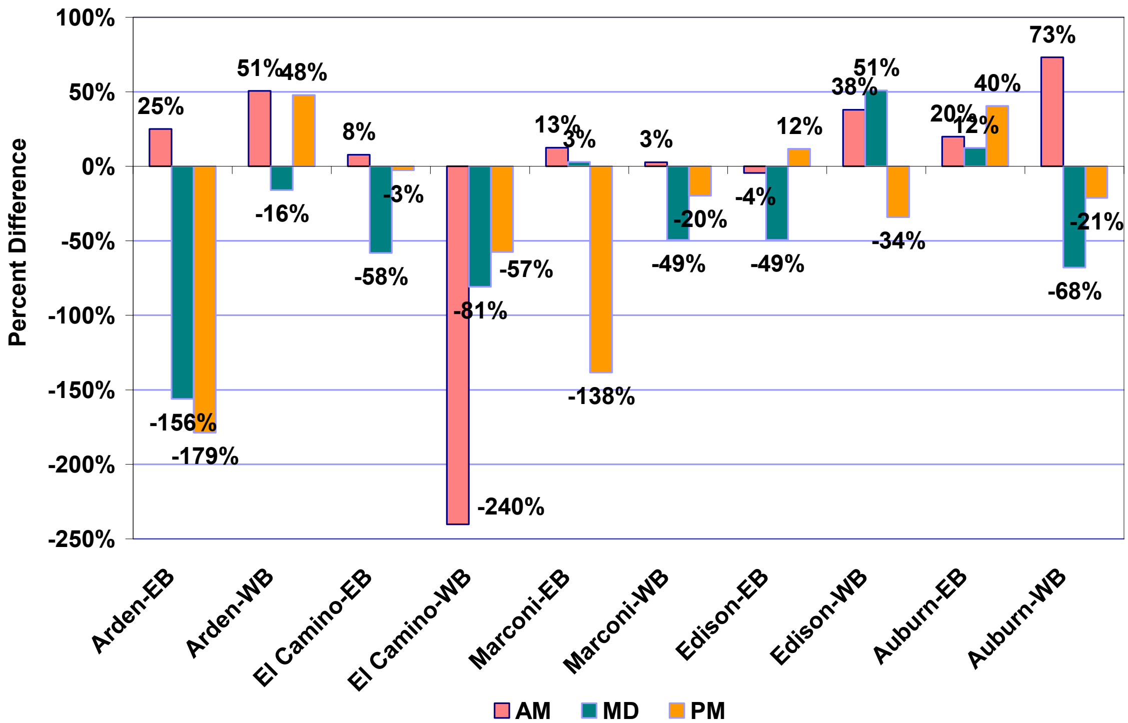


Figure 4-6. Comparison of Cross Street Travel Time Reliability Before and After TSP

5. SUMMARY AND CONCLUSIONS

5.1 INTRODUCTION

This report presented the evaluation strategies and objectives, the data collection methodologies, and the results of the national evaluation of the Sacramento – Watt Avenue Transit Signal Priority Deployment.

5.2 SUMMARY OF APPROACH AND FINDINGS

The results of the analyses performed are summarized here according to the two evaluation objectives:

- Assess the impacts of TSP on bus travel times and travel time reliability.
- Assess the impacts of TSP on traffic mobility.

5.2.1 Impacts of TSP on Bus Travel Times and Travel Time Reliability

In order to assess the impacts of TSP on transit travel times, the evaluation team conducted on-board observations of buses traveling along the corridor before and after deployment of transit signal priority. The evaluation team also obtained automated GPS data for buses operating on the corridor with and without TSP emitters.

From analysis of the manual data collection[11] it was found that, in most cases, TSP equipped buses experienced fewer red lights at TSP intersections than non-TSP equipped buses. It was also found that, on average, TSP equipped buses experienced less time waiting for green lights than non-TSP equipped buses (the difference in average time to wait for a green light was approximately 20 seconds less for TSP equipped buses). Similarly, TSP equipped buses experienced less signal delay at TSP intersections than non-TSP equipped buses (while the total signal delay experienced at non-TSP intersections was similar for all buses).

From the GPS data analysis[12] it was found that the average travel time for TSP equipped buses was between 14 and 71 seconds less than for non-TSP buses traveling over the same segments. This amounts to a 4 percent decrease in bus travel times. For the control intersections (i.e., those without TSP), the travel times for TSP and non-TSP buses were similar, indicating that this difference can be attributed to the TSP.

Because the overall travel time savings due to TSP (less than 1 minute per run on average), was small compared to the total travel time (about 40 minutes), the operational impacts of the Sacramento TSP deployment were minimal. These small time savings were not enough to allow RT to modify their schedules or otherwise change their operations.

Among other factors, this limited benefit may be due in part to the low density of the TSP intersections in the study corridor. The study area includes only 15 TSP equipped intersections out of a total of 29 intersections over a route nearly 5 miles in length. The route also includes 38 bus stops, which means that the bus spends a good deal of time loading and unloading

[11] Note that the results of the manual data collection were not found to be statistically significant.

[12] Note that the results of the GPS data analysis were found to be statistically significant.

passengers. Over the course of an average run, it was found that each bus spent approximately 25 minutes of each run traveling, 5 minutes loading and unloading passengers, and 10 minutes waiting at traffic signals. Of the time spent at traffic signals, about 4 minutes were spent waiting for green lights, with the remainder spent waiting for the queue to begin moving and reaching the intersection. Since the TSP on Watt Avenue only has the potential to reduce the "waiting time" (4 minutes per intersection, on average), the potential for an operational impact of TSP in Sacramento was small. The addition of queue jumps[13] at select intersections could eliminate much of the time spent waiting for the queue to dissipate after the light turns green (6 minutes per intersection, on average).

The results do not indicate that the addition of TSP improved travel time reliability. For the segments with TSP, TSP buses experienced better travel time reliability than non-TSP buses in two of the six time periods (as compared to one out of the six time periods when looking at non-TSP intersections).

5.2.2 Impacts of TSP on Traffic Mobility

In order to assess the impacts of TSP on traffic mobility, the evaluation team conducted floating car runs along a portion of Watt Avenue and on sections of five of Watt Avenue's cross-streets. The team collected these data both before and after TSP was deployed along the corridor, and then compared the data to determine if the addition of TSP had an impact on traffic mobility along the corridor. The evaluation team looked at both travel time and travel time reliability.

While the system was intended to improve transit on-time performance and reliability,[14] it seems that it may have also produced the residual benefit of travel time improvements of approximately 10 percent to the overall traffic. Travel time reliability on Watt Avenue also improved during this timeframe; in the absence of other factors, presumably due to the implementation of transit signal priority.

Travel times on Watt Avenue cross-streets increased in three-quarters of the cases, indicating that TSP may have had a negative impact on the cross-streets. Travel time reliability on the cross-streets showed mixed results. Travel time reliability improvements were observed in approximately 50 percent of the cases.

5.3 CONCLUSIONS

Based on the results of this evaluation and the conclusions drawn, the hypotheses stated up front have either been supported by the results of the evaluation, have not been supported by the results of the evaluation, or are inconclusive at this time. The conclusions for each of the hypotheses are as follows.

- Hypothesis: TSP will improve transit mobility and performance by reducing travel times through the study area and by minimizing signal delay. *This hypothesis is supported by the analysis performed of GPS data for buses operating along Watt Avenue with and without TSP.* From the GPS data analysis it was found that the average travel time for TSP equipped buses was between 14 and 71 seconds less than for non-TSP buses traveling over the same segments. This amounts to a 4 percent decrease in bus travel times. For the control

[13] The bus approaches queue jump intersections in the right-turn lane, and a separate signal head provides an advance green to the bus so that they can "jump the queue."

[14] Note that the results of the floating car run analysis were not found to be statistically significant.

intersections (i.e., those without TSP), the travel times for TSP and non-TSP buses were similar, indicating that this difference can be attributed to the TSP.

- Hypothesis: TSP will improve travel time reliability and schedule reliability. *This hypothesis is not supported.* For the segments with TSP, TSP buses experienced better travel time reliability in two of the six time periods (as compared to one out of the six time periods when looking at non-TSP intersections).
- Hypothesis: TSP will improve traveler mobility in the corridor by reducing vehicle delay and travel times. *This hypothesis is inconclusive.* Although difficult to state with much certainty, the results indicate that the addition of TSP on Watt Avenue had somewhat of a positive impact on Watt Avenue traffic and somewhat of a negative impact on cross-street traffic.

APPENDIX A:

ANALYSES OF BUS TRAVEL TIME DATA

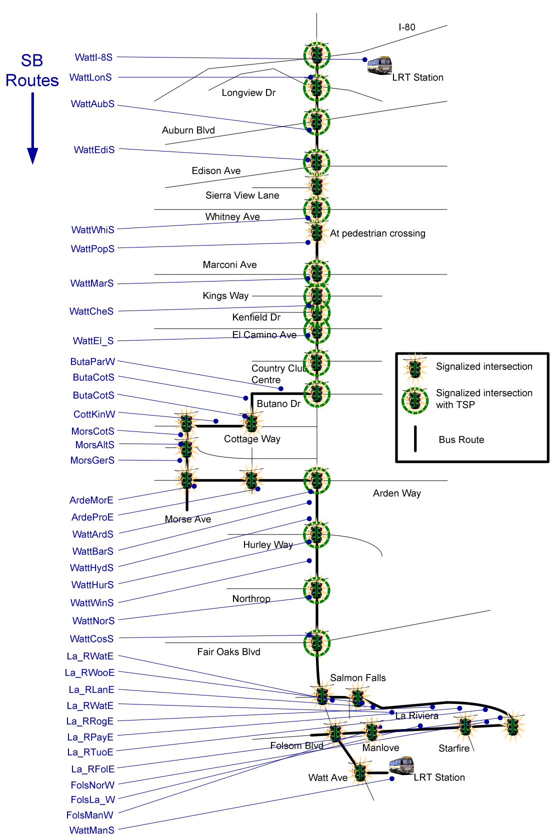
BACKGROUND

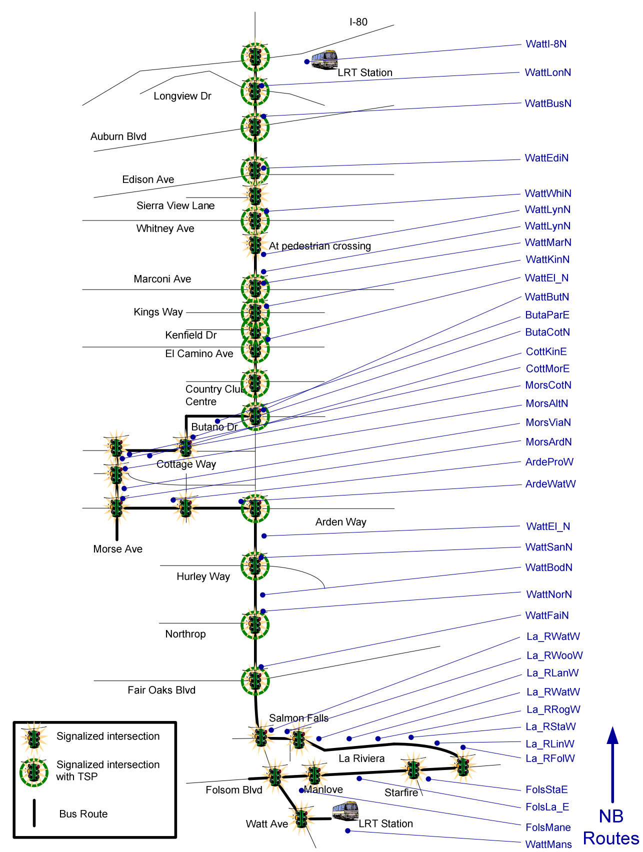
Two approaches were used to collect bus travel time information for this study. The first approach, called on-board observations below, was to place observers on buses to record travel time information. Each observer would board a bus at either Manlove LRT Station (for northbound runs) or the I-80 LRT Station (for southbound runs), ride the bus as it traversed the route, record timestamps and other data at key events that occurred along the route. This approach had the advantage that the on-board observer could record timestamps for a number of different events, including when the bus entered a queue at a signalized intersection. It had the disadvantages that it was more error prone, subjective, and costly. This limited the number of travel time runs completed and introduces uncertainty in the accuracy of the recorded data.

The second approach, called GPS observations, was to obtain data from buses on the routes of interest that were equipped with GPS receivers and on-board hardware that archived timestamp information when a bus arrived at a stop and periodically archived timestamp information while between stops. This approach had the advantages that (a) it was relatively inexpensive to gather the data, so data for a large number of runs was obtained, and (b) the data was not subjective because it was interpreted by an observer. The main disadvantage was that the while driving timestamps were taken only every 500 ft, so that it was not possible to accurately determine when a bus entered the back of a queue at a signalized intersection. This appendix presents the results of the analysis of both types of bus travel time data.

THE STUDY AREA

The maps below show the study area for which bus travel time data was recorded.





In these maps, the bus stops for the southbound runs are listed on the left, with the list on the right being the bus stops for the northbound runs. The on-board observations occurred only for the area indicated.

Because GPS data was archived for all the runs made by equipped buses during the observational period, the GPS data also includes an area north of the indicated region that was not equipped with TSP equipment. In particular, the study area included two northbound routes (80IB and 84IB) and two southbound routes (80OA and 84OA). The southernmost point on these routes was the WattManS station shown on the maps, but the routes extended north beyond the Watt-8N/Watt-8S stations at the northern edge of the maps. The following table lists the stop numbers that bound the regions that were used in analyzing the GPS data.

Route	From Stop	To Stop	Description
80IB	WattManS Stop 1	WattI-8N Stop 39	Northbound route from the Manlove LRT Station in the south to the I-80 LRT Station in the north. This is on the study route.
	WattI-8N Stop 39	WattE_SN Stop 51	Northbound route north of the study area, but still on Watt Avenue.
	WattChan Stop 53	DesiGrew Stop 68	Northbound route north of the study area and not on Watt Avenue.
84IB	WattManS Stop 1	WattI-8N Stop 39	Northbound route north of the study area, but still on Watt Avenue.
	WattI-8N Stop 39	WattE_SN Stop 51	Northbound route north of the study area, but still on Watt Avenue.
	WattE_SN Stop 51	WattManS Stop 66	Northbound route north of the study area and not on Watt Avenue.
80OA	DesiGrew Stop 1	WattDons Stop 18	Southbound route north of the study area and not on Watt Avenue.
	WattDons Stop 18	WattI-8S Stop 29	Southbound route north of the study area but still on Watt Avenue.
	WattI-8S Stop 29	WattManS Stop 66	Southbound route from the I-80 LRT Station in the north to the Manlove LRT Station in the south. This is the study route.
84OA	WattElvs Stop 1	WattDons Stop 20	Southbound route north of the study area and not constrained to Watt Avenue.
	WattDons Stop 20	WattI-8S Stop 31	Southbound route north of the study area but still on Watt Avenue.
	WattI-8S Stop 31	WattManS Stop 68	Southbound route from the I-80 LRT Station in the north to the Manlove LRT Station in the south. This is the study route.

THE BUS SCHEDULE

The following table lists the bus schedule for the five buses that pass through the study area on weekdays. (This schedule was valid during the 2005 data collection period, but the schedule was similar during the other years.)

Weekday Bus Schedule															
Time	Run 8001			Run 8002			Run 8003			Run 8004			Run 8005		
	Rte	Schedule		Rte	Schedule		Rte	Schedule		Rte	Schedule		Rte	Schedule	
6:00	80OA	5:56	6:33	84IB	5:37	6:12	84OA	6:28	7:06				80IB	6:25	7:03
7:00	84IB	6:55	7:38	84OA	7:24	8:03	80IB	7:25	8:03	80OA	6:55	7:34			
8:00	84OA	8:39	9:18	80IB	8:25	9:03				84IB	7:55	8:33	80OA	8:09	8:49
9:00	80IB	9:40	10:15				80OA	9:08	9:46	84OA	9:39	10:18	84IB	8:55	9:30
10:00				80OA	10:08	10:46	84IB	10:10	10:45	80IB	10:40	11:15	84OA	10:38	11:16
11:00	80OA	11:20	12:01	84IB	11:10	11:45							80IB	11:40	12:15
12:00	84IB	12:10	12:45				84OA	11:53	12:31	80OA	12:23	13:01			
13:00				84OA	12:53	13:31	80IB	12:55	13:30	84IB	13:25	14:00	80OA	13:23	14:01
14:00	84OA	13:53	14:31	80IB	13:55	14:30	80OA	14:38	15:16				84IB	14:25	15:00
15:00	80IB	14:55	15:30	80OA	15:38	16:16	84IB	15:25	16:00	84OA	15:08	15:46			
16:00	80OA	16:40	17:20	84IB	16:40	17:18				80IB	16:10	16:48	84OA	16:06	16:46
17:00	84IB	17:40	18:18				84OA	17:12	17:52				80IB	17:10	17:48
18:00				84OA	18:27	19:07	80IB	18:10	18:48	80OA	17:57	18:37			
19:00	840A	19:27	20:07	80IB	19:25	19:59				84IB	18:40	19:15	80OA	18:56	19:36
20:00	80IB	20:25	20:59				80OA	19:53	20:26	84OA	20:42	21:20			
21:00				80OA	21:05	21:41	84IB	21:03	21:37						
22:00	80OA	22:08	22:41												

ON-BOARD OBSERVATIONS

The following approach was used to collect on-board observation data. An observer would board a bus at either Manlove LRT Station (for northbound runs) or the I-80 LRT Station (for southbound runs), ride the bus as it traversed the route, record timestamps and other data at key events that occurred along the route.

- For each bus stop at which the bus stopped, the observer recorded a timestamp when the bus stopped, when passenger loading was complete, and when the bus began moving again. They could also record auxiliary information such as the number of passengers boarding and disembarking the bus.
- For each bus stop at which the bus did not stop, the observer recorded a timestamp when the bus passed the stop.
- For each signalized intersection at which the bus was stopped by the signal, the observer recorded a timestamp when the bus first stopped at the back of the queue, when the light turned green, when the bus started moving again after the light turned green, and when the bus entered the intersection. They could also record auxiliary information such as if the bus had to wait through multiple signal cycles.
- For each signalized intersection at which the bus was not stopped, the observer recorded a timestamp when the bus entered the intersection.

These observations resulted in the following measures of bus operations that were available for analysis.

Boarding Time	This is the elapsed time between when a bus stops at a bus stop to load and unload passengers and when the last passenger is loaded or unloaded.
Merging Time	This is the elapsed time between when the last passenger is loaded or unloaded at a bus stop and when the bus successfully merges into traffic.
Waiting for First Green	This is the elapsed time between when a bus stops at the end of a queue while waiting for a green light and when the light first turns green.
Waiting for Movement	This is the elapsed time between when a light first turns green and when the bus (waiting at the end of the queue) first begins moving.
Clearing Intersection	This is the elapsed time between when a bus first begins moving after waiting for a green light and when the bus clears an intersection. If a bus does not clear the intersection during the first available green cycle, this time will include time spent waiting for the next green light and waiting for movement after getting the next green light.
Cycle Failure	This occurs when a bus, after stopping in a queue at a red light, does not clear the intersection during the first green light cycle after the red light at which the bus first stopped.
Signal Delay	This is the time spent waiting at a signal, defined as the sum of Waiting for First Green and Waiting for Movement. Note that it excludes Clearing Intersection, the third element associated with the time spent at a red light.
Travel Time	This is the time a bus spends traveling between intersections and/or bus stops.

Travel time runs were collected during the period March 10 through 21, 2003 (before TSP was installed) and the period April 26 through 30, 2004 (after TSP was installed). A total of 233 travel times were collected before TSP was installed, with 128 travel times collected after TSP was installed. Because only some buses were equipped with TSP devices and, even if equipped, only some drivers utilized the devices, only a fraction of the after TSP travel times were for buses with TSP on. The following table summarizes the number of travel time runs that were performed.

Travel Time Runs

Type of Run		TSP On	TSP Off
Period	Before	0	233
	After	66	62

During the after-deployment data collection, observers often had difficulty keeping up with the data collection process, and many travel time runs included missing data. The following table summarizes the travel time runs for which data is missing:

Phase III Travel Time Runs		
Category	**TSP**	
	On	**Off**
Missing intersection data	4	10
Missing bus stop data	23	12
Missing intersection and bus stop data	15	19
No missing data	24	21
TOTAL	66	62

Because the focus of the analysis will be on the signal delay at TSP-enabled intersections, the number of travel time runs with missing data at TSP-enabled intersections is also of interest. The following table summarizes this information.

Phase III Travel Time Runs		
Category	**TSP**	
	On	**Off**
Missing TSP intersection data	16	17
No missing TSP intersection data	50	45
TOTAL	66	62

When conducting run-based analyses (e.g., total signal delay per run), only travel time runs for which there was not missing TSP intersection data was used. When conducting intersection-based analyses, all the data was used.

GPS OBSERVATIONS

Following the difficulties with the 2004 observations, RT volunteered to assign newly acquired GPS-equipped buses to the study route and to archive the GPS locations for analysis by the Evaluation Team. The GPS devices on these buses automatically recorded timestamps at bus stops and at regular intervals between stops, as well as the dwell time at each stop (i.e., the amount of time during which the door was open), the odometer reading, the GPS coordinates, and other values. The following fields are those that were important for analyzing the in-vehicle data:

- CDLRoute. A string that indicates the route on which a bus is currently traveling.
- StopNumber. A number that indicates, for the route indicated by CDLRoute, which stop number the bus is at or approaching.
- EventTime_UTC. A time stamp equal to the number of seconds since 1/1/1970.
- Odometer. The number of feet traveled since the bus began service that day.
- StopDwellTime. The number of seconds the bus was stopped with the door open (i.e., for passenger loading and unloading).
- Latitude and Longitude. The current position of the bus.
- EventType. A coded number indicating why the bus recorded a record. Some of the important EventType values are 2 (more than 500 ft traveled since recording last point), 3

(stopped at a bus stop), 4 (drove past a bus stop), 5 (stopped for passengers at a location other than a bus stop), 6 (operator assigned a new route), and 11 (end of route).

The Evaluation Team had hoped to use the GPS coordinates and the timestamps to identify the signal delay. Identifying the timestamp at which a bus first stopped (or reached a predetermined low speed) as it approached a signal could be used to estimate the time at which the bus entered a queue. The timestamp at which the GPS coordinates for a bus were the same as an intersection could indicate the time at which a bus cleared an intersection. The difference between these two values could provide an estimate of signal delay.

Unfortunately, the RT GPS devices were programmed to record timestamps at 500-foot intervals, an interval that is too coarse to accurately determine signal delay. (Because a bus spends time in a signal queue stopped, no timestamps will be recorded during the time the bus was in the queue.) For this reason, the GPS data was used to generate drive times (i.e., total time minus dwell time) that could be compared between buses with and without TSP.

CLEANING THE GPS DATA

Ideally, the in-vehicle data would have consisted of a series of data records which, when processed in chronological order for a specific file, would have proceeded progressively through the bus routes that were part of each run and, within each route, proceed progressively through each stop on each route. One could look for the EventType 6 to identify the start of a route, skip over EventType 2 records to find the time at which the bus reached each stop (indicated by EventType 3 and 4), and end the route when EventType 11 occurred. While this was generally true for the data, a review of the data indicated that anomalies existed. To determine whether any of these anomalies would significantly impact the analysis, software and database queries were developed to detect those anomalies that did exist (see the list below).

Same time stamp. Some records had the same time stamp, so that there was not a reliable way to know which event occurred first. In most cases (see table below), this occurred when a bus was traveling past a bus stop just after it recorded an EventType 2 record and would not affect an analysis.

Extracted from qTest_TimeStampDup							
FileID	TimeStamp	Odometer	EventType	CDLRoute	Stop	Lat	Long
1	1114961614	80939	2	80IB	32	38.622662	-121.382843
1	1114961614	80987	4	80IB	33	38.622860	-121.382881

In other cases, such as the one below, the in-vehicle system seemed to record data in the wrong order, marking a stop on route 80IB before that route actually began.

Extracted from qTest_TimeStampDup							
FileID	TimeStamp	Odometer	EventType	CDLRoute	Stop	Lat	Long
54	1116186861	517963	15	80OA	65	38.553490	-121.372459
54	1116186861	523763	2	80OA	66	38.553490	-121.372459
54	1116186861	517963	5	80OA	-1	38.553490	-121.372459
54	1116186862	517963	16	80OA	65	38.553490	-121.372459
54	1116186863	517963	14	80OA	65	38.553490	-121.372459
54	1116186863	523763	11	80OA	-1	38.553490	-121.372459
54	1116186863	523763	3	80IB	1	38.553490	-121.372459
54	1116186864	523763	6	80IB	-1	38.553490	-121.372459
54	1116186865	523763	9	80IB	1	38.553490	-121.372459
54	1116186866	523763	10	80IB	1	38.553490	-121.372459

The Evaluation Team used software tools to identify the 1,776 cases in which this occurred and adjust the data so that the time sequence was consistent.

Route records after end of route. In some cases (see table below), records associated with a route occurred after the end of the route was noted (EventType 11).

FileID	TimeStamp	Odometer	EventType	CDLRoute	Stop	Lat	Long
1	1114974996	392979	11	80OA	66	38.553509	-121.372482
1	1114974997	392979	14	80OA	65	38.553509	-121.372482
1	1114974997	392979	6	80IB	-1	38.553509	-121.372482

In other cases, records associated with a route occurred before the EventType 11 record occurred to indicate the route had started.

FileID	TimeStamp	Odometer	EventType	CDLRoute	Stop	Lat	Long
2	1115046368	242301	15	84IB	72	38.715061	-121.392120
2	1115046368	242301	5	84OA	-1	38.715061	-121.392120
2	1115046369	242301	16	84IB	72	38.715061	-121.392120
2	1115046370	242301	14	84IB	72	38.715061	-121.392120
2	1115046370	242301	11	84IB	73	38.715061	-121.392120
2	1115046371	242301	6	84OA	-1	38.715061	-121.392120

The Evaluation Team verified that, in all cases, these anomalies involved time differences of only 1 or 2 seconds, which could be safely ignored in the analysis. The data was adjusted to move the start/end of route marker to before/after the timestamp.

Short-term anomalies. The Evaluation Team noted that cases existed where otherwise good data was temporarily interrupted by a few errant records. In some cases, a single data point might be inserted with a different route than the surrounding data points. In others, as in the table below, it appeared that system operations were temporarily interrupted.

FileID	TimeStamp	Odometer	EventType	CDLRoute	Stop	Lat	Long
1	1114992575	776817	3	80IB	20	38.596169	-121.392197
1	1114992596	776961	11	80IB	20	38.596512	-121.392220
1	1114992639	158	8		-1	38.599609	-121.392212
1	1114992658	444	14		-1	38.600300	-121.392220
1	1114992659	478	6	80IB	-1	38.600441	-121.392220
1	1114992660	478	9	80IB	1	38.600441	-121.392220
1	1114992661	478	10	80IB	1	38.600441	-121.392220
1	1114992665	684	4	80IB	22	38.600819	-121.392242

The Evaluation Team noted that these interruptions sometimes resulted in skipped stops, but determined that these interruptions did not indicate any other type of corruption in the data. This type of anomaly did not require any correction to the data, though it did mean that data for some routes was incomplete.

Repeated stops. The Evaluation Team identified 241 cases where the same stop number occurred more than once within a 30 minute period for same bus. The example in the table below, in which the data indicates the bus drove past a stop, then stopped for passengers away from the stop, then drove past the stop again was typical.

FileID	TimeStamp	Odometer	EventType	CDLRoute	Stop	Lat	Long
7	1115236270	510883	2	84OA	26	38.657211	-121.382927
7	1115236278	511152	4	84OA	27	38.656326	-121.383080
7	1115236284	511255	5	84OA	27	38.656029	-121.383003
7	1115236303	511305	4	84OA	27	38.656326	-121.383080
7	1115236350	511757	2	84OA	27	38.654739	-121.383018
7	1115236366	512163	3	84OA	28	38.653542	-121.383080

Other types of multiple stop records (e.g., EventType 4 on two successive records, the first stop occurred several successive times) also occurred. Initially, the Evaluation Team believed that it would be safe to ignore the sections of routes with these anomalies since there were only 241 such anomalies out of more than 30,000 route segments. However, ignoring these anomalies introduced missing segments in many of the 523 runs for which data was available.

The Evaluation Team manually reviewed each of these anomalies and identified which of the repeated timestamps was most likely to correctly identify when the bus stopped at or passed by a bus stop. Factors such as the odometer distance to the preceding and following bus stops and the EventType helped guide these decisions. In the above example, the Evaluation Team recoded the two records with EventType 4 (drove past a bus stop) to EventType 2 (bus is driving) and recoded the EventType 5 record (stopped for passengers at a location other than a bus stop) to EventType 3 (stopped at a bus stop).

Checking the data. After correcting for the above anomalies, the Evaluation Team checked whether the resulting data followed the expected order described at the beginning of this section, with the exception that gaps would sometimes exist between stops on a route when the in-vehicle system failed temporarily or when repeated stops had been ignored. The data passed this test successfully, indicating that it was now ready for analysis.

OVERVIEW OF THE ANALYSIS APPROACH

The purpose of this analysis was to detect changes in bus travel times in Sacramento due to the deployment of TSP. The basic approach was to compare travel times for buses equipped with TSP with those not equipped with TSP. Making these comparisons was made complicated by several factors, such as the following:

- TSP only affected the time spent waiting at traffic signals, not the other elements of bus travel time (e.g., loading time, unloading time, travel time). Since the signal delay was only a fraction of the total travel time, changes in signal delay could be difficult to detect in terms of the total travel time. (The problem would be even worse if passenger loading and unloading time were included.)
- Buses that were ahead of schedule have timing checkpoints at which they wait to re-synchronize with their schedule. Improvements in travel time associated with TSP could be offset by increased checkpoint wait times. The only checkpoints in the route considered during this study were at the northern and southernmost stops.
- Because of changes in the level of congestion, travel times varied throughout the day. This analysis created bins by time of day so that travel times are compared for bus runs that occurred during times of day when travel conditions were similar.
- Because of differences in congestion in Northbound and Southbound directions and differences between the number of left- and right-hand turns, it may not be appropriate to compare northbound and southbound travel times. This analysis treated those two types of runs separately.
- Some intersections had unusual characteristics (e.g., unprotected left-hand turn) that resulted in very high variability in the delay time there. Inclusion of these intersections in the analysis would have resulted in high variability in the signal delays that would have diluted the ability to detect improvements brought about by the TSP. This analysis ignored some such intersections and treated other separately.
- The route includes both intersections for which TSP was deployed and intersections for which it was not. Including non-TSP intersections in the analysis could dilute the ability to detect the effect of TSP for intersections where it was used.

The overall approach taken in this analysis can be thought of in terms of three steps. The first step identified different characteristics that could affect bus travel times and categorized the observations into different bins that were similar in terms of these characteristics. For example, one set of bins was determined by time of day, so that travel times that occurred during times of day when congestion was high were not compared to travel times that occurred when congestion was low.

The second step compared travel time variables for observations within each bin that did and did not have TSP. These comparisons started with those characteristics directly tied to how TSP could reduce travel times, such as signal delay and the fraction of buses that stopped at a signal, and continued up the chain of cause-and-effect to estimate the final impact of TSP on bus travel times. These comparisons also considered changes in both bus travel times and travel time variability. Because the bins were created so that bus runs within each bin should have had similar travel times, and differences in the observed travel times can be ascribed to the presence of TSP.

The final step considered the observed impacts of the TSP and estimated the extent to which the observed changes could result in operational improvements. For example, the fractional decrease in travel times was computed to determine the likelihood that any travel time improvements could result in operational improvements such as more frequent bus runs or fewer buses being able to provide the same level of service for the existing runs. This step also considered how different operating characteristics might impact the impact of TSP. For example, TSP might be more effective on a bus route with a large number of signalized intersections and few bus stops.

CAUTIONS IN INTERPRETING THESE RESULTS

While collecting this data, some observers reported difficulties in accurately recording all of the required data. In some cases, observers simply fell behind in the recording task and would have to skip some recordings in order to catch up. In other cases, observers reported difficulties in determining exactly when the bus entered the back of a queue at a signal. The observers felt as if there might be considerable variations in how different observers recorded signal delay, while the other observed times would be more consistent between different observers.

Difficulties were also encountered with the GPS data. At times, the on-board recorders would archive multiple entries for a single stop or the driver would switch the recorder over to the next route before reaching the end of the preceding one. A significant amount of data cleaning was required to process this data, and some of this cleaning process required a subjective determination of which of two archived bus stop time stamps corresponded to the actual time the bus stopped to load passengers.

VALIDATING TSP OPERATION

The first step in analyzing the effectives of the TSP operations was to verify the operational characteristics of the system. The Evaluation Team was supplied a list of the signal controllers on Routes 80 and 84 for which TSP was to be enabled. After collecting travel time data along those routes, the Evaluation Team also gathered signal controller logs that indicated when the signal controllers received a signal priority or preemption request.[15] The corresponding travel time data collection occurred from 4/26/2004 to 4/30/2004.

[15] Logs were provided for all of the TSP equipped intersections except Watt Ave & the I-80 Off Ramp and Watt Ave and Fair Oaks Blvd. Because it was not clear whether this omission was merely accidental or meant that TSP was not enabled at those intersections, these two intersections were excluded from the remainder of the analysis.

Dates of Signal Controller Logs		
Data Type	**Start Date**	**End Date**
Watt Ave & I-80 Off Ramp	No data	
Watt Ave & Longview	4/29/2004	5/8/2004
Watt Ave & Auburn Blvd	5/3/2004	5/8/2004
Watt Ave & Edison	4/28/2004	5/8/2004
Watt Ave & Whitney	5/3/2004	5/8/2004
Watt Ave & Marconi	4/25/2004	5/8/2004
Watt Ave & Kings Way	4/25/2004	5/8/2004
Watt Ave & Kenfield Way	4/26/2004	5/8/2004
Watt Ave & El Camino	4/26/2004	5/8/2004
Watt Ave & Country Club	4/28/2004	5/8/2004
Watt Ave & Butano Drive	4/25/2004	5/8/2004
Arden Way & Watt Ave	4/25/2004	5/8/2004
Watt Ave & Hurley Way	4/25/2004	5/8/2004
Watt Ave & Northrop	4/26/2004	5/8/2004
Watt Ave & Fair Oaks Blvd	No data	

Because of line-of-sight and other issues, the receiver at the signal controller does not always receive a valid signal priority request when a bus approaches an intersection. The following table indicates, for each intersection that included a TSP transponder, the fraction of the time that a controller received a priority request when a bus stopped at the signal. (The table only includes those runs made during the periods for which signal controller logs were available and for which the bus did wait for the indicated signal to turn green.)

Number of Times TSP Was Activated When Bus Stopped at a Signal						
Southbound TSP			Signalized Intersection	Northbound TSP		
Activated	Not Activated	Percent		Activated	Not Activated	Percent
***	***	***	Watt Ave & I-80 Off Ramp	***	***	***
1	0	100%	Watt Ave & Longview	1	1	50%
*	*		Watt Ave & Auburn Blvd	*	*	*
3	5	38%	Watt Ave & Edison	7	5	58%
*	*	*	Watt Ave & Whitney	*	*	*
11	1	92%	Watt Ave & Marconi	19	6	76%
6	1	86%	Watt Ave & Kings Way	14	4	78%
4	1	80%	Watt Ave & Kenfield Way	10	5	67%
13	8	62%	Watt Ave & El Camino	5	4	56%
*	*	*	Watt Ave & Country Club	*	*	*
9	1	90%	Watt Ave & Butano Drive	5	4	56%
22	3	88%	Arden Way & Watt Ave	23	6	79%
16	1	94%	Watt Ave & Hurley Way	10	4	74%
6	3	67%	Watt Ave & Northrop	3	1	75%
***	***	***	Watt Ave & Fair Oaks Blvd	***	***	***
91	24	79%	Totals	115	42	73%

Note: * The Opticom logs for this intersection did not include any data for the time period during which travel times were collected. TSP activations did occur in the following week.

*** Opticom logs were not available for these intersections

For the purposes of this table, a signal priority request that was recorded with a timestamp within 15 minutes of the recorded arrival time of the bus at the queue for that intersection was considered to apply for that point in the route. (Times much shorter than 15 minutes were deemed likely to omit “matching” priority requests because of differences in the travel time data collection and signal controller clocks. Times much longer than 15 minutes were deemed likely to introduce spurious matches, such as when a bus is on the returning part of a route.)

A similar analysis was conducted for all times that a bus with TSP passed an intersection, regardless of whether the bus stopped at that intersection. TSP was only activated when observers noted that the bus stopped at an intersection and never activated when a bus continued through an intersection without stopping.[16]

THE COLLECTED DATA

One of the other factors that helps determine the portions of the bus routes to include in the analysis is the completeness of the data. During the after data collection on-board observations,

[16] The Evaluation Team was not certain whether the Opticom logs only recorded entries when the Opticom unit altered the signal timing, or recorded entries whenever a signal was detected.

some observers missed some of the time stamps during some runs. The following table lists the number of travel time runs for which a different number of measurements was successfully made.

Number of Time Elements Measured per Travel Time Run						
Direction	Bus Stop		Signals		Travel Segments	
	Number	Count	Number	Count	Number	Count
Northbound	37	148	24	161	64	142
	36	13	23	14	63	13
	35	10	22	4	62	13
	34	2	21	0	61	3
	Other	7	20	0	Other	9
			Other	1		
Southbound	37	144	24	0	64	138
	36	12	23	157	63	8
	35	8	22	13	62	10
	34	9	21	6	61	10
	Other	8	20	3	Other	15
			Other	2		

Note that about 80 percent of the runs have complete data, but that many additional runs could be added if the missing data were congregated at only a few intersections. A review of the data indicated that this was not the case. Consequentially, run and segment based statistics will be accumulated only for runs where the data is complete.

In the GPS data, one or more segments were missing from a number of the travel time runs. This was important because the travel time was computed as the difference between the elapsed time and the dwell time, and missing data results in missing dwell time, which will increase the travel times. This meant that only segments for which a complete set of segment measurements was available could be used in the analysis. The following table summarizes the number of segments for which travel time data is available for each of the routes, with the segment column reporting the minimum and maximum segment numbers and the total number of segments for which travel time data was available. (The table only includes those variations which occurred for more than one run.)

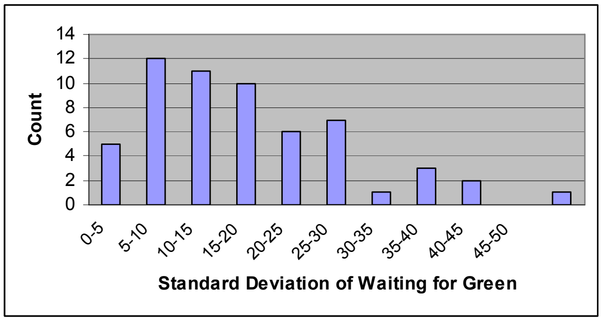
Route	Stop Numbers		Number of Valid Data Items Per Run		Number of Runs
	Min	Max	Segments	Stops	
80IB	1	68	67	68	88
	1	66	65	66	23
	1	67	66	67	18
	1	65	64	65	6
84IB	1	73	72	73	59
	1	72	71	72	16
	1	74	73	74	13
	1	73	69	71	6
	1	74	70	72	3
	1	72	68	70	2
	1	73	70	72	2
80OA	1	65	64	65	86
	1	66	65	66	50
	2	65	63	64	8
	1	63	62	63	2
840A	1	67	66	67	77
	1	68	67	68	18
	1	67	62	64	9
	68	68	0	1	2
	1	65	64	65	2

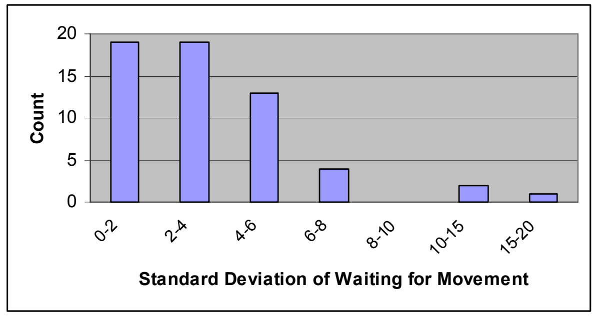
Note that a significant number of the cases where data was missing occurred at the end of the routes. In order to increase the number of valid runs for analysis, the last few stops from each run were excluded. The table below indicates for each route the stops that were included in the analysis.

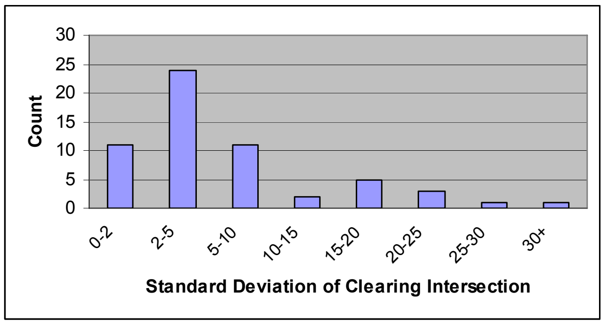
Route	Stop Numbers		Number of Runs
	Min	Max	
80IB	1	65	135
84IB	1	72	88
80OA	2	65	144
840A	1	67	95

A SEARCH FOR OUTLIER INTERSECTIONS

The basic approach used in this analysis will be to compare intersection signal delay, with and without TSP. Before making these comparisons, it will be useful to identify those intersections with unusually high variability in their signal delay and consider whether those intersections require special treatment. The following charts show the distribution of the standard deviations of the observed times waiting for a green light, waiting for movement after a green light, and clearing the intersection.







These charts suggest several intersections that might be considered outliers in the analysis.

Folsom at Watt, Southbound. The standard deviation for Waiting for Green was 84.6 seconds. This was an unprotected left-hand turn at which long delays sometimes occurred. TSP will not be deployed at this intersection. This intersection is omitted from the remaining analysis.

Watt at Fair Oaks, Northbound. The standard deviation for Waiting for Green was 40.4 seconds, Waiting for Movement was 17.8 seconds, and Clearing Intersection was 56.2 seconds. The bus does not turn at this intersection. TSP will be deployed there. There appears to be nothing about this intersection that would warrant excluding it from the analysis.

Watt at Arden, Northbound. The standard deviation for Waiting for Green was 40.3 seconds, Waiting for Movement was 5.0 seconds, and Clearing Intersection was 25.5 seconds. The bus makes a protected left turn at this intersection. TSP will be deployed there. The fact that the bus makes a left turn makes this intersection different from others, so it will be considered separately.

Watt at Folsom, Northbound. The standard deviation for Waiting for Green was 35.4 seconds, Waiting for Movement was 13.4 seconds, and Clearing Intersection was 18.5 seconds. The bus makes a right turn at this intersection. TSP will not be deployed there. There appears to be nothing about this intersection that would warrant excluding it from the analysis.

Watt at Auburn, Northbound. The standard deviation for Waiting for Green was 26.8 seconds, Waiting for Movement was 10.3 seconds, and Clearing Intersection was 19.8 seconds. The bus does not turn at this intersection. TSP will be deployed there. There appears to be nothing about this intersection that would warrant excluding it from the analysis.

Butano at Watt, Northbound. The standard deviation for Waiting for Green was 36.1 seconds, Waiting for Movement was 5.2 seconds, and Clearing Intersection was 20.7 seconds. The bus makes a left turn at this intersection. The fact that the bus makes a left turn makes this intersection different from others, so it will be considered separately.

Morse at Arden, Southbound. The standard deviation for Waiting for Green was 36.7 seconds, Waiting for Movement was 1.9 seconds, and Clearing Intersection was 20.8 seconds. The bus makes a left hand turn at this intersection. The fact that the bus makes a left turn makes this intersection different from others, so it will be excluded from the analysis.

A similar analysis of the GPS data identified the following between-stop segments with high variability in the travel times.

From Manlove Station to after the turn onto Folsom (Stop 1), Northbound. This segment included the checkpoint at Manlove Station. The exact time of the start of each run was uncertain, so this segment was excluded from the analysis.

From La Riveria near Watt (Stop 12) to Watt after Fair Oaks (Stop 13), Northbound. This segment included the Watt at Fair Oaks intersection noted above as being associated with high signal delay.

From Watt South of Arden (Stop 17) to after the turn onto Arden (Stop 18), Northbound. This segment included the left turn from Watt to Arden noted above and was treated separately in the analysis.

From Butano before Watt (Stop 28) to after the turn onto Watt (Stop 29), Northbound. This segment includes the left turn from Butano to Watt noted above and was treated separately in the analysis.

From the I-80 Station (Stop 29) to after the turn onto Watt (Stop 30), Southbound. This segment included the checkpoint at Manlove Station. The exact time of the start of each run was uncertain, so this segment was excluded from the analysis.

From Morse before Arden (Stop 44) to after the turn onto Arden (Stop 45), Southbound. This segment included the left turn from Morse to Arden that was noted above.

From Watt before Fair Oaks (Stop 53) to La Riveria just after the turn off from Watt (Stop 54), Southbound. This segment included the TSP intersection of Watt Avenue and Fair Oaks Blvd and the left turn from Watt to La Riveria. The TSP intersection is an important intersection that is important to keep in the analysis. This segment was treated as a TSP segment.

From Folsom just before Manlove (Stop 65) to Manlove Station (Stop 66), Southbound. This segment included the checkpoint at Manlove Station, making the end time of this segment uncertain. Also, drivers sometimes changed route settings before reaching Manlove Station, so that data was often missing for the last several segments. This segment should be ignored in the analysis.

A review of the map on the first page of this appendix provides some additional information on these intersections. The southernmost intersections (from the Manlove LRT Station to the intersection of La Riviera and Watt) were characterized as Suburban Arterial. This portion of the route is mostly off of Watt Avenue and includes a number of turns. TSP was not deployed at these intersections. The next portion northwards is on Watt Ave between La Riviera and Arden Way and includes 4 signalized intersections, all TSP equipped. This portion, labeled High-Speed Suburban Arterial, ends with a left-hand turn onto Arden Way. The next portion, labeled Urban Arterial, occurs on roads west of Watt Avenue from the intersection of Watt Avenue and Arden Way in the south to the intersection of Watt Avenue and Butano Drive in the north. This portion of the route includes many turns. Only the intersections at the start and end of this portion of the route are TSP equipped. The final portion of the route runs on Watt Avenue from

Butano Drive to Longview Drive. All but one of the intersection signals in this area were equipped with TSP, with the exception being at Sierra View Lane.

ROUTE CHARACTERISTICS

During field observations, the Evaluation Team noted that the study route could be sub-divided into four parts based on the characteristics of the road. The following paragraphs describe these subdivisions.

Suburban Arterial. This included the portion of the route from just north of the Manlove LRT station up to and including the intersection of Watt Avenue and La Riviera. This subdivision was mostly off of Watt Avenue and included three turns. It included 6 signalized intersections, none of which were equipped with TSP.

High-speed Suburban Arterial. This includes the portion of the route on Watt Avenue from just north of the intersection of Watt Avenue and La Riviera to the intersection of Watt Avenue and Arden Way. This portion of the route includes 4 signalized intersections, all equipped with TSP, with no turns.

Urban Arterial. This included the portion of the route from the intersection of Watt Avenue and Arden Way to the intersection of Butano Drive and Watt Avenue. This subdivision was mostly off of Watt Avenue and included six turns. It included 5 signalized intersections, plus a signalized pedestrian crosswalk. No TSP is deployed at these intersections.

Low-speed Suburban Arterial. This included the portion of the route from the intersection of Watt Avenue and Butano Drive to the intersection of Watt Avenue and the I-80 entrance ramp. This portion of the route included 10 signalized intersections, with all but one equipped with TSP. There were no turns. It also included a signalized pedestrian crossing.

DATA GROUPINGS

Consideration of the factors discussed in the preceding sections led to definition of the following groupings that were used in the analysis.

Segment	On-Board Observation Definition	GPS Data Definition
Non-TSP Suburban Arterial	From Folsom, just east of Watt, to La Riveria, just east of Watt, excluding the intersection at Folsom and La Riveria.	Routes 80IB and 84IB from stop 2 to stop 12, excluding stop 4 to stop 5. Route 80OA from stop 54 to stop 65, excluding stop 61 to stop 62. Route 84OA from stop 56 to stop 67, excluding stop 63 to stop 64.
TSP High-Speed Suburban Arterial	From Watt, just north of La Riveria, to Watt, just south of Arden Way.	Routes 80IB and 84IB from stop 12 to stop 17. Route 80OA from stop 47 to stop 54. Route 84OA from stop 49 to stop 56.
Non-TSP Urban Arterial	From Arden Way, just west of Watt, to Butano Drive, just west of Watt, excluding the pedestrian crossing on Morse Avenue.	Routes 80IB and 84IB from stop 18 to stop 28. Route 80OA from stop 38 to stop 46. Route 84OA from stop 40 to stop 48.
TSP Low-Speed Suburban Arterial	From Watt, just north of Butano Drive, to the bus stop on Watt, just south of the I-80 off ramp, excluding the pedestrian crossing near Whitney Avenue and the intersection at Sierra View Lane.	Routes 80IB and 84IB from stop 29 to stop 38. Route 80OA from stop 30 to stop 38. Route 84OA from stop 32 to stop 40.
Non-TSP Right Hand Turns	The intersection of La Riveria with Folsom, southbound. The intersection of La Riveria with Watt, northbound.	Route 80OA from stop 61 to stop 62. Route 84OA from stop 63 to stop 64.
Non-TSP Left Hand Turns	The intersection of Folsom with La Riveria, northbound. The intersection of Watt with La Riveria, southbound.	Routes 80IB and 84IB from stop 4 to stop 5.
TSP Right Hand Turns	The intersection of Arden Way with Watt and Watt and Butano, southbound.	Route 80OA from stop 46 to stop 47. Route 84OA from stop 48 to stop 49.
TSP Left Hand Turns	The intersection of Watt with Arden Way and Butano at Watt, northbound.	Routes 80IB and 84IB from stop 17 to stop 18. Routes 80IB and 84IB from stop 28 to stop 29.
Non-TSP Watt North		Routes 80IB and 84IB from stop 40 to stop 50. Route 80OA from stop 18 to stop 28 and Route 84OA from stop 20 to stop 30.

Because the GPS segments are based on the locations of bus stops and the on-board observation segments are based on intersection locations, there are some differences between these definitions. The TSP High-Speed Suburban Arterial GPS segment includes the non-TSP intersection at Watt Avenue and La Riveria. The TSP Low-Speed Suburban Arterial GPS segment includes the right turn from Watt to Butano for southbound runs and the left turn from Butano to Watt in the other direction, as well as the pedestrian crossing near Whitney and the non-TSP intersection at Sierra View Lane. Because of these differences between the two types of data, comparisons cannot between the on-board observation and GPS data.

THE DIRECTION OF TRAVEL

The Evaluation Team reported that congestion seemed to be worse in the northbound than the southbound direction. The following table demonstrates this difference, with northbound runs averaging about 31 minutes for total travel time (excluding time at bus stops) and southbound runs averaging just over 28 minutes.

Bus Delay by Direction of Travel, On-board Observations					
Direction	**Delay Type**	**Min**	**Avg**	**Max**	**Stnd Dev**
Northbound	Signal Delay	3.0	8.5	17.1	2.8
Northbound	Travel Time	14.3	22.2	30.0	2.4
Southbound	Signal Delay	1.8	6.7	12.2	2.0
Southbound	Travel Time	17.8	21.6	27.4	1.7

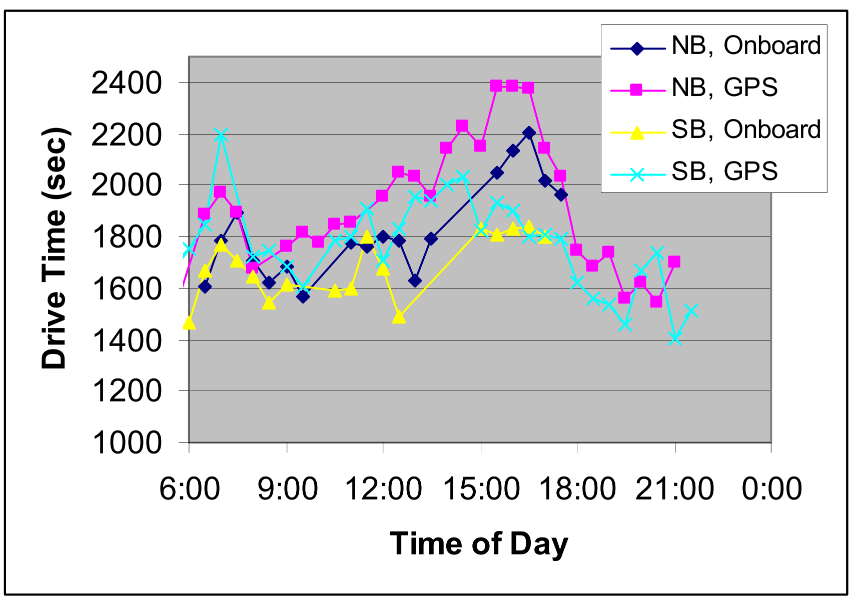
The same analysis applied to the GPS data collected on weekdays yields the following results.

Bus Delay by Direction of Travel, GPS Data					
Direction	**Delay Type**	**Min**	**Avg**	**Max**	**Stnd Dev**
Northbound	Drive Time	23.3	32.3	44.7	4.7
Southbound	Drive Time	17.8	29.2	38.6	3.4

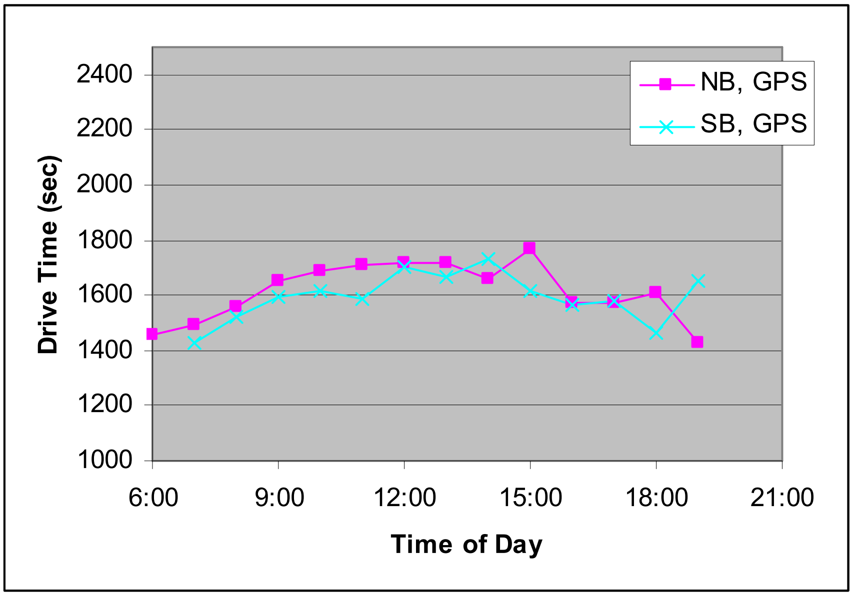
As with the on-board observations, the times for the northbound direction are longer than those for the southbound direction. Because of these differences, the analysis of the data for northbound and southbound routes was conducted separately.

THE TIME OF DAY

Another factor that could confound the analysis of the travel time data is the time of day. Evaluation Team observers had noted that that congestion was less early in the morning and late at night. The following chart shows the average weekday drive times observed at different times of day (from the on-board and GPS observations combined).



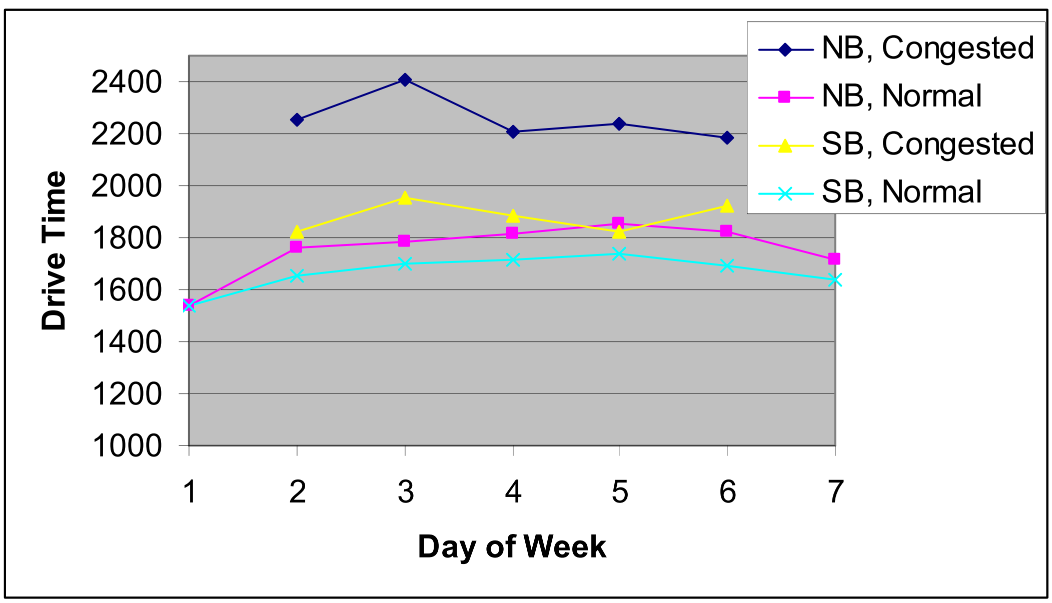
. The weekend drive times (from GPS observations, only) are depicted in the chart below.



Based on these charts, bus runs on weekdays with start times between 2:00 pm and 6:00 pm were labeled as high congestion runs, with runs occurring at other times labeled as normal congestion runs.

THE DAY OF THE WEEK

The chart below depicts the average drive time observed from the GPS data by the day of the week. (In this chart, the numbers 1 through 7 represent the days Sunday through Saturday, respectively.)



CONTROLLING FOR OTHER POTENTIAL CONFOUNDING FACTORS

The end objective of this analysis is to estimate the effectiveness of TSP by comparing bus travel times and signal delays before and after TSP was deployed. However, a number of factors other than TSP (e.g., congestion, signal timing settings) can impact travel times and signal delays. Thus, it is useful to assess the before and after data collection information to determine if changes have occurred that might bias the travel time and signal delay comparisons. The evaluation team asked the stakeholders if changes had occurred that might bias the comparison, and no such changes were identified – the general congestion levels were similar, the bus schedules were the same, and the signal timings had not changed.

This observation can be supported by reviewing the observed travel times and signal delays at non-TSP intersections and for buses where TSP was not in use. The following two tables list the observed total signal delay at non-TSP intersections for the travel time runs made in 2003 and for those made in 2004, with the non-TSP and TSP runs listed separately.

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
NB, Peak	114.9	47.1	32	153.3	55.3	6	141.8	57.5	6
NB, Off Peak	75.9	36.7	84	79.0	41.0	15	80.9	34.0	20
SB, Peak	199.9	47.6	34	173.4	40.3	5	171.5	49.7	4
SB, Off Peak	120.4	51.5	83	146.6	56.6	13	103.3	44.4	18

Some differences definitely exist between the average signal delay at non-TSP intersections in these runs, though there is not a systematic difference – in most cases, the signal delay for TSP equipped buses is a bit less, and in some cases it is more. These differences will be used as a control when comparing signal delay for non-TSP intersections.

COMPARING SIGNAL DELAY, WITH AND WITHOUT TSP

The tables below list the average observed signal delay for the different classes of intersections where the bus did not turn.

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
Non-TSP Suburban Arterial									
NB, Peak	13.9	16.9	32	23.5	41.6	6	16.7	20.3	6
NB, Off Peak	13.5	14.9	84	14.0	14.0	15	18.5	15.1	20
SB, Peak	20.7	18.3	34	23.6	28.6	5	22.8	22.0	4
SB, Off Peak	20.7	19.8	83	23.1	18.4	13	21.8	15.7	18

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
Non-TSP Urban Arterial									
NB, Peak	80.0	41.0	32	105.5	35.8	6	99.7	32.9	6
NB, Off Peak	48.6	29.5	84	48.5	25.9	15	50.0	29.1	20
SB, Peak	147.6	53.6	34	130.2	68.4	5	125.3	24.5	4
SB, Off Peak	86.5	43.9	83	99.5	55.3	13	66.6	41.3	18

Shorter signal delay was observed in ten of the 16 comparisons for intersections not equipped with TSP and for which the bus did not turn. The following two tables are for intersections equipped with TSP.

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
TSP Low-speed Suburban Arterial									
NB, Peak	204.8	66.6	32	172.3	48.8	6	162.7	74.1	6
NB, Off Peak	134.7	63.0	84	145.9	57.2	15	138.1	55.3	20
SB, Peak	136.9	54.9	34	119.6	41.2	5	99.8	33.8	4
SB, Off Peak	116.9	56.1	83	109.5	47.2	13	88.4	43.6	18

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
TSP High-speed Suburban Arterial									
NB, Peak	71.7	41.8	32	34.2	25.3	6	73.7	53.1	6
NB, Off Peak	35.4	39.6	84	40.1	35.7	15	47.2	33.9	20
SB, Peak	69.9	46.4	34	63.4	44.1	5	56.8	44.4	4
SB, Off Peak	48.2	39.8	83	78.4	53.3	13	45.6	42.0	18

Shorter signal delay was observed in eleven of these sixteen comparisons, which is little different from that for non-TSP intersections. The next set of tables is for intersections at which the bus turned right. The observed signal delay did not indicate any improvement for TSP equipped buses.

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
Non-TSP Right-hand Turns									
NB, Peak	20.9	21.9	32	24.3	22.2	6	25.5	17.0	6
NB, Off Peak	13.8	15.6	84	16.5	18.1	15	12.5	14.4	20
SB, Peak	15.1	16.8	34	11.4	12.6	5	12.5	13.9	4
SB, Off Peak	7.6	11.2	83	10.4	12.3	13	8.6	9.6	18

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
TSP Right-hand Turns									
SB, Peak	27.0	29.3	34	19.6	25.0	5	29.0	20.2	4
SB, Off Peak	35.0	30.7	83	31.2	26.1	13	32.3	25.6	18

Shorter signal delay was observed at intersections where the bus was turning left, as demonstrated in the following two tables.

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
Non-TSP Left-hand Turns									
SB, Peak	16.5	14.4	34	8.2	14.3	5	11.0	7.5	4
SB, Off Peak	5.7	9.4	83	13.6	11.4	13	6.3	9.0	18

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
TSP Left-hand Turns									
NB, Peak	110.7	62.5	32	98.8	36.6	6	83.8	20.2	6
NB, Off Peak	116.6	52.5	84	122.9	59.1	15	87.5	51.8	20

So, the on-board observations produced little indication that TSP decreased signal delay. As already noted, this could be due to the small sample sizes in the after observations. The on-board observers also reported difficulty in clearly identifying the time at which the bus entered the queue at a traffic signal, which could have diluted the effect of TSP on signal delay. (Recall that TSP would only be expected to shave a few seconds from the average signal delay at an intersection, so even a little relatively small variation in how different observers defined the end of the queue could make detecting the effect of TSP difficult to detect.)

COMPARING DRIVE TIME, WITH AND WITHOUT TSP

The following table compares the drive times from on-board observations.

Route / Congestion Level	2003: Pre TSP			2004: No TSP			2004: TSP		
	Avg	Stnd Dev	N	Avg	Stnd Dev	N	Avg	Stnd Dev	N
NB, Peak	2740.9	290.0	32	2771.8	310.7	6	2535.5	275.1	2
NB, Off Peak	2170.6	257.5	84	2491.1	257.4	7	2185.6	222.6	11
SB, Peak	2324.5	187.1	34	2217.5	238.3	2	2268.0	0.0	1
SB, Off Peak	2023.4	256.1	83	2195.1	179.7	8	1922.6	242.3	10

This table indicates that TSP may have resulted in a modest reduction in travel times, though the number of cases with complete data in 2004 was too small to produce reliable results.

OTHER COMPARISONS OF ONBOARD OBSERVATIONS

Other measures of the effect of TSP are (1) increasing the frequency with which a vehicle passes through a signal without experiencing a red light, (2) decreasing the delay experienced when a vehicle does experience a single red light, (3) decreasing the frequency with which a vehicle experiences multiple red lights, and (4) decreasing the delay experienced when a vehicle experiences multiple red lights. The first table examines the effect of TSP on the frequency with which a bus experienced a red light or experienced multiple red lights at the same intersection.

Route/ Congestion	No Red			One Red			Multi Red		
	2003: Pre-TSP	2004: No TSP	2004: TSP	2003: Pre-TSP	2004: No TSP	2004: TSP	2003: Pre-TSP	2004: No TSP	2004: TSP
TSP Intersections									
NB, Peak	5.1	5.0	7.2	7.4	7.6	5.7	0.5	0.4	0.2
NB, Off Peak	6.7	6.0	5.6	6.0	6.6	7.2	0.3	0.4	0.2
SB, Peak	6.7	8.2	7.8	6.3	4.8	5.2	0.0	0.0	0.0
SB, Off Peak	7.8	7.9	8.4	5.2	5.1	4.6	0.0	0.0	0.0
Non-TSP Intersections									
NB, Peak	6.6	5.8	5.4	6.3	7.2	7.6	0.1	0.0	0.0
NB, Off Peak	6.8	6.4	6.0	6.1	6.5	7.0	0.1	0.1	0.1
SB, Peak	6.2	6.0	5.6	6.4	6.4	7.3	0.4	0.6	0.1
SB, Off Peak	6.8	6.2	7.1	6.0	6.5	5.5	0.2	0.3	0.4

The time spent waiting for a green light is examined in the next table.

Signal Delay	2003: Pre TSP		2004: No TSP		2004: TSP	
	μ	σ	μ	σ	μ	σ
TSP Intersections						
NB, Peak	280.5	82.4	214.0	59.2	196.8	60.8
NB, Off Peak	228.5	83.3	230.4	52.8	192.3	79.4
SB, Peak	169.8	65.6	133.1	57.9	143.3	62.0
SB, Off Peak	132.0	59.7	125.4	60.2	99.9	34.9
Non-TSP Intersections						
NB, Peak	148.6	58.0	158.3	56.8	180.0	39.1
NB, Off Peak	123.4	61.2	113.3	53.8	121.0	55.8
SB, Peak	186.8	64.5	166.6	55.0	159.3	35.1
SB, Off Peak	126.9	54.2	146.0	56.6	104.2	51.7

The next table is for the total signal delay.

Total Signal Delay	2003: Pre TSP		2004: No TSP		2004: TSP	
	μ	σ	μ	σ	μ	σ
TSP Intersections						
NB, Peak	419.3	112.3	382.0	109.6	329.0	137.9
NB, Off Peak	316.3	104.2	364.5	99.5	313.2	88.7
SB, Peak	239.4	79.6	195.8	66.6	203.4	59.5
SB, Off Peak	177.5	69.8	173.1	67.0	146.5	48.2
Non-TSP Intersections						
NB, Peak	205.2	79.2	222.5	89.7	251.6	76.8
NB, Off Peak	167.1	63.3	178.3	64.9	185.5	65.0
SB, Peak	229.3	70.3	239.1	72.6	213.1	53.3
SB, Off Peak	154.9	61.5	189.3	69.6	142.5	68.9

The effect of TSP at individual intersections is demonstrated in the following two tables, with the first being for northbound buses and the second for southbound.

Red Light Wait Time	2003: Pre TSP			2004: No TSP			2004: TSP		
	No Wait (%)	Avg Wait (seconds)	Max Wait (seconds)	No Wait (%)	Avg Wait (seconds)	Max Wait (seconds)	No Wait (%)	Avg Wait (seconds)	Max Wait (seconds)
Watt at Fair Oaks	37	37	98	26	43	330	23	47	180
Watt at Northrop	84	7	27	81	6	28	84	5	13
Watt at Hurley	55	20	63	32	13	39	52	10	47
Watt at Arden	5	58	154	10	61	132	3	36	101
Butano at Watt	9	57	137	6	57	118	9	47	101
Watt at Country Club	66	26	61	87	3	11	97	0	0
Watt at El Camino	63	33	145	58	10	69	61	6	21
Watt at Kenfield	77	20	46	55	23	39	53	20	39
Watt at Kings	53	28	58	45	16	42	41	24	42
Watt at Marconi	33	38	90	6	34	69	19	35	74
Watt at Whitney	65	23	71	48	22	60	50	23	67
Watt at Edison	28	30	85	63	31	51	48	25	44
Watt at Auburn	16	34	87	17	43	72	15	33	82
Watt at Longview	73	12	66	58	12	32	64	13	32
Watt at Off Ramp	66	50	96	90	39	57	66	31	82

Number of Red Lights	2003: Pre TSP			2004: No TSP			2004: TSP		
	No Wait (%)	Avg Wait (seconds)	Max Wait (seconds)	No Wait (%)	Avg Wait (seconds)	Max Wait (seconds)	No Wait (%)	Avg Wait (seconds)	Max Wait (seconds)
Watt at I-80 Off Ramp	59	20	62	48	16	54	57	18	56
Watt at Longview	81	26	64	81	17	31	85	19	26
Watt at Auburn	21	37	83	21	34	72	23	34	73
Watt at Edison	72	26	69	76	30	52	69	18	52
Watt at Whitney	53	28	60	64	20	47	73	8	41
Watt at Marconi	38	32	81	48	28	72	58	27	83
Watt at Kings Way	59	12	43	77	6	18	79	12	26
Watt at Kenfield	86	9	41	87	18	33	82	12	28
Watt at El Camino	65	54	82	41	45	74	30	31	63
Watt at Country Club	57	18	60	93	4	5	94	6	8
Watt at Butano	51	17	64	60	19	51	68	20	58
Arden at Watt	28	28	88	26	27	58	21	29	77
Watt at Hurley	40	23	63	41	26	59	45	19	47
Watt at Northrop	60	14	42	80	8	31	69	15	43
Watt at Fair Oaks	43	46	108	31	57	108	34	52	97

COMPARING TRAVEL TIMES FOR GPS OBSERVATIONS

The travel time analysis presents the results of the analysis of GPS data collected from TSP and non-TSP equipped buses traveling their routes during May of 2005. Because of the nature of this data, signal delay was not measured directly. Instead, the travel times between adjacent bus stops was available and used to infer information about signal delay by identifying the between-stop segments that contained one or more TSP equipped intersection. The table below lists travel times for buses equipped with TSP and those not equipped with TSP.

Route	TSP	Travel Times (sec)		Count
		Avg	Stnd Dev	
NB, Weekday, Peak	TSP	2248	229	26
	No TSP	2265	203	24
NB, Weekday, Off Peak	TSP	1787	189	84
	No TSP	1858	175	41
NB, Weekend	TSP	1630	175	39
	No TSP	1678	166	26
SB, Weekday, Peak	TSP	1854	186	26
	No TSP	1917	158	25
SB, Weekday, Off Peak	TSP	1696	189	92
	No TSP	1710	187	45
SB, Weekend	TSP	1576	143	42
	No TSP	1637	156	28

This table indicates that TSP reduced average travel times by between 14 seconds (for weekday southbound trips during off peak traffic periods) and 71 seconds (for weekday northbound trips during off peak traffic periods). Only the northbound, weekday, off peak and southbound, weekend comparison are statistically significant at the 5 percent confidence level. The following table lists results restricted to segments that include a TSP-equipped intersection.

Route	TSP	Travel Times (sec)		Count
		Avg	Stnd Dev	
NB, Weekday, Peak	TSP	1405	164	26
	No TSP	1421	164	25
NB, Weekday, Off Peak	TSP	1025	150	85
	No TSP	1099	124	41
NB, Weekend	TSP	919	132	42
	No TSP	1003	127	27
SB, Weekday, Peak	TSP	1054	120	28
	No TSP	1106	116	28
SB, Weekday, Off Peak	TSP	959	131	92
	No TSP	948	146	45
SB, Weekend	TSP	896	95	45
	No TSP	955	110	29

In this case, the southbound, weekday, off peak runs actually show an increase in travel times between buses equipped and not equipped with TSP. All the other groups show a statistically significant decrease in travel times, except for the northbound, weekday, peak runs, where the difference is not statistically significant.

Despite the fact that many of these differences are statistically significant, they could have resulted from something other than the presence of TSP. To test for this possibility, travel time statistics were determined for those portions of the route that did not include TSP equipped intersections. Because other factors that could affect travel time, such as the driver and the level of congestion, were the same for the portions of the same trip through TSP and non-TSP intersections, this approach controls for these other factors. The following table lists statistics about the travel times for the segments in the study area that do not include TSP intersections and for buses equipped or not equipped with TSP transponders, as indicated in the "TSP" column.

Route	TSP	Travel Times (sec)		Count
		Avg	Stnd Dev	
NB, Weekday, Peak	TSP	842	94	26
	No TSP	852	80	24
NB, Weekday, Off Peak	TSP	758	82	85
	No TSP	759	84	41
NB, Weekend	TSP	702	80	39
	No TSP	676	59	26
SB, Weekday, Peak	TSP	810	103	26
	No TSP	826	96	25
SB, Weekday, Off Peak	TSP	737	83	93
	No TSP	763	75	46
SB, Weekend	TSP	685	80	42
	No TSP	689	78	28

While the travel times were often smaller for the TSP equipped buses than those not equipped, this differences were much smaller than for the TSP segments, and were only statistically significant for the southbound, weekday, off peak segments. This supports the claim that the travel time reductions are due to TSP.

APPENDIX B:

BEFORE AND AFTER FLOATING CAR RUN DATA

A summary of the non-transit traffic performance on Watt Avenue is presented in the following tables. The first table summarizes the travel time averages, while the second table presents the travel time reliability. The travel time reliability is defined as the variability of the travel time runs *one standard deviation* away from the average. The larger the value, the less the travel time reliability along this corridor.

Summary of Non-Transit Travel Time Averages (Minutes)

	AM (7-9am)		Midday (11am-1pm)		PM (4-6pm)	
Corridor / Direction	**Phase II**	**Phase III**	**Phase II**	**Phase III**	**Phase II**	**Phase III**
Watt Avenue – Segment III (Alta Arden Way to Butano Drive)						
NB	1:14	1:11	1:46	1:07	1:32	1:25
SB	1:30	1:06	1:21	1:07	1:25	1:26
Watt Avenue – Segment IV (Country Club Center to Auburn Boulevard)						
NB	5:48	5:28	6:15	5:22	6:11	7:04
SB	5:03	4:08	4:52	4:16	4:18	4:01
Arden Way						
EB	6:37*	6:01*	4:46	5:39*	6:06	6:54*
WB	5:00*	5:07	5:29	5:50	5:02	5:25
El Camino Avenue						
EB	4:49	4:47	4:52	5:21	6:14	6:29
WB	5:34	5:38	5:53	6:39	6:00	7:03
Marconi Avenue						
EB	4:26	5:20	4:56	5:09	6:23	6:51
WB	5:37	5:33	5:09	5:54	4:43	5:35
Edison Avenue						
EB	6:45	7:03	5:23	5:47	6:00	6:11
WB	6:16	6:22	6:01	5:49	6:04	6:08
Auburn Boulevard						
EB	3:41	4:25	4:09	4:12	8:08	5:43
WB	6:24	4:56*	5:04	4:42*	4:29	5:22*

*Note: The sample size for these runs was less than five.

Summary of Non-Transit Travel Time Reliability (Minutes)

	AM (7-9am)		Midday (11am-1pm)		PM (4-6pm)	
Corridor / Direction	**Phase II**	**Phase III**	**Phase II**	**Phase III**	**Phase II**	**Phase III**
Watt Avenue – Segment III (Alta Arden Way to Butano Drive)						
NB	+/- 0:29	+/- 0:37	+/- 0:50	+/- 0:21	+/- 0:49	+/- 0:24
SB	+/- 0:20	+/- 0:14	+/- 0:20	+/- 0:14	+/- 0:18	+/- 0:22

Watt Avenue – Segment IV (Country Club Center to Auburn Boulevard)						
NB	+/- 2:15	+/- 1:06	+/- 1:17	+/- 0:54	+/- 1:38	+/- 1:06
SB	+/- 1:45	+/- 1:00	+/- 1:44	+/- 0:51	+/- 1:00	+/- 0:46
Arden Way						
EB	+/- 1:38*	+/- 1:13*	+/- 0:21	+/- 0:54*	+/- 0:41	+/- 1:55*
WB	+/- 1:11*	+/- 0:35	+/- 0:58	+/- 1:08	+/- 0:59	+/- 0:31
El Camino Avenue						
EB	+/- 0:46	+/- 0:42	+/- 0:51	+/- 1:20	+/- 1:34	+/- 1:37
WB	+/- 0:24	+/- 1:20	+/- 1:07	+/- 2:01	+/- 1:01	+/- 1:36
Marconi Avenue						
EB	+/- 1:02	+/- 0:54	+/- 0:45	+/- 0:43	+/- 0:52	+/- 2:04
WB	+/- 1:40	+/- 1:37	+/- 0:50	+/- 1:15	+/- 0:57	+/- 1:08
Edison Avenue						
EB	+/- 1:50	+/- 1:55	+/- 0:34	+/- 0:51	+/- 0:51	+/- 0:45
WB	+/- 1:26	+/- 0:54	+/- 0:52	+/- 0:26	+/- 0:51	+/- 1:08
Auburn Boulevard						
EB	+/- 0:52	+/- 0:42	+/- 0:43	+/- 0:38	+/- 3:00	+/- 1:47
WB	+/- 2:03	+/- 0:33*	+/- 0:38	+/- 1:04*	+/- 0:38	+/- 0:46*

*Note: The sample size for these runs was less than five.

APPENDIX C:

POWER ANALYSES CONDUCTED IN PREPARATION FOR "BEFORE" TRANSIT DATA COLLECTION

BACKGROUND

The decision as to how large a sample shall be taken is a fundamental aspect of the plan for an investigation that involves data collection efforts. If a difference actually exists between two population means but the samples taken are too small, the observed difference in the sample means may be insignificant. However, somewhat larger samples may have produced significant results. On the other hand, one does not want to take samples larger than necessary to establish the mean difference as this would spend valuable project funding that could have been better expended elsewhere.

For the Sacramento-Watt Avenue Transit Priority and Mobility Enhancement Demonstration project, power analysis was investigated to address the question, *how many transit runs data are needed to show meaningful results?* A transit run is defined as a trip taken by a bus from an origin to a destination point. Meaningful results are the "desired" reductions in transit travel times.

To make the decision of how large a sample size is needed, practical experience must be relied on for answers to these questions:

1. How large a difference (d) would be of practical importance in the population? For the Sacramento-Watt Avenue Transit Priority and Mobility Enhancement Demonstration project, the analyses were conducted for 5, 10, 20, and 30 percent reduction in the transit travel time.

2. What estimate can be made for the sample variance?

3. How much risk can be taken of deciding that a difference exists when it really is zero? This decision is the choice of α (e.g., $\alpha = 0.05$).

4. How much risk can be taken of deciding that a difference is zero when it really is as large as the predetermined value d? This decision is the choice of β (e.g., β = 0.6). A β of 0.6 would mean that the probability of detecting a difference between two sample means is 60 percent.

When these four values (d, σ, α, and β) have been chosen, an individual can determine the necessary sample size (N) by using some algebra. Please refer to the following example for more details.

POWER ANALYSIS CONDUCTED USING PILOT EXISTING DATA

To obtain a more accurate power analysis, it is suggested that some pilot existing data (i.e., before the actual data collection starts) are used to determine the values (d) and (σ). Therefore, the table below shows a summary of existing data for transit travel times (data were provided by Sacramento County). Please note that those travel times are in minutes and they include the segment from Kings Way to I-80, where most of the variations in transit travel time tend to occur on Watt Avenue. In addition, those travel times include the overall travel time minus the dwell time (i.e., the time the bus spends loading and/or unloading passengers). Please note that the travel times included northbound (NB) runs that were conducted throughout the entire day (i.e., peak times and off-peak times). This is to ensure a larger variation in the data and hence a more conservative in the analysis. Please note that travel times were normally distributed and no transformation in the data was needed.

	N	Minimum	Maximum	Mean	Std Deviation
Total Time	26	6.15	20.883	11	3.4

Let us assume the following: 5, 10, 15, 20, and 30 percent reductions in the transit travel times; α = 0.05 with a two sided test; and β = 0.6, 0.7, and 0.8. The following equation is then used to determine the number of transit runs needed:

$N = \sigma^2/d^2 * (Z\alpha/2 + Z\beta)^2$, where

σ = 3.4

d = 11*0.05 or 0.1 or 0.15 or 0.20 or 0.3 (i.e., 5, 10, 15, 20, and 30 percent reductions)

α = 0.05 (for two sided test, look up Z value of 0.975; i.e., 1-0.05/2=0.975)=1.96

β = 0.6, 0.7, and 0.8 = 0.253, 0.525, and 0.842, respectively (look up Z value of 0.4, 0.3, and 0.2; e.g., 1-0.6=0.4)

The following table summarizes the number of transit runs needed for each percent reduction and β:

	5% (0.55 min)	10% (1.1 min)	15% (1.65)	20% (2.2)	30% (3.3)
$\beta = 0.6$	187	47	21	12	5
$\beta = 0.7$	236	59	26	15	7
$\beta = 0.8$	300	75	33	19	8

This means that based on the existing transit travel times, a total number of 187 transit data runs are needed to have a 60 percent chance of observing an actual 5 percent reduction in transit travel time on Watt Avenue between Kings Way and I-80. As shown in the table, the sample size needed (i.e., the number of bus runs) will increase as the power of the test increases (i.e., β of 0.6 to 0.7 to 0.8). Most researchers usually use β of 0.7 or 0.8. In addition, the sample size will increase as the reduction difference increases (i.e., from 5 to 10 to 15 percent, etc). This means that a larger sample size is needed to detect a smaller difference in the data. Therefore, we would need a larger sample size to detect a 5 percent reduction in transit travel times compared to a 10 or 20 percent reduction.

The Evaluation team intends to collect 24 transit runs every day. Therefore, for a period of two weeks, a total number of 24*10=240 transit data runs will be obtained, which should be sufficient to detect a 5 percent reduction difference (60 percent probability). This should be sufficient as the power analysis was conducted based on only 26 transit runs with a large variation. Furthermore, after collecting data during the first week, power analyses will be conducted again to confirm the results obtained in this report.

POWER ANALYSIS CONDUCTED USING ACTUAL DATA COLLECTED

The table below shows a summary of existing data for transit travel times. Please note that those travel times are in minutes and they include the segment IV (Kings Way to I-80) where most of the variations in transit travel time tend to occur on Watt Avenue. In addition, those travel times include the overall travel time minus the dwell time (i.e., the time the bus spends loading and/or unloading passengers). Again, the data for the NB were used as the standard deviation is larger and the analysis will be more conservative. Please note that travel times were normally distributed and no transformation in the data was needed.

Travel Time	N	Minimum	Maximum	Mean	Std Deviation
Northbound	117	6.65	15.43	10.32	1.96
Southbound	117	5.10	11.33	7.92	1.24

Let us assume the following: 5, 10, 15, 20, and 30 percent reductions in the transit travel times; α = 0.05 with a two-sided test (a two-sided test was used for purposes of analysis since the direction of expected change could not be specified with certainty); and $\beta = 0.6$, 0.7, and 0.8. The following equation is then used to determine the number of transit runs needed:

$N = \sigma^2/d^2 * (Z\alpha/2 + Z\beta)^2$, where

$\sigma = 1.96$

d = 10.3*0.05 or 0.1 or 0.15 or 0.20 or 0.3 (i.e. 5, 10, 15, 20, and 30 percent reductions)

α = 0.05 (for two-sided test, look up Z value of 0.975; i.e., 1-0.05/2=0.975)=1.96

β = 0.6, 0.7, and 0.8 = 0.253, 0.525, and 0.842, respectively (look up Z value of 0.4, 0.3, and 0.2; e.g., 1-0.6=0.4)

The following table summarizes the number of transit runs needed for each percent reduction and β:

	5% (0.52 min)	**10% (1.03 min)**	**15% (1.55 min)**	**20% (2.06)**	**30% (3.09)**
$\beta =$ **0.6**	70	18	8	5	2
$\beta =$ **0.7**	88	23	10	6	3
$\beta =$ **0.8**	112	29	13	8	4

This means that based on the existing transit travel times, a total number of 112 transit data runs are needed to have a 80 percent chance of observing an actual 5 percent reduction in transit travel time on Watt Avenue between Kings Way and I-80. As shown in the table, the sample size needed (i.e., the number of bus runs) will increase as the power of the test increases (i.e., β of 0.6 to 0.7 to 0.8). In addition, the sample size will decrease as the reduction difference increases (i.e., from 5 to 10 to 15 percent, etc). This means that a larger sample size is needed to detect a smaller difference in the data. Therefore, we would need a larger sample size to detect a 5 percent reduction in transit travel times compared to a 10 or 20 percent reduction.

Overall, the Evaluation team collected 117 transit runs in each direction, which based on these analyses, should be sufficient to detect significant and meaningful results, even as low as 5 percent reductions in the travel times.

APPENDIX D:

POWER ANALYSES CONDUCTED IN PREPARATION FOR "AFTER" TRANSIT DATA COLLECTION

OVERVIEW

The purpose of this analysis is to understand the likelihood of detecting improvements in bus travel times in Sacramento due to the deployment of TSP based on the sample sizes that are affordable for measuring bus travel times. The basic approach to be used is to perform a power analysis of the statistical tests that will be used to estimate the effect of TSP on bus travel times. However, measuring the effect of TSP on bus travel times is made complicated by several factors, such as the following:

- TSP only affects the time spent waiting at traffic signals, not the other elements of bus travel time (e.g., loading time, unloading time, travel time). Statistics that use total travel time to measure the effect of TSP may not be as powerful as statistics that use other measures more directly related to signal delay.
- Buses that are ahead of schedule have timing checkpoints at which they wait to re-synchronize with their schedule. Improvements in travel time associated with TSP could be offset by increased checkpoint wait times.
- Because of changes in the level of congestion, travel times vary throughout the day. It may be appropriate to analyze travel times from different times of day separately.
- Because of differences in congestion in Northbound and Southbound directions and differences between the number of left- and right-hand turns, it may be appropriate to analyze the two directions of travel separately.
- Some intersections have unusual characteristics (e.g., unprotected left-hand turn) that result in very high variability in the delay time there. Inclusion of these intersections in an analysis could result in artificially high variability, which dilutes the statistical power of the analysis.
- At some intersections, the bus waited through multiple signal cycles
- The route includes both intersections for which TSP will be used and intersections for which it will not. Including non-TSP intersections in the analysis could dilute the ability to detect the effect of TSP for intersections where it is used.

Therefore, the first step in this analysis will be to review the characteristics of the routes being studied and the observed travel times during Phase II observations in order to identify the best approach for detecting the effect of TSP on bus travel times.

It is also worth noting that the Sacramento TSP will act by beginning a green cycle 15-seconds early and/or extending the green cycle by 15-seconds when a bus is detected on the road leading up to the signalized intersection. Thus, the primary effects of TSP should be to:

- Increase the number of instances where a bus has little or no waiting time at a signal because the signal either extends longer to allow the bus pass or turns green sooner as the bus approaches the signal.
- Decrease the time spent waiting in a queue at a signal because the signal turns green sooner when a bus is waiting in a queue.

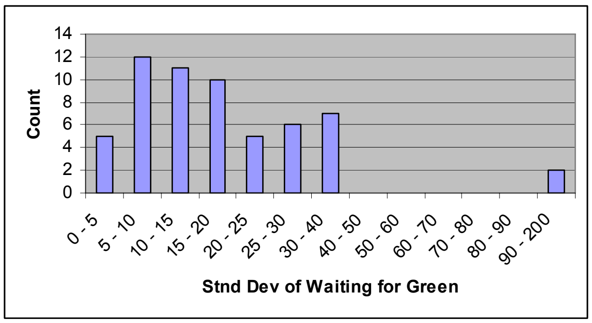
- Reduce the number of times a bus sits through multiple cycles because the increased green time allows the bus to pass through the signal during the first green cycle.

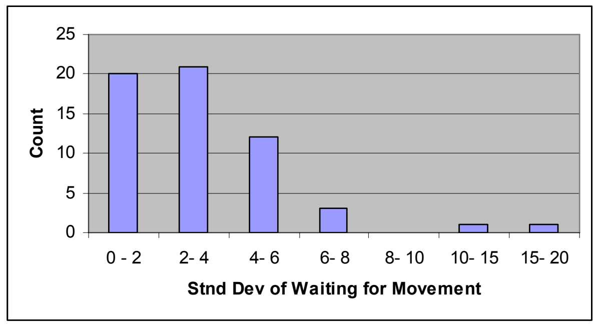
By considering the impact of the proposed TSP plan on these direct measures, we can estimate the impact of TSP on signal delay and travel time. A power analysis calculation can then determine the sample size required to detect the expected decrease in signal delay.

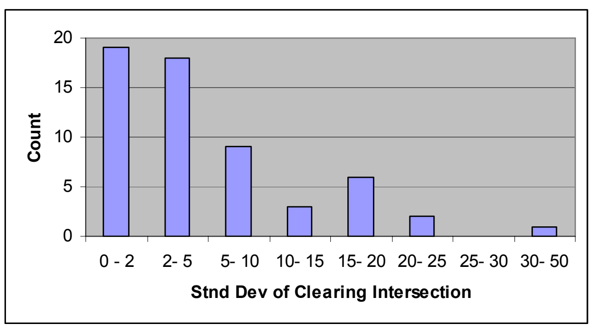
In addition to estimating the impact of TSP on bus travel times, we will also evaluate changes in these direct measures.

CHARACTERIZING ROUTE TRAVEL TIMES

The first step will be to identify intersections that had unusually high variation in the signal delay at those intersections. The following charts depict the variation in the different components of signal delay.







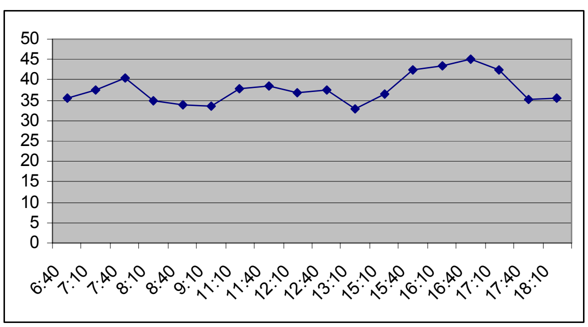
These charts indicate that there are several outliers in these measurements that might indicate intersections with unusual activities. These outliers are noted in the following table.

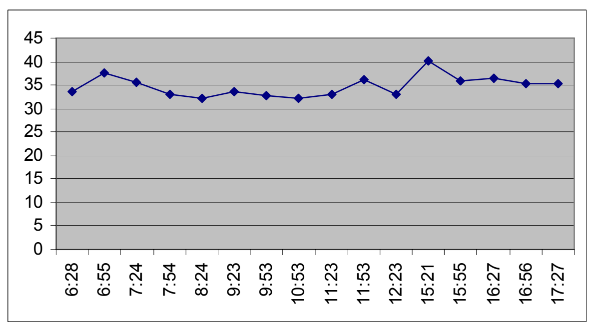
Intersection	Description
Folsom at La Riveria, Northbound	Standard deviation of waiting for first green of 198 seconds. This was an unprotected left-hand turn at which long delays sometimes occurred. TSP will not be deployed at this intersection. This intersection is omitted from the remaining analysis.
Folsom at Watt, Southbound	Standard deviation of waiting for first green of 92 seconds. This is a left-hand turn at which long delays sometimes occurred. TSP will not be deployed at this intersection. This intersection is omitted from the remaining analysis.
Watt at Fair Oaks, Northbound	Standard deviation of waiting for movement of 18 seconds and of clearing intersection of 47 seconds.
Watt at Auburn, Northbound	Standard deviation of waiting for movement of 11 seconds.

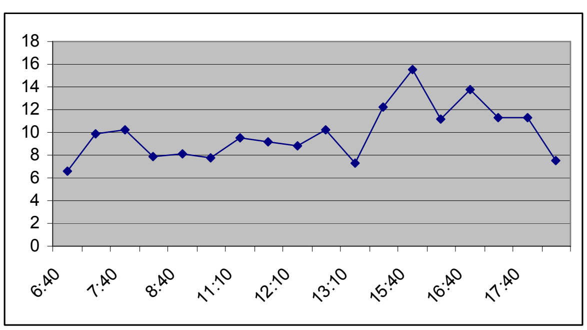
As noted, two of these intersections exhibited very large variability in the signal delays because of anomalies at those locations. Also, TSP will not be deployed at these intersections. Those intersections will be omitted from the remainder of this analysis.

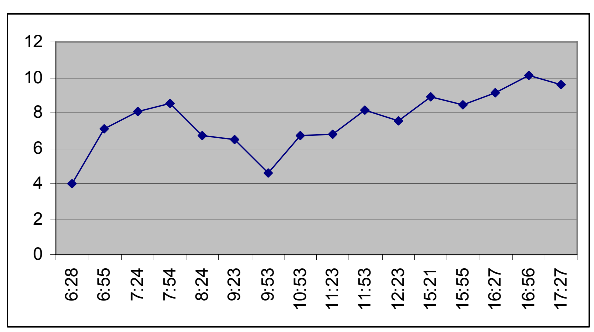
EXAMINING VARIATION WITH TIME OF DAY

The following charts depict the variation in travel time (top charts) and signal delay (bottom charts) with time of day for Northbound (on the left) and Southbound (on the right) runs. These charts suggest that there is an effect of time of day on the travel times, probably due to increased congestion during the morning and afternoon peak demand periods.









Because this congestion-related variation could dilute the power of signal delay comparisons, the travel time runs were categorized as either peak or off-peak runs according to whether significant additional delay occurred during the time period for the run. In particular, the following classifications were used:

- For Northbound runs, runs whose scheduled start time occurred between 3:10 pm and 5:40 pm were classified as peak. All other runs were classified as off-peak.
- For Southbound runs, runs whose scheduled start time occurred at 7:24 am, 7:54 am, or between 5:21 pm and 5:27 pm were classified as peak. All other runs were classified as off-peak.

The following table summarizes the characteristics of the signal delays for these runs.

Signal Delay, All Intersections				
Route	**Statistic**	**Peak**	**Off Peak**	**Total**
Northbound	N	32	85	117
	Avg	12.62	8.82	9.86
	Stnd Dev	3.18	2.34	3.09
Southbound	N	69	48	117
	Avg	8.61	6.23	7.63
	Stnd Dev	1.75	1.91	2.16
Total	N	101	133	234
	Avg	9.88	7.89	8.75
	Stnd Dev	2.96	2.52	2.89

Of particular interest is the signal delay for the intersections where TSP will be deployed, as summarized in the following table.

Signal Delay, TSP Signals Only				
Route	**Statistic**	**Peak**	**Off Peak**	**Total**
Northbound	N	32	85	117
	Avg	9.20	6.05	6.92
	Stnd Dev	2.63	1.87	2.53
Southbound	N	69	48	117
	Avg	4.79	3.66	4.32
	Stnd Dev	1.51	1.49	1.59
Total	N	101	133	234
	Avg	6.19	5.19	5.62
	Stnd Dev	2.82	2.09	2.48

These statistics are sufficient to support a power analysis to indicate the sample size requirements for a Phase III travel time data collection in order to detect different levels of possible decrease in signal delay that might occur. The following table summarizes the results of this power analysis.

Required Sample Size to Detect Change in Signal Delay, TSP Signals Only							
Direction	**Congestion**	**Power = 0.6**			**Power = 0.8**		
		Δ=10%	**Δ=15%**	**Δ=20%**	**Δ=10%**	**Δ=15%**	**Δ=20%**
Northbound	**Peak**	389	24	11	***	79	22
	Off Peak	60	20	10	198	39	19
	All	84	27	14	286	55	26
Southbound	**Peak**	77	22	11	574	47	21
	Off Peak	***	62	23	***	917	57
	All	85	28	14	299	56	26
Total	**Peak**	293	51	24	***	133	48
	Off Peak	106	33	17	412	68	32
	All	101	37	20	250	70	35

Note: *** indicates that the indicated difference cannot be detected with the desired power.

During the Phase III analysis, the signal delay for the non-TSP intersections will be of interest as a measure of changes in the overall level of congestion that may exist between the Phase II and Phase III data collection periods. For example, if the non-TSP intersections show a strong increase in signal delay between Phase II and Phase III, then a similar effect for TSP intersections would mute the effect of the TSP. The signal delay statistics for the non-TSP intersections are in the table below.

Signal Delay, non-TSP Signals Only				
Route	**Statistic**	**Peak**	**Off Peak**	**Total**
Northbound	**N**	32	85	117
	Avg	3.42	2.77	2.95
	Stnd Dev	1.32	1.06	1.17
Southbound	**N**	69	48	117
	Avg	3.82	2.57	3.31
	Stnd Dev	1.17	1.01	1.27
Total	**N**	101	133	234
	Avg	3.69	2.70	3.13
	Stnd Dev	1.23	1.04	1.23

RUNS WITH CYCLE FAILURES

After completing the above analysis, it was noted that cycle failures (i.e., the failure of a bus to make it through an intersection during a single signal cycle) can significantly impact the variability between bus travel times. It might be the case that, if runs with cycle failures were excluded, the reduction in signal delay variability would make it easier to detect a decrease in signal delay. A separate analysis could be used to evaluate a change in the number of cycle failures that occur.

The following table characterizes the signal delays for bus runs with different numbers of cycle failures.

Number of Cycle Failures	Runs	Average Signal Delay	Signal Delay Standard Deviation
0	436	252.21	127.39
1	25	367.48	169.69
2	6	481.33	286.88
3	1	767.00	

As is apparent, each cycle failure typically resulted in about a 115 second increase in the average signal delay. However, each failure also resulted in a significant increase in the variation in the amount of signal delay – the standard deviation between runs with the same number of cycle failures increases significantly as the number of cycle failures increases. The following table presents signal delay statistics for those runs without cycle failures.

Signal Delay, TSP Intersections, Excluding Runs with Cycle Failures				
Route	**Statistic**	**Peak**	**Off Peak**	**Total**
Northbound	**N**	23	76	99
	Avg	8.62	6.02	6.63
	Stnd Dev	2.34	1.90	2.28
Southbound	**N**	67	48	115
	Avg	4.71	3.66	4.27
	Stnd Dev	1.45	1.49	1.55
Total	**N**	90	124	214
	Avg	5.71	5.11	5.45
	Stnd Dev	2.42	2.09	2.25

As expected, excluding runs in which cycle failure occurred decreased both the average signal delay and the standard deviation of the signal delay. However, the decrease in the signal delay standard deviation did not result in the need for smaller sample sizes.

EXPECTED DECREASE IN SIGNAL DELAY

One limitation of the power analyses performed was that the required sample size depended critically on the extent to which TSP would decrease signal delay. It is possible to compare the proposed TSP approach with the observed signal delay information to estimate the impact TSP will have on those signal delays. Then, a power analysis can be performed with these estimates of the expected change in signal delay to estimate the sample size needed to detect that size decrease, if it occurs.[17]

The proposed TSP will decrease signal delay by:

- Extending a green cycle by up to 15 seconds if a bus approaches a signal towards the end of the green cycle.
- Beginning a green cycle up to 15 seconds early if a bus is waiting in a queue at a signal.

Combining this approach with the data collected during Phase II suggests the following method for estimating the expected impact of the TSP on signal delay:

- For TSP signals where a cycle failure did not occur and the Waiting for Green time was less than 15 seconds, replace the Waiting for Green time with 15 seconds.
- For TSP signals where a cycle failure did not occur and the Waiting for Green time was greater than 15 seconds, decrease the Waiting for Green time by 15 seconds. This approach is probably conservative because some buses may benefit from both an extended green in the previous cycle (shortening the queue) and a shortened wait for the next green.
- For TSP signals where a cycle failure did occur, use the same approach as above – this approach is probably conservative since the bus would probably benefit from the TSP during each cycle.
- For non-TSP signals, do not modify the signal delay.

All in all, this should provide a conservative estimate of the expected decrease in signal delay that will occur. Applying these impact formulae to the observed data generates the following results of the expected impact of the proposed TSP on signal delay.

[17] This approach has a secondary benefit of proposing a method for estimating the signal delay / travel time decrease associated with TSP. If later observations validate this approach, then other locations may want to apply the approach when they consider the benefits of TSP for their transit systems.

Current Signal Delay and Expected Signal Delay, TSP Signals Only							
Route	Statistic	Peak		Off Peak		Total	
		No	TSP	No	TSP	No	TSP
Northbound	**N**	32	32	85	85	117	117
	Avg	9.20	7.39	6.05	4.63	6.92	5.39
	Stnd Dev	2.63	2.42	1.87	1.65	2.53	2.25
Southbound	**N**	69	69	48	48	117	117
	Avg	4.79	3.39	3.66	2.51	4.32	3.03
	Stnd Dev	1.51	1.23	1.49	1.15	1.59	1.27
Total	**N**	101	101	133	133	234	234
	Avg	6.19	4.66	5.19	3.87	5.62	4.21
	Stnd Dev	2.82	2.52	2.09	1.80	2.48	2.17

The following table lists the sample size required to detect ($\alpha = 0.05$) this change in signal delay.

Required Sample Size to Detect Expected Change in Signal Delay, TSP Signals Only				
Direction	Congestion	Power = 0.6	Power = 0.7	Power = 0.8
Northbound	**Peak**	11	15	21
	Off Peak	7	9	13
	All	11	15	20
Southbound	**Peak**	5	6	8
	Off Peak	7	10	13
	All	7	9	12
Total	**Peak**	15	20	27
	Off Peak	10	13	18
	All	12	16	21

Note that these results indicate that a relatively small sample will suffice for the Phase III observations.

OTHER MEASURES OF THE EFFECT OF TSP

Previously, it was noted that the direct effects of TSP on signal delay will be through increasing the number of instances where a bus has little or no waiting time at a signal, decreasing the time spent waiting in a queue at a signal, and reducing the number of times a bus sits through multiple cycles. This section lists statistics on these measures so they can be compared to Phase III data that will be collected data.

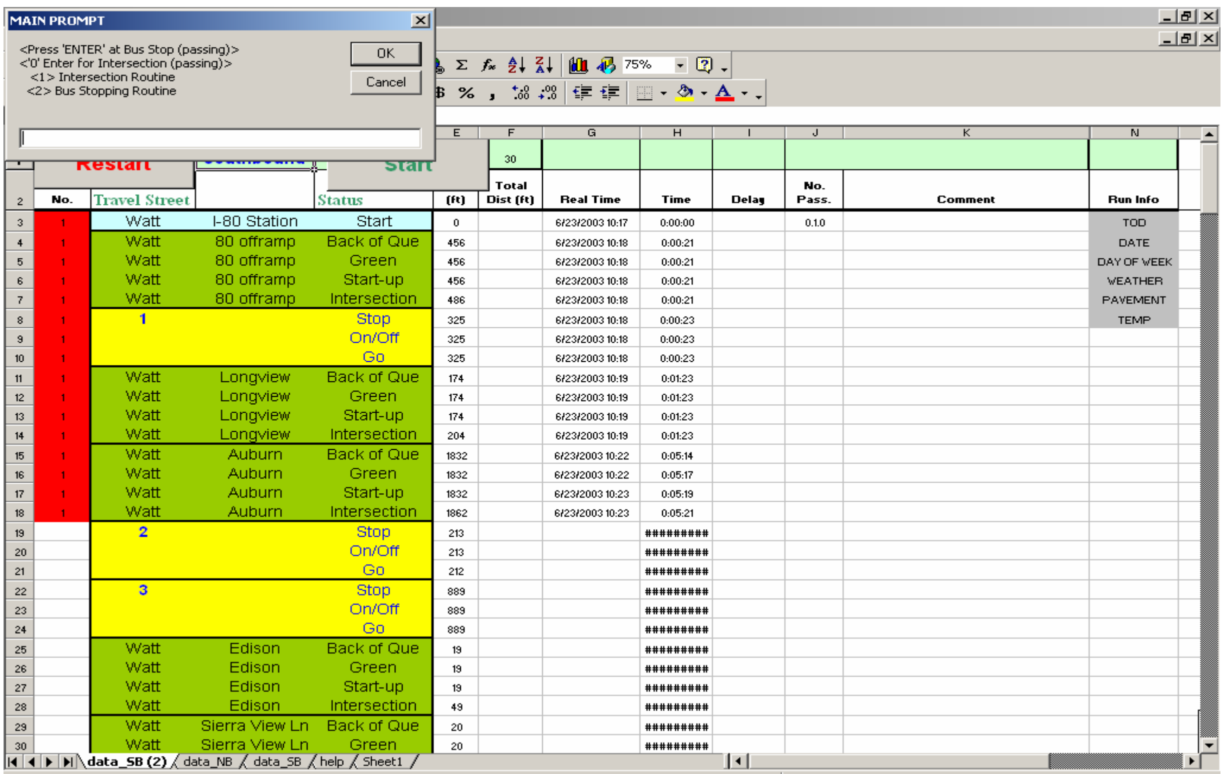
Cycle Failures, TSP Signals Only					
Northbound		**Southbound**		**Total**	
Peak	**Off Peak**	**Peak**	**Off Peak**	**Peak**	**Off Peak**
9 of 32 (28%)	9 of 85 (11%)	2 of 69 (3%)	0 of 48 (0%)	11 of 101 (11%)	9 of 133 (7%)

APPENDIX E:

DESCRIPTION OF SOFTWARE USED FOR DATA COLLECTION

The software used for data collection is solely a Microsoft® Excel spreadsheet with Visual Basic applications. The software was developed primarily to perform the collection of timestamps by implementing a series of keystrokes using an external numeric keypad device. The software was tailored to fit specific events on the bus route allowing the operator to capture a timestamp associated with each event. The program merely utilizes the "now()" function in Excel to produce the timestamp based on the computer's system clock. A Visual Basic-looped routine that uses operator prompts to place now() timestamps in appropriate Excel cells associated with the static list of events. The program assigns each timestamp in a streaming list displayed parallel to the event list allowing the user to monitor the data as it is collected. Figure E-1 shows a screen shot of the program in the "main prompt" mode. The event list is displayed on the left. All intersections are highlighted in green, and bus stops in yellow allowing the user to prepare for the next event.

Figure E-1: Program Operations



The program is ultimately broken into four looped routines, which are run at the main prompt (Figure E-2). The main prompt gives the user a choice to access each mode depending on which event is occurring, with subsequent prompts for additional inputs depending on the mode.

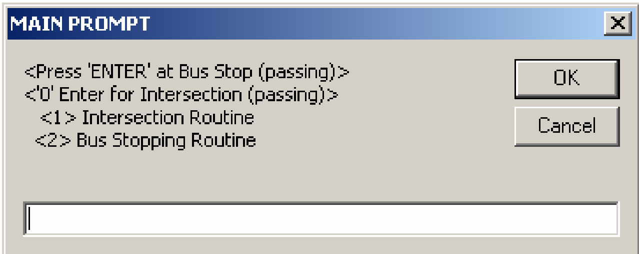


Figure E-2: Main Prompt

The following list identifies the 4 possible routines at the main prompt:

- Bus Stop (passing mode).
- Bus Stop (stopped mode).
- Intersection (passing mode.)
- Intersection (stopped mode).

The Bus Stop (passing mode) option is enabled by pressing the enter key at the main prompt as the transit vehicle passes the bus stop, assigning a timestamp of the same value for each of the three timestamp fields. The three timestamps are all collected simultaneously using a single keystroke.

The Bus Stop (stopped mode) is enabled by pressing the number 2 followed by the enter key. The program immediately collects a timestamp identifying when the vehicle stopped and prompts the user to enter the number of passengers boarding and exiting (Figures E-3 and E-4). Several keystrokes were eliminated by the application of a number convention that uses a period-delimited structure to discriminate the boarding and alighting. The user is required to input the data in the following sequence: the number of passengers boarding with a bus pass, the number of passengers boarding with cash, and the number of passengers alighting) The program stores the period-delimited string into a single field that is separated after the data is processed. Again, three timestamps are recorded during a bus stop event:

- The time the bus arrives at the bus stop.
- The time when all passengers have boarded and paid.
- The time the bus re-enters the traffic stream.

Figure E-3. Boarding & Alighting

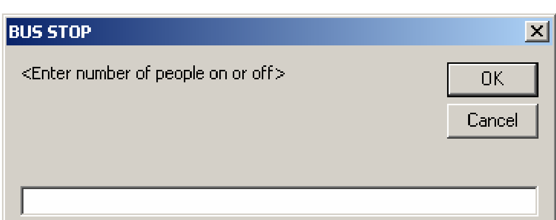
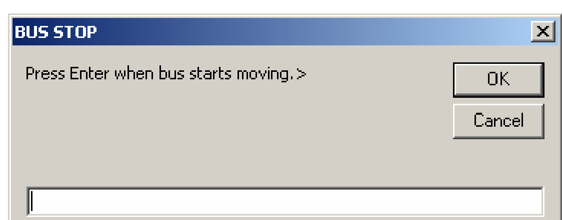


Figure E-4. Re-entry to Roadway



The Intersection (passing mode) operates similar to the bus-passing mode such that it records a timestamp for each of the four time elements at the intersection. All four timestamps are identical, generated by typing "0" followed by the enter key at the main prompt.

The Intersection (stopped mode) records the four timestamps, yet records them individually as the operator keys them in. An input box prompts the user for the next interval after each entry until all four timestamps have been recorded.

The four timestamps are:

- The time the bus arrives at the back of the queue at the intersection.
- The time the signal turns green.
- The time the bus begins moving (denoting start-up delay).
- The time the bus crosses the intersection stop bar.

Additional routines were introduced to cope with the realities of data collection while riding the bus. Adding a re-start feature allows the operator to suspend normal input for real time editing purposes such as a missed event or an event captured too early. The save feature operated from the keypad was added to prevent any loss of data if a battery failure were to occur. The option to add comments is available for the identification observed events such as wheelchair or bike boarding of which influences the travel time.

The program has been effective in capturing a robust detailed picture of traffic and transit operations. The program captures the timing of events occurring along the route. After the collection, the streaming list of timestamps was finally transferred into a database for further evaluation. Critical information was derived from the delta times or the timing between events. The database is a resource that also functions as a place to store and retrieve all data. The collection software and database both are kept in a simple format to allow others to edit for future changes.