Next Generation Transit Signal Priority with Connected Vehicle Technology

CVI UTC

CONNECTED VEHICLE/INFRASTRUCTURE UNIVERSITY TRANSPORTATION CENTER (CVI-UTC)

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Connected Vehicle/Infrastructure UTC

The mission statement of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) is to conduct research that will advance surface transportation through the application of innovative research and using connected-vehicle and infrastructure technologies to improve safety, state of good repair, economic competitiveness, livable communities, and environmental sustainability.

The goals of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) are:

- Increased understanding and awareness of transportation issues
- Improved body of knowledge
- Improved processes, techniques and skills in addressing transportation issues
- Enlarged pool of trained transportation professionals
- Greater adoption of new technology

Abstract

This project utilized connected vehicle (CV) technology allowing two-way communication among vehicles and infrastructure to develop a next-generation Transit Signal Priority (TSP) system that does not have to rely on conventional TSP sensors. The research team extended a previously proposed TSP system based on CV technology (TSPCV) to handle conflicting requests and to coordinate passage between intersections in a travel corridor. The proposed TSP mechanisms minimize installation and maintenance costs by eliminating the need for local agencies to perform a level of service (LOS) study and/or volume/capacity (v/c) ratio for potential TSP intersections before installation. Simulation-based evaluation results showed that, compared to conventional TSP mechanisms, the proposed TSP logic reduces bus delays between 5% and 48% (TSPCVM) and decreases the delay of a bus progressing along a corridor between 35% and 68% (TSPCV-C). The range of improvement corresponds to the four different v/c ratios tested, which were 0.5, 0.7, 0.9 and 1.0. In most cases, the proposed TSP logic caused no negative effects.

A field experiment conducted on the Connected Vehicle test bed on the Virginia Smart Road, located at the Virginia Tech Transportation Institute (VTTI) in Blacksburg, Virginia, validated the performance of the proposed TSPCV system. The TSPCV algorithm provided green traffic signal timing to buses with different arrival times with a 100% success rate. It also reduced delays for a bus with a speed of 45 mph and a traffic signal with a 90-second cycle length and 30 seconds of green time by as much as between 32% and 75%. Moreover, the field experiment showed that two Global Positioning System (GPS) devices (regular and differential) performed almost identically and, in an aggregate sense, the difference in their performance was not statistically significant. This finding facilitates the large-scale implementation of TSP, since regular GPS devices are much cheaper than differential GPS devices and operated just as well for TSPCV.

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Chapter 1. Introduction

Background

For years, Transit Signal Priority (TSP) has been proposed and studied as an efficient way of improving transit operations. TSP offers preference to transit vehicles at signalized intersections and has been proven valuable in reducing transit travel time and improving both schedule adherence and customer ride quality. Furthermore, TSP has shown the ability to cancel out the negative effects of an outdated timing plan [1]. The technology has been applied in many cities in Europe, Asia, and North America. Many large cities in the U.S., including Seattle, Portland, Los Angeles, and Chicago have implemented the TSP system as well [2].

Past studies have shown that the benefits of TSP, in terms of bus travel time-savings, vary significantly (Table 1). Among the 13 quantitative TSP studies we reviewed, the travel time savings ranged between 0.9% and 71%. Only one out of the 13 studies, however, investigated performance benefits based on a field test, which was deployed in Arlington, Virginia [3]. Results indicated that bus travel time was reduced by 0.9%, but that total delay was increased by 1%. A closer investigation of that particular TSP system indicates at least two possible reasons for the mixed outcome: first, the TSP logic was too simple (a green extension of only 5 seconds); and second, the progression between adjacent intersections was not coordinated.

These shortcomings highlight gaps in the research literature. No study to date has investigated the coordination of adjacent intersections for TSP. Additionally, no research has been completed combining TSP with connected vehicle (CV) technology. Currently, there is an ongoing project that aims to design a multi-modal intelligent traffic signal system that will operate in a CV environment: the Multi-Modal Intelligent Traffic Signal System (MMITSS) project. MMITTSS investigates TSP at a fairly high level and is a valuable guideline for TSP research, but it does not provide detailed information for the TSP algorithm.

TSP also faces other widespread deployment challenges. One problem is its potential adverse effect on side streets. Especially for intersections that are nearly operating at their full capacity, the benefit of adding TSP is controversial [4]. Another potential challenge is timing. Because of the uncertainty associated with the arrival time of a bus, the TSP procedure usually moves a large portion of the green light time away from side streets to the street the bus is traveling on. In a worst-case scenario, the bus arrives during the next cycle without taking advantage of the green time extension, while the vehicles on the side street wait and accumulate delay [3]. Of course, this causes significant adverse effects on traffic conditions.

To properly address these challenges, a next-generation TSP logic based on CV technology (TSPCV) was proposed in [5]. This new TSP takes advantage of the resources provided by CV technology, including two-way communications between the bus and the traffic signal controller, accurate bus location detection and prediction, and knowledge of the number of passengers. The key feature of the TSPCV logic is green time reallocation, which moves green time instead of adding extra green time. The TSPCV logic was also designed to be conditional. That is, the delay per person serves as the most important criterion determining whether or not TSP is to be granted. Based on simulation results, the proposed TSPCV was shown to provide buses with more accuracy and better effectiveness than conventional TSP. Furthermore, it accommodated a greater percentage of transit buses than conventional TSP. Its performance was compared against conventional TSP (CTSP) and no TSP (NTSP) conditions under various congestion levels. The results show that the TSPCV greatly reduced the bus delay at signalized intersections without causing statistically significant negative effects on side streets.

Table 1. Summary of past TSP studies

Place Tested	# of Buses	Evaluation Tool	Arrival Time Forecast	TSP Type	Performance Measurements	TSP Result	Reference #
Hypothetical Intersection	1	PARAMICS	Online Micro-Simulation	TSP with AVL*	Average bus delay Non-peak	-24.81%	8
					Average bus delay peak	+28.92%	
					Side street delay	+23.3%~55.2%	
Minneapolis	1	AIMSUN	Average from historical GPS data	TSP with AVL	Bus travel time AM peak	-12~15%	2
					Bus travel time PM peak	+4~11%	
Hypothetical Network with 3 Intersections	1	TEXSIM	Not clear	TSP with AVL	Stop delay Vehicles in bus's direction	-6%~10%	9
					Stop delay Vehicles in cross street	+2%~26%	
Vancouver, BC	1	VISSIM	Linear model fit by past data	TSP with AVL	Bus travel time	-33%	10
					Cross street delay	Negligible	
Newark, NJ	1	WATSIM	Historical data, No AVL	Conventio nal	Travel time Bus	-10%~20%	12
					Travel time Auto (main street.)	-5%~10%	
Hypothetical Intersection	1	NETSIM	N/A	Adaptive TSP	Total delay	-3%~71%	11
Ann Arbor, MI	1	NETSIM	Check in/Check out	Conventio nal	Delay bus	little benefit	3
					Delay auto	increase	
Arlington, VA	1	INTEGRA-TION + Field Test	Average from historical GPS data	TSP with AVL	Reliability	+3.2%	13
					Bus travel time	-0.9%	
					Total delay per vehicle	1%	
					Total delay per person	0.60%	
Portland, OR, Pilot Routes	1	unknown	unknown	unknown	Bus travel time	-10%	4
					On-time performance	+8%-10%	
Seattle, WA, Rainier	1	unknown	unknown	unknown	Priority bus delay	-34%	4
					Bus stops	-24%	
					Bus travel time	-8%	
Los Angeles, CA, Metro Rapid	1	unknown	unknown	unknown	Bus travel time	-8%~10%	4
Bremerton, WA	1	unknown	unknown	unknown	Bus travel time	-10%	4
Chicago, IL, Cermak	1	unknown	unknown	unknown	Bus travel time	2-3-min decrease from 13-17 min	4

*Automatic Vehicle Location (AVL)

Research Objectives

The research in this report builds on the TSPCV structure proposed in [5]. TSPCV was designed to accommodate one request at a time at one single intersection. The first part of this research examines a proposed logic for accommodating multiple requests for TSP. The second part of this research focuses on coordinating TSP requests across multiple intersections in a corridor. The third part of this research addresses the lack of field tests found in the literature through a field test of TSPCV performed on the Connected Vehicle test bed on the Virginia Smart Road located at the Virginia Tech Transportation Institute (VTTI) in Blacksburg, Virginia.

Conflicting TSP Requests

Like many other advanced TSP strategies [9, 14-16], TSPCV was developed to accommodate one single bus at a time. In the case that multiple conflicting TSP requests are made, the system was designed to serve the first request only. A closer examination of the current "first-come, first-served" way of solving conflicting priority requests revealed that not only does it not provide any benefits, but that it also deteriorates the TSP system. A 13% extra bus delay was observed with the first-come, first-served strategy compared to the NTSP option [17].

Very few studies have investigated the problem of conflicting TSP requests. Ma et al. developed two methods for accommodating multiple TSP requests. The first is passive bus priority for an exclusive bus lane that maximizes person capacity [18]. The second is using a decision tree to decide serve sequence [19]. He et al. presented a heuristic algorithm that reduces bus delay up to 50% compared to the "first-come, first-served" system [20]. Zlatkovic et al. proposed a logic that always provides first priority to the direction with the green phase on [17]. This algorithm shows a benefit of a more than 30% reduction in traffic light delay. However, both algorithms have room to be improved. First, He's algorithm was designed to generate significant benefits only during oversaturated conditions. Second, both were developed for the condition when only two strategies are applied: "green extension" and "red truncation" [21]. These algorithms are not applicable to complicated TSP strategies like TSPCV. Third, they also do not consider adverse effects on other traffic users. Hence, an enhanced TSPCV logic is required that accommodates conflicting TSP requests while causing no negative effects for other traffic users.

Bus Progression

All of the advanced TSP systems reviewed were developed in the context of one isolated intersection [8,16]. In fact, even for conventional TSP, a bus's progression along a corridor is often overlooked. There have only been a few limited studies on this topic. Skabardonis first pointed out that coordination between adjacent intersections is important for TSP [22]. He proposed that the decision to grant TSP at one signal should consider whether this effort would be wasted at the downstream intersection. Although Skabardonis did not personally evaluate his proposal, the importance of this suggestion was proven quantitatively by multiple studies [23-25]. Ngan demonstrated that bus delay increases by 6% without coordination between adjacent intersections. Six percent may seem marginal at first glance, but if compared to the average delay savings (10%–20%) observed by various conventional TSP studies [1-3, 9], almost one-third of the benefit is sacrificed. Ma's studies [25, 26] show that, supposing TSP is not granted to buses that cannot make it through the downstream intersection, bus delay does not increase significantly, while other traffic users' delay could be significantly reduced.

Enabling coordination among traffic signals along a corridor has even more significance for a TSPCV system. One limitation of the previously developed TSPCV mechanism is that its performance is affected greatly by the spacing to the downstream intersection. TSPCV requires a certain distance for the bus to adjust its speed to ensure maximum performance. The bus must be capable of being granted TSP no matter when the TSP is requested and the start time of the TSP must minimize any adverse effects. The previous study used a 0.5-mile speed-adjustment distance, which is the average intersection spacing in the United States [27, 28], and which appears to be a sufficient distance. However, not all intersections are 0.5 miles away from each other. There is the possibility that a bus receiving TSP at an upstream intersection is stopped by the traffic signal at a downstream intersection when the two intersections are located too closely. Such an undesired stop could occur either because TSP is not able to start as needed for reasons like the requirement for a minimum green time or because all the candidate TSP start times lead to substantial adverse effects. Consequently, the delay reduced at the upstream intersection could be lost if the TSP bus stops at the downstream intersection due to lack of progression. But what if a bus is able to adjust speed for the downstream intersection before it arrives at the upstream intersection? In a sense, this "extends" the length between intersections that are too closely spaced.

TSP Field Experiment

Only one out of 13 studies that the project team reviewed investigated the performance benefits of TSP based on a field test. The only field-evaluation-based TSP was deployed in Arlington, Virginia [12]. Consequently, the current research is one of very few TSP studies involving both simulation and field experimentation. The TSP experiment in this project was aimed at (a) validating that the proposed TSPCV algorithm works in a connected vehicle infrastructure (CVI) environment and (b) estimating selected performance measures. Thus, the experiment focused on implementing TSPCV on the Virginia Smart Road, confirming hardware and software compatibility, measuring performance, and comparing the effectiveness of regular and differential Global Positioning System (GPS) devices.

Chapter 2. Transit Signal Priority for Conflicting Request

TSPCV was designed to handle only one request for TSP. In a real-world implementation, however, more than one bus might request TSP for a given intersection. The research in this chapter proposes a logic to extend TSPCV to accommodate multiple requests and tests the effectiveness of that logic through theoretical analysis and simulation.

The research objectives for this phase were as follows:

1. Enhance the previously developed TSPCV logic to accommodate multiple conflicting TSP requests. Since the enhanced TSPCV is capable of dealing with multiple TSP requests, to distinguish it from the previous TSPCV logic, the new logic will be referred to as Transit Signal Priority with Connected Vehicle Technology Accommodating Multiple Buses (TSPCVM).
2. Evaluate the newly upgraded TSPCVM logic.

Logic Architecture Description

Since the proposed TSPCVM logic is built upon the previously developed TSPCV logic, several core characteristics are inherited from the previous logic. First, the cooperation between transit buses and traffic signals is required and enabled. When a bus approaching an intersection sends a priority request, not only does the traffic controller try to accommodate the bus, but the bus also needs to travel at a reasonable speed to minimize the effort from the signal. The bus speed is recommended based on the remaining/expected queue, road geometry, and the normal signal timing plan. Secondly, the TSP logic proposed is green time reallocation; in other words, instead of adding additional green time to the original timing plan, the proposed TSP logic splits the original green time and moves part of it to when green time is most needed by a transit bus. Finally, TSP green time is granted conditionally based on two criteria: schedule adherence and delay per person. Many of the functions are made possible by CV technology, including two-way communications between the bus and the traffic signal controller, accurate bus location detection and prediction, and knowledge of the number of passengers.

The TSPCVM logic is activated every time a bus sends out a TSP request. When the TSPCVM logic is called, it will check two criteria before computing a TSP timing plan. The first criterion checks whether the bus is behind schedule and the second one verifies whether this TSP request conflicts with any previously accepted request. If the first criterion is not met, then no TSP is granted. If the second criterion is not fulfilled, then the logic degrades into the previously developed TSPCV logic. The bus will be accommodated through the single TSP request mechanism, which is TSPCV. More specific descriptions of the TSPCVM logic are discussed later in this chapter.

Error! Reference source not found. displays the architecture of the TSPCVM. The logic is composed of t hree major components:

1. **Arrival time prediction component**. The arrival time ranges of all buses approaching the subject intersection are predicted.
2. **TSP timing plan and bus speed calculation component**. Given the arrival time ranges, the algorithm generates a timing plan that will have minimum impact on general traffic users and calculates the corresponding recommended bus speeds.

3. **Logic assessment and implementation component**. The TSP timing plan is compared against the normal signal time (winning timing overwrites the other timing) and the recommended bus speeds will be transmitted to the approaching buses.

Detailed information regarding the three components of TSPCV is provided in the literature [13, 29].

The following sections present the logic of TSPCVM in more detail.

Arrival Time Prediction Component

Every time a bus approaches the intersection, the arrival time prediction component is activated and predicts the arrival time for all the buses that are traveling toward the intersection. One of the great advantages of integrating TSP into a CV system is the two-way communications between roadside equipment (RSE) and traffic users, which in this case is the bus. A CV-equipped bus communicates with traffic signal controllers and is capable of receiving speed instructions. It is assumed that the desired speed of an approaching bus could vary between ~10% above and ~20% below the speed limit. Therefore, the prediction result generated from this component is not a set of fixed numbers; instead, it is a set of time ranges. Arrival time ranges are computed for all approaching buses so that the buses can adjust their travel speed to cooperate with the TSP strategy.

TSP Timing Plan and Bus Speed Calculation Component

The TSP timing plan and bus speed calculation component is called right after the arrival time prediction component. It identifies all buses approaching the intersection and judges whether the TSP requests conflict. Conflicting TSP requests are defined as multiple TSP green time requests within one signal cycle. If no conflicting request is detected, the logic degrades into the single-bus TSPCV logic; otherwise, the component proceeds to compute the potential TSP green time for all buses. The potential TSP green time is calculated based on the goal of inserting TSP green time exactly where it is needed for the duration it is needed. The duration of the TSP green time is determined so that the queue is cleared before the bus arrives at the intersection. In other words, the bus will catch up with the end of the queue right at the stop bar of the intersection. The calculation of the real-time queue length estimation is based on the model developed by Liu [30], which is an extension of the shock wave theory. The arrival information of other vehicles at the end of the queue is acquired using CV technology.

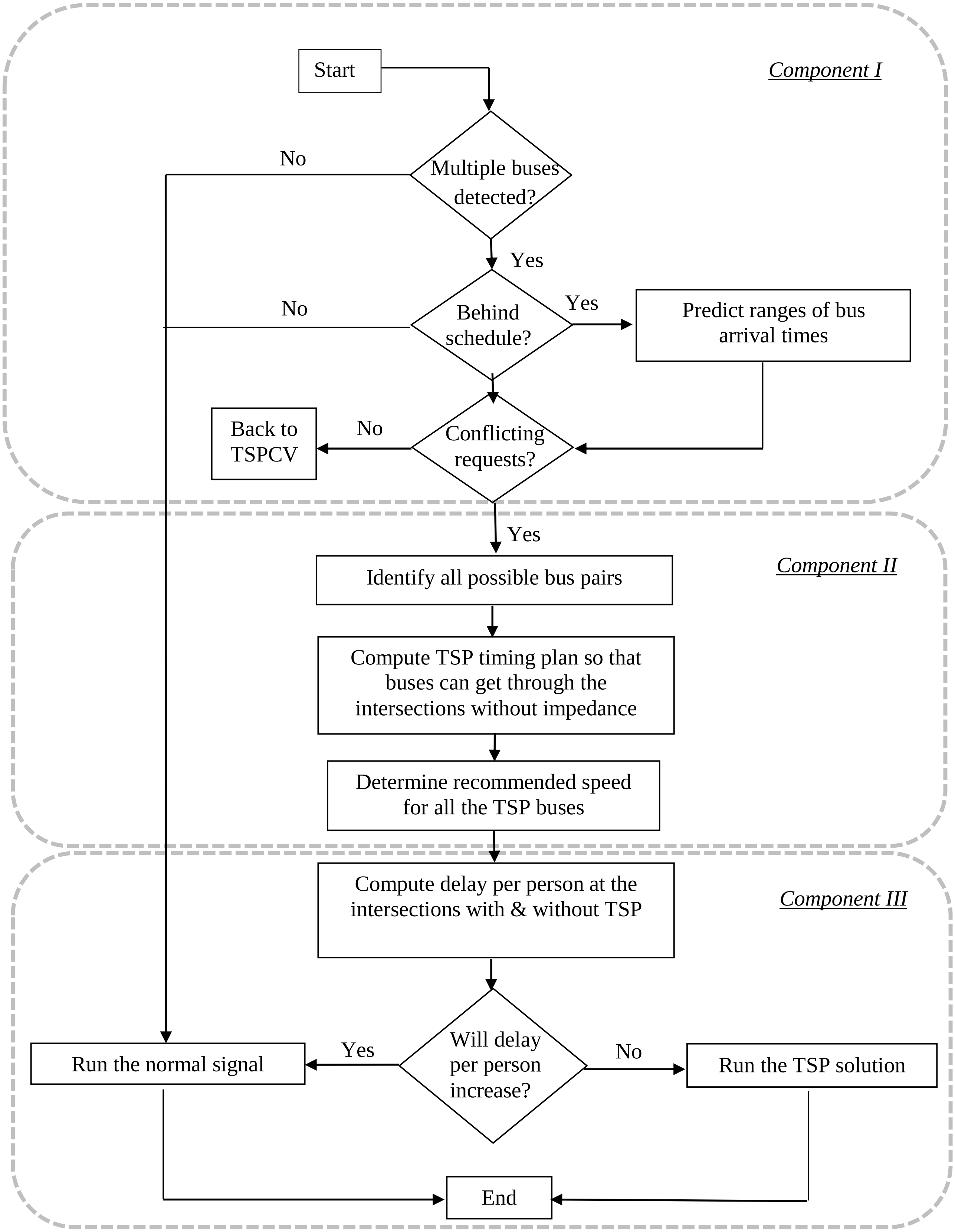

Figure 1. The structure of TSPCVM.

The cycle length will be the same even when the TSP green time is inserted because the TSP green time is spliced from the original green time in the direction of the bus. The inserted green time taken from the approaching bus's direction is 100% used in clearing the traffic for that direction. Therefore, theoretically speaking, not a single second is wasted during the TSP. Strictly speaking, the extra TSP green time is "moved" rather than "inserted" or "added." This feature greatly minimizes the adverse effects compared to conventional TSP, which adds extra green time that no other traffic users except the bus can make use of.

The ranges of predicted bus arrival times are passed on from the last step for the TSP timing plan calculation. Therefore, the corresponding potential TSP green time is a group of ranges of TSP green start times and end times. The number of ranges equals to the number of conflicting TSP requests. While there will be numerous TSP timing plans depending on when the buses arrive, the identified potential TSP green time is first filtered using the following rules:

1. A maximum of two TSP green times should be granted within one signal cycle. If three or more conflicting TSP requests are made, the algorithm identifies all possible two-bus pairs and then accommodates the bus pair associated with the least travel time of all vehicles.
2. If two conflicting TSP buses are traveling toward each other from opposite directions, it is preferred that they travel through the intersection within one single TSP green time.
3. It is preferred that a TSP green time starts at the end of the phase rather than cutting into the middle of a non-TSP signal phase (for better safety and meeting drivers' expectations).
4. If TSP green time has to start in the middle of a phase, it is preferred that the bus travel at its normal speed.
5. A minimum green time is required for both the TSP green time and the original timing plan.

Based on these rules, the algorithm finds a pool of preferred TSP start and end times from the time ranges during which TSP can possibly start and end while fitting them into an optimization algorithm. This optimization algorithm is activated every time a TSP request is received; it finds the value of choice variables $T_{TSPendi}$ to minimize total per person delay at the intersection for a preset time interval. The objective function estimating total per person delay can be expressed as follows.

The choice variables include: $T_{TSPend1}$, $T_{TSPend2}$… $T_{TSPendk}$.

$$\text{Minimize}\left(\sum_{cycle=1}^{cycle=\text{n}} \int_0^T D_i * Occ_i + \sum_{K=1}^{k} \sum_{cycle=1}^{cycle=\text{n}} \int_0^T D_{bus\_k} * Occ_{bus\_k}\right) \tag{1}$$

which are subject to:

$$\sum_j (G_{j\_before\_k} + G_{j\_after\_k}) + G_{TSP\_k} + G_{remain\_k} = T = constant$$

$$T_{TSPend\_k} - T_{TSPs\_k} = G_{TSP\_k}$$

$$T_{BAlow\_k} \leq T_{TSPend\_k} \leq T_{BAup\_k}$$

$$T_{TSPs\_k} = \sum_j G_{j\_before\_k}$$

$$G_{j\_before\_k} + G_{j\_after\_k} = Constant$$

$$G_{j\_before\_k} \geq G_{min} \ or \ G_{j\_before\_k} = 0$$

$$G_{j\_after\_k} \geq G_{min} \ or \ G_{j\_after\_k} = 0$$

$$G_{TSP\_k} \geq G_{min} \ or \ G_{TSP\_k} = 0$$

$$G_{remain\_k} \geq G_{min} \ or \ G_{remain\_k} = 0$$

(2)

where:

k: the number of conflicting TSP requests
T: cycle length at the intersection
Di: delay of vehicle i
D_{bus_k}: delay of bus k
Occ_i: occupancy on vehicle i
Occ_{bus_k}: occupancy on the bus k
$G_{j\_before\_k}$: green time for phase j (1, 2, or 3) before TSP green granted for bus k
$G_{j\_after\_k}$: green time for phase j (1, 2, or 3) after TSP green granted for bus k
G_{TSP_k}: TSP green time granted for bus k
G_{remain_k}: remaining green time for lane group with bus after taking out the TSP green granted for bus k
G_{min}: minimum green time requirement
T_{TSPend_k}: end time of TSP green granted for bus k
T_{TSPs_k} : start time of TSP green granted for bus k
T_{BAlow_k} : lower bound of bus arrival time range of bus k
T_{BAup_k} : upper bound of bus arrival time range of bus k

The optimization algorithm finds a set of TSP green times associated with the least delay for all vehicles. Computation power is not an issue here. Based on the case study performed, the algorithm can finish within a second. Therefore, implementing this logic on a real-time basis is feasible. Once the timing plan is generated, the recommended bus speeds are computed so that buses travel through the intersection right after the queues in front are cleared and before TSP green phases end.

Logic Assessment and Implementation Component

After a TSP timing plan is determined, the algorithm compares the "with TSP" scenario against the "normal timing" scenario. Since the number of passengers onboard is likely to be known in a CV environment, the per person delay performance measure is used. Per person delay is calculated for a number of consecutive signal cycles starting from the TSP-implemented cycle. In this study, a TSP timing plan is only implemented when its corresponding per person delay is less than the NTSP scenario.

During implementation, two major steps are conducted. First, an instruction is given to a bus about the recommended speed. Second, the signal time is altered to accommodate TSP green. A possible buffer green time is given to a bus in case it is not expected to reach the intersection in time. The TSP green time can be extended up to 5 seconds to accommodate the random delay.

Evaluations

Study Site

The potential performance of TSPCVM was tested using a VISSIM model of the intersection of Emmet Street and Barracks Road in Charlottesville, Virginia, as shown in Figure 2. The model was calibrated to match the real world, which was achieved by adjusting the car-following model parameters to reach a realistic saturation flow rate at the intersection. The model was also visually examined by the research team to ensure the validity of the simulation. The current signal cycle at the intersection is 160 seconds.

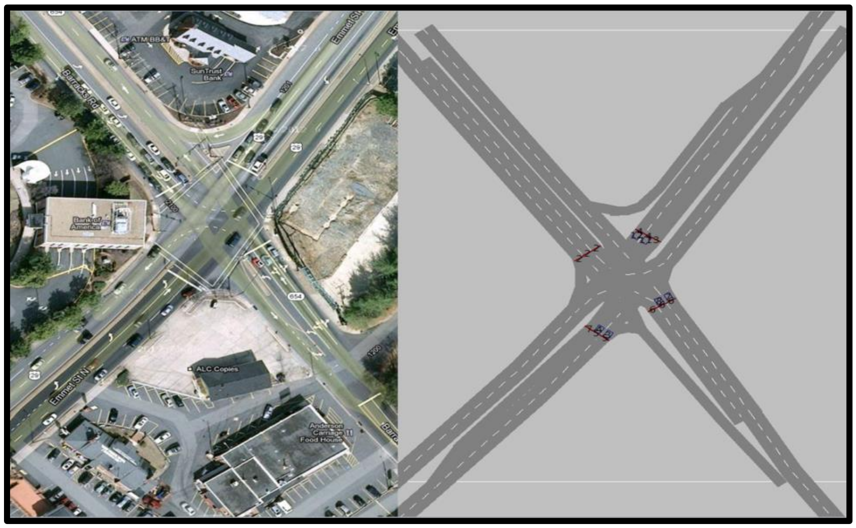

Figure 2. Study site: Emmet St. and Barracks Rd. intersection, Charlottesville, VA [Source: Map data ©2015 Google].

Methodology

Both analytical tests and simulation evaluations were performed for the proposed TSPCVM as well as conventional TSP (CTSP) and no TSP (NTSP) cases. The analytical test was based on a deterministic calculation. It considered all the possible conflicting scenarios and quantified the performance by averaging the measurement of effectiveness (MOE) computed for all the scenarios. The simulation evaluation also considered uncertainty due to vehicle interactions and inter-arrival times. This evaluation better mimics the real world and quantifies the performance more realistically. Both evaluation methods are essential in order to achieve a comprehensive understanding of the logic. The CTSP logic compared here is the first-come, first-served TSP. This is not only because the first-come, first-served TSP is the current common practice, but also because all the aforementioned research uses first-come, first-served TSP as the control group. By making a comparison against the same benchmark, the advantage of TSPCVM is clearly presented. CTSP grants 10 seconds of extra green time to buses that arrive within 10 seconds of the end of the normal green time. In case the bus cannot make it through the intersection within 10 seconds, CTSP will add up to 5 seconds to the previous 10 seconds to accommodate the late arrival. When multiple TSP requests are made within one signal cycle, only one request is accommodated by CTSP. This logic follows the actual implementation in Northern Virginia described in [31].

All three logic cases were investigated under three scenarios:

1. Two conflicting requests from opposite directions
2. Two conflicting requests from perpendicular directions
3. Three conflicting requests from three directions

The research assumes buses are traveling toward the intersection from three different directions. All the bus lines have mid-block bus stops located about 750 feet upstream of the intersection. With the speed limit of 40 mph, it is assumed buses can travel within a speed range between 30 mph and 45 mph. The TSP logic is activated when buses pass 0.5 miles upstream of the intersection. The optimization algorithm minimizes the total per person delay at the intersection for three signal cycles. Three cycles are used because this period is long enough to capture residual effects caused by TSP and short enough not to interfere with another TSP. Three 160-second cycles are about the minimum headway between buses. The buses traveling in the system are assumed to carry 40 riders and their average dwell time at the bus stops is 30 seconds with 2 seconds standard deviation. These attributes regarding the buses were obtained from a National Cooperative Highway Research Program (NCHRP) study investigating bus rapid transit [32]. The bus dwell time variation was set moderately low since CV technology improves dwell time prediction and minimizes forecast deviation.

The MOEs used are bus delay and total travel time of all travelers. Bus delay quantifies the effectiveness of various TSP treatments, while the total travel time demonstrates whether any adverse effects are caused.

To consider the effect of simulation randomness, at least 10 simulation runs were performed for each scenario, and the MOEs for each scenario were averaged from the output of all simulation runs. The minimum sample size requirement was checked to make sure that a sufficient number of simulation runs was achieved to represent the entire population. Minimum sample size was calculated using the formula recommended by the Virginia Department of Transportation (VDOT) [33], which is:

$$\mathrm{N} = Z^2 * S_s^2/(X_s * E)^2 \tag{3}$$

where:

Z: Number of standard deviations away from the mean corresponding to the required confidence level in a normal distribution. In this study, confidence level is set to be 95%.
Ss: Sample standard deviation
Xs: Sample mean
E: Tolerable error. In this study, *E* = 10%.

Finally, all the differences were checked for statistical significance to ensure that all the improvements or adverse effects claimed in the result session were statistically significant. A paired two-tailed *t*-test was utilized, since the data used in the comparison were collected from the same site. The confidence level tested was 95%.

Analytical Test

In order to prove the benefit of TSPCVM on a theoretical level, the performance of TSPCVM accommodating two conflicting TSP requests was estimated first through analysis. The stop delay of buses and all other traffic users was calculated using a deterministic computation. In order for the evaluation to be fair, all possible TSP activation scenarios needed to be considered and averaged to find the assessment results. The cycle length at the intersection was 160 seconds. Since a TSP can be activated at any given second, and two bus lines were under consideration, there are 160 × 160 = 25,600 possible TSP activation situations. The stop delay for buses and all other traffic users was calculated by averaging these 160 × 160 situations. All three treatments were computed and compared. Field peak-hour volume data, which was a near-capacity situation, were applied (volume/capacity [v/c] = 0.9). The results are summarized in Table 2, which presents the performance of TSPCVM accommodating two different kinds of conflicting TSP requests: two buses coming from opposite directions (Opp) and buses coming from perpendicular directions (Perp). Both per person delay of all traffic users and bus delay were compared. The results show that TSPCVM is superior to CTSP regardless of the conflict conditions tested in this evaluation. While CTSP showed comparable benefits over two conflicting scenarios, TSPCVM demonstrated more advantages when buses were coming from opposite directions. Not only is bus delay reduced more, but delay per person is also minimized to a greater magnitude. This observation is intuitive because two buses traveling in opposite directions can be accommodated in a single TSP green. As a result, more bus passengers are provided with preference at the same time while fewer disturbances are caused for other traffic users.

Table 2. Analytical Assessment of Various TSP Treatments

	NTSP	CTSP	TSPCVM	NTSP/TSPCV	NTSP/CTSP	CTSO/TSPCV
Delay Per Person (Opp) (Sec)	49.5	49.2	44.3	10.5%	0.8%	9.8%
Delay Per Person (Perp) (Sec)	49.5	49.2	46.0	7.2%	0.7%	6.5%
Bus Delay (Opp) (Sec)	105.4	99.2	51.8	50.9%	5.9%	47.8%
Bus Delay (Perp) (Sec)	117.2	109.4	65.4	44.2%	6.6%	40.3%

Table 3. TSP Granting Condition – Perpendicular Direction

	Main St.	Minor St.	Both Buses	None
count	13800	10828	972	0
%	53.9%	42.3%	3.8%	0.0%

Table 4. TSP Granting Condition – Opposite Direction

	Main St. 1	Main St. 2	Both Buses	None
count	11032	9460	5108	0
%	43.1%	37.0%	20.0%	0.0%

Simulation-based Evaluation in VISSIM

While the analytical test results show significant benefits under the proposed TSPCVM logic, they do not consider any variability due to vehicle interactions and inter-arrival times. A microscopic traffic simulator can assess the performance of the proposed TSP under more plausible conditions. The microscopic simulation software package VISSIM [34] was used to evaluate the proposed TSP logic for a CV environment. A Component Object Model (COM) interface was used to assess information available within a CV environment [35]. The evaluation was performed under the assumption that only transit buses are connected to traffic signal controllers and that other traffic users do not have CV equipment; in other words, 0% CV market penetration except for buses. The end of queue was estimated based on incoming vehicles and outgoing vehicles at the intersection. The detailed algorithm can be found in the model developed by Liu [30], which is an extension of the shock wave theory. The data extracted via the COM interface included speed and position of bus, number of passengers onboard, number of potential passengers at the bus stop, number of vehicles passing the intersection, and traffic volume from all four approaches. Also, the COM interface was used to change the signal-timing plan during the simulation. All programs were coded in VBA and implemented in Microsoft Excel.

The simulation test network was calibrated to better match the real world. The measurement utilized was saturation flow rate. In order to reduce the saturation flow rate to a realistic range, the default settings of the Wiedemann 74 car following model were adjusted. Average standstill distance was raised to 7.5, the additive part to 3, and the multiplicative part to 4. After adjustments to the parameters, saturation flow rate was reduced to an average of 1,838 veh/h/ln. This is consistent with Highway Capacity Manual (HCM) 2010, which states that the saturation flow rate on an urban street segment is 1,800 veh/h/ln [36].

The simulation-based evaluations compared all three scenarios, as follows:

1. Two conflicting requests from opposite directions
2. Two conflicting requests from perpendicular directions
3. Three conflicting requests from three directions

Each scenario was run at least 10 times with random seeds, which ensured that the results would show statistical significance with a 95% confidence level and 5% tolerance error. The sample size was sufficiency assessed using the formula recommended by VDOT [33].

All the differences shown in Tables 4 through 12 have been checked for statistical significance. The differences that are NOT significant are underlined and in italics. All other changes were determined to be statistically significant at $\alpha = 0.05$.

Conflicting Requests From Opposite Directions

As noted, the test network was a calibrated model of the intersection at Emmet Street and Barracks Road in Charlottesville, Virginia. Vehicle volumes and turning movements were actual morning peak-hour data collected from the site. Bus dwelling time at the stop was 30 seconds average with a standard deviation of 2 seconds. A pair of transit buses was designed to arrive every 494 seconds. Given the cycle length of 160 seconds at the intersection, the interval of bus arrival was exactly 3 cycles plus 14 seconds. Also, the headway between the two buses within a pair was increased by 14 seconds every time another pair of buses was generated. This research purposely designed the offset and headway to be 14 seconds so that buses within one single simulation run would arrive at different times relative to signal cycles; hence the simulation results would be less biased.

The results from the simulation are shown in Table 5. Bus delay and the total travel time of all vehicles were summarized and averaged from all simulation runs. The proposed TSP treatment was compared with NTSP and CTSP conditions and a *t*-test was performed to validate the statistical significance of the differences. In sum, the results of the simulation support the findings from the analysis. Compared to the other scenarios, significant improvements are observed. The delay of all buses is reduced by 44% compared to CTSP and 50% compared to NTSP. Delay of all traffic users is slightly minimized as well. The amount of improvement for the two bus lines differed. Partially, this is because the traffic volume traveling the same direction as the second bus line was less. As a result, the algorithm tended to provide greater preference for bus line 1. The other reason is that a larger portion of buses on line 2 arrived during the green phase. Hence, the room for improvement is less compared to line 1.

Table 5. Two Conflicting Requests from Opposite Directions

	TSPCVM	CTSP	NTSP	ITSP/CTSP	ITSP/NTSP
Bus 1 Delay (Sec)	16.4	38.3	46.6	57.3%	64.9%
Bus 2 Delay (Sec)	24.2	34.2	34.4	29.1%	29.5%
Total Bus Delay (Sec)	40.6	72.5	81.0	44.0%	49.8%
Total Travel Time (Sec)	579802.7	612359.3	613774.1	-5.3%	-5.5%

Conflicting Requests from Perpendicular Directions

The setting of the simulation for the conflicting requests from perpendicular directions scenario was mostly the same as the previous scenario, except that the buses were coming from perpendicular directions. Again, this research purposely designed the offset and headway to be 14 seconds so that buses within one single simulation run would arrive at different times relative to signal cycles, and the simulation results would therefore be less biased.

The results from the simulation are shown in Table 6. Bus delay and the total travel time of all vehicles are summarized and averaged from all simulation runs. The proposed TSP treatment is compared with the NTSP and CTSP conditions and a *t*-test was performed. The simulation results support the findings from the analysis. The delay of all buses is reduced by 31% compared to CTSP and 35% compared to NTSP. Regardless of the fact that the delay for all traffic users rises slightly, the differences are statistically insignificant. Interestingly, buses on the minor street show larger improvement than buses on the principal street. One major reason is that a larger margin for improvement exists for the minor street buses. Therefore, when granted with TSP, minor street buses tend to generate more delay savings. Hence, even though fewer minor street buses receive TSP, more benefit is observed.

Table 6. Two Conflicting Requests from Perpendicular Directions

	TSPCVM	CTSP	NTSP	ITSP/CTSP	ITSP/NTSP
Main St. Bus Delay (Sec)	42.0	52.7	53.4	20.4%	21.5%
Minor St. Bus Delay (Sec)	40.6	66.9	73.2	39.4%	44.6%

Total Bus Delay (Sec)	82.5	119.6	126.6	31.0%	34.8%
Total Travel Time (Sec)	551599.7	530469.6	533278.0	*4.0%*	*3.4%*

Conflicting Requests from Three Directions

The setting of the simulation in the conflicting requests from three directions scenario is mostly consistent with the previous scenarios, except that one more bus line was included. The same bus schedule generated in the previous two scenarios was adopted. The consideration again was to ensure that buses within one single simulation run would arrive at different times relative to signal cycles, making the simulation results less biased.

The results from the simulation are shown in Table 7. The magnitude of improvement is not as significant as for the two conflicting-requests conditions because the nature of TSPCVM only allows a maximum of two TSP grants at a time. As a result, when more than two TSP requests were made, at least one bus did not receive TSP treatment. Although this fact reduces the size of improvement, the results still show an 18% reduction in bus delay compared to CTSP and a 21% drop compared to NTSP. Again, no adverse effects on other traffic users were caused by TSPCVM. Overall, TSPCVM does show an advantage over CTSP on total travel time of all traffic users.

Table 7. Conflicting Requests from Three Directions

	TSPCVM	CTSP	NTSP	ITSP/CTSP	ITSP/NTSP
Main St. Bus 1 Delay (Sec)	41.7	46.1	49.9	9.5%	16.5%
Main St. Bus 2 Delay (Sec)	32.5	34.5	34.7	5.9%	6.5%
Minor St. Bus Delay (Sec)	50.6	70.8	72.9	28.5%	30.6%
Total Bus Delay (Sec)	124.8	151.3	157.5	17.6%	20.8%
Total Travel Time (Sec)	608602.9	617539.6	613305.6	-1.4%	*-0.8%*

Sensitivity Analysis on Congestion Levels

In order to verify that the findings from the experiment were consistent with various congestion levels, a sensitivity analysis was conducted comparing TSPCVM against CTSP. Since the field-collected traffic volume data occurred at a v/c ratio of 0.9, three other scenarios were tested: v/c = 0.5, v/c = 0.7, and v/c = 1.0. The results are presented in Table 8 through Table 13.

All three scenarios show similar trends with respect to how TSPCVM performs under various congestion levels. When the congestion level is low, TSPCVM helps reduce bus delays up to about 44% compared to CTSP. As the congestion level rises, the benefit of TSPCVM decreases, while no extra delay is caused. This is because the algorithm is designed to be conditional on per person delay. When the volume grows closer to the capacity, a lower portion of the green time will be granted to TSPCVM to prevent TSP from causing extra delay for other travelers. As a result, the benefit will drop correspondingly, while adverse effects on side streets will still be kept under a certain level. It is interesting to see that even when the v/c ratio equals 0.9, the benefit of TSPCVM is still significant, but then drops dramatically when v/c becomes 1.0. However, even when v/c = 1.0, TSPCV is still superior to conventional TSP. Furthermore, the TSPCVM logic only shows an unbalanced preference under near-capacity conditions. When the v/c level is low, the improvements observed by different bus lines are similar. As the congestion level rises, so does the difference in delay savings rises. In some cases, the logic would even sacrifice one bus line in order to achieve an overall delay reduction.

As shown in Table 8 and Table 9, the greatest delay reduction is observed when conflicting TSP requests come from opposite directions. The performance of TSPCVM reacts to changes in congestion level in the same fashion as described above. Statistically significant total travel time reduction is observed under all congestion levels tested.

Table 8. Sensitivity Analysis for Conflicting Requests from Opposite Directions (Bus Delay)

		v/c = 0.5	v/c = 0.7	v/c = 0.9	v/c = 1.0
TSPCVM	Main St. Bus 1 Delay (Sec)	18.1	16.9	16.4	33.0
	Main St. Bus 2 Delay (Sec)	17.1	17.1	24.2	47.2
	Total Bus Delay (Sec)	**35.2**	**34.1**	**40.6**	**80.2**
CTSP	Main St. Bus 1 Delay (Sec)	32.5	35.4	38.3	47.1
	Main St. Bus 2 Delay (Sec)	28.2	29.7	34.2	50.5
	Total Bus Delay (Sec)	**60.7**	**65.1**	**72.5**	**97.7**
Improvement	Main St. Bus 1 Delay	44.4%	52.2%	57.3%	30.1%
	Main St. Bus 2 Delay	39.3%	42.4%	29.1%	6.5%
	Total Bus Delay	**42.0%**	**47.7%**	**44.0%**	**17.9%**

Table 9. Sensitivity Analysis for Conflicting Requests from Opposite Directions (Total Delay)

v/c	TSPCVM (h)	CTSP (h)	Diff	*t*-test
0.5	91.7	93.8	2.3%	6.80E-07
0.7	122.8	128.5	4.4%	7.81E-05
0.9	161.1	170.1	5.3%	1.84E-07
1.0	197.3	204.1	3.3%	3.00E-02

Table 10 and Table 11 demonstrate how bus delay savings and total travel time change with congestion level when conflicting TSP requests come from perpendicular directions. The performance of TSPCVM mostly reacts to congestion level change in the same fashion as described above. When the traffic volume is at capacity, the logic sacrifices the bus line on the main street to achieve overall bus delay improvement. TSPCVM reduces delay for other traffic users when v/c = 0.5. No statistically significant adverse effect is observed under all other congestion levels.

Table 10. Sensitivity Analysis for Conflicting Requests from Perpendicular Directions (Bus Delay)

		v/c = 0.5	v/c = 0.7	v/c = 0.9	v/c = 1.0
TSPCVM	Main St. Bus Delay (Sec)	24.6	28.9	42.0	71.7
	Minor St. Bus Delay (Sec)	40.0	41.5	40.6	43.7
	Total Bus Delay (Sec)	64.6	70.4	82.5	115.4
CTSP	Main St. Bus Delay (Sec)	43.7	47.6	52.7	54.5
	Minor St. Bus Delay (Sec)	63.9	65.8	66.9	66.9
	Total Bus Delay (Sec)	107.6	113.4	119.6	121.4
Improvement	Main St. Bus Delay	43.7%	39.4%	20.4%	-31.5%
	Minor St. Bus Delay	37.4%	36.9%	39.4%	34.6%
	Total Bus Delay	39.9%	38.0%	31.0%	5.0%

Table 11. Sensitivity Analysis for Conflicting Requests from Perpendicular Directions (Total Delay)

v/c	TSPCVM (h)	CTSP (h)	Diff	*t*-test
0.5	92.9	96.0	3.3%	0.0001
0.7	132.3	132.2	*-0.1%*	0.8938
0.9	179.9	173.0	*-4.0%*	0.0821
1.0	206.6	206.7	*0.1%*	0.9849

Table 12 and Table 13 demonstrate how bus delay savings and total travel time change with congestion level in the three conflicting TSP requests scenario. The performance of TSPCVM mostly reacts to congestion level change in the same fashion as described above. When the traffic volume is at capacity, the logic sacrifices bus line 1 on the main street to achieve overall bus delay improvement. No statistically significant adverse effects are observed under all congestion levels.

Table 12. Sensitivity Analysis for Conflicting Requests from Three Directions (Bus Delay)

	v/c	0.5	0.7	0.9	1.0
TSPCVM	Main St. Bus 1 Delay (Sec)	33.3	37.2	41.7	57.8
	Main St. Bus 2 Delay (Sec)	25.9	26.8	32.5	47.5
	Minor St. Bus Delay (Sec)	53.3	55.1	50.6	54.3
	Total Bus Delay (Sec)	**112.4**	**119.1**	**124.8**	**159.6**
CTSP	Main St. Bus 1 Delay (Sec)	36.8	40.8	46.3	51.4
	Main St. Bus 2 Delay (Sec)	27.6	29.7	34.7	51.4
	Minor St. Bus Delay (Sec)	64.0	66.0	70.0	67.4
	Total Bus Delay (Sec)	**124.6**	**136.5**	**151.0**	**170.2**
Improvement	Main St. Bus 1 Delay	9.6%	8.9%	10.1%	-12.4%
	Main St. Bus 2 Delay	6.4%	9.8%	6.4%	7.6%
	Minor St. Bus Delay	16.7%	16.5%	27.7%	19.4%
	Total Bus Delay	**9.8%**	**12.8%**	**17.4%**	**6.2%**

Table 13. Sensitivity Analysis for Conflicting Requests from Three Directions (Total Delay)

v/c	TSPCVM (h)	CTSP (h)	Diff	*t*-test
0.5	84.2	87.3	3.5%	0.046
0.7	116.2	120.3	3.4%	0.020
0.9	169.1	171.8	1.6%	0.088
1.0	188.4	188.2	*-0.1%*	0.642

Conclusions

This research fills in the knowledge gap and provides methods to resolve multiple conflicting TSP requests at an isolated intersection. The method overcomes the challenges of the conventional "first come, first served" strategy and presents significant improvement in bus service performance. At the same time, the logic also minimizes the interruption caused by providing TSP green time.

The TSPCVM logic proposed was built upon the foundation of previously developed TSPCV logic. It inherits the merits of TSPCV, which are vehicle–infrastructure cooperation and green time reallocation. These two features greatly increase the portion of TSP-accommodated buses and minimize unused TSP green time. In addition, the improved TSP, taking advantage of two-way communications and additional and more-accurate information provided by CV technology, is capable of accommodating multiple conflicting TSP requests. The logic incorporates an algorithm that prioritizes the buses coming from different approaches and solves for the premium signal timing that minimizes the total delay at the intersection. By determining the total number and sequence of the buses accommodated, the most bus delay is saved while the least total delay for all motorists is achieved.

Both analytical tests and simulation evaluations were performed to evaluate the TSPCVM logic. The results show that, when under moderate-volume conditions, bus delay is reduced by approximately 40% to 50%. Furthermore, the performance of TSPCVM was compared against CTSP conditions under various congestion levels and various conflicting conditions. Results demonstrate that the TSPCVM logic reduces bus delay between 5% and 48% compared to CTSP. The range of improvement corresponding to four different v/c ratios (0.5, 0.7, 0.9, and 1.0) was tested. Based on the results, it can be concluded that the proposed TSPCVM would greatly reduce bus delay at signalized intersection, no matter what the congestion level and conflicting conditions are.

The effect on other traffic users of TSPCVM was evaluated under various congestion conditions, including a near-capacity traffic volume condition. The results show that, under all circumstances, TSPCVM caused no adverse effects. Hence, TSPCVM minimizes installation and maintenance cost in the sense that it eliminates the need for local agencies and departments of transportation (DOTs) to perform a study of level of service (LOS) and/or v/c ratio for potential TSP intersections before installation.

Chapter 3. Transit Signal Priority Supporting Transit Progression

The initial design of TSPCV considers only one intersection. In a real-world implementation, however, coordination between closely spaced intersections might be necessary to maintain the time savings acquired by using TSP. The research in this chapter thus proposes a logic to coordinate TSPCV between intersections and tests the effectiveness of that logic through analysis and simulation.

Research Objectives

This chapter proposes a coordinated TSPCV (TSPCV-C), which has the following features:

1. Adopts TSP green reallocation strategy
2. Enables bus–signal cooperation
3. Grants conditional TSP
4. Realizes coordination among traffic signals
5. Formulates and solves Binary Mixed Integer Linear Programs (BMILP) applicable to any intersection

TSPCV-C Logic Highlights

The proposed TSPCV-C logic has the following key features.

Rolling Horizon Framework

The BMILP model is updated every time a bus is to pass an intersection on a rolling horizon framework. When activated, the system first identifies all the intersections downstream that are closely located and lists them as intersections of interest. Then, the model solves for the set of decision variables that fulfill its objective function. In this case, the decision variables include the signal plan for each intersection and the recommended bus speed leading toward each intersection. Although the decision variables are computed for all intersections of interest, only the variables associated with the first intersection are implemented. The whole process starts again as soon as the bus passes the first intersection.

Transit–Signal Cooperation

Cooperation between transit buses and the traffic signal is required and enabled. When a bus approaching an intersection sends a priority request, not only does the traffic controller try to accommodate the bus, but the bus also needs to travel at a reasonable speed to increase the portion of buses that can be granted TSP. The speed should fall into a range predefined by users, such as local DOTs. As shown in Figure 3, the prediction regarding bus arrival is a time range instead of a specific timestamp. The bus speed is recommended based on the remaining/expected queue, road geometry, and the normal signal timing plan.

Coordination Among Intersections

The problem is formulated so that all closely located intersections are considered together as a whole system. It is necessary in the sense that as long as the bus cannot pass any of the closed located intersections, the TSP received at the upstream intersections are wasted. Therefore, when the bus cannot receive TSP at one downstream intersection and the link immediately upstream of that intersection is too short for the bus to make adjustments, adjustment will be made ahead of time before the bus even reaches the upstream intersections. In a sense, this mechanism “extends” the length between intersections that are too closely located. Hence, bus progression is maintained and the delay savings gained from upstream intersections are preserved along a corridor.

Green Time Reallocation

As shown in Figure 3, the TSPCV-C adopts the strategy of green time reallocation. In order to better demonstrate the approach of interest, only the green time on that approach is colored green; others phases are colored blue. The figure demonstrates that, instead of adding additional green time to the original timing plan, the proposed TSPCV-C splits the original green time and reassigns part of it to when the green time is most needed by a transit bus. The cycle length will be the same even when the TSPCV-C green time is inserted, because the TSPCV-C green time is spliced from the green time of the direction of the approaching bus. Strictly speaking, the extra TSPCV-C green time is "moved" rather than "inserted" or "added." The inserted green time taken from the bus's approaching direction is 100% used to clear the traffic for that direction. This mechanism makes sure that all the TSPCV-C green time is fully used either by discharging the remaining queue or by letting the bus pass. Therefore, theoretically speaking, not a single second is wasted during the TSPCV-C. Compared to the conventional TSP, unnecessary TSP green time is reduced to a minimum.

Conditional TSP Grant

TSP green time is granted conditionally based on two criteria: schedule adherence and delay per person. The mechanism checks (1) whether the bus is behind schedule and (2) whether the implementation of this TSP request increases total delay per person at all intersections of interest. The TSP request is granted to the bus only if both criteria are satisfied.

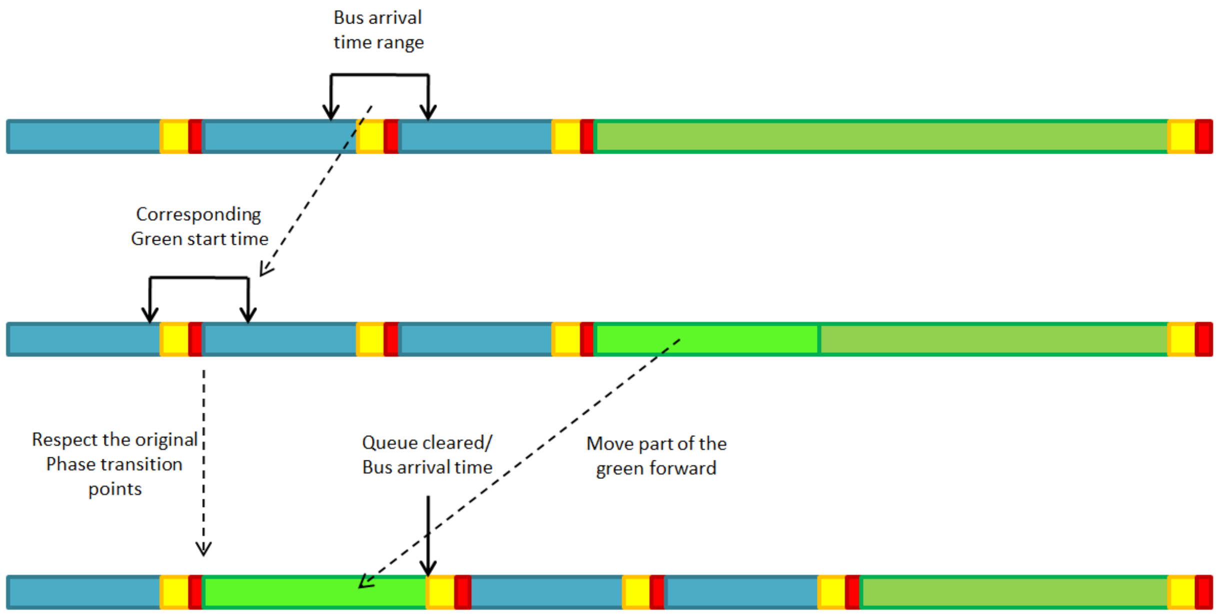

Figure 3. Illustration of green time reallocation.

TSPCV-C Logic Architecture Description

This section provides a step-by-step description of the TSPCV-C logic. Figure 4 displays the TSPCV-C architecture in a flow chart. The logic is composed of three major components: (1) bus detection, (2) TSP timing plan and bus speed calculation, and (3) logic assessment and implementation.

Bus Detection Component

This is the first step of the TSPCV-C mechanism, and is activated when a bus passes an activation point. The activation point is either at an upstream intersection or a user-predefined distance upstream of an intersection. When activated, the system checks the state of the bus and determines whether it is eligible to be granted TSP. The state examined in this design is schedule adherence. The system proceeds to the next step only if the bus is behind its schedule. Otherwise, the TSP process is terminated.

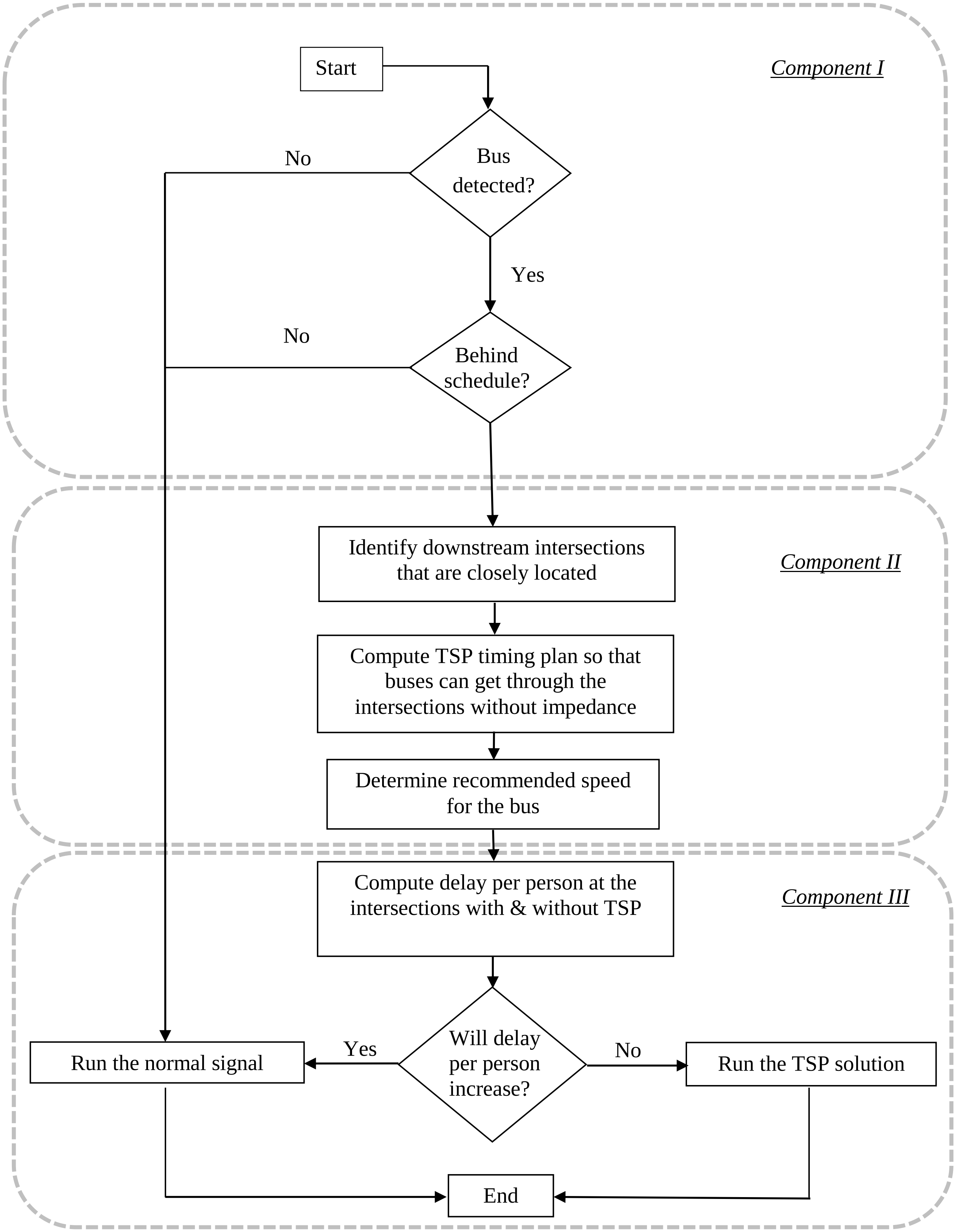

Figure 4. The structure of TSPCV-C.

TSP Timing Plan and Bus Speed Calculation Component

In this step, the algorithm generates a timing plan that will have minimum impact on general traffic users and calculates the corresponding recommended bus speed.

The scope of the system first needs to be determined. All intersections closely located immediately downstream of the activation point are identified. A user-predefined distance is used as the threshold of being "close." Then, a set of state variables and decision variables is generated for each intersection that falls within the system scope. These variables are the input for the BMILPs formulated in the following section. By solving the BMILP problem using a standard branch-and-bound routine, the following output is found: a link-specific advisory bus speed leading toward each intersection and a signal timing plan for each intersection inside the system scope.

Logic Assessment and Implementation Component

In this step, the TSP timing plan is compared against the normal signal time (winner overwrites the other) and the recommended bus speed is transmitted to the coming bus.

After a TSP timing plan is determined, the algorithm compares the "with TSP" scenario against the "normal timing" scenario. Since the number of passengers onboard is likely to be known in a CV environment, the per person delay performance measure is used. Per person delay is calculated for a predefined duration of time starting from the TSP-implemented cycle. In this research, a TSP timing plan will only be implemented when its corresponding per person delay is less than the NTSP scenario.

During implementation, two major steps are conducted. First, an instruction is given to a bus about the desired recommended speed. Second, a buffer green time is possibly given to a bus if it is not expected to make it through the intersection in time. The TSP green time would be extended up to 5 seconds to accommodate the random delay.

Problem Formulation

Assumptions

The proposed model makes the following assumptions:

- Traffic light cycle length is fixed.
    - This assumption could be relaxed by removing constraint #7 (see below). In this case, G'_{mnk} and G''_{mnk} become additional decision variables. However, loosening this assumption is likely to interrupt the progression of private vehicles.
- The sequence of signal phases does not change.
    - This assumption could be relaxed by adding a set of binary decision variables indicating if two signal phases are next to each other.
- General traffic is assumed to enter the road network at a constant rate.
    - However, when computing delay for private vehicles, intersections downstream of a signal follow the platoon dispersion model [36].
- A maximum of one TSP is granted within one signal cycle.
    - The consideration of multiple TSPs can be achieved by duplicating the decision variables and loosening the maximum TSP constraint.

Notation

Table 14 defines the symbols and parameters used below.

Table 14. Symbols and Parameters

Symbol	Parameter
a	Numbering for intersection legs. It indicates the leg that the TSP bus is traveling on.
b	Numbering for intersection legs defined locally with respect to leg "*a*" in a clockwise direction. It indicates the leg that the TSP bus is traveling toward.
C_k	Cycle length at the intersection *k*
D_b	Delay of bus
D_v	Delay of private vehicles
F	Rate that a platoon disperses over time and space
G_{abk}	Duration of the original green time for movement that TSP bus makes (from leg *a* to leg *b*) at the intersection *k*
G'_{abk}	Duration of the TSP green time for movement that TSP bus makes (from leg *a* to leg *b*) at the intersection *k*
G''_{abk}	Duration of the revised green time for movement that TSP bus makes (from leg *a* to leg *b*) which starts after TSP green at the intersection *k*
G_{min}	Minimum green time requirement
G_{mnk}	Duration of the original green time for movement from leg *m* to leg *n* at the intersection *k*
G'_{mnk}	Duration of the revised green time for movement from leg *m* to leg *n* which starts before TSP green at the intersection *k*
G''_{mnk}	Duration of the revised green time for movement from leg *m* to leg *n* which starts after TSP green at the intersection *k*
k	Number for intersections identified that are closely located with each other
L^Q_{abk}	Distance between the bus and the front stop line when the bus stops for the front queue at the intersection *k*. It is associated with the bus coming from leg *a* and traveling toward leg *b*.
L^A_{abk}	Distance between the bus and the front stop line when the TSP mechanism is activated at the intersection *k*. It is associated with the bus coming from leg *a* and traveling toward leg *b*. It has a predefined value: L^A
L_k	Distance between the intersection *k* and *k-1*
m	Numbering for intersection legs
$\mathcal{M}$	Arbitrary large positive constant
n	Numbering for intersection legs defined locally with respect to leg "*a*" in a clockwise direction
N_c	Total number of signal cycles considered. It is a user-defined value.
N_I	Total number of intersections
N_k	Sequence of signal cycle when TSP green starts
N_k^A	Sequence of signal cycle when TSP mechanism is activated
N_L	Total number of legs
Occ_b	Occupancy on the bus
Occ_i	Occupancy on vehicle *i*
Q_k^t	Number of vehicles arriving at time *t*
Q_{mnk}	Residual queue for movement from leg *m* to leg *n* at the intersection *k*
R_{mnk}	Red time in one cycle for movement from leg *m* to leg *n* at the intersection *k* (seconds)
s_k	Saturation flow rate at the intersection *k*

t	Timestamp in seconds
t_{qk}	Queue dissipating time at the intersection *k-1*
T_{abk}^{A}	Time when the TSP mechanism is activated at the intersection *k*. It is associated with the bus coming from leg *m* and traveling toward leg *n*.
v_k	Recommended speed for bus approaching the intersection *k* (mph)
V_k	Speed limit on link leading towards intersection *k* (mph)
v_{Q1}	Speed of queuing shockwave (mph)
v_{Q2}	Speed of discharging shockwave (mph)
v_{Q3}	Speed of departure shockwave (mph)
YR	Transition time. It is the sum of yellow time and red time.
Δ_{mnk}	Permission of reallocating TSP green into the phase for movement from leg *m* to leg *n* at the intersection *k*
δ_{mnk}	Permission of reallocating TSP green right after the phase for movement from leg *m* to leg *n* at the intersection *k*
Θ_{abk}	Start of TSP green signal for movement from leg *a* to leg *b* at the intersection *k* (fraction of cycle length)
Ψ_{abk}	TSP green signal ratio for movement from leg *a* to leg *b* at the intersection *k*
Ω_{mnk}	Start of the original green signal for movement from leg *m* to leg *n* at the intersection *k* (fraction of cycle length)

Decision Variables

The set of control variables can be specified as follows.

Three variables are continuous variables.

vn_k recommended speed for bus approaching the intersection *k* (mph)

Θ_{abk} start of TSP green signal for movement from leg *a* to leg *b* at the intersection *k* (fraction of cycle length)

Ψ_{abk} TSP green signal ratio for movement from leg *a* to leg *b* at the intersection *k* (fraction of cycle length)

Two variables are binary variables.

Δ_{mnk} permission of reallocating TSP green into the phase for movement from leg *m* to leg *n* at the intersection *k*

$\boldsymbol{\delta_{mnk}}$ permission of reallocating TSP green right after the phase for movement from leg *m* to leg *n* at the intersection *k*

Objective Function

The optimization algorithm is designed to find a set of decision variables that minimize the total delay of all traffic users. The objective function estimating total per person delay can be expressed as follows in Equation (4):

$$\mathbf{Min} \sum_{k=1}^{K} \left[\sum_{cycle=1}^{cycle=N_c} \sum_{T=1}^{C} \sum_{i} Occ_i + D_b * Occ_b \right]$$

(4)

Bus Delay Computation

The value of D_b is formulated as a binary equation. The binary parameter indicates whether or not the bus is impeded by the queue, as demonstrated in Figure 5. The effect of the residual queue is considered. The delay calculation is based on the real-time queue length estimation model developed by Liu [30], which is an extension of the shock wave theory.

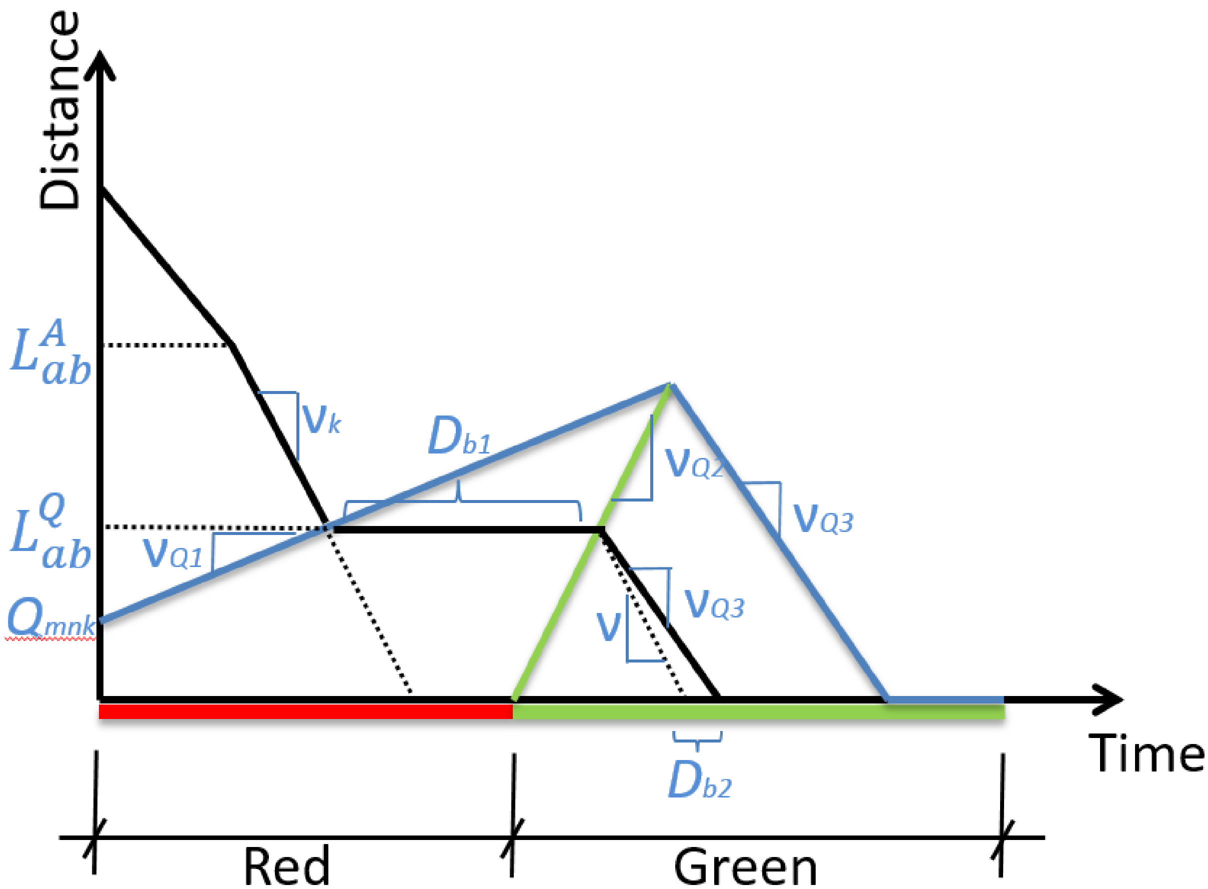

Figure 5. Bus delay computation.

As shown in Figure 5, the black line indicates the trajectory of a bus, the blue line is the end of queue, and the green line is the dissipating front of the queue. Figure 5 describes the case in which the bus is impeded by the queue and experiences delay. As demonstrated, the delay D_b consists of two parts. Part 1, D_{b1}, is the extra time the bus spends waiting in the queue. Part 2, D_{b2}, is the delay due to slower speed when following queuing vehicle in front. The magnitude of delay is solved using trigonometry, as presented in Equations (5) and (6).

$$D_{b1} = \frac{v_{Q2} * (1 - \Psi_{abk}) * C_k + Q_{mnk}}{v_{Q2}} + \frac{(L^Q_{ab} - Q_{mnk}) * (v_{Q2} - v_{Q1})}{v_{Q1} * v_{Q2}},$$
$$\forall\, m = a; \quad n = b; \quad k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1]$$

(5)

$$\boldsymbol{D_{b2}} = \frac{\boldsymbol{L_{ab}^{Q}} * (\boldsymbol{v_k} - \boldsymbol{v_{Q3}})}{\boldsymbol{v_k} * \boldsymbol{v_{Q3}}}, \quad \forall\, \boldsymbol{a} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L}]; \;\; \boldsymbol{b} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L} - \boldsymbol{1}]; \quad \boldsymbol{k} = \boldsymbol{1}, \dots, \boldsymbol{N_I};$$

(6)

L_{ab}^{Q} is the distance between the bus and the front stop line when the bus stops for the front queue. It is acquired by solving Equation set (7). In the equation set, the first part of the equation describes the trajectory of the end of the accumulating queue, while the second part represents the trajectory of the approaching bus.

$$\begin{cases} \boldsymbol{L_{ab}^{Q}} = \boldsymbol{v_{Q1}} * \boldsymbol{t} + \boldsymbol{Q_{mnk}} \\ \boldsymbol{L_{ab}^{Q}} = -\boldsymbol{v_k} * \boldsymbol{t} + \boldsymbol{L_{ab}^{A}} + \boldsymbol{v} * \boldsymbol{T_{ab}^{A}} \end{cases}, \quad \forall\, \boldsymbol{m} = \boldsymbol{a}; \;\; \boldsymbol{n} = \boldsymbol{b}; \;\; \boldsymbol{k} = \boldsymbol{1}, \dots, \boldsymbol{N_I}; \;\; \boldsymbol{a} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L}]; \;\; \boldsymbol{b} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L} - \boldsymbol{1}]$$

(7)

Thus, the total delay of bus is given by substituting Equation (7) into Equations (5) and (6):

$$\begin{aligned} \boldsymbol{D_b} = {} & \frac{\boldsymbol{v_{Q2}} * (\boldsymbol{1} - \boldsymbol{\Psi_{abk}}) * \boldsymbol{C_k} + \boldsymbol{Q_{mnk}}}{\boldsymbol{v_{Q2}}} \\ & + \frac{(\boldsymbol{v_{Q1}} * \boldsymbol{L_{ab}^{A}} + \boldsymbol{v_{Q1}} * \boldsymbol{v_k} * \boldsymbol{T_{ab}^{A}} - \boldsymbol{v_{Q1}} * \boldsymbol{Q_{mnk}}) * (\boldsymbol{v_{Q2}} - \boldsymbol{v_{Q1}})}{\boldsymbol{v_{Q1}} * \boldsymbol{v_{Q2}} * (\boldsymbol{v_{Q1}} + \boldsymbol{v_k})} \\ & + \frac{(\boldsymbol{v_{Q1}} * \boldsymbol{L_{ab}^{A}} + \boldsymbol{v_{Q1}} * \boldsymbol{v_k} * \boldsymbol{T_{ab}^{A}} + \boldsymbol{v_k} * \boldsymbol{Q_{mnk}}) * (\boldsymbol{v_k} - \boldsymbol{v_{Q3}})}{\boldsymbol{v_k} * \boldsymbol{v_{Q3}} * (\boldsymbol{v_{Q1}} + \boldsymbol{v_k})}, \\ & \forall\, \boldsymbol{m} = \boldsymbol{a}; \;\; \boldsymbol{n} = \boldsymbol{b}; \;\; \boldsymbol{k} = \boldsymbol{1}, \dots, \boldsymbol{N_I}; \;\; \boldsymbol{a} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L}]; \;\; \boldsymbol{b} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L} - \boldsymbol{1}] \end{aligned}$$

(8)

Details of how v_{Q1}, v_{Q2}, and v_{Q3} are computed are provided in the literature [30]. .

Delay of General Traffic Users

General traffic is assumed to enter the road network at a constant rate. Therefore, for the approaches (side streets) that do not have upstream intersections, the delay calculation is based on the real-time queue length estimation model developed by Liu [30]. For other approaches that are downstream of another intersection, the platoon dispersion model is applied [37]. In other words, when the upstream intersection is discharging the queue ($t < t_{qk}$), the vehicle arrival rate at time t at the downstream intersection can be expressed as,

$$\boldsymbol{Q_k^t} = \boldsymbol{s_{k-1}}(\boldsymbol{1} - (\boldsymbol{1} - \boldsymbol{F})^{\boldsymbol{t}}), \qquad \forall\, \boldsymbol{k} = \boldsymbol{2}, \dots, \boldsymbol{N_I}$$

(9)

After the queue at the upstream intersection is fully discharged, ($t > t_{qk}$), then,

$$\boldsymbol{Q_k^t} = \boldsymbol{s_{k-1}}(\boldsymbol{1} - (\boldsymbol{1} - \boldsymbol{F})^{\boldsymbol{t_{qk}}}) \times (\boldsymbol{1} - \boldsymbol{F})^{\boldsymbol{t} - \boldsymbol{t_{qk}}}, \qquad \forall\, \boldsymbol{k} = \boldsymbol{2}, \dots, \boldsymbol{N_I}$$

(10)

The total delay is computed by integrating the number of people waiting at the intersection over time.

Constraints

(1) **Queue clearance constraint.** When a bus is granted TSP, this bus should arrive after its front queue is fully discharged. As shown in Figure 6, the TSP green should start before the bus arrives. Hence, the bus catches up to the rear end of the front queue at the stop bar. This can be expressed as:

$$(\boldsymbol{\Theta}_{abk} + \boldsymbol{\Psi}_{abk}) * \boldsymbol{C}_k - \frac{\boldsymbol{L}_{abk}^A}{\boldsymbol{v}_k} - \boldsymbol{T}_{abk}^A + \left(\boldsymbol{N}_k - \boldsymbol{N}_k^A\right) * \boldsymbol{C}_k = \boldsymbol{0}, \;\; \forall \boldsymbol{a} \in [\boldsymbol{1}, \dots, \boldsymbol{N}_L]; \;\; \boldsymbol{b} \in [\boldsymbol{1}, \dots, \boldsymbol{N}_L - \boldsymbol{1}]; \;\;\; \boldsymbol{k} = \boldsymbol{1}, \dots, \boldsymbol{N}_I \quad (11)$$

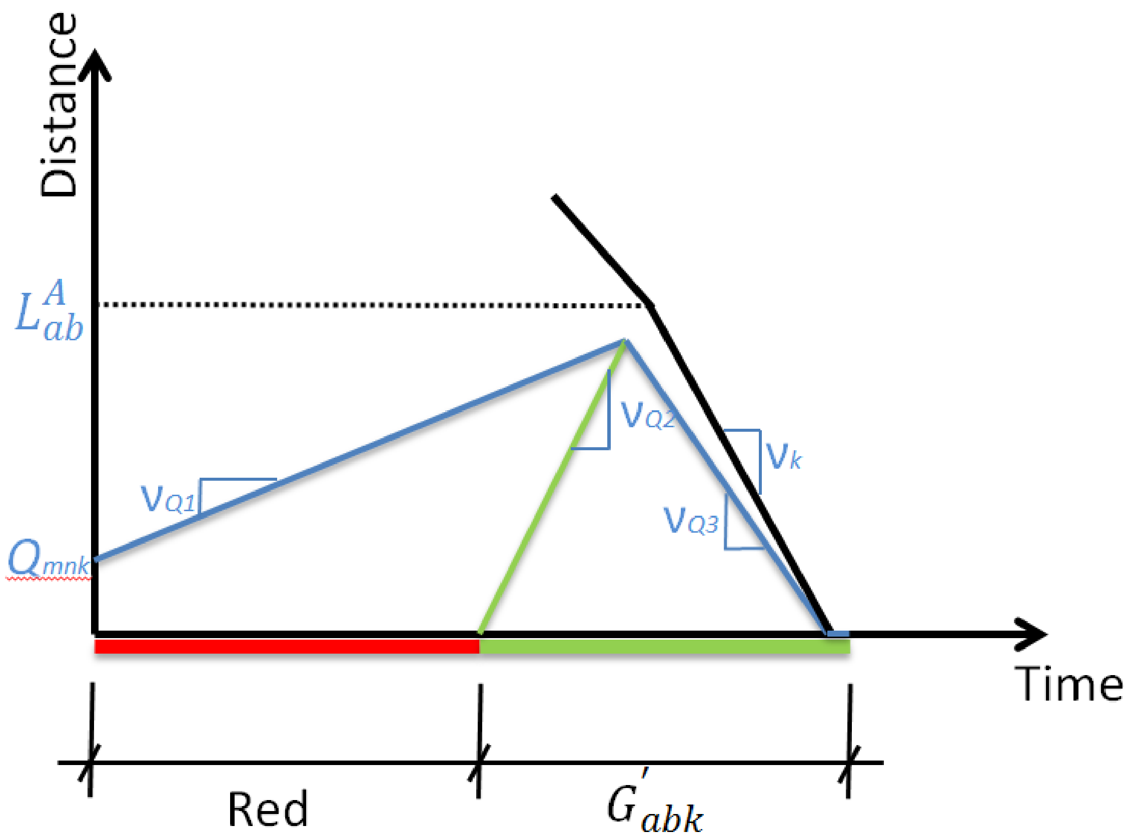

Figure 6. Illustration of the queue clearance constraint.

(2) **Bus progression constraint**. As soon as the bus passes the nearest intersection, the next stage of the TSP mechanism for the immediate downstream intersection is activated. Note that, with TSP, the bus travels through the intersection without impedance, which can be expressed as:

$$\boldsymbol{T}_{ab(k+1)}^A = \boldsymbol{T}_{abk}^A + \frac{\boldsymbol{L}_{abk}^A}{\boldsymbol{v}_k}, \;\; \forall \boldsymbol{a} \in [\boldsymbol{1}, \dots, \boldsymbol{N}_L]; \;\; \boldsymbol{b} \in [\boldsymbol{1}, \dots, \boldsymbol{N}_L - \boldsymbol{1}]; \;\;\; \boldsymbol{k} = \boldsymbol{1}, \dots, \boldsymbol{N}_I \quad (12)$$

(3) **Road geometry constraint.** In case the distance to the next intersection is smaller than the predefined TSP activation distance:

$$\boldsymbol{L_{abk}^{A} = \min(L^{A}, L_{k})}, \quad \forall\, \boldsymbol{a} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L}]; \;\; \boldsymbol{b} \in [\boldsymbol{1}, \dots, \boldsymbol{N_L - 1}]; \;\; \boldsymbol{k = 1, \dots, N_I} \tag{13}$$

(4) **Maximum TSP constraint**. Δ_{mnk} is a binary indicator. If $\Delta_{mnk}= 1$, TSP green is inserted into the phase for movement from leg *m* to leg *n* at the intersection *k*. Similarly, if $\delta_{mnk} = 1$, then the TSP green is inserted after the phase ends for movement from leg *m* to leg *n*. This constraint requires that a maximum of one TSP green is permitted within one single signal cycle for each intersection, which can be specified as:

$$\sum_{n=1}^{N_L-1} (\Delta_{mnk} + \delta_{mnk}) \leq 1, \quad \forall\; m = 1, \dots, N_L;\; n = 1, \dots, N_L - 1;\; m \neq a;\; n \neq b;\; k = 1, \dots, N_I \tag{14}$$

(5) **Bus speed constraint.** To limit the interference a TSP bus causes on its surrounding traffic and to ensure the feasibility of bus speed adjustment, the advisory bus speed is constrained within a range relative to the link speed limit:

$$80\% * V_k \leq v_k \leq 110\% * V_k, \quad \forall\; k = 1, \dots, N_I \tag{15}$$

(6) **Assigned TSP constraint**. This constraint ensures that the relocating TSP green is consistent with the actual starting time of the TSP green; in other words, that when $\Delta_{mnk}= 1$, the TSP start time falls within the original green time for movement from leg *m* to leg *n*. When $\delta_{mnk} = 1$, then the start of TSP green would follow at the end of the green time for movement from leg *m* to leg *n*. It is specified by equations (16) and (17). $\mathcal{M}$ is an arbitrary large positive number:

$$(\Omega_{mnk} * C_k) * \Delta_{mnk} < \Theta_{abk} * C_k < \Omega_{mnk} * C_k + G_{mnk} + \mathcal{M} * (1 - \Delta_{mnk}), \quad \forall\; m = 1, \dots, N_L;\; n = 1, \dots, N_L - 1;\; m \neq a;\; n \neq b;\; k = 1, \dots, N_I;\; a \in [1, \dots, N_L];\; b \in [1, \dots, N_L - 1] \tag{16}$$

$$(\Omega_{mnk} * C_k + G_{mnk}) * \delta_{mnk} \leq \Theta_{abk} * C_k \leq \Omega_{mnk} * C_k + G_{mnk} + \mathcal{M} * (1 - \delta_{mnk}), \quad \forall\; m = 1, \dots, N_L;\; n = 1, \dots, N_L - 1;\; m \neq a;\; n \neq b;\; k = 1, \dots, N_I;\; a \in [1, \dots, N_L];\; b \in [1, \dots, N_L - 1] \tag{17}$$

(7) **Duration of green constraint.** The duration of green time for all movements does not change after TSP green is granted. This constraint automatically ensures that cycle length does not change after the reallocation of TSP green.

$$G_{mnk} = G'_{mnk} + \Delta_{mnk} * G''_{mnk}, \qquad \forall\; m = 1, \dots, N_L;\; n = 1, \dots, N_L - 1;\; k = 1, \dots, N_I \tag{18}$$

$$G''_{mnk} = \Delta_{mnk} * (G_{mnk} - (\Theta_{abk} - \Omega_{mnk}) * C_k + YR),$$
$$\forall\, m = 1, \dots, N_L; \quad n = 1, \dots, N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1] \tag{19}$$

Note: By dividing part of the original green time for the bus TSP green, extra transit time (yellow + red) is needed. This extra time is taken from the phase of direction in which the bus travels. Therefore, the constraint for this specific movement is slightly different:

$$G_{abk} = \Psi_{abk} * C_k + G''_{abk} + \left[\sum_{m=1}^{N_L}\sum_{n=1}^{N_L-1}(2 * \Delta_{mnk}) + \sum_{m=1}^{N_L}\sum_{n=1}^{N_L-1}(\delta_{mnk})\right] * YR,$$
$$\forall\, m = 1, \dots, N_L; \quad n = 1, \dots, N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1] \tag{20}$$

(8) **Minimum green requirement**. The duration of green time for all movements, including reallocated TSP green, should follow the minimum green requirement to ensure sufficient clearance time.

$$G_{mnk} \geq G_{min}, \quad \forall\, m = 1, \dots, N_L; \quad n = 1, \dots, N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1] \tag{21}$$

$$G'_{mnk} \geq G_{min}, \quad \forall\, m = 1, \dots, N_L; \quad n = 1, \dots, N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1] \tag{22}$$

$$G''_{mnk} = \Delta_{mnk} * (G_{mnk} - (\Theta_{abk} - \Omega_{mnk}) * C_k + YR) \geq \Delta_{mnk} * G_{min},$$
$$\forall\, m = 1, \dots, N_L; \quad n = 1, \dots, N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1] \tag{23}$$

$$G'_{abk} = \Psi_{abk} * C_k \geq G_{min}, \quad \forall\, k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1] \tag{24}$$

$$G''_{abk} \geq G_{min}, \quad \forall\, m = 1, \dots, N_L; \quad n = 1, \dots, N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \dots, N_I; \quad a \in [1, \dots, N_L]; \quad b \in [1, \dots, N_L - 1] \tag{25}$$

Evaluations

Study Site

A study site with two consecutive intersections on Route 50 in Fairfax, Virginia, was selected for evaluating the proposed logic. The intersections, as presented in Figure 7, were the joints of Route 50 with Sullyfield Circle and Centreville Road. The intersection spacing was 0.14 miles. The site was chosen because the signal timing is coordinated and was calibrated shortly before the traffic volume data were collected [38].

Figure 7. Study site [Source: Map data ©2015 Google].

Methodology

Both an analytical evaluation and a microscopic simulation-based evaluation were performed. The analytical evaluation was a deterministic calculation that quantified the performance of the proposed TSP logic on a theoretical level. In this evaluation, all possible TSP activation scenarios were considered. Considering that a TSP request can be made at any point over the cycle length of an intersection, an unbiased performance measure can be acquired by averaging the performance of all possible TSP activation scenarios. However, this kind of evaluation cannot consider the stochastic nature of the traffic, whereas a simulation-based evaluation considers variability due to vehicle interactions and inter-arrival times [39]. So, in this sense, a simulation evaluation is a more plausible performance assessment.

Four different control strategies were compared in both evaluations:

- ***TSPCV*** – The previously developed intelligent transit signal priority logic. TSPCV does not coordinate between intersections. The TSP system for a specific intersection activates when the bus passes the immediate upstream intersection.
- ***TSPCV-C*** – The proposed control strategy with coordination among intersections that are closely located. It also has all the features that TSPCV has.
- ***CTSP*** – The conventional TSP logic compared here is TSP with an Automatic Vehicle Location (AVL) system. In other words, CTSP uses the state-of-the-art TSP plus a more accurate bus arrival time forecast module. The difference between CTSP and TSPCV is that the logic CTSP utilizes is a simple one (green extension only) with no cooperative interactions between the bus and the traffic signal controller. CTSP will grant 10 seconds of extra green time to buses that arrive within 10 seconds of the end of normal green time. In case the bus cannot make it through the intersection within that 10 seconds, CTSP will add up to 5 seconds to the previous 10 seconds to accommodate the late arrival. The logic follows the actual implementation in Northern Virginia [12].

- ***NTSP*** – This control runs the background signal timing plan, without taking any control action in response to bus appearance.

Inputs to the model included the following:

- The signal timing plan was adopted from the site, which was updated shortly before the traffic volume data were collected [38]. The site was actuated and coordinated. The cycle length on the corridor was 120 seconds.
- Vehicle volumes and turning movements were actual peak-hour data collected from the site.
- To consider the effect of a bus stop, it was assumed that a bus was traveling eastbound on Route 50 with a mid-block bus stop located 750 feet upstream of the first intersection.
- The speed limit on Route 50 is 45 mph; therefore, buses were allowed to travel within a speed range between 35 mph and 50 mph (i.e., between 20% below and 10% above speed limit).

$$80\% * V_k \leq v_k \leq 110\% * V_k, \quad \forall\, k = 1, \dots, N_I \tag{26}$$

- The TSP logic was activated when buses passed 0.5 miles upstream of the first intersection.

$$L_{abk}^{A} = \min(0.5, L_k), \;\; \forall\, a \;\in [1, \dots, N_L]; \;\; b \;\in [1, \dots, N_L - 1]; \quad k = 1, \dots, N_I \tag{27}$$

- As previously noted, a duration of time needs to be predefined for the per person delay calculation. In this case study, a duration of three signal cycles was adopted. This should be long enough to capture residual effects caused by TSP and short enough to prevent including another TSP request, given that three cycles of the 120-second cycle are about equal to the minimum bus headway.

Several assumptions were made for the buses. The values were adopted from NCHRP research regarding bus rapid transit [32]:

- Bus occupancy = 40 passengers.
- Private vehicle occupancy = 1.2 passengers.
- Dwell time at bus stops = 30 seconds with 2 seconds standard deviation. Considering that CV technology is capable of providing accurate dwell time prediction, the variation was set to be moderately low.
- Bus headway = 6 minutes.

Therefore, the objective function was specified as shown in Equation (28):

$$\text{Min} \sum_{k=1}^{2} \left[\sum_{cycle=1}^{cycle=3} \sum_{T=1}^{120} \sum_{i} Occ_i + D_b * Occ_b \right] \tag{28}$$

The MOEs used were bus delay and the total travel time of all travelers. Bus delay quantifies the effectiveness of various TSP treatments, while the total travel time demonstrates whether any adverse effect is caused.

Finally, all the differences were checked for statistical significance to ensure that all the improvements or adverse effects were statistically significant. A paired two-tailed *t*-test was used, since the data in the comparison were collected from the same site. The confidence level tested was 95%.

Analytical Evaluation

The analytical evaluation was a deterministic calculation that quantified the performance of the proposed TSP logic on the theoretical level.

- Volume was the average flow rate collected from the study site during peak hour, and was a near-capacity situation.
- The signal timing plan was adopted from the current timing plan in the field.
- The saturation flow rate was borrowed from the default value in Synchro, which is 1,900 veh/h/ln.
- The queue length at the stop bar was estimated based on the constant arrival rate assumption.
- All possible TSP activation scenarios were considered.
- The cycle length at the intersection was 120 seconds.
- Assuming a TSP could be activated at any given second, there were 120 possible situations. The stop delay for a bus was calculated by averaging these 120 situations.
- The program was coded in VBA and run on an i5-2400 3.10 GHz processor with 8 GB RAM.
- The computation time for all 120 situations took less than 20 seconds.
- All three treatments were computed and compared to the NTSP condition.

The spacing between the two intersections was 0.14 miles. Under such conditions, TSPCV showed a slight improvement over CTSP, with a reduction of around 7%, while TSPCV-C overcame the effect of the short intersection spacing and demonstrated a much greater benefit with a 55% delay reduction. Since the small spacing of the two intersections significantly reduced the flexibility of TSPCV, the portion of buses able to receive TSPCV from both intersections decreased. However, it can be expected that, as the spacing increases, the flexibility of TSPCV will also increase, thereby further reducing the associated bus delay.

A sensitivity analysis on the intersection spacing was performed based on deterministic computation. The results are presented in Figure 8 and Figure 9. The results show that the performance of CTSP was not affected by intersection spacing, since a fixed proportion of buses received CTSP treatment. The benefit of TSPCV is positively correlated with the intersection spacing. Although TSPCV provides a small benefit over CTSP in the 0.14-mile-spacing condition, its advantage over CTSP becomes more obvious as the spacing increases to over 0.24 miles. When spacing reaches 0.54 miles, the delay reduction increases to a sizable improvement of 59% (compared against CTSP bus delay). It is clear that, if the intersection spacing keeps rising, TSPCV will show a benefit similar to TSPCV-C. The benefit of TSPCV-C grows significantly (to 75%) when the intersection spacing increases from 0.14 to 0.24 miles, but it quickly levels off as the spacing increases to over 0.24 mile. The phenomenon demonstrates that TSPCV-C is not completely immune to spacing change. Nevertheless, TSPCV-C always demonstrates greater improvement than the other two treatments, no matter what the spacing size.

At all levels of intersection spacing, the condition of total delay is similar. CTSP increases the delay of all vehicles, while TSPCV and TSPCV-C reduce the total delay. The reduction of total delay comes from two sources. One is the delay savings from bus passengers. The other is from the private vehicles that are discharged in front of the TSP bus. Although small in magnitude, TSPCV-C also shows less total delay compared to TSPCV and CTSP.

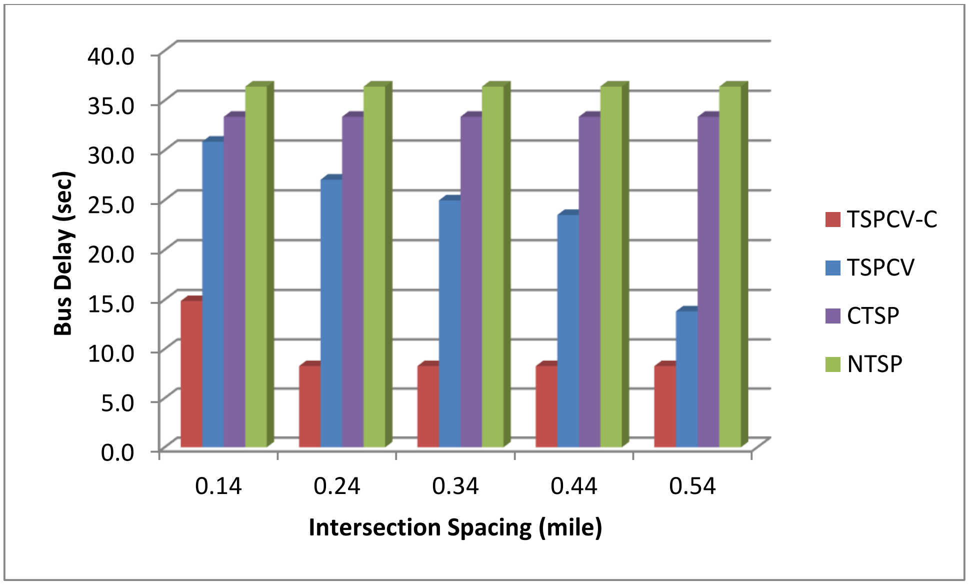

Figure 8. Bus delay under various intersection spacing.

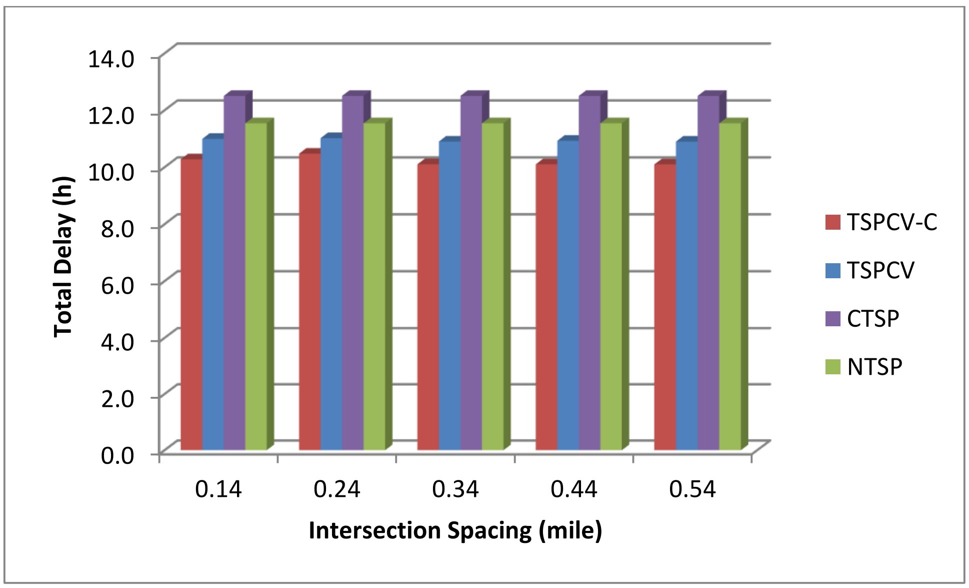

Figure 9. Total delay under various intersection spacing.

Simulation-based Evaluation in VISSIM

While the analytical test results show significant benefits under the proposed TSPCV-C logic, they do not consider any variability due to vehicle interactions and inter-arrival times. A microscopic traffic simulator can assess performance under more plausible conditions. The microscopic simulation software package VISSIM [34] was used to evaluate the proposed TSP logic for a CV environment. A COM interface was used to assess information that would be available within a CV environment [35]. The evaluation was performed under the assumption that only transit buses were connected to the traffic signal controller and other traffic users did not have CV devices; in other words, 0% CV market penetration except for buses. The end of the queue was estimated based on incoming vehicles and outgoing vehicles at the intersection. The detailed algorithm can be found in the model developed by Liu [30], which is an extension of the shock wave theory. The input to this algorithm was the average flow rates from all travel directions. The data extracted via COM interface included speed and position of the bus, the number of passengers on board, the number of potential passengers at the bus stop, the number of vehicles passing the intersection, and traffic volume from all four approaches. In addition, the COM interface was used to change the signal timing plan during the simulation. All programs were coded in VBA and implemented in Microsoft Excel.

As noted, the test network was a calibrated model of two consecutive intersections on Route 50 in Fairfax, Virginia. Vehicle volumes and turning movements represent actual peak-hour data collected from the site. Bus dwelling time at the stop was 30 seconds average with a standard deviation of 2 seconds. A transit bus was scheduled to arrive every 375 seconds. Given that the cycle length was 120 seconds at the intersection, the interval of bus arrivals was exactly 3 cycles plus 15 seconds. This research purposely designed the offset to be 15 seconds so that buses within one single simulation run would arrive at different times relative to signal cycles, making the simulation results less biased.

To consider the effect of simulation randomness, 20 simulation runs were performed for each scenario, and the MOEs for each scenario were averaged from the output of each of the 20 runs. Minimum sample size requirement was checked to make sure that a sufficient number of simulation runs was achieved to represent the entire population. Minimum sample size was calculated using the formula recommended by VDOT [33], which is:

$$\mathrm{N} = Z^2 * \frac{S_s^2}{(X_s * E)^2}, \tag{29}$$

where:
Z is the number of standard deviations away from the mean corresponding to the required confidence level in a normal distribution. In this research, confidence level was set to be 95%.
S_s is the sample standard deviation.
X is the sample mean.
E is tolerable error. In this research, E = 10%.

The results from the simulation are shown in Table 15. The bus delay and total travel time of all vehicles were summarized and averaged from 20 simulation runs. All three TSP treatments were compared with the NTSP condition, and a *t*-test was performed to validate the differences from a statistical perspective. When two intersections were closely located (0.14 miles), TSPCV and CTSP showed minor improvement over the NTSP condition, while TSPCV-C decreased bus delay significantly (by 37%). Since the delay savings generated by TSPCV and CTSP are not statistically significant, only TSPCV-C showed a benefit for a bus traveling through closely spaced intersections under near-capacity volume.

Generally speaking, the simulation results support the findings from the analytic evaluation. Although the percentage of delay savings observed from the simulation is a little less than that from the analytical test, the magnitude of the delay savings is actually very similar. The difference is caused by the fact that the analytical test only calculated change in stop delay, while the simulation considers other delays as well. Therefore, the total delay measured in the simulation is larger than that of the analytical evaluation. The same magnitude change with a larger denominator means a smaller magnitude in percentage change.

The research also collected travel time data for all traffic users, which is included in Table 15. TSPCV-C and TSPCV had a minor adverse effect on other traffic users. This is likely due to the delay estimation module embedded in the TSPCV-C logic not being able to accurately predict the effect of the queue-spill-back condition. Since the peak-hour data collected from the field were near full capacity, spill-back condition was observed. Hence, some TSP requests were granted regardless of the fact that extra delay would be caused. However, as noted above, the effect was still minimal (less than 1% increase in travel time). When translated into delay increase, TSPCV-C caused about 1 second delay per person.

Table 15. Simulation-based Assessment on Various TSP Treatments

	Bus delay (sec)	% Saving	Std_Dev	*T*-test	Total TT (h)	% Saving	Std_Dev	*T*-test
TSPCV-C	42.4	37.1%	4.5	6.7E-08	256.9	-0.6%	2.9	6.8E-07
TSPCV	55.9	4.0%	7.2	3.4E-01	256.8	-0.5%	3.3	1.1E-05
CTSP	57.4	1.4%	7.8	2.9E-01	254.6	0.3%	2.8	1.8E-01
NTSP	58.1	0.0%	8.3	N/A	255.4	0.0%	2.8	N/A

Sensitivity Analysis on Congestion Levels

In order to verify that the findings from the experiment are consistent with various congestion levels, a sensitivity analysis was conducted. Because TSPCV cannot perform well under such close intersection spacing, a sensitivity study on congestion levels was not conducted for TSPCV. Since the field collected volume data are at a v/c ratio of 1.0, three other scenarios were tested: v/c = 0.5, v/c = 0.7 and v/c = 0.9. The results are presented in Figure 10 and Figure 11.

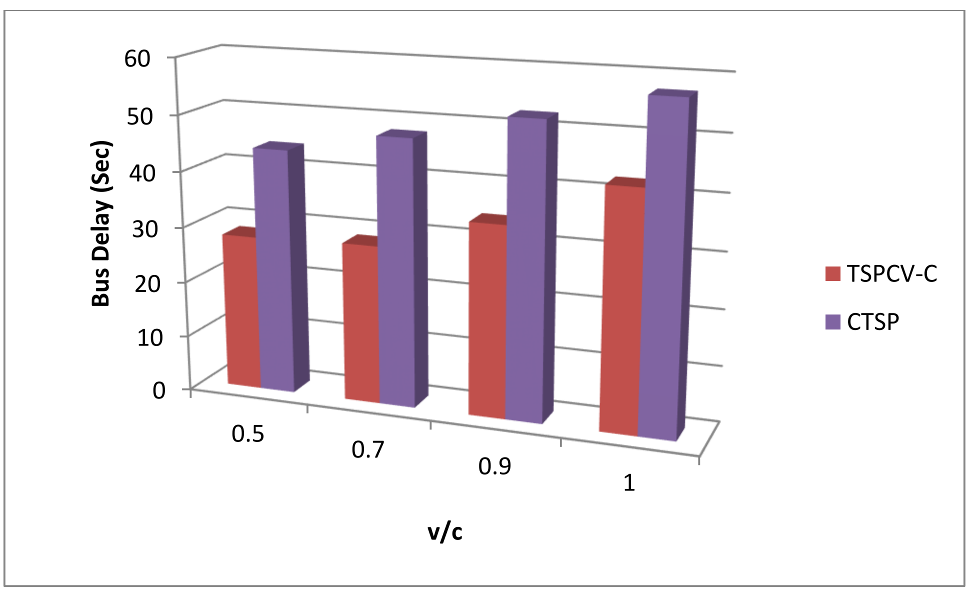

Figure 10. Bus delay under various congestion levels.

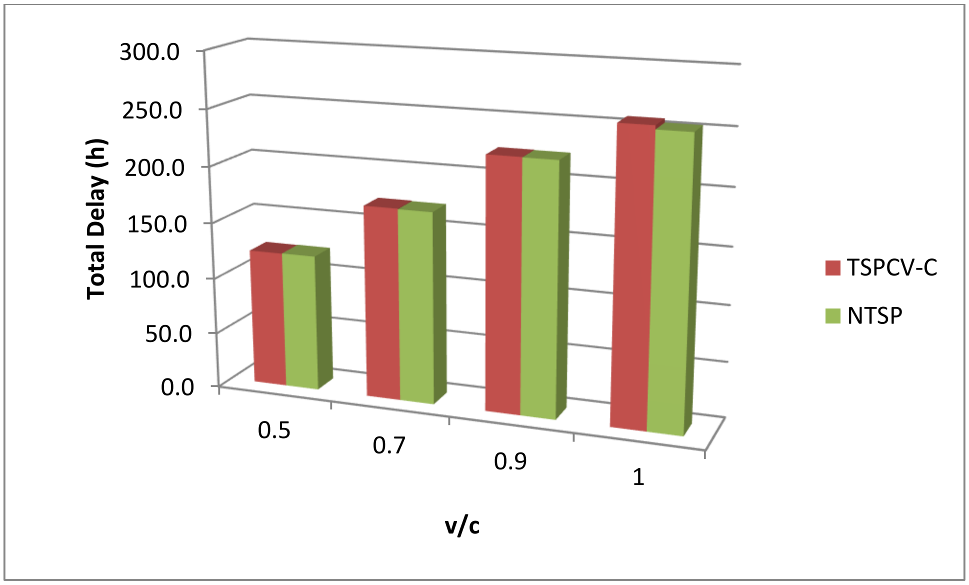

Figure 11. Total delay under various congestion levels.

When the congestion level is low, TSPCV-C reduces bus delays significantly under all levels of v/c ratios. The greatest reduction (about 68%) is observed when the v/c ratio equals 0.7. The smallest reduction in delay (about 35%) occurs when the v/c ratio equals 1.0. In between these two v/c ratios, as the congestion level increases, the benefit of TSPCV-C decreases, while no extra delay is caused. This is because the algorithm is designed to be conditional on the per person delay. When the volume becomes closer to the capacity, an increasing portion of the bus fleet will not be granted TSPCV priority to prevent TSP from causing extra delay on other travelers. As a result, the benefit drops correspondingly, while adverse effects on side streets are still kept under a certain level. When the v/c ratio drops below 0.7, most of the buses are granted TSP, and the performance of TSPCV is no longer restricted by congestion level but is bound by other considerations, like the minimum green time requirement. Hence, the negative correlation between bus delay and v/c ratio levels off.

As noted, delay per person at the intersection is a measure that reflects adverse effects caused by TSP. The results indicate that TSPCV-C did not cause additional per person delay at various v/c ratios except when v/c equals 1.0, and are consistent with the previous results that during high-volume conditions (v/c = 1.0), TSPCV-C shows minor adverse effects on other traffic users. However, the results also reveal that, when volume decreases below capacity (v/c = 1.0), TSPCV-C caused no statistically significant increase in delay. On the other hand, applying TSPCV-C results in significant reduction in the bus delay.

Conclusions

In this chapter, a per person based delay optimization method was proposed for an intelligent TSP logic that enables bus–signal cooperation and coordination among consecutive signals in the CV environment. This TSP logic, called TSPCV-C, provides a method to secure the mobility benefit generated by the intelligent TSP logic along a corridor so that the bus delay saved at an upstream intersection is not wasted at the downstream intersections. The problem is formulated as a Binary Mixed Integer Linear Program (BMILP), which is solved by a standard branch-and-bound routine. Minimizing per person delay has been adopted as the criterion for the model. The TSPCV-C is also designed to be conditional. That is, TSP is granted only when the bus is behind schedule and the granting of TSP causes no extra total delay. The evaluation of TSPCV-C shows the following:

- TSPCV-C reduces bus delay by up to 75% compared to CTSP. Its performance is superior to any other TSP logic (TSPCV or CTSP) no matter what the size of the intersection spacing. The logic produces its optimum performance as long as the signal space is above 0.24 miles. But, even when the spacing is less than 0.24 miles, it can still reduce bus delay by about 59%.
- The advantage of TSPCV-C over TSPCV drops as the intersection spacing increases. When spacing is above 0.5 miles, the two logics show similar performance. Therefore, it is recommended to set 0.5 miles as a threshold for activating TSPCV-C logic. In other words, the coordination among consecutive intersections is only necessary when they are located less than a half-mile apart.
- TSPCV-C logic is beneficial for all levels of v/c ratio. When the v/c ratio is above 0.7, bus delay reduction is negatively correlated to the congestion level. This is because the algorithm is designed to be conditional on the per-person delay. When the volume becomes closer to the capacity, a decreasing portion of the bus fleet will be granted TSPCV priority to prevent TSP from causing extra delay to other travelers. When v/c drops below 0.7, the performance of TSPCV-C reaches its optimum and the delay savings start to level off.
- The effect of TSPCV-C on other traffic users was evaluated under various congestion conditions, including near-capacity volume conditions. The results show that, for congestion levels below capacity, TSPCV-C causes no adverse effects. Although a few adverse effects on side streets are expected when the volume reaches capacity, the delay increase is minor and less than 1 second per person, and is thus negligible.
- TSPCV-C reduces costs for local agencies and DOTs because they do not have to perform an LOS and/or v/c ratio study for potential TSP intersections before installing TSPCV-C.

Chapter 4. Transit Signal Priority Based on Connected Vehicle Technology Experiment

Of the 13 studies reviewed by the project team, only one investigated the performance benefits of TSP based on a field test [12]. If TSP is to be more widely adopted, real-world validation of the system's benefits and effectiveness is necessary. In this phase of the research, TSPCV was tested on the Virginia Smart Road. This makes the current research one of very few TSP studies involving both simulation and a field experiment.

Research Objectives

The main purpose of this phase of the research was to validate that the proposed TSPCV algorithm works in a CVI environment and to estimate some performance measures. Specific objectives were as follows:

1. To implement TSPCV on the Virginia Smart Road.
2. To confirm software and hardware compatibility.
3. To compare TSPCV performance and two types of GPS devices (regular and differential).

Experiment Logic Description

The arrival of a transit bus at a signalized intersection depends on traffic signal phasing and bus speed, which are mainly subject to roadway geometry, roadway speed limit, and the speed of other vehicles in front of the bus on the road upstream of the intersection.

Figure 12 shows possible arrival times at 0.5 miles from the signalized intersection on the Smart Road (the distance of the RSE to the intersection) with the assumption that the bus maintains a constant speed for 0.5 miles until it reaches the intersection. For those cases when the bus can pass through the intersection during the original green phase or even yellow phase, there is no need for TSP. When the bus arrives during the red phase of the original signal phasing, then TSP can be beneficial and provide the bus a short green time to pass through the intersection earlier than the next green of the original signal phasing as shown in Figure 12.

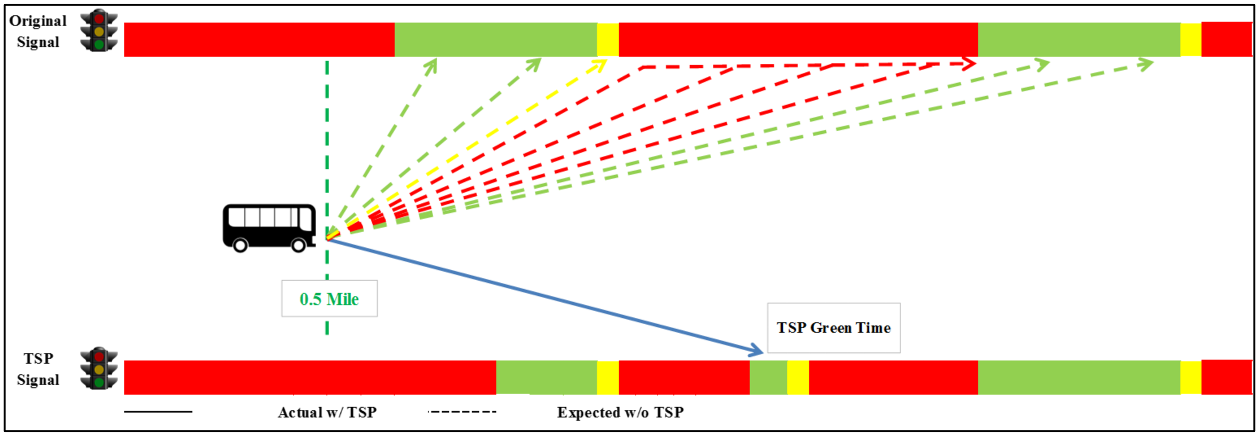

Figure 12. Possible arrival times at 0.5 miles to a signalized intersection and TSP green time allocation.

Based on the previously described TSPCV logic architecture, key components of TSPCV for the experiment were defined as follows (see Figure 13 for details):

- Bus Detection Component
  - An approaching vehicle (in the experiment, an Infiniti FX35 [2005] enabled with CV features that served as a surrogate for a bus) passed the activation point (0.5 miles to the intersection, which is the distance of the RSE [Savari StreetWave] to the intersection) and activated the TSP algorithm.
    - Bus speed and location were measured with two GPS devices: regular GPS (NextGen data acquisition system [DAS] head unit) and differential GPS (Novatel Flexpak6, located in the trunk).
    - The communication between the bus and RSE was provided via onboard equipment (OBE), a Savari OBE S100.
    - Parametric data were collected by a NextGen DAS (see Appendix A for details), such as:
      - GPS position
      - GPS speed
      - Network speed
      - Turn signal
      - Brake
      - Accelerator position
      - RPM
    - The algorithm ran on a Dell Latitude E6430s laptop, Core i5 vPro, which was connected to the vehicle's GPS devices (either regular GPS or differential GPS depending on the scenario) to receive the bus location and communicated with the RSE and traffic signal controller (custom proprietary interface with D4 Controller) to send the commands.
  - After TSP activation, the algorithm checked the state of the bus and expected arrival time at the intersection.
  - If the bus could not reach the intersection during the original green time, then the TSP algorithm modified the signal timing and the system proceeded to the next step. Otherwise, the TSP process was terminated and signal timing was not modified.
- TSP Timing Plan and Bus Speed Calculation Component
  - The algorithm generated a timing plan and calculated the corresponding recommended bus speed.
  - Advisory bus speed was calculated based on a solved BMILP in the algorithm.
- Logic Assessment and Implementation Component
  - The TSP timing plan was compared against the normal signal time (the best timing plan overwrites the other) and the recommended bus speed was transmitted to the bus. Instructions were given to the bus driver about the desired recommended speed. (In the experiment, it could be either announced via the display screen [HDMI Feelworld 5" HD TFT LCD monitor] or read by a project team member.)
  - A buffer green time was possibly given to the bus if the bus was not expected to make it through the intersection in time. The TSP green time could be extended up to 5 seconds to accommodate the random delay. All required computations were run on the laptop inside the vehicle.

It should be noted that the “d” distance (in Figure 13) is the distance required for the vehicle to achieve the required speed at the 0.5-mile point (which was identified via trial and error based on the experiment roadway geometry and selected speed limit for the bus).

Details of all the equipment used in the field test are provided in Appendix A.

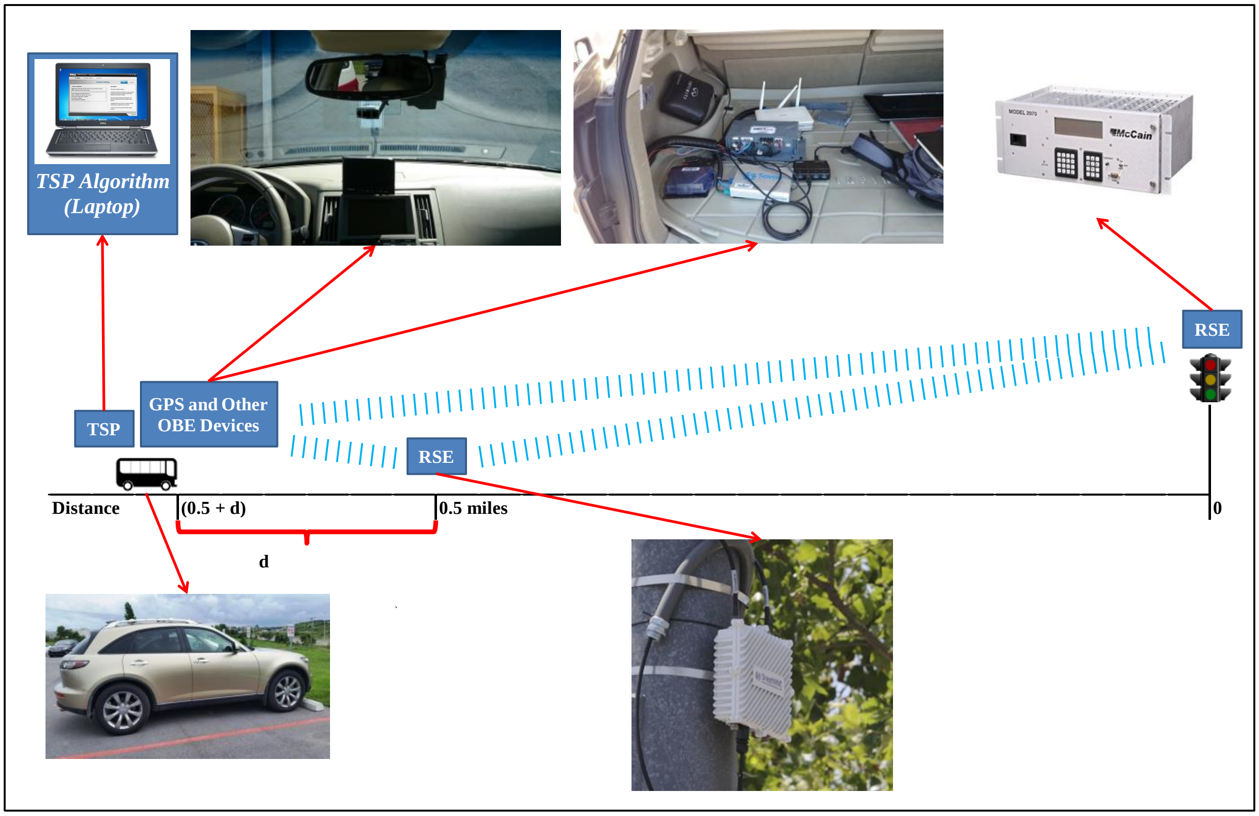

Figure 13. TSPCV experiment structure.

Figure 14 demonstrates the data flow diagram of the TSPCV experiment between different involved units: vehicle and GPS devices, RSE at 0.5 miles to the intersection, and RSE and traffic signal controller located at the intersection. The main flow of data and communication was as follows:

- Original signal phasing from traffic signal controller to TSPCV on laptop in vehicle (red arrows)
- Data from either regular GPS or differential GPS to TSPCV on laptop in vehicle (green arrows)
- TSPCV signal phasing from TSPCV on laptop in vehicle to traffic signal controller (blue arrows)
- TSPCV logic (black arrows)

The signal phasing was coded as follows:

- Code 1: Red
- Code 2: Yellow
- Code 3: Green

The TSPCV algorithm receives vehicle location and speed from the GPS devices (either regular or differential) as well as current (original) signal phasing from the traffic signal controller. Based on the logic, if the vehicle is behind schedule the algorithm sends back appropriate TSPCV signal phasing (translated into codes 1, 2, or 3) to the traffic signal controller. If there is no need to implement TSPCV signal phasing, then the current (original) signal phasing continues.

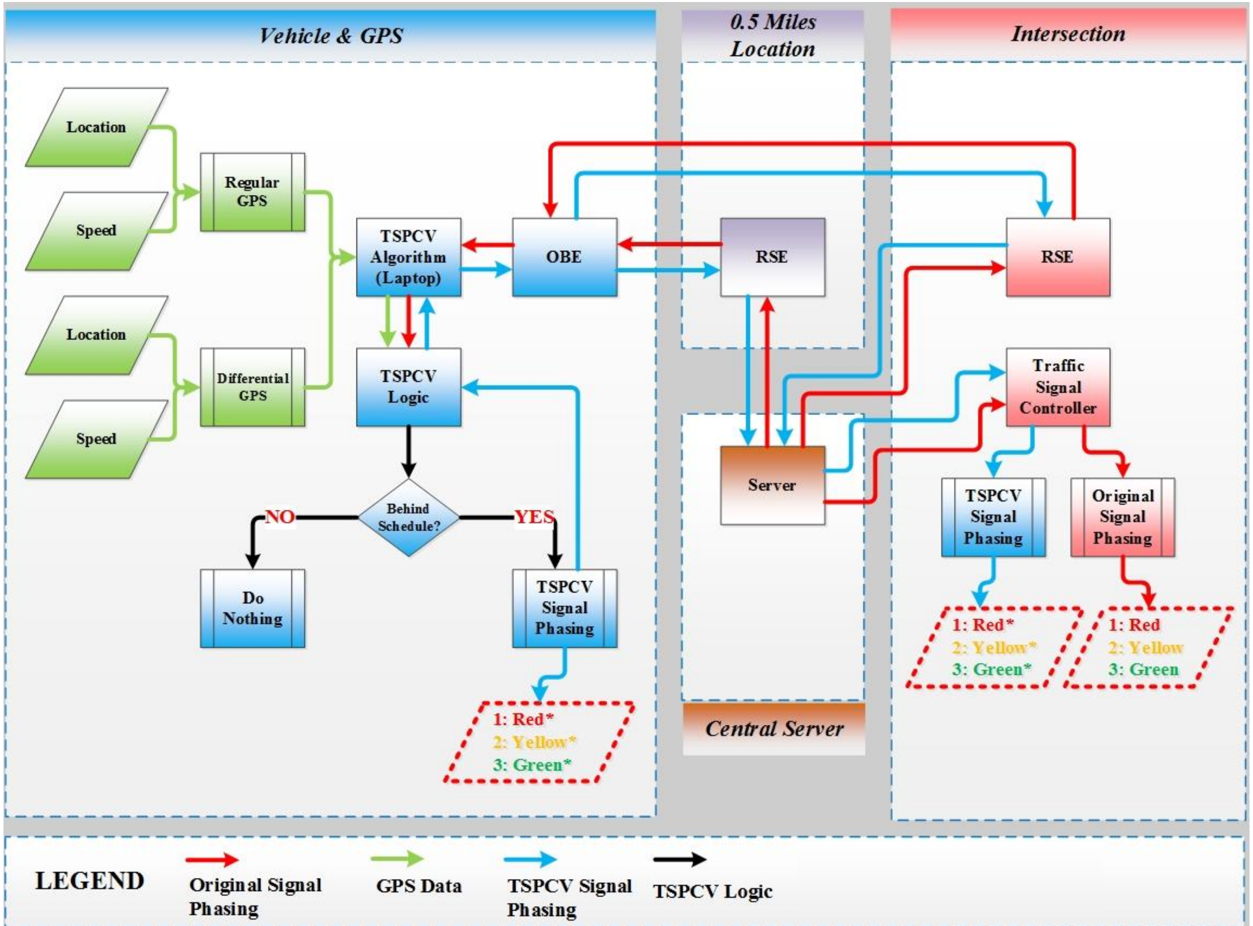

Figure 14. TSPCV experiment data flow diagram.

Experiment Site

Figure 15 shows the experiment site. The Smart Road is highlighted in orange.

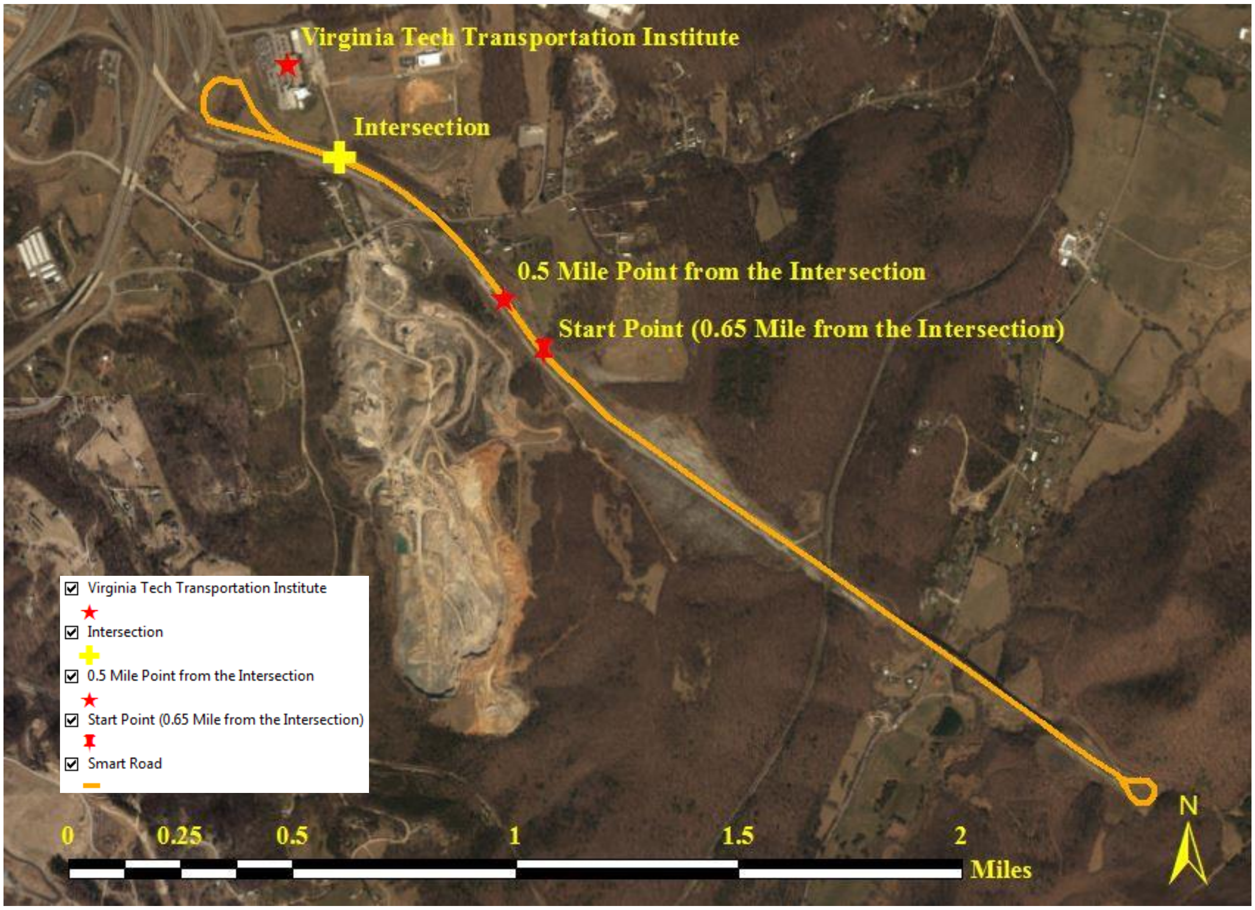

Figure 15. Experiment site [Source: Map data ©2015 Google].

The project team started each trial of the experiment at the "Start Point," which was approximately 0.65 miles from the intersection on the Smart Road. The project team identified the value of "d" (in Figure 13) as approximately 0.15 miles from the Start Point. Starting each trial at this point ensured reaching the required speed (45 mph, which will be explained in the next section) at the 0.5-mile point from the intersection (the point where the proposed TSPCV started to work). Figure 16 shows the signalized intersection used for the experiment. The project team entered the intersection in the direction indicated by the arrow on the figure.

Figure 16. Experiment signalized intersection [Source: Map data ©2015 Google].

Experimental Scenarios

The following scenarios were of interest to the project team.

Signal phasing

TSP is most effective in an urban or suburban area on a major arterial where traffic is heavy. Therefore, the experiment replicated a scenario of this type. A 90-second cycle length was adopted. As discussed in the previous chapter, traffic light cycle length was fixed and the sequence of signal phases did not change (two of the model assumptions). The project team decided to include a short green time for the signalized intersection because it could provide a better situation for validating the proposed TSPCV by having a long red time, implemented as follows:

- Cycle time 90 seconds: green time = 30 seconds, no left turn; yellow time = 3 seconds; all-red time = 2 seconds, and red time = 55 seconds).

Arrival types

The TSPCV mechanism's reliability was investigated to determine if TSPCV could perform properly under different activation scenarios. One major difficulty was that the arrival of the bus could conflict with the minimum green time requirement for the other three approaches to the intersection. As shown in Figure 12, there are different possibilities for bus arrival times during the red time of the original signal phasing. The question of interest in this case was whether or not the mechanism could lead the vehicle to avoid the minimum green time window and successfully provide a TSP green phase. To measure the performance of the proposed TSPCV at different arrival times of red time, the project team categorized them into three groups: beginning of red, middle of red, and end of red.

GPS devices

- Regular GPS (GPS from NextGEN DAS head unit)
- Differential GPS (Novatel Flexpak6)

Differential GPS devices are more accurate than regular GPS devices but cost much more.

Speed limit

Since the TSPCV was being tested on a major arterial, 45 mph was adopted as the speed limit. This is the most commonly posted speed limit for this class of roadway.

Table 16 summarizes the experimental scenarios and number of trials for each scenario that was tested on the Virginia Smart Road. The experiment included 36 trials in all. As previously noted, the project team was interested in different red phase arrival times. Through trial and error, the team determined that a starting point about 0.65 miles from the intersection (see **Error! Reference source not found.**) would a llow a driver to reach about 45 mph at the 0.5-mile point from the intersection and that a bus maintaining a speed of 45 mph could reach the intersection in about 55 seconds. To ensure different arrival times during the red phase of original signal cycle, the team started the traffic signal at different points in its original cycle (see Table 16). "Cycle length start time" in Table 16 thus refers to the point in the original signal cycle coinciding with the departure of the vehicle from its initial location 0.65 miles from the intersection.

Table 16. TSP Experiment Scenarios

TSP Experiment Scenarios		Regular GPS Trials (#)	Differential GPS Trials (#)
Cycle Length Start Time (sec.)	40	10	3
	50	3	2
	60	3	3
	70	3	3
	80	3	3
Subtotal Number of Trials (#)		*22 Trials*	*14 Trials*
Total Number of Trials (#)		**36 Trials**	

Notes:

- Speed limit was 45 mph for all trials.
- "Cycle Length Start Time" is X seconds (i.e., either 40 sec. or 50 sec. or 60 sec. or 70 sec. or 80 sec.) after the start of original signal cycle and it is the departure time at each trial.

Prior to the experiment, the project team visually confirmed the compatibility of the algorithm and the equipment (OBE and RSE) at Virginia Smart Road and tried the algorithm several times to ensure TSPCV performance.

Data Collection

All experimental data were recorded for the full duration of each trial, from the trial's beginning until it ended a few feet after the vehicle passed through the intersection. Critical data items collected included:

- Time
- Original timing plan
- TSP timing plan (activated after the bus passed the 0.5-mile point)
- Bus speed

- Bus location
- Distance to intersection
- Phase at the intersection (prior to the bus passing the 0.5-mile location; based on "Original Timing Plan" and then "TSP Timing Plan" afterward)

After the experiment, the team compiled all recorded data and performed the analyses discussed in the following sections.

Analyses

The following sections summarize each main scenario (speed limit of 45 mph and usage of regular or differential GPS device). A summary table for each trial is provided in Appendix B.

Because the research team started the traffic signal at a predefined point of the signal cycle (see Table 16) at the same time the bus left its starting point 0.65 miles from the intersection (see **Error! Reference source not found.**), the bus's arrival time at the intersection could be predicted. This value, called the "Predicted Relative Cycle Length Arrival Time without TSP at 0.5 Miles" was calculated using the following formula:

$$PRC_{AT} = \left[\left({}^{D}/_{V}\right) + C_{ST}\right] - (n \times C) \tag{30}$$

where:

- PRC_{AT} is the Predicted Relative Cycle Length Arrival Time without TSP at 0.5 miles;
- V is bus speed (m/s);
- D is distance to intersection (m) [0.5 mile = 804.672 m];
- C_{ST} is cycle length start time (sec.);
- n is the number of passed signal cycles (if bus arrives at the same signal cycle, then $n = 0$; for the next signal cycle $n = 1$ and so on.);
- C is original cycle length without TSP [90 sec.].

PRC_{AT} could be any number between 0 and 90—from 0 to 55, the traffic light would be red; from 55 to 85, it would be green; from 85 to 88, it would be yellow; and from 88 to 90, it would be all red. With trial and error, the project team could identify the range of "Cycle Length Start Time" in which the bus would arrive at different points of the original red time (i.e., Cycle Length Start Time = either 40, 50, 60, 70, or 80 sec.).

Speed Limit = 45 mph and Regular GPS

In this scenario, the vehicle enabled with the regular GPS device drove about 45 mph at 0.5 miles from the intersection and then, depending on predicted arrival time at the intersection, the driver was advised by the algorithm to maintain an appropriate speed that would allow the vehicle to pass the intersection at a TSP-provided green light. Table 17 summarizes this scenario and its trials. The proposed TSP succeeded in giving the vehicle the green light in all trials, and on average the amount of saved time due to the TSP algorithm varied from 9.7 sec. (39%) for arriving almost at the end of the red light cycle of the intersection to 38.7 sec. (70%) for arriving almost at the early red light cycle of the intersection.

Since this was the first set of trials, the team repeated this trial (starting at the 40-second point of the original intersection signal phasing at start point) more than the other trials to become familiar with the performance of the TSP algorithm; however, this precaution was unnecessary since the algorithm worked well for all trials.

Table 17. CV-TSP Experiment: Speed Limit = 45 mph, Regular GPS

Cycle Length Start Time sec.) & Trial	Speed at 0.5 Miles (mph)	Predicted Relative Cycle Length Arrival Time without TSP at 0.5 Miles	Predicted Original Light Ball State without TSP	Predicted Overall Time to Pass the Intersection without TSP	Actual Light Ball State with TSP	Actual Overall Time to Pass the Intersection with TSP	Green Extension (Sec.)	Delay $_{w/o\ TSP}$ (Sec.)	Delay $_{TSP}$ (Sec.)	Reduced Delay (Sec.)	Reduced Delay (%)
40-1	43.3	7.3	Red	105.0	Green	63.0	0	65.0	23.0	42.0	65%
40-2	45.5	4.6	Red	105.0	Green	61.0	0	65.0	21.0	44.0	68%
40-3	44.9	5.6	Red	105.0	Green	65.0	2	65.0	25.0	40.0	62%
40-4	44.4	3.3	Red	105.0	Green	63.0	0	65.0	23.0	42.0	65%
40-5	46.1	90.0	Red	105.0	Green	63.0	0	65.0	23.0	42.0	65%
40-6	42.9	7.0	Red	105.0	Yellow	80.0	5	65.0	40.0	25.0	38%
40-7	43.3	5.9	Red	105.0	Green	66.0	3	65.0	26.0	39.0	60%
40-8	41.7	8.3	Red	105.0	Yellow	70.0	5	65.0	30.0	35.0	54%
40-9	41.4	8.0	Red	105.0	Green	67.0	4	65.0	27.0	38.0	58%
40-10	42.0	3.9	Red	105.0	Green	65.0	2	65.0	25.0	40.0	62%
Avg.	**43.5**	**5.4**	**Red**	**105.0**	**Green**	**66.3**	**2.1**	**65.0**	**26.3**	**38.7**	**60%**
50-1	40.4	19.4	Red	95.0	Green	58.0	2	55.0	18.0	37.0	67%
50-2	43.2	15.8	Red	95.0	Green	56.0	0	55.0	16.0	39.0	71%
50-3	43.8	15.4	Red	95.0	Green	56.0	0	55.0	16.0	39.0	71%
Avg.	**42.5**	**16.9**	**Red**	**95.0**	**Green**	**56.7**	**0.7**	**55.0**	**16.7**	**38.3**	**70%**
60-1	43.3	25.9	Red	85.0	Green	56.0	0	45.0	16.0	29.0	64%
60-2	44.4	24.2	Red	85.0	Green	56.0	1	45.0	16.0	29.0	64%

Cycle Length Start Time sec.) & Trial	Speed at 0.5 Miles (mph)	Predicted Relative Cycle Length Arrival Time without TSP at 0.5 Miles	Predicted Original Light Ball State without TSP	Predicted Overall Time to Pass the Intersection without TSP	Actual Light Ball State with TSP	Actual Overall Time to Pass the Intersection with TSP	Green Extension (Sec.)	Delay $_{w/o\ TSP}$ (Sec.)	Delay $_{TSP}$ (Sec.)	Reduced Delay (Sec.)	Reduced Delay (%)
60-3	43.8	26.1	Red	85.0	Green	56.0	0	45.0	16.0	29.0	64%
Avg.	**43.8**	**25.4**	**Red**	**85.0**	**Green**	**56.0**	**0.3**	**45.0**	**16.0**	**29.0**	**64%**
70-1	45.0	35.5	Red	75.0	Green	58.0	1	35.0	18.0	17.0	49%
70-2	43.1	36.5	Red	75.0	Green	59.0	3	35.0	19.0	16.0	46%
70-3	45.7	34.0	Red	75.0	Green	55.0	0	35.0	15.0	20.0	57%
Avg.	**44.6**	**35.3**	**Red**	**75.0**	**Green**	**57.3**	**1.3**	**35.0**	**17.3**	**17.7**	**50%**
80-1	44.4	44.0	Red	65.0	Green	54.0	0	25.0	14.0	11.0	44%
80-2	42.9	47.0	Red	65.0	Green	56.0	0	25.0	16.0	9.0	36%
80-3	45.5	43.2	Red	65.0	Green	56.0	1	25.0	16.0	9.0	36%
Avg.	**44.3**	**44.7**	**Red**	**65.0**	**Green**	**55.3**	**0.3**	**25.0**	**15.3**	**9.7**	**39%**

Notes:

$$Delay_{w/o\,TSP} = POT - {}^{D}/_{V} \times 3600 \quad (31)$$

$$Delay_{TSP} = AOT - {}^{D}/_{V} \times 3600 \quad (32)$$

- Delay$_{w/o\ TSP}$: Delay without TSP (sec.)
- Delay $_{TSP}$: Delay with TSP (sec.)
- POT: Predicted overall time to pass the intersection without TSP (sec.)
- AOT: Actual overall time to pass the intersection with TSP (sec.)
- V: Bus speed (m/s)
- D: Distance to intersection (m) [0.5 mile = 804.672 m]

$$Reduced\ Delay\ (Sec.) = Delay_{w/o\,TSP} - Delay_{TSP} \quad (33)$$

$$Reduced\ Delay\ (\%) = (Delay_{w/o\,TSP} - Delay_{TSP})/(Delay_{w/o\,TSP}) \quad (34)$$

Figure 17 to Figure 21 show the profiles of the original signal phasing and TSP signal phasing for the average of each set of trials (i.e., starting at 40 sec., 50 sec., 60 sec., 70 sec., and 80 sec. of original signal phasing). The figures include the location of the 0.5-mile point and also the predicted overall time without TSP as well as the actual overall time with TSP measured during the experiment. Figure 22 summarizes the average of all sets of trials for this scenario.

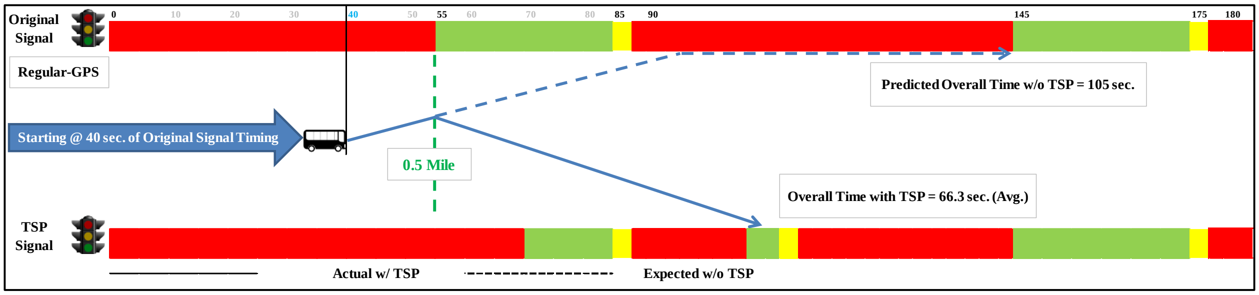

Figure 17. Speed limit = 45 mph, regular GPS, and starting at 40 sec. of original signal.

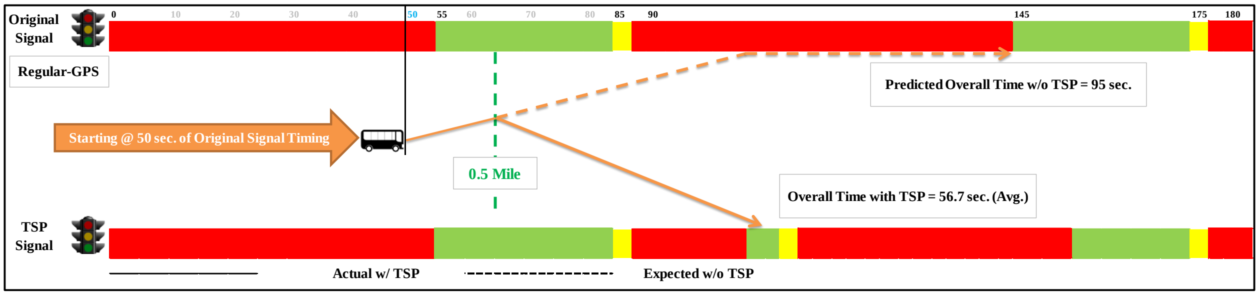

Figure 18. Speed limit = 45 mph, regular GPS, and starting at 50 sec. of original signal.

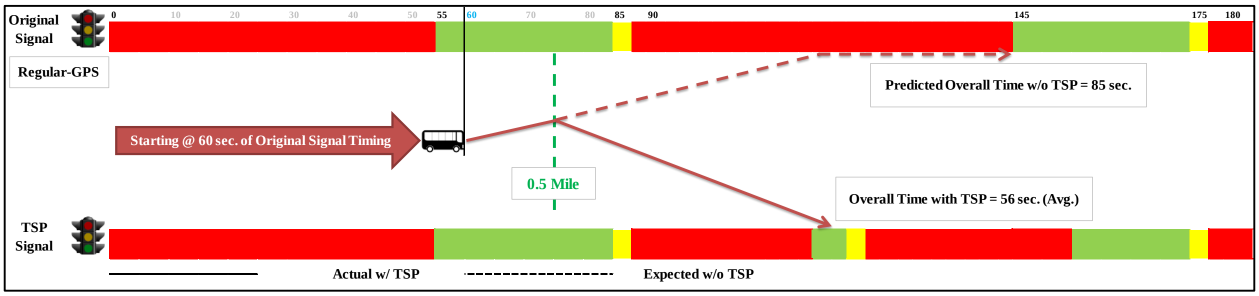

Figure 19. Speed limit = 45 mph, regular GPS, and starting at 60 sec. of original signal.

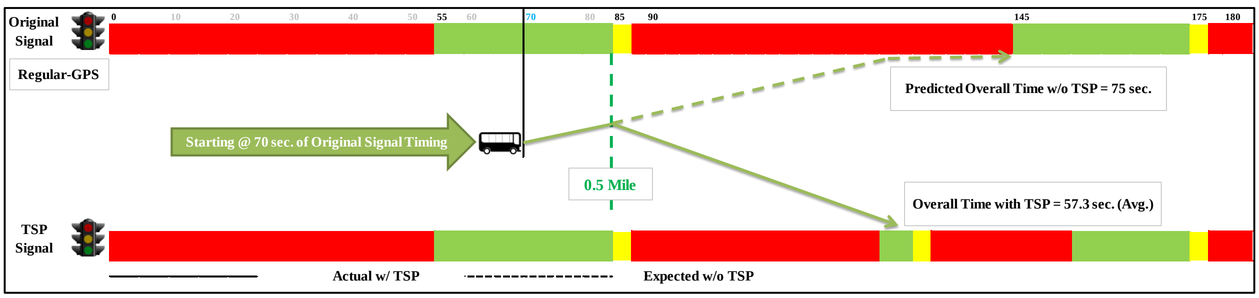

Figure 20. Speed limit = 45 mph, regular GPS, and starting at 70 sec. of original signal.

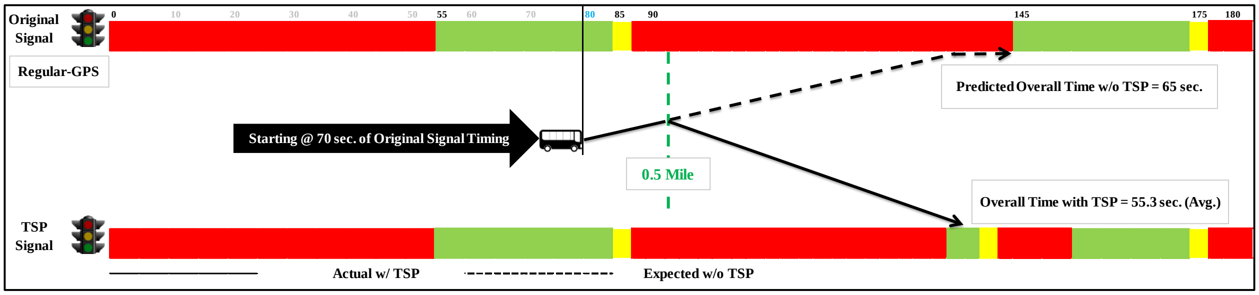

Figure 21. Speed limit = 45 mph, regular GPS, and starting at 80 sec. of original signal.

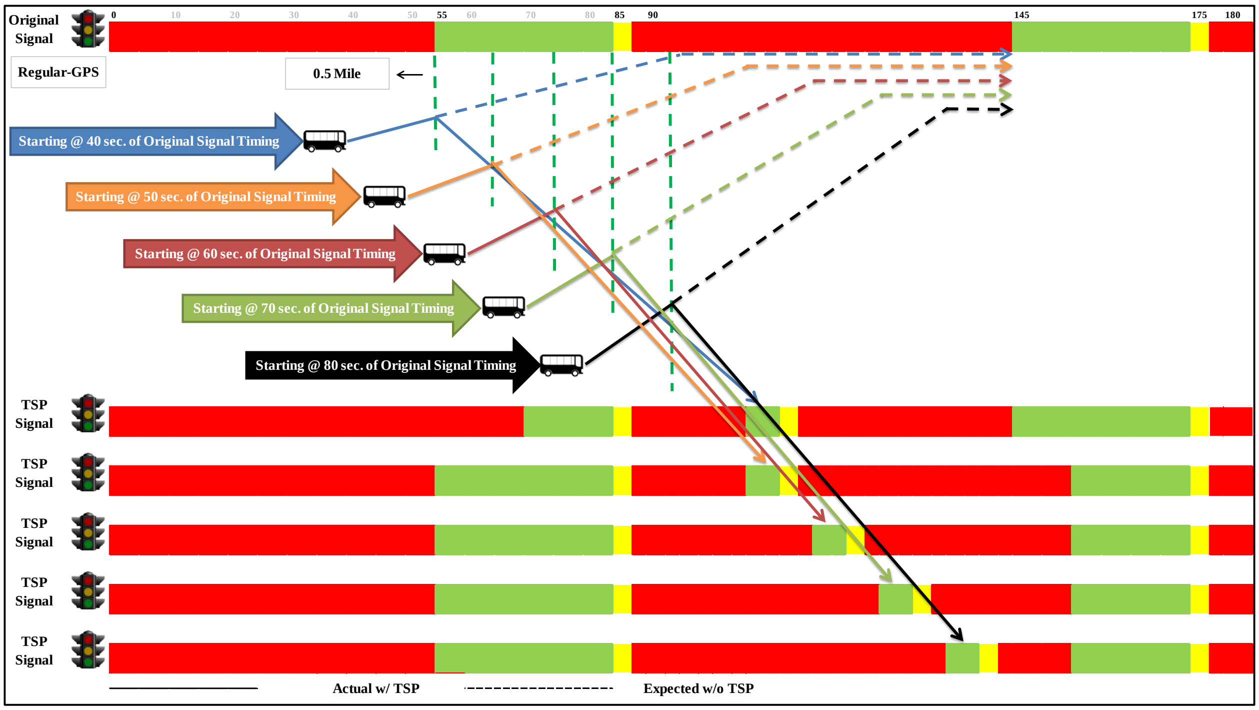

Figure 22. Speed limit = 45 mph, regular GPS, and all starting points.

Speed Limit = 45 mph and Differential GPS

In this scenario, the vehicle enabled with the differential GPS device drove at about 45 mph at 0.5 miles from the intersection and then, depending on its predicted arrival time at the intersection, the driver was advised by the algorithm to maintain a speed that would allow the vehicle to pass the intersection at a TSP-provided green light. Table 18 summarizes this scenario and its trials. The proposed TSP succeeded in giving the vehicle the green light in all trials, and on average the amount of saved time due to the TSP algorithm varied from 8.0 sec. (32%) for arriving almost at the end of the red light cycle of the intersection to 41.0 sec. (75%) for arriving almost at the early red light cycle of the intersection.

Table 18. CV-TSP Experiment: Speed Limit = 45 mph, Differential GPS

Cycle Length Start Time sec.) & Trial	Speed at 0.5 Miles (mph)	Predicted Relative Cycle Length Arrival Time without TSP at 0.5 Miles	Predicted Original Light Ball State without TSP	Predicted Overall Time to Pass the Intersection without TSP	Actual Light Ball State with TSP	Actual Overall Time to Pass the Intersection with TSP	Green Extension (Sec.)	Delay $_{w/o\ TSP}$ (Sec.)	Delay $_{TSP}$ (Sec.)	Reduced Delay (Sec.)	Reduced Delay (%)
40-1	48.6	89.8	Red	105.0	Green	64.0	0	65.0	24.0	41.0	63%
40-2	47.2	1.9	Red	105.0	Green	65.0	2	65.0	25.0	40.0	62%
40-3	46.4	4.0	Red	105.0	Green	62.0	0	65.0	22.0	43.0	66%
Avg.	**47.4**	**1.9**	**Red**	**105.0**	**Green**	**63.7**	**0.7**	65.0	23.7	**41.3**	**64%**
50-1	46.8	13.1	Red	95.0	Green	54.0	0	55.0	14.0	41.0	75%
50-2	49.8	10.8	Red	95.0	Green	54.0	0	55.0	14.0	41.0	75%
Avg.	**48.3**	**11.9**	**Red**	**95.0**	**Green**	**54.0**	**0.0**	55.0	14.0	**41.0**	**75%**
60-1	44.3	24.4	Red	85.0	Green	57.0	2	45.0	17.0	28.0	62%
60-2	46.7	23.4	Red	85.0	Green	59.0	3	45.0	19.0	26.0	58%
60-3	44.3	25.1	Red	85.0	Green	58.0	2	45.0	18.0	27.0	60%
Avg.	**45.1**	**24.3**	**Red**	**85.0**	**Green**	**58.0**	**2.3**	45.0	18.0	**27.0**	**60%**
70-1	45.5	32.7	Red	75.0	Green	55.0	0	35.0	15.0	20.0	57%
70-2	46.7	30.9	Red	75.0	Green	54.0	0	35.0	14.0	21.0	60%
70-3	49.4	27.4	Red	75.0	Green	51.0	0	35.0	11.0	24.0	69%
Avg.	**47.2**	**30.3**	**Red**	**75.0**	**Green**	**53.3**	**0.0**	35.0	13.3	**21.7**	**62%**
80-1	43.6	44.5	Red	65.0	Green	56.0	1	25.0	16.0	9.0	36%
80-2	45.7	41.6	Red	65.0	Green	57.0	3	25.0	17.0	8.0	32%
80-3	39.3	49.7	Red	65.0	Green	58.0	3	25.0	18.0	7.0	28%
Avg.	**42.9**	**45.3**	**Red**	**65.0**	**Green**	**57.0**	**2.3**	25.0	17.0	**8.0**	**32%**

Figure 23 to Figure 27 show the profiles of the original signal phasing and TSP signal phasing for the average of each set of trials (i.e., starting at 40 sec., 50 sec., 60 sec., 70 sec., and 80 sec.). The graphs include the location of the 0.5-mile point and also the predicted overall time without TSP as well as the actual overall time with TSP measured during the experiment. Figure 28 summarizes the average of all sets of trials for this scenario.

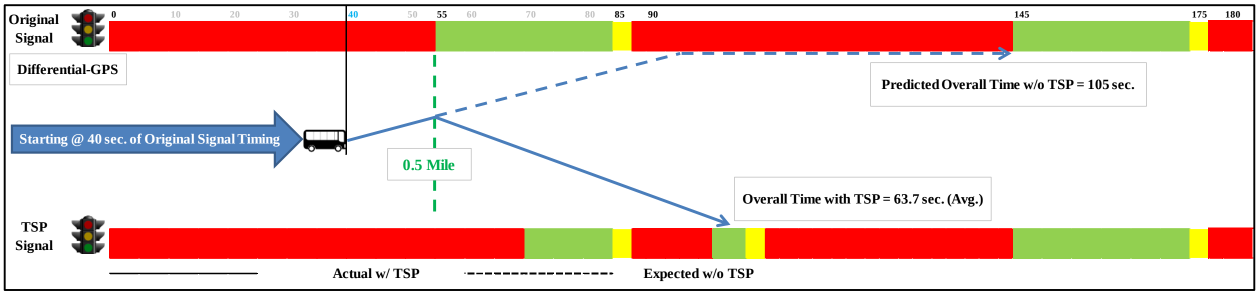

Figure 23. Speed limit = 45 mph, differential GPS, and starting at 40 sec. of original signal.

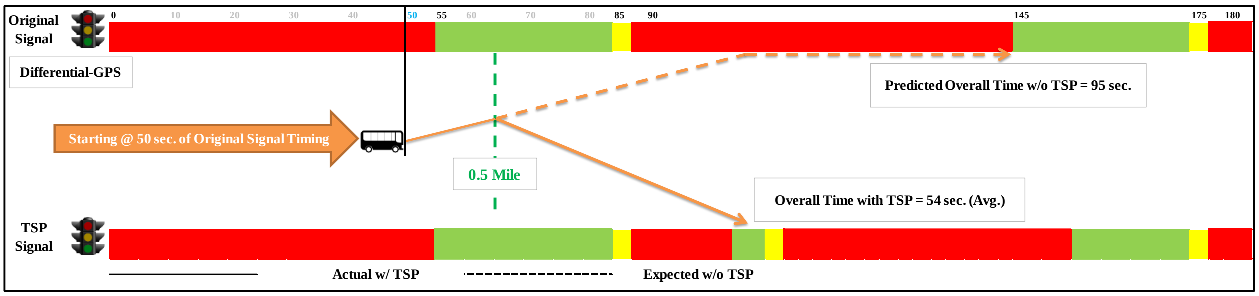

Figure 24. Speed limit = 45 mph, differential GPS, and starting at 50 sec. of original signal.

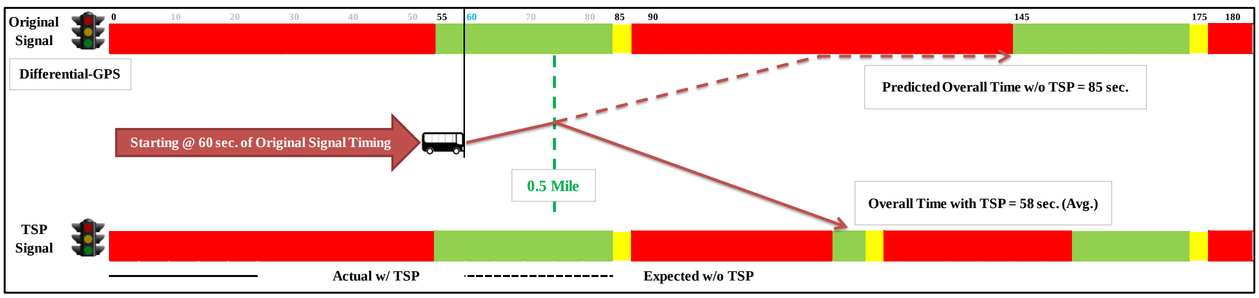

Figure 25. Speed limit = 45 mph, differential GPS, and starting at 60 sec. of original signal.

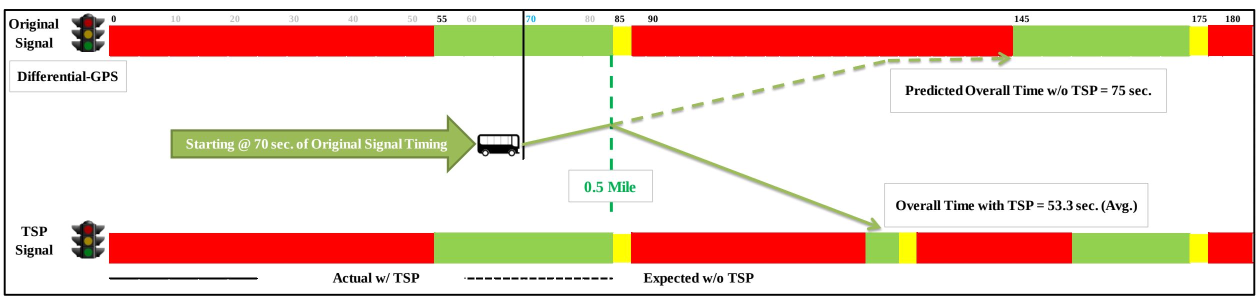

Figure 26. Speed limit = 45 mph, differential GPS, and starting at 70 sec. of original signal.

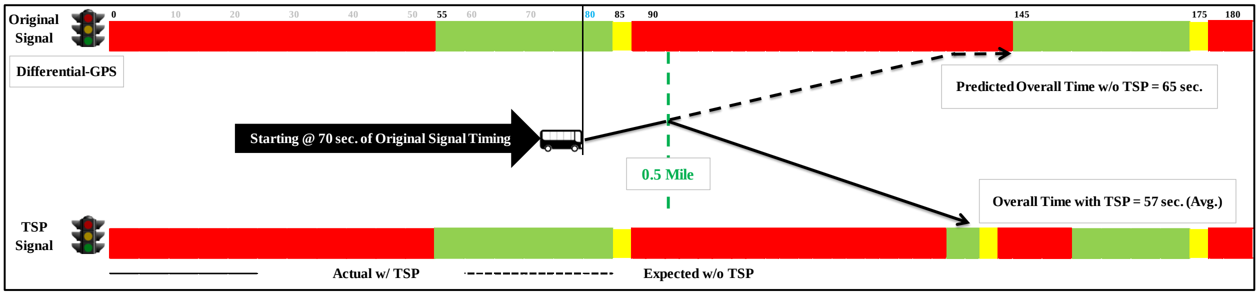

Figure 27. Speed limit = 45 mph, differential GPS, and starting at 80 sec. of original signal.

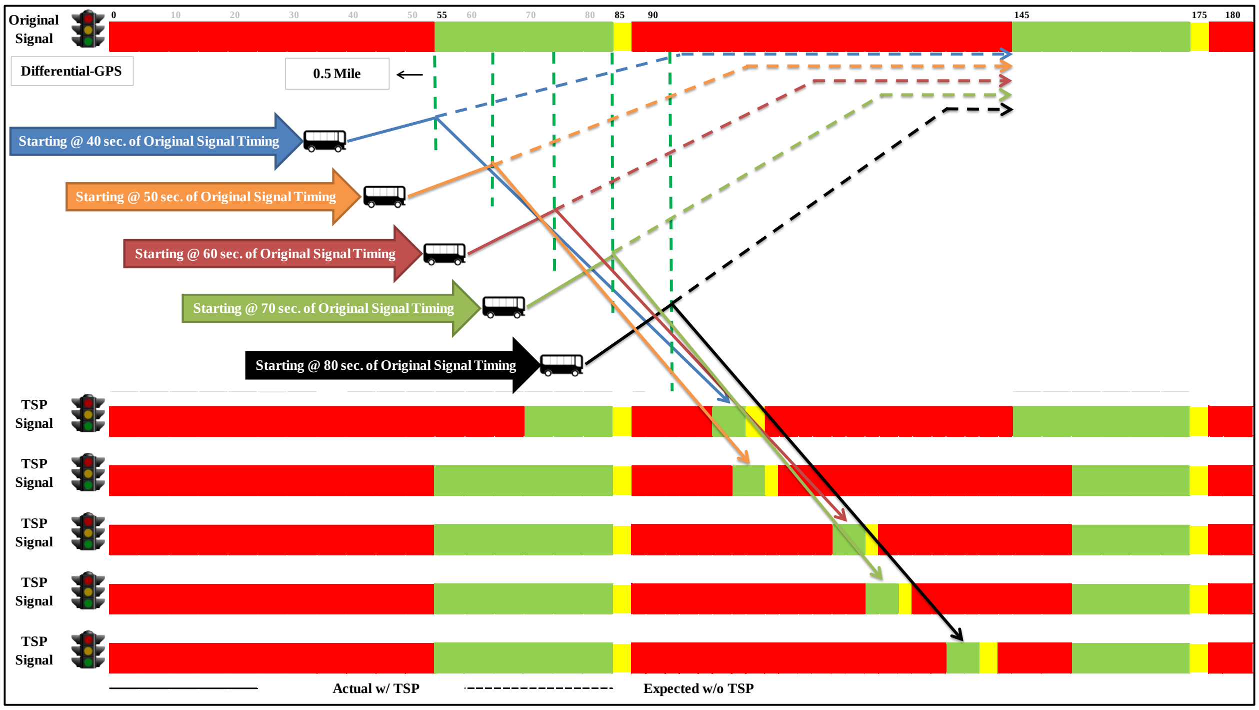

Figure 28. Speed limit = 45 mph, differential GPS, and all starting points.

Evaluation

The TSPCV experiments were evaluated based on the success rate and reduced delays for different red time arrival times.

Success Rate

Table 19 summarizes the proposed TSPCV algorithm for different scenarios. Generally, the proposed method could provide the green time for the bus 100% of the time. About 50% of the time (both regular and differential GPS devices), the bus operated without needing a green extension.

Table 19. Success Rates for Different Relative Cycle Length Arrival Times

Scenario	Cycle Length Start Time	#	# TSP Green Provided	%	# TSP Green with Shorter Delay	%	# TSP Green with Shorter Delay without Green Extension	%
45 mph (Regular GPS)	40	10	10	100%	10	100%	4	40%
	50	3	3	100%	3	100%	2	67%
	60	3	3	100%	3	100%	1	33%
	70	3	3	100%	3	100%	1	33%
	80	3	3	100%	3	100%	2	67%
	All	**22**	**22**	**100%**	**22**	**100%**	**10**	**45%**
45 mph (Differential GPS)	40	3	3	100%	3	100%	2	67%
	50	2	2	100%	2	100%	2	100%
	60	3	3	100%	3	100%	0	0%
	70	3	3	100%	3	100%	3	100%
	80	3	3	100%	3	100%	0	0%
	All	**14**	**14**	**100%**	**14**	**100%**	**7**	**50%**

Relationship Between Delay Reduction and Original Red Light Arrival Time

Table 20 compares the amount of reduced delay time with TSP and without TSP for the average performance of each set of trials in each scenario. Figure 29 shows the delay reduction in seconds and Figure 30 shows the delay reduction as a percentage.

Table 20. Reduced Delays for Different Red Light Arrival Times

Scenario	Cycle Length Start Time	Trial	Predicted Relative Cycle Length Arrival Time without TSP at 0.5 Miles	Reduced Delay (Sec.)	Reduced Delay (%)
45 mph (Regular GPS)	**40**	Avg.	5.4	38.7	60%
	50	Avg.	16.9	38.3	70%
	60	Avg.	25.4	29.0	64%
	70	Avg.	35.3	17.7	50%
	80	Avg.	44.7	9.7	39%
45 mph (Differential GPS)	**40**	Avg.	1.9	41.3	64%
	50	Avg.	11.9	41.0	75%

	60	Avg.	24.3	27.0	60%
	70	Avg.	30.3	21.7	62%
	80	Avg.	45.3	8.0	32%

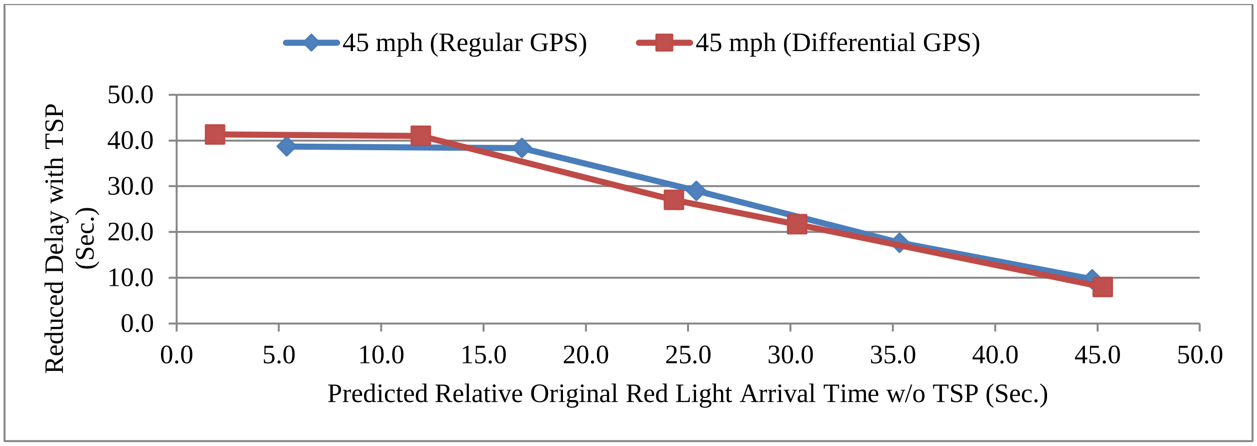

Figure 29. Reduced delays (sec.) for different red light arrival time.

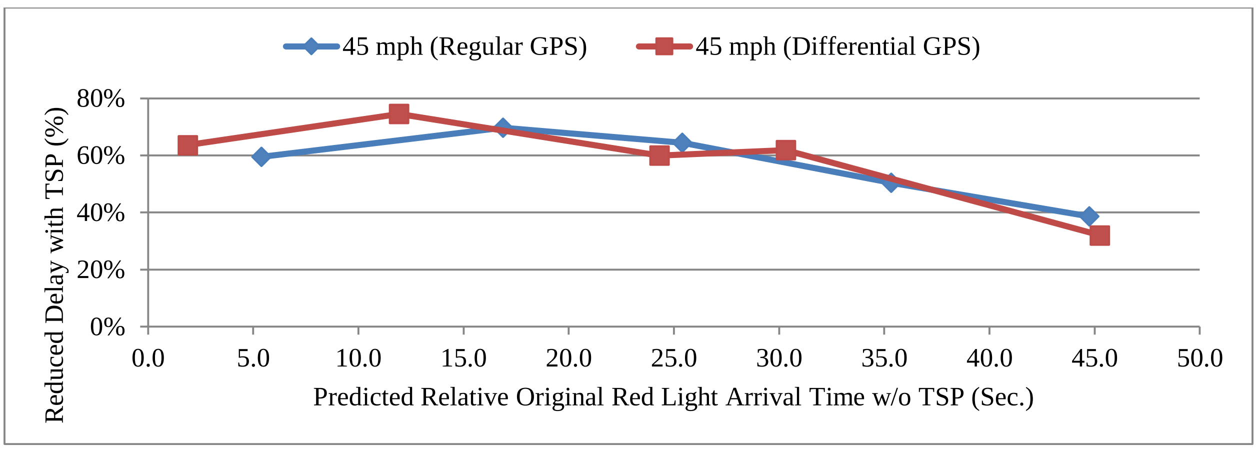

Figure 30. Reduced delays (%) for different red light arrival time.

As expected, TSP saved more time when the bus arrived at the beginning of the red light signal phasing because it could avoid longer red light signal timing for the bus. However, when the bus arrived later (mid-red or late red), the overall time saved decreased accordingly.

GPS Type Effect

Table 21 shows matching cases among trials with regular GPS and those with differential GPS. Since there were different numbers of trials for some scenarios, the project team randomly selected an equal number of trials from each scenario.

Table 21. Matching cases for regular GPS and differential GPS.

TSP Experiment Scenarios	Regular GPS	Differential GPS
Speed Limit	45	45
Matching Cases	40 × 3	40 × 3
	50 × 2	50 × 2
	60 × 3	60 × 3
	70 × 3	70 × 3
	80 × 3	80 × 3
Subtotal for each GPS Type	**14**	**14**

Since TSP was successful for all experiments, and in all trials with regular GPS and with differential GPS, the bus could pass the intersection during a green light, two factors could explain the difference in terms of the operation of the two GPS devices:

- Actual overall time to pass the intersection
- Reduced delay (in seconds and percentages)
- Green extension duration

Table 22 and Table 23 summarize these two values for both devices.

Table 22. Actual Overall Times and Green Extension Times for Regular GPS

Cycle Length Start Time	Trial	Actual Overall Time to Pass the Intersection with TSP	Reduced Delay (Sec.)	Reduced Delay (%)	Green Extension
40	1	63.0	42.0	65%	0
	6	80.0	42.0	65%	5
	9	67.0	38.0	58%	4
50	2	56.0	39.0	71%	0
	3	56.0	39.0	71%	0
60	1	56.0	29.0	64%	0
	2	56.0	29.0	64%	1
	3	56.0	29.0	64%	0
70	1	58.0	17.0	49%	1
	2	59.0	16.0	46%	3
	3	55.0	20.0	57%	0
80	1	54.0	11.0	44%	0
	2	56.0	9.0	36%	0
	3	56.0	9.0	36%	1
Mean	**-**	**59.1**	**26.4**	**56%**	**1.1**

Table 23. Actual Overall Times and Green Extension Times for Differential GPS

Cycle Length Start Time	Trial	Actual Overall Time to Pass the Intersection with TSP	Reduced Delay (Sec.)	Reduced Delay (%)	Green Extension

40	1	64.0	41.0	63%	0
	2	65.0	40.0	62%	2
	3	62.0	43.0	66%	0
50	1	54.0	41.0	75%	0
	2	54.0	41.0	75%	0
60	1	57.0	28.0	62%	2
	2	59.0	26.0	58%	3
	3	58.0	27.0	60%	2
70	1	55.0	20.0	57%	0
	2	54.0	21.0	60%	0
	3	51.0	24.0	69%	0
80	1	56.0	9.0	36%	1
	2	57.0	8.0	32%	3
	3	58.0	7.0	28%	3
Mean	**-**	**57.4**	**26.9**	**57%**	**1.1**

A paired *t*-test was done to check whether the mean actual overall time to pass the intersection, mean reduced delay (in seconds and percentages), and also mean green extension time of the two devices were statistically different. Table 24 through Table 27 show the results.

As the tables show, *p*-values for all tests are larger than 0.05. This indicates that there is no significant difference between the two devices. Table 24 shows the results of the comparison for “Actual Overall Time to Pass the Intersection.” In an aggregate sense, the difference in overall time to pass the intersection is not statistically significant ($p = 0.099$). There is also a high correlation between “Actual Overall Time to Pass the Intersection” between the two devices (Pearson correlation = 0.752), which indicates the two devices operated almost comparably. Table 25 and Table 26 show the results for “Reduced Delay (Sec.)” and “Reduced Delay (%),” respectively. Both tables show that the differences between the two devices are not statistically significant; moreover, a high correlation between the values of Regular GPS and Differential GPS (Pearson correlation = 0.975 and Pearson correlation = 0.867) indicates that the two devices have almost comparable performance.

Table 27 shows the results of the comparison for “Green Extension.” Again, in an aggregate sense, the difference in green extension time is not statistically significant ($p = 0.452$). Moreover, there is no correlation between the green extension times for the two devices (Pearson correlation = −0.04), which indicates that the green extension times for the two devices were random and not subject to the GPS device.

This is an important finding, one that shows no statistically significant difference between the operation of regular GPS and differential GPS for TSP. This finding can facilitate the large-scale implementation of TSP, which is advantageous since regular GPS devices are much cheaper than differential GPS devices.

Table 24. Results of *T*-test Using Paired Two Sample for Means for Actual Overall Time to Pass the Intersection

	Regular GPS	*Differential GPS*
Mean	59.14285714	57.42857143
Variance	48.13186813	16.10989011
Observations	14	14
Pearson Correlation	**0.751780297**	
Hypothesized Mean Difference	0	
df	13	
t Stat	1.356060398	
P(T<=t) One-tail	**0.0990837**	
t Critical One-tail	1.770933396	
P(T<=t) Two-tail	0.198167378	
t Critical Two-tail	2.160368656	

Table 25. Results of *T*-test Using Paired Two Sample for Means for Reduced Delay (Sec.)

	Regular GPS	*Differential GPS*
Mean	26.35714286	26.85714286
Variance	156.8626374	168.7472527
Observations	14	14
Pearson Correlation	**0.9752537**	
Hypothesized Mean Difference	0	
df	13	
t Stat	-0.65058114	
P(T<=t) One-tail	**0.2633243**	
t Critical One-tail	1.770933396	
P(T<=t) Two-tail	0.526648636	
t Critical Two-tail	2.160368656	

Table 26. Results of *T*-test Using Paired Two Sample for Means for Reduced Delay (%)

	Regular GPS	*Differential GPS*
Mean	0.564480282	0.572553161
Variance	0.014742095	0.021868368
Observations	14	14
Pearson Correlation	**0.8674915**	
Hypothesized Mean Difference	0	
df	13	
t Stat	-0.40883589	
P(T<=t) One-tail	**0.3446576**	
t Critical One-tail	1.770933396	
P(T<=t) Two-tail	0.689315193	
t Critical Two-tail	2.160368656	

Table 27. Results of *T*-test Using Paired Two Sample for Means for Green Extension Time

	Regular GPS	*Differential GPS*
Mean	1.071428571	1.142857143
Variance	2.840659341	1.67032967
Observations	14	14
Pearson Correlation	**-0.04035877**	
Hypothesized Mean Difference	0	
df	13	
t Stat	-0.12345172	
P(T<=t) One-tail	**0.4518188**	
t Critical One-tail	1.770933396	
P(T<=t) Two-tail	0.903637666	
t Critical Two-tail	2.160368656	

Conclusions

The proposed TSPCV algorithm was tested on the Connected Vehicle test bed on the Virginia Smart Road. The project team assessed the proposed TSP using several different scenarios and trials. The findings of the field experiment are as follows:

1. The proposed TSPCV algorithm worked properly in a CVI environment.
2. The implementation of the proposed TSPCV algorithm was successful for different scenarios (two GPS devices and several different arrival times).
3. Software and hardware worked properly.
4. The proposed TSPCV algorithm provided green time and shorter overall time to pass the intersection (in comparison with no TSP) for the bus at a 100% success rate.

5. About 50% of the time (using both regular and differential GPS devices), a green extension was needed.
6. The proposed TSPCV saved more time when the bus arrived at the beginning of the red light signal phasing because it could avoid longer red light signal timing for the bus. However, when the bus arrived later (mid-red or late red) the overall saved time decreased accordingly.
7. A performance comparison of the regular and differential GPS devices revealed that the two devices operated almost comparably and, in an aggregate sense, the difference in their performance was not statistically significant. The comparison was based on overall time to pass the intersection and green extension duration. This finding can facilitate the large-scale implementation of TSP since regular GPS devices are much cheaper than differential GPS devices and operate just as well for TSPCV.

Limitations of the Experiment

Although the assessed scenarios sufficiently validated the proper performance of the proposed TSPCV on the Virginia Smart Road, future research in real-world conditions seems necessary because in this experiment the success rate was high due to full control over bus speed. Unless we have a bus-only lane in the real world, there may be some queues and unexpected delays at intersections, and the success rate may go down in the real-world situation. In the future, testing the proposed TSPCV under real-world conditions seems necessary to monitor its performance with a queue of other vehicles and unexpected delays at the intersection. In addition, the testing of regular and differential GPS was conducted in a mostly open-sky environment, rather than an urban canyon condition. The performance of the regular GPS is not likely to be as good as observed in this study.

Chapter 5. Conclusions and Recommendations

Transport agencies have long recognized the value and importance of providing preference to transit buses at signalized intersections. However, concerns about the uncertainty of TSP performance and possible adverse effects associated with implementing TSP have held back the extensive deployment of this technology. To address this issue, the research for this project has advanced TSP logic with a collection of techniques that can grant TSP to buses with more accuracy, better effectiveness, and higher reliability, while causing minimal adverse effects to other roadway users.

The system of TSP techniques presented here was developed in the context of a CV environment. The first stage of this research developed logic to resolve conflicting TSP requests at an isolated intersection. It is built upon the foundation of the TSPCV logic developed previously and inherits three innovative concepts.

- The first concept is the idea of green time reallocation. Instead of adding additional green time to the original timing plan, the proposed TSP logic splits the original green time and moves part of it to when green time is most needed by a transit bus. Since the moved green time is fully used on discharging vehicles, time wasted is largely avoided and any associated adverse effects are minimized. In addition, since the TSP green time is able to start at almost any time, a much greater portion of buses can take advantage of the TSP mechanism.
- The second concept is the idea that buses can cooperate with the signal to perform TSP. By having the bus vary its speed, and consequently its arrival time, the flexibility of TSP strategies is further improved because buses can avoid arriving during all-red phases or during minimum green time for other approaches. Furthermore, the flexibility of bus arrival time also enables the TSP green to start when the least per person delay at the intersection will occur. This improvement ensures that almost every single bus can be granted TSP. However, the reception of TSP is not guaranteed; instead, it is conditional based on traffic condition and schedule adherence.
- The last, but most important, concept is that this TSP system is conditional on the per person delay of all roadway users. This criterion represents a balance of interest between public transportation users and private vehicles. It also ensures that the implementation of TSP will not cause adverse effects for other roadway users.

Together, these three concepts help achieve maximum bus fleet coverage, maximum bus delay reduction, and least delay for all motorists. In addition to the TSPCV logic, the enhanced logic incorporates an algorithm that prioritizes buses coming from different approaches and solves for the best signal timing to minimize the total delay at the intersection. By determining the total number and sequence of buses accommodated, the maximum reduction of bus delay is achieved, while, at the same time, the total delay of all motorists is minimized.

The enhanced logic was evaluated using a theoretical analysis and simulation-based evaluation. Three conflicting scenarios were tested: 1) two conflicting requests from opposite directions, 2) two conflicting requests from perpendicular directions, and 3) three conflicting requests from three directions. The theoretical computation and simulation-based evaluation both showed consistent results. TSPCVM outperforms CTSP and reduces bus delay between 5% and 48%. The range of improvement corresponds to the four different v/c ratios tested, which were 0.5, 0.7, 0.9, and 1.0, respectively. Delay reduction increased as v/c ratio decreased. TSPCVM generated more benefit when buses were coming from opposite directions. Not only was there a greater reduction in bus delay, but delay per person was also minimized to a greater magnitude. The least improvement occurred when accommodating three conflicting requests. Both the theoretical analysis and simulation evaluation showed that the proposed TSP logic resulted in no significant negative effects.

The second stage of this research solves the problem of maintaining bus progression along a corridor of interest. Again, it is built upon the foundation of the TSPCV logic developed in the previous stage and inherits all three innovative concepts. In this case, the embedded algorithm optimizes the signal time of all intersections along the corridor as a whole. It ensures that the bus which is granted TSP is able to travel through the entire corridor without stopping, and at the same time, maintains the least total delay for all motorists. This mechanism prevents the benefit buses receive at one intersection from being lost at the next, with the precondition that no adverse effect is caused. Theoretical analysis reveals that, without the consideration of bus progression, the previously developed TSPCV mechanism is able to generate sizable benefit when the spacing between signals is large. But this benefit declines greatly as the spacing narrows. TSPCV-C always demonstrated superior improvement compared with the other two treatments for the spacing cases considered in this study. The benefit of TSPCV-C grew slightly with the intersection spacing, but it did not always necessarily maintain a positive correlation. A sensitivity study on congestion level was performed for TSPCV-C. Four different v/c ratios were tested, which were 0.5, 0.7, 0.9, and 1.0. Results show that the TSPCV-C logic reduced the bus delay between 35% and 68% compared to CTSP. The results also show that, for congestion levels below capacity, TSPCV-C caused no adverse effects. Although a few adverse effects on side streets were observed when the volume reached capacity, the total delay increase was very minor. The magnitude of this increase was less than 1 second per person.

The third stage of this study was a field experiment conducted on the Virginia Smart Road. Different scenarios were tested to validate the performance of the proposed TSP. The proposed TSP algorithm could save time—as much as between 12% and 39%—for a bus traveling at a speed of 45 mph and a traffic signal with a 90-second cycle length with 30 seconds of green time. The project team assessed the proposed TSP using several different scenarios and trials for different arrival times during a red signal. The proposed TSPCV algorithm worked properly in a CVI environment for different scenarios, as did the implemented software and hardware. The proposed TSPCV algorithm provided green time for the bus at a 100% success rate and saved more time when the bus arrived at the beginning of the red light signal phasing because it could avoid longer red light timing for the bus. However, when the bus arrived later (mid-red or late red), the overall saved time decreased accordingly. Comparison of two types of GPS devices (regular and differential) revealed almost identical performance.

The value of the proposed TSP techniques is shown in several ways. First of all, by implementing these techniques, a much higher percentage of transit buses are able to benefit from the TSP mechanism, which will eventually lead to an improved transit service with less delay, higher mobility, and better quality of service. Secondly, the techniques also relieve agencies from the major concern that TSP interrupts the progression on side streets and causes tremendous delay on other traffic users. Hence, this feature allows DOTs to reduce costs since they will not have to perform a study of LOS and/or v/c ratio for every potential TSP intersection before installation. Since local agencies and DOTs do not need to validate potential TSP intersections for adverse effects before installation, the proposed TSP techniques could further reduce installation and maintenance costs. One can expect that, with this newly developed TSP system, more intersections may be installed with TSP, better riding experiences will be achieved, and higher transit ridership will be observed. All of these changes may promote a mode switch from private vehicles to public transportation and eventually lighten the burden on the existing road network and improve traffic conditions. Finally, the proposed technique is one of the few Intelligent Transportation System (ITS) applications capable of being realized in the early stages of ITS rollout. The concept is made possible by CV technology, which provides two-way communications and additional and more-accurate information. In order to achieve the best performance of this system of TSP technology, it would be preferable for all traffic users to be equipped with CV technology. Nevertheless, unlike most other ITS applications, the proposed TSP techniques can produce sizable benefits even when only buses are equipped. This feature makes the proposed TSP techniques a good starting point to promote the ITS system at the early stage of ITS technology deployment.

The field experiment of the proposed algorithm assures expected performance for one single intersection for different scenarios. Moreover, the field experiment showed that two GPS devices (regular and differential) operated almost the same and, in an aggregate sense, the difference in their performance was not statistically significant. This finding can facilitate the large-scale implementation of TSP since regular GPS devices are much cheaper than differential GPS devices and operated just as well for TSPCV.

Future research could consider consolidating all the techniques into an ultimate TSP logic. This TSP would be able to accommodate multiple conflicting TSP requests for buses traveling on a road network. This scenario would become more complicated, as maintaining bus progression will cause significantly more complications than the isolated-intersection scenario. Apart from that, additional condition criteria could also be tested instead of per person delay; testing could include, for example, fuel consumption, emissions, etc. In addition, the implementation of a real-world experiment of the proposed TSP techniques is worth investigating, as the experiment performed on the Virginia Smart Road was done under special conditions that enabled the project team to control the bus’s speed. Investigation of the proposed TSPCV under real-world conditions seems necessary to monitor TSPCV performance with a queue of other vehicles and unexpected delays at the intersection.

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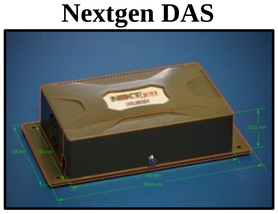
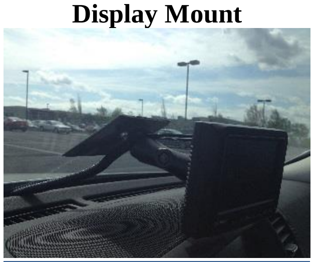
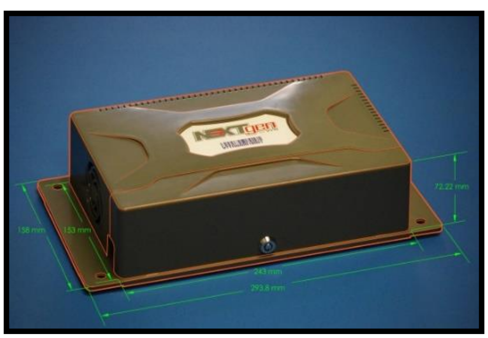
Appendix A. Equipment Details Installed on "[Vehicle No.] 26 – 2005 Infiniti FX35 Gold [at VT]"

Device	Details	Location
Nextgen DAS 	9-40 volt power input Ethernet Port Serial Port USB Port 3 CAN Ports NTSC video ports Cellular Wi-Fi Bluetooth Power Connection – 12V through ignition Network Connection – CAN port through OBD cable Location: rear of vehicle (trunk) 4 video channels – up to 6 video inputs Video Quad: 640x480 **Parametric Data Collected:** GPS Position GPS Speed Network Speed Turn signal Brake Accelerator position RPM	Trunk
Head Unit	Cabin audio 3 axis accelerometers 3 axis gyroscopes • Face Camera - VTTI CAMFV (NG Head Unit)	Behind rearview mirror

Device	Details	Location
	• 70° FOV (Standard Car Face View) • Horizontal = 64.5° • Vertical = 52.8° Forward Camera - Dallmeier (Inside NG Head Unit) • 80° FOV • Horizontal = 68.4° • Vertical = 54.6°	
Network Box 	Standard Variables Collected: Acceleration, Brake, RPM	Beneath driver side dashboard
Savari OBE 	Savari OBE S100	Trunk
Hard Drive	Data Collection Depository	Inside of DAS
Router 	ASUS RT-N12 Wireless-N300 Router	Trunk
DGPS 	Novatel Flexpak6	Trunk
Display Screen 	HDMI Feelworld 5" HD TFT LCD Monitor	Mounted on dashboard

Device	Details	Location
Display Mount 	Monitor mount	Dashboard
Novatel Antenn 	GPS-702-GGL	Mounted on the roof
DSRC/GPS Antenna 	Hirschmann antenna	Mounted on the roof

NextGEN Data Acquisition System (DAS):



Communication Ports:

- Ethernet Port
- Serial Port
- USB Port
- 3 CAN Ports (used for interfacing with vehicle networks)
- NTSC video ports

Onboard Wireless:

- Cellular
- Wi-Fi
- Bluetooth

Base Sensor Suite:

- Real Time H264 Encoding
- 4 multiplexed video channels permitting up to 6 total video inputs
- Machine Vision
- Lane tracker
- Face and Head Pose tracker
- Real Time G711 Encoding for capturing cabin audio
- Sound level meter
- 3 axis accelerometers
- 3 axis gyroscopes
- Radar
- Other sensors supported as needed

NextGEN Head Unit:

The Head Unit contains 3-axis accelerometer and 3-axis gyro. It can capture GPS and camera views: forward, cabin, and face.

Network Box:

Interface between vehicle and DAS collecting vehicle network variables.

Standard Variables Collected: Acceleration, Brake, RPM

DGPS: Novatel Flexpak6

Enclosures

FlexPak-G2™ OEMStar

Performance[1]

Channel Configuration
14 GPS L1
12 GPS L1 + 2 SBAS
10 GPS L1 + 4 GLO L1
8 GPS L1 + 6 GLO L1
8 GPS L1 + 4 GLO L1 + 2 SBAS
10 GPS L1 + 2 GLO L1 + 2 SBAS
7 GPS L1 + 7 GLO L1
14 GLO L1

Signal Tracking

GPS	L1
GLONASS	L1
SBAS	

Horizontal Position Accuracy (RMS)

Single Point L1	1.5 m
SBAS[2]	0.7 m
DGPS	0.5 m

Measurement Precision (RMS)

	GPS	GLO
L1 C/A code	5 cm	35 cm
L1 Carrier phase	0.6 mm	1.5 mm

Maximum Data Rate

Measurements	10 Hz
Position	10 Hz

Time to First Fix

Cold start[3]	65 s
Hot start[4]	35 s

Signal Reacquisition

L1	< 1.0 s (typical)

Time Accuracy

GPS[2,5]	20 ns RMS
GLONASS[5,6]	40 ns RMS

Velocity Accuracy	< 0.05 m/s RMS
Velocity[7]	< 515 m/s

Physical and Electrical

Dimensions	147 x 113 x 45 mm
Weight	313 g

Power

Input voltage	+ 6 to +18 VDC
Power Consumption[8]	0.6 W

Antenna LNA Power Output

Output voltage	5 V nominal
Maximum current	100 mA

Connectors

Power	4-pin LEMO
Antenna	TNC-female
USB	Mini-B
Serial Port	DB9 male
Input/Output Port	DB9 female

Communication Ports

1 RS-232	230,400 bps
1 RS-232 or RS-422	230,400 bps
1 USB port	12 Mbps

1 I/O port (PPS, Event 1, Position Valid, VARF)

Environmental

Temperature	
Operating	-40°C to +75°C
Storage	-40°C to +85°C
Humidity	95% non-condensing
Immersion	IEC 60529 IPX7
Vibration	MIL-STD-810F
Compliance	FCC, CE Industry Canada

Features

- Field upgradable software
- Auxiliary strobe signals including a configurable PPS output for time synchronization and event inputs

Included Accessories

- Serial cable (null)
- I/O cable
- USB cable
- Automotive 12 VDC power adapter with 6A slow-blow fuse

Optional Accessories

- GPS-700 series antennas
- ANT series antennas
- Serial cable (straight)
- FlexPak Heading Kit

Firmware Options

- ALIGN
- GL1DE
- RAIM
- API

(Source: http://www.novatel.com/assets/Documents/Papers/FlexPak6.pdf)

Novatel Antenna

GPS-702-GGL - L1/L2/L-Band, GPS+GLONASS kinematic, zero-offset antenna, TNC connector

Antennas

GPS-701-GG and GPS-702-GG

Performance

3 dB Pass Band

L1	1588.5±23.0 MHz (typical)
L2	1236±18.3 MHz (typical)

Out-of-Band Rejection

L1±100 MHz	30 dBc (typical)
L2±200 MHz	50 dBc (typical)
LNA Gain	29 dB (typical)

Gain Roll-Off (from Zenith to Horizon)

L1	13 dB
L2	11 dB
Noise Figure	**2.0 dB (typical)**
VSWR	≤2.0 : 1
L1-L2 Differential Propagation Delay	5 ns (maximum)
Nominal Impedance	50 Ω
Altitude	9,000 m

Physical and Electrical

Dimensions
185 mm diameter² x 69 mm

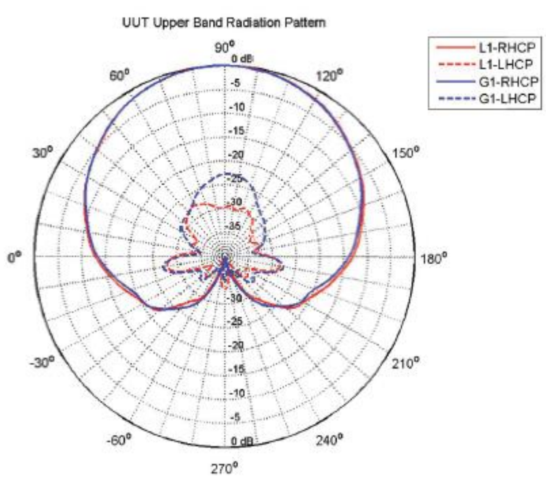
Weight	500 g
Power	
Input Voltage	+4.5 to +18.0 VDC
Power Consumption	35 mA (typical)
Connector	TNC female

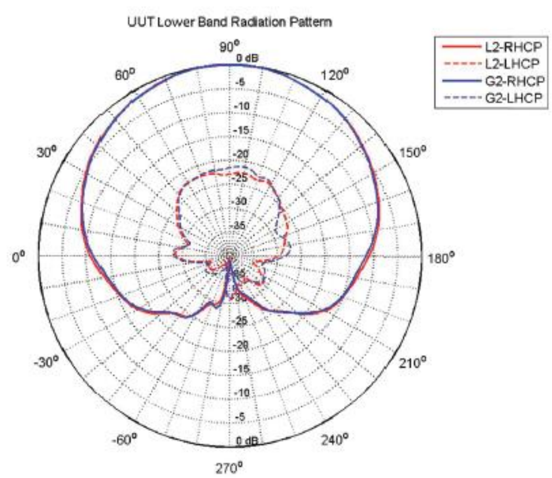
Environmental

Temperature	
Operating	-40°C to +85°C
Storage	-55°C to +85°C
Humidity	95% non-condensing
Vibration (operating)	
Random	MIL-STD-202F
Sinusoidal	SAEJ1211, Section 4.7
Shock	IEC 68-2-27 (Ea)
Bump	IEC 68-2-29 (Eb)
Salt Spray	MIL-STD-810F, 509.4
Waterproof	IEC 60529 IPX7
Compliance	FCC, CE
RoHS	EU Directive 2002/95/EC

Elevation Gain Patterns²

These plots represent the typical right-hand polarized (RHP) and left-hand polarized (LHP) normalized radiation patterns for the L1 frequency and the L2 frequency, respectively.





HDMI FEELWORLD 5" HD TFT LCD Monitor

Specification	
Display panel size	TFT LCD 5.0inch 1152000Pixels
Panel type	TFT LCD
Resolution	800*480
Max resolution	1920x1440
Horizontal frequency range	30-60kHz
Field frequency range	60Hz ~ 75Hz
Distance	0.045 (W) x 0.135 (H)
Display ratio	16:9
Brightness	350cd/m²
Contrast	500:1
Response time	10ms
Viewing angle	70°/70° (L/R); 50°/70° (U/D)
Backlight	LED
Signal input	HDMI, VIDEO, AUDIO
Supported format	480i, 480p, 576i, 576p, 720p, 1080i, 1080p
Video color system	PAL-4.43; NTSC-3.58
Input power voltage range	DC6-24V
Power consumption	≤7W
Standby current	≤50mA
Working temperature	-20~55°C
Storage temperature	-30~65°C
Size	146 x 100 x 39mm
Net weight (only the monitor)	260g

Savari OBE

PRODUCT SPECIFICATIONS FOR S100

Processor	500Mhz AMD Geode LX800
Memory	256MB DDR DRAM
Storage	512MB Compact Flash
DSRC Radio	IEEE 802.11a 5Ghz, 600mW 28dBm TX, -94dBm RX Sensitivity
WiFi Radio	IEEE 802.11b/g 2.4Ghz, 400mW 26dBm TX, -97dBm RX Sensitivity
Channel Width	5/10/20/40 Mhz
DSRC Antenna	5dBi@5GHz RP-SMA
WiFi Antenna	3dB @ 2.4GHz RP-SMA
Ethernet	One (1) 10/100 (RJ-45) port with Auto Uplink™
Console	standard RS-232C interface with DB-9 male connector
Power Supply	15V, 1.2A DC jack or Power over Ethernet. Car power adapter (12v, 2Amps)
Temperature	-31C to +75C
Form Factor	16cm X 10cm
GPS	SiRF STAR III e/LP, 20 channel, USB based. Accuracy: 5m 2D RMS w/ WAAS, 10m 2D RMS w/o WAAS
Bluetooth	Class II (10mtrs) USB dongle, 1 mW, +4 dBm TX power
Standards Compliance	IEEE 802.11 a/b/g/n, IEEE 802.11p, IEEE 1609.3, IEEE 1609.4
Security	WPA2, WPA, AES-CCMP, TKIP, 64/128bit WEP, IEEE 802.1x, MAC, IPSec & SSL
3G	AT&T 3G Sierra Wireless USB modem

DSRC Antenna: Hirschmann

RFC-195LL Extension cable 5.0M, DSRC Fakra Z-f (2x) waterproof
RFC-195LL Extension cable 5.0M, DSRC Fakra C-f (2x) waterproof

Head Unit Accelerometer and Gyroscope Specifications

A. Accelerometer Specifications:

Symbol	Parameter	Test conditions	Min.	Typ.(2)	Max.	Unit
FS	Measurement range(3)	FS bit set to 0	±1.7	±2.0		g
		FS bit set to 1	±5.3	±6.0		
Dres	Device resolution	Full-scale = ±2 *g* T = 25 °C, ODR1=40 Hz		1.0		mg
		Full-scale = ±2 *g* T = 25 °C, ODR2=160 Hz		2.0		
		Full-scale = ±2 *g* T = 25 °C, ODR3 = 640 Hz		3.9		
		Full-scale = ±2 *g* T = 25 °C, ODR4 = 2560 Hz		15.6		
So	Sensitivity	Full-scale = ±2 *g* 12 bit representation	952	1024	1096	LSb/g
		Full-scale = ±6 *g* 12 bit representation(4)	316	340	364	
TCSo	Sensitivity change vs temperature	Full-scale = ±2 *g* 12 bit representation		0.025		%/°C
Off	Zero-g level offset accuracy(5),(6)	Full-scale = ±2 *g* X, Y axis	-100		100	mg
		Full-scale = ±2 *g* Z axis	-200		200	
		Full-scale = ±6 *g* X, Y axis(4)	-100		100	
		Full-scale = ±6 *g* Z axis(4)	-200		200	
TCOff	Zero-g level change vs temperature	Max delta from 25 °C		0.2		mg/°C
NL	Non linearity(4)	Best fit straight line X, Y axis Full-scale = ±2 *g* ODR = 40 Hz		±2		% FS
		Best fit straight line Z axis Full-scale = ±2 *g* ODR = 40 Hz		±3		
CrAx	Cross axis(4)		-5		5	%

B. Gyroscope Specifications:

Parameter	Test Condition	Typical Specifications	Unit
Measurement Range	4x OUT (amplified)	±100	°/s
	OUT (not amplified)	±400	°/s
Sensitivity	4x OUT (amplified)	10	mV/ °/s
	OUT (not amplified)	2.5	mV/ °/s
Sensitivity change versus temperature	Delta from 25°C	0.037	%/°C

Asus Wireless Router (wired)

ASUS RT-N12 Wireless-N300 Router

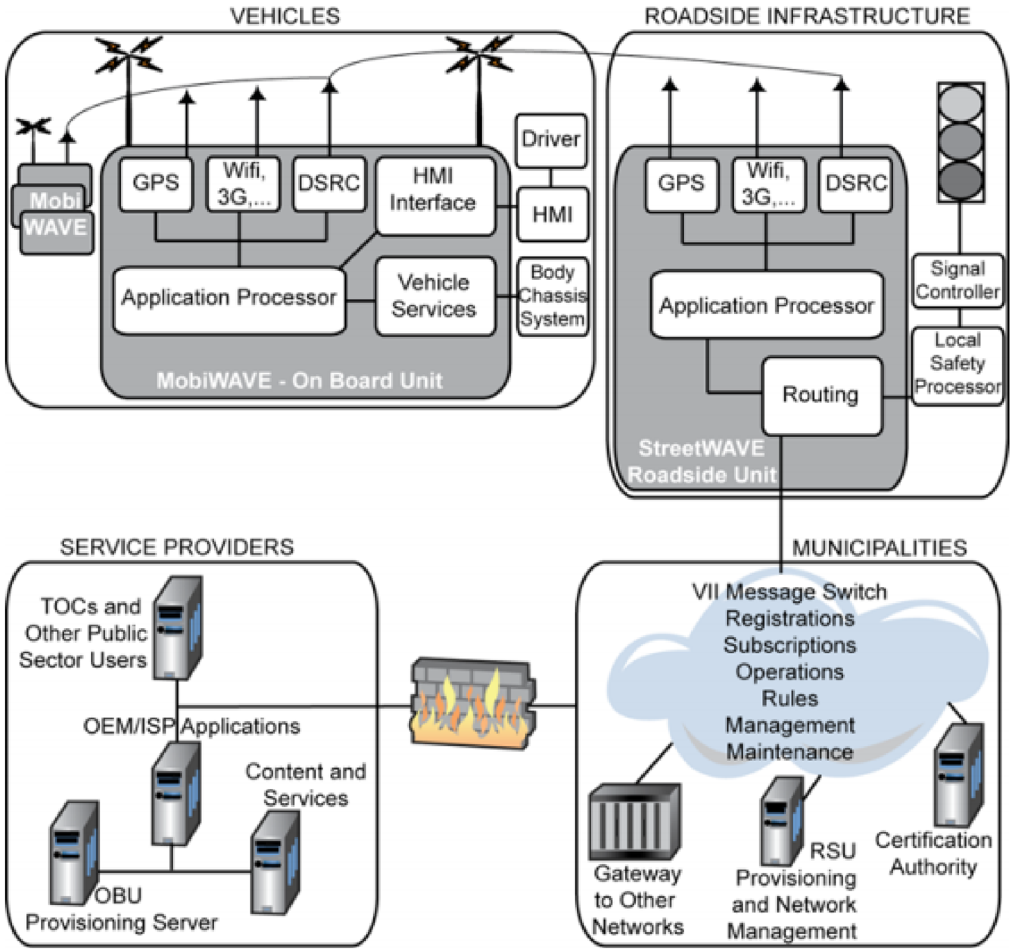
Network Standard	IEEE 802.11b, IEEE 802.11g, IEEE 802.11d, IEEE 802.3, IEEE 802.11i, IPv4
Product Segment	N300 complete networking; 300Mbps
Data Rate	802.11b : 1, 2, 5.5, 11Mbps 802.11g : 6,9,12,18,24,36,48,54Mbps 802.11n : up to 300Mbps
Antenna	Detachable dipole antenna x 2
Operating Frequency	2.4GHz
Encryption	64-bit WEP, 128-bit WEP, WPA2-PSK, WPA-PSK
Firewall & Access Control	Firewall: NAT and SPI (Stateful Packet Inspection), intrusion detection including logging Logging: Dropped packet, security event, Syslog Filtering: Port, IP packet, URL Keyword, MAC address Authentication: MAC address Access Control
Management	UPnP, DNS Proxy, DHCP
Utilities	Device Discovery: Discover router in network and help user to invoke Web Configuration page EZSetup: Help you to setup wireless and Internet connection easily Firmware Restoration: Restore firmware while system enters rescue mode
Ports	1 x RJ45 for 10/100 BaseT for WAN, 4 x RJ45 for 10/100 BaseT for LAN
Button	WPS Button, Reset Button
Power Supply	AC Input : 110V~240V(50~60Hz) DC Output : 12 V with max. 1 A current
OS Support	Windows® 8 , 32bit/64bit Windows® 7 , 32bit/64bit Windows® Vista , 32bit/64bit Windows® XP , 32bit/64bit Mac OS X Linux
Environmental	Operating Temperature: 0 °C to 40 °C (32 °F to 104 °F) Storage Temperature: -20 ° to 70 ° C (-4 °F to 158 °F) Operating Humidity: 10 % to 90 % (Non-condensing) Storage Humidity: 5 % to 95 % (Non-condensing)
Dimensions	179 x 119 x 37 cm (WxDxH)
Weight	300 g

StreetWAVE™ – Roadside Unit

Product Specifications

Component	Description
Processor	500Mhz AMD Geode LX800
Memory	256MB DDR DRAM
Storage	4GB Compact Flash
DSRC Radio	IEEE 802.11a 5Ghz, 600mW 28dBm TX, -94dBm RX Sensitivity
WiFi Radio	IEEE 802.11b/g 2.4Ghz, 400mW 26dBm TX, -97dBm RX Sensitivity
Channel Width	5/10/20/40 Mhz
DSRC & WiFi Antenna Connectors	N-Type Male
Ethernet	Two (2) 10/100 (RJ-45) ports with Auto Uplink™
Console	RS-232C interface
Power Supply	15V, 1.2A DC jack or Power over Ethernet.
Temperature	-31C to +75C
Dimensions	8" (L) x 8 1/2"(H) x 2 3/4" (D)
GPS	SiRF STAR III e/LP, 20 channel, USB based. Accuracy : 5m 2D RMS w/ WAAS, 10m 2D RMS w/o WAAS
Standards Compliance	IEEE 802.11 a/b/g/n, IEEE 802.11p, IEEE 1609.X
Security	WPA2, WPA, AES-CCMP, TKIP, 64/128bit WEP, IEEE 802.1x, MAC, IPSec & SSL
Enclosure	NEMA 67 rating, pole mount.

System Architecture



VII System Architecture

Traffic Signal Controller

Custom proprietary interface with D4 Controller

Laptop

Dell Latitude E6430s, Core i5 vPro

Appendix B. TSP Experiment Trials

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	43	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	57	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	7	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	48	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	63	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	42	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	46	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	55	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	5	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	50	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	61	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	44	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	45	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	56	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	6	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	49	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	2	sec.
Actual Overall Time to pass the intersection w/ TSP	65	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	40	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 4)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	4	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	53	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	3	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	52	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	63	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	42	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 5)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	5	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	46	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	50	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	90	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	55	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	63	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	42	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 6)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	6	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	43	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	57	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	7	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	48	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	2	Yellow
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	5	sec.
Actual Overall Time to pass the intersection w/ TSP	80	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	25	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 7)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	7	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	43	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	56	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	6	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	49	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	3	sec.
Actual Overall Time to pass the intersection w/ TSP	66	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	39	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 8)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	8	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	42	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	58	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	8	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	47	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	2	Yellow
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	5	sec.
Actual Overall Time to pass the intersection w/ TSP	70	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	35	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 9)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	9	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	41	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	58	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	8	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	47	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	4	sec.
Actual Overall Time to pass the intersection w/ TSP	67	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	38	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 40 Sec. of Original Signal (# 10)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	10	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	42	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	54	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	4	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	51	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	2	sec.
Actual Overall Time to pass the intersection w/ TSP	65	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	40	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 50 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	50	sec.
Bus Speed at 0.5 mile	40	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	59	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	19	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	36	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	95	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	2	sec.
Actual Overall Time to pass the intersection w/ TSP	58	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	37	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 50 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	50	sec.
Bus Speed at 0.5 mile	43	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	56	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	16	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	39	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	95	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	39	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 50 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	50	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	55	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	15	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	40	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	95	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	39	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 60 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	60	sec.
Bus Speed at 0.5 mile	43	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	56	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	26	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	29	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	85	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	29	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 60 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	60	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	54	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	24	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	31	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	85	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	1	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	29	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 60 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	60	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	56	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	26	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	29	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	85	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	29	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 70 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	70	sec.
Bus Speed at 0.5 mile	45	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	55	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	35	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	20	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	75	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	1	sec.
Actual Overall Time to pass the intersection w/ TSP	58	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	17	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 70 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	70	sec.
Bus Speed at 0.5 mile	43	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	57	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	37	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	18	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	75	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	3	sec.
Actual Overall Time to pass the intersection w/ TSP	59	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	16	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 70 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	70	sec.
Bus Speed at 0.5 mile	46	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	54	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	34	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	21	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	75	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	55	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	20	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 80 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	80	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	54	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	44	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	11	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	65	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	54	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	11	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 80 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	80	sec.
Bus Speed at 0.5 mile	43	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	57	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	47	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	8	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	65	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	9	sec.

Speed Limit = 45 mph, Regular GPS, and Starting at 80 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_1	
GPS	Regular	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	80	sec.
Bus Speed at 0.5 mile	46	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	53	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	43	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	12	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	65	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	1	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	9	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 40 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	49	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	50	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	90	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	55	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	64	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	41	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 40 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	47	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	52	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	2	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	53	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	2	sec.
Actual Overall Time to pass the intersection w/ TSP	65	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	40	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 40 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	40	sec.
Bus Speed at 0.5 mile	46	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	54	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	4	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	51	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	105	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	62	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	43	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 50 Sec. of Original Signal (# 1)

	Experiment Summary		
	Driver	Driver_2	
	GPS	Diff.	
	Trial	1	
	Speed	45	mph
	Cycle length	90	sec.
	Red	55	sec.
	Green	30	sec.
	Yellow	3	sec.
	All Red	2	sec.
No	Start Time of Cycle length	50	sec.
	Bus Speed at 0.5 mile	44	mph
	Estimated TT at 0.5 mile w/o TSP (from start point)	55	sec.
	Predicted Cycle length arrival time at 0.5 mile w/o TSP	15	sec.
	Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
	Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	40	sec.
	Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	95	sec.
	Actual Light Ball State EB at Intersection w/ TSP	#N/A	#N/A
	TSP Success Status based on the Actual Light Ball State EB at Intersection	#N/A	
	Green Extension at Intersection	#N/A	
	Green Extension at Intersection (Duration)	0	sec.
	Actual Overall Time to pass the intersection w/ TSP	#N/A	sec.
	Evaluation		
	#N/A		
	#N/A	#N/A	sec.

Note: An error occurred during this trial.

Speed Limit = 45 mph, Differential GPS, and Starting at 50 Sec. of Original Signal (# 2)

Experiment Summary			
Driver		Driver_2	
GPS		Diff.	
Trial		2	
Speed		45	mph
Cycle length		90	sec.
Red		55	sec.
Green		30	sec.
Yellow		3	sec.
All Red		2	sec.
Start Time of Cycle length	*Component I*	50	sec.
Bus Speed at 0.5 mile		#N/A	mph
Estimated TT at 0.5 mile w/o TSP (from start point)		#N/A	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP		#N/A	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP		#N/A	#N/A
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP		#N/A	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP		#N/A	sec.
Actual Light Ball State EB at Intersection w/ TSP		#N/A	#N/A
TSP Success Status based on the Actual Light Ball State EB at Intersection		#N/A	
Green Extension at Intersection		#N/A	
Green Extension at Intersection (Duration)		0	sec.
Actual Overall Time to pass the intersection w/ TSP		#N/A	sec.
Evaluation			
#N/A			
#N/A			
#N/A		#N/A	sec.

Note: An error occurred during this trial.

Speed Limit = 45 mph, Differential GPS, and Starting at 50 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	50	sec.
Bus Speed at 0.5 mile	47	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	53	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	13	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	42	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	95	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	54	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	41	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 50 Sec. of Original Signal (# 4)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	4	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	50	sec.
Bus Speed at 0.5 mile	50	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	51	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	11	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	44	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	95	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	54	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	41	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 60 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	60	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	54	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	24	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	31	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	85	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	2	sec.
Actual Overall Time to pass the intersection w/ TSP	57	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	28	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 60 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	60	sec.
Bus Speed at 0.5 mile	47	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	53	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	23	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	32	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	85	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	3	sec.
Actual Overall Time to pass the intersection w/ TSP	59	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	26	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 60 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	60	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	55	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	25	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	30	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	85	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	2	sec.
Actual Overall Time to pass the intersection w/ TSP	58	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	27	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 70 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	70	sec.
Bus Speed at 0.5 mile	46	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	53	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	33	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	22	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	75	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	55	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	20	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 70 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	70	sec.
Bus Speed at 0.5 mile	47	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	51	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	31	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	24	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	75	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	54	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	21	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 70 Sec. of Original Signal (#3)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	70	sec.
Bus Speed at 0.5 mile	49	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	47	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	27	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	28	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	75	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	No	
Green Extension at Intersection (Duration)	0	sec.
Actual Overall Time to pass the intersection w/ TSP	51	sec.
Evaluation		
TSP was successful!		
TSP Performance was better than w/o TSP! ==========>	24	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 80 Sec. of Original Signal (# 1)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	1	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	80	sec.
Bus Speed at 0.5 mile	44	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	54	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	44	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	11	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	65	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	1	sec.
Actual Overall Time to pass the intersection w/ TSP	56	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	9	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 80 Sec. of Original Signal (# 2)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	2	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	80	sec.
Bus Speed at 0.5 mile	46	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	52	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	42	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	13	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	65	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	3	sec.
Actual Overall Time to pass the intersection w/ TSP	57	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	8	sec.

Speed Limit = 45 mph, Differential GPS, and Starting at 80 Sec. of Original Signal (# 3)

Experiment Summary		
Driver	Driver_2	
GPS	Diff.	
Trial	3	
Speed	45	mph
Cycle length	90	sec.
Red	55	sec.
Green	30	sec.
Yellow	3	sec.
All Red	2	sec.
Start Time of Cycle length	80	sec.
Bus Speed at 0.5 mile	39	mph
Estimated TT at 0.5 mile w/o TSP (from start point)	60	sec.
Predicted Cycle length arrival time at 0.5 mile w/o TSP	50	sec.
Predicted Light Ball State EB based on ETT at 0.5 mile w/o TSP	1	Red
Predicted Waiting Time at Intersection based on ETT at 0.5 mile w/o TSP	5	sec.
Predicted Overall Time to pass the Intersection at 0.5 mile w/o TSP	65	sec.
Actual Light Ball State EB at Intersection w/ TSP	3	Green
TSP Success Status based on the Actual Light Ball State EB at Intersection	Yes	
Green Extension at Intersection	Yes	
Green Extension at Intersection (Duration)	3	sec.
Actual Overall Time to pass the intersection w/ TSP	58	sec.
Evaluation		
TSP was successful with Green Extension!		
TSP Performance was better than w/o TSP! ==========>	7	sec.