

TRANSIT SIGNAL PRIORITY WITH CONNECTED VEHICLE TECHNOLOGY

Prepared by

The University of Virginia



**The Pennsylvania State University ❖ University of Maryland
University of Virginia ❖ Virginia Polytechnic Institute and State
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16. Abstract A new TSP logic was proposed, taking advantage of the resources provided by Connected Vehicle (CV) technology, including two-way communication between the bus and the traffic signal controller, accurate bus location detection and prediction, and the number of passengers. The TSP logic used was green time re-allocation, which only moves green time instead of adding extra green time. The TSP was also designed to be conditional. That is, delay per person was used as one of the most important criteria to decide whether TSP is to be granted. The logic developed in this research project was evaluated in two ways with analytical and microscopic simulation approaches. In each evaluation, the proposed TSP was compared against two scenarios: no TSP and conventional TSP. The measures of effectiveness used were bus delay and per person delay of all traffic users. Evaluation results show that the proposed TSP logic reduces bus delay from 84% to 9% compared to conventional TSP and from 88% to 36% compared to the no-TSP condition. The range of improvement corresponds to the four different v/c ratios tested, which are 0.5, 0.7, 0.9, and 1.0. No negative effects were caused by the proposed TSP logic.			
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1 Introduction

The transit bus, as a transportation mode, is presently being utilized in almost every city around the world. By its nature, the transit bus is designed to efficiently move large numbers of passengers through areas with dense population. Because of this, many believe that preference should be given to transit buses at signalized intersections. By having the traffic signal plan adjusted according to bus arrivals, the delay that transit buses experience at intersections would be reduced, and therefore, travel time can be saved and transit service quality can be increased. This action of providing preference to transit buses is referred to as Transit Signal Priority (TSP).

Conventionally, TSP is activated when a transit bus sends out a request when it is approaching the traffic signal-controlled intersection. In most cases, the logic of TSP is a simple extension to or early start of its original green time. To decide which logic should be used, a quick calculation is performed on site, driven by a bus arrival time model based on historical data. If the bus is expected to arrive shortly before its original green time, the green time starts early; if the bus is expected to arrive shortly after its original green time, the green time is extended. This type of TSP logic is restricted in many ways. Most importantly, because the data fed into the model are either outdated or not accurate, the bus arrival time forecast could be severely biased. The inaccurate forecast of bus arrival time could lead to the waste of extra TSP green time and cause unnecessary adverse effects on side streets. Additionally, even with extension and/or early start, conventional TSP green time can only cover a small portion of a traffic signal cycle; therefore, a large portion of the buses may not benefit from employing TSP.

To properly address these problems, a more sophisticated algorithm is needed which would provide service to a greater proportion of transit buses and would consider progression between adjacent intersections. This cannot be easily accomplished using inaccurate and outdated data collected from conventional sensors, such as loop detectors or video cameras. Therefore, it is necessary to strengthen conventional TSP with the new, emerging technology called “Connected Vehicle.” This technology puts diagnostic sensors onto vehicles and collects data transmitted wirelessly between vehicles and nearby infrastructures. Instead of relying on conventional data collection equipment, it collects more accurate information. Additional measurements that were previously unavailable include vehicle speeds, positions, arrival rates, rates of acceleration and deceleration, queue lengths, number of passengers, and stopped time.

With this extra information, many applications are made possible. These applications are usually categorized into improving safety, enhancing mobility, and minimizing environmental impact. It is important to understand that not all applications share the same interest among state and local transportation agencies, but TSP with Connected

Vehicle is one of the Connected Vehicle applications that best serve the interests of transportation agencies and their constituents. According to the AASHTO Connected Vehicle Infrastructure Deployment Analysis [1], TSPCV is one of the key applications that would enhance mobility. It is also confirmed by the USDOT, which includes TSPCV in its list of High-Priority Dynamic Mobility Applications [2].

TSPCV is one of the few applications that would generate benefits even at the early stage of a Connected Vehicle system rollout. By nature, transit buses are typically good targets for equipping highly customized electronic devices. According to 2006 data, the number of transit buses deployed in the United States is around 70,000 [1]. Therefore, the cost of investing in TSP would be relatively modest compared to other applications, which may require almost ubiquitous coverage for effectiveness. Putting aside the cost, it will take time for Connected Vehicle to reach a certain level of market penetration. It has been forecasted by the AASHTO research team that at least 10 years will be necessary for Connected Vehicle to reach 90% of market penetration [1]. This is an optimistic forecast, given that the FHWA predicts 9 years for market rates to reach 50% and 30 years to reach 90% [3]. The growth rate would follow an S-Curve, which means low initial growth, max middle years growth, and flatter growth in later years. In other words, a long period of time is expected before the Connected Vehicle market rate rises above 50%, and that is under the assumption of mandatory devices in new cars. In the worst case, without mandate, the market rate could possibly level off before it reaches 90%. This is exactly the case with Anti-lock Braking Systems [1].

Although the importance of TSP with Connected Vehicle has been identified by most agencies, the mechanism of how TSPCV works is yet to be determined. An up-to-date definition of TSPCV is found in “Updated description on USDOT High-Priority Dynamic Mobility Applications” [2]. This guideline proposes that, when equipped with on-board equipment, transit vehicles should be able to communicate information such as passenger count data, service type, scheduled and actual arrival time, and heading information to roadside equipment via Dedicated Short Range Communications (DSRC). Clearly, this definition is not sufficient for field implementation.

Therefore, in this research, the team developed a new TSP method designed to fully realize the Connected Vehicle technology based on two-way communications between transit bus and traffic signal, and among the transit buses and vehicles. This next-generation Transit Signal Priority would not have to rely on conventional TSP sensors. This is because CV technology will provide better real-time information of bus location and number of passengers to support the proposed TSP logic. It is expected that with better data, bus arrival time could be predicted with higher accuracy. Therefore, with the help of CV technology, the logic of TSP could be more flexible than simple “green extension” or “red truncation.” The CV-based logic will grant extra TSP green time more

precisely to where it is most needed. Less waste of extra TSP green time would mean a less adverse side-streets effect.

The remainder of this report reviews the relevant literature, explains the need for research, states the rationale of TSPCV, presents test results and findings, and identifies the contributions.

2 Literature Review

This literature review was undertaken to understand the need to research this area and to understand the state-of-the-art of TSP logic. This section organizes the discussion of literature into four sections: conventional TSP logic, state-of-the-art TSP logic for one-bus scenario, TSP in Virginia, and TSP evaluation.

2.1. Conventional TSP Logic

For years, Transit Signal Priority has been proposed and studied as an efficient way of improving transit operation. It provides preference to transit at traffic signalized intersections and has potential in reducing transit travel time and improving schedule adherence and customer ride quality. Furthermore, it has also been shown that TSP has the ability to cancel out some of the adverse effects of outdated timing plans [4]. The technology has been applied in many cities in Europe, Asia, and North America. In the United States, the cities of Seattle, Portland, Los Angeles, Chicago, and other large cities have implemented conventional TSP systems [5].

However, conventional TSP shows shortcomings, which have limited the promotion of TSP. One big disadvantage is its adverse effect on side streets. Especially for intersections that are nearly operating at their capacity, the benefit of adding TSP is controversial [6]. Another potential challenge of the current TSP is bus arrival time prediction. Because of the uncertainty of buses' arrival times, the extended green time usually takes a large portion of the green time that is supposed to be assigned to side streets. In some cases, the bus would arrive in the next cycle without taking advantage of any of the green time extended, while the vehicles on the side street keep waiting and accumulating delay time. This causes significant adverse effects on traffic.

In Canada, a project team consisting of professionals from a wide range of municipalities representing both traffic and transit agencies once developed a list of issues related to

TSP [7]. In the United States, transportation and emergency personnel from the Washington, D.C. area have identified questions about and reservations against the deployment of TSP systems [8]. Together, a list of needs, issues, and concerns related to TSP was made to guide this research. The list is presented as follows:

- A balance needs to be maintained between transit and non-transit users. It is the goal to reduce transit signal delay, but it is also important to consider the impact on side streets.
- Minimizing transit travel time will improve schedule flexibility and reduce operation cost.
- Improvement on schedule adherence is as important as travel time savings.
- Bus priority system should be included in a larger ITS system with improved rider information.

2.2. State of the Art TSP for One Bus Scenario

To address the shortcomings of conventional TSP technology, research efforts have been dedicated to finding advanced TSP logic. Advanced TSP, also known as intelligent TSP, improves on conventional TSP in three essential aspects: arrival time prediction module, TSP logic library, and selective priority.

For the arrival time prediction module, unlike conventional TSP, which uses fixed location check-in and check-out detectors [6], intelligent TSP takes advantage of automatic vehicle location (AVL) systems that are common on transit buses today [5][9][10][11][12]. The upgraded AVL hardware helps TSP logic respond to real-time traffic and transit conditions, which is critical to arrival time prediction. The better precision of traffic and transit information greatly improves the accuracy of bus arrival time prediction. In addition to hardware upgrades, Lee et al. [9] took TSP one step further and proposed to use a high-performance online microscopic simulation model for the purpose of predicting transit travel time. Nevertheless, not all prediction models are so complicated; for example, Ekeila et al. [11] utilized a simple linear model based on historical data.

A number of new TSP strategies have been added to the TSP logic library. Apart from the basic TSP strategies, which are “green extension,” “red truncation,” and “phase skipping” [9], green time extension at other phase transitions is made possible with higher transit information precision [10]; cycle extension has been proposed and found to be beneficial during rush hours [11]; compensation has been introduced to limit the adverse effects on side streets by cutting or skipping the time from the non-bus phase, and finally combining TSP consideration into adaptive signal control [5] [12]. All of

these strategies aim for one goal: maximizing the benefits of TSP while minimizing the negative impact on side streets.

Selective priority is also an enhancement to TSP that is meant to reduce adverse effects on non-transit users. Balke et al. [10] and Skabardonis [13] proposed that TSP logic should consider selective priority, which means to grant priority only to transit buses that meet certain requirements, such as deviation from schedule or average headway. This kind of TSP requires additional mechanisms to determine if the bus meets the criteria. The mechanism will make sure that no unnecessary delay is added to non-transit users, for instance, if the bus is on schedule. A secondary benefit of granting selective priority is less transit travel time variability. Unreliability in service can increase uncertainty and anxiety among passengers [14]. By improving schedule adherence, better public transportation service would be achieved. A simulation study on conditional TSP has shown that selective priority would bring statistically significant improvements of 3.2% in bus service reliability and 0.9% for bus travel time [15].

It is noted that there is no completed research strengthening TSP with Connected Vehicle technology. Currently, there is one ongoing project that aims at designing a multi-modal intelligent traffic signal system that would operate in a Connected Vehicle environment – the Multi-Modal Intelligent Traffic Signal System (MMITSS) project [16]. This MMITSS project investigates TSP at a high level without developing actual algorithms under a connected vehicle environment.

2.3. TSP in Virginia

A few TSPs have been installed in Virginia, and one of them has been studied [17][18]. The study corridor is part of US 1 (i.e., Richmond Highway) in Northern Virginia, which extends over 8 miles and covers a total of 27 traffic-signalized intersections. Both field evaluation and simulation studies were performed. Interestingly, this report is the only documented field evaluation found so far of TSP. The logic used in this TSP system was simple “green extension,” even though the system was equipped with Global Positioning System (GPS) receivers providing bus location information at a second-by-second resolution. The field implementation showed that there was no statistically significant benefit produced by the TSP system and the simulation study confirmed the field evaluation. The simulation study also revealed that the performance of TSP was not influenced by congestion level, frequency of transit vehicles, or bus stop location. A closer investigation of that particular TSP system indicated at least two possible reasons why the benefit was insignificant. First, the TSP logic on that corridor was too simple (only green extension of 5 seconds at a 180-second cycle length). As a result, only a

small portion (i.e., 2.8%) of the buses took advantage of TSP. The time saved from such a small proportion does not make a big difference, nor was the adverse effect significant. Second, the progression between adjacent intersections was not coordinated. Five out of the 27 intersections in the study area were not equipped for TSP. Hence, the time savings of a bus gained from a TSP-equipped intersection would be canceled out by stopping at non-TSP intersections. It should be noted that the City of Arlington is not currently operating buses equipped with TSP on this portion of the US 1 corridor.

2.4. TSP Evaluations

The benefits of implementing TSP vary significantly from site to site. Table 1 summarizes TSP benefits and dis-benefits from various research efforts. The travel time savings could be as low as 2% [10] or as high as 71% [12]. Therefore, it is necessary to perform an evaluation of new TSP logic at specific sites before implementation. Although TSP has been installed in many cities, it appears that very few of them were followed up and evaluated after installation. The most common way to evaluate TSP logic is through simulation; only one out of 13 studies investigated the performance benefits based on field testing [17]. Various simulation models have been utilized in the past, including PARAMICS [9], AIMSUN [5], TexSIM [10], VISSIM [11][13], NETSIM [4][12], and WATSim [6]. Some models require C programming language to accommodate this new bus arrival time prediction model [9]. Some require C++ programming to set up the communication between the simulator and an external TSP application [5].

Table 1 Summary of TSP Benefits/Disbenefits Based on Simulation Evaluation

Location	TSP Type	Measurements		Result	Reference
Hypothetical Intersection	TSP with AVL	average bus delay	non-peak	24.81% decrease	[9]
			peak	-28.92%	
		side street delay		23.30%-55.23% increase	
Minneapolis	TSP with AVL	Bus travel time	AM peak	12- 15% decrease	[5]
			PM peak	4- 11% decrease	
Hypothetical network with 3 intersections	TSP with AVL	stop delay	veh in Bus' direction	6%-10% decrease	[10]
			cross street	2% - 26%	
Vancouver	TSP with AVL	Bus travel time		33%	[11]
		cross street delay		Not significant	
Newark, NJ	Conventional	travel time	Bus	10%- 20% decrease	[4]
			auto (main st)	5%-10% decrease	
Hypothetical Intersection	Adaptive TSP	Total delay		3.04%-71.03% decrease	[12]
Ann Arbor, Michigan	Conventional	delay	bus	little benefit	[6]
			auto	increase	
Arlington, Virginia	TSP with AVL	reliability		3.20%	[14]
		Bus travel time		-0.90%	
		Total delay	per veh	1%	
per person	0.60%				
Portland, OR, Pilot Routes	N/A	Bus Travel Time		10% decrease	
		On-Time Performance		8%-10% improvement	
Seattle, WA, Rainier	N/A	Priority Bus Delay		34% decrease	
		Bus Intersection Stops		24% decrease	
		Bus Travel Time		8% decrease	
Los Angeles, CA, Metro Rapid	N/A	Bus Travel Time		8%-10% decrease	
Bremerton, WA	N/A	Bus Travel Time		10% decrease	
		Stopped Delay/Vehicle		Insignificant	
Chicago, IL, Cermak	N/A	Bus Travel Time		2-3-min decrease from 13-17 min	

3 Logic Architecture Description

Based on the background information collected, it is clear that several aspects can be improved for the current TSP strategies. First, combining TSP with Connected Vehicle technology is believed to be beneficial. This is because CV technology may provide better real-time information of bus location and number of passengers to support better TSP performances. Second, with the help of CV technology, the logic of TSP could be more flexible than simple “green extension” and/or “red truncation.” The CV-based logic will grant extra TSP green time more precisely to where it is most needed. The less waste of extra TSP green time, the less adverse side street effects will be. Third, the logic of TSP should be able to resolve the conflict between general traffic users and public transportation users and find an optimal balance.

The proposed logic is based on the idea that the bus could cooperate with the traffic signal to perform TSP. In contrast to current TSP logic, where a bus approaching an intersection sends a priority request and the traffic controller tries to accommodate it without additional interactions, the proposed logic would include cooperation between the bus and the traffic signal controller. The cooperation would require a bus to travel at a reasonable speed, which is recommended based on road geometry, a normal signal timing plan, and the remaining/expected queue. The proposed TSP logic would implement the 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 mostly needed by a transit bus. Furthermore, in addition to schedule adherence, the logic would account for delay per person as a conditional criterion to grant the TSP green time. The delay per person measurement indicates the trade-off between travel time saved by the bus and travel time wasted by side streets. Therefore, the logic is expected to have more control on adverse side effects than basic “green extension” and “red truncation.” Connected Vehicle technology will provide two-way communication between the bus and the traffic signal controller, including accurate bus location detection and prediction, and the number of passengers. Figure 1 shows the architecture of the proposed TSP with Connected Vehicle technology for the One Bus Scenario with a near-side bus stop. This TSP logic is composed of three major components:

1. Arrival time prediction component, in which two time ranges are predicted: bus arrival time ranges at the bus stop as well as at the subject intersection.
2. TSP timing plan and bus speed calculation component, in which, given the arrival time ranges, the algorithm generates a timing plan that will have minimum impact on general traffic users and calculates corresponding recommended bus speed.

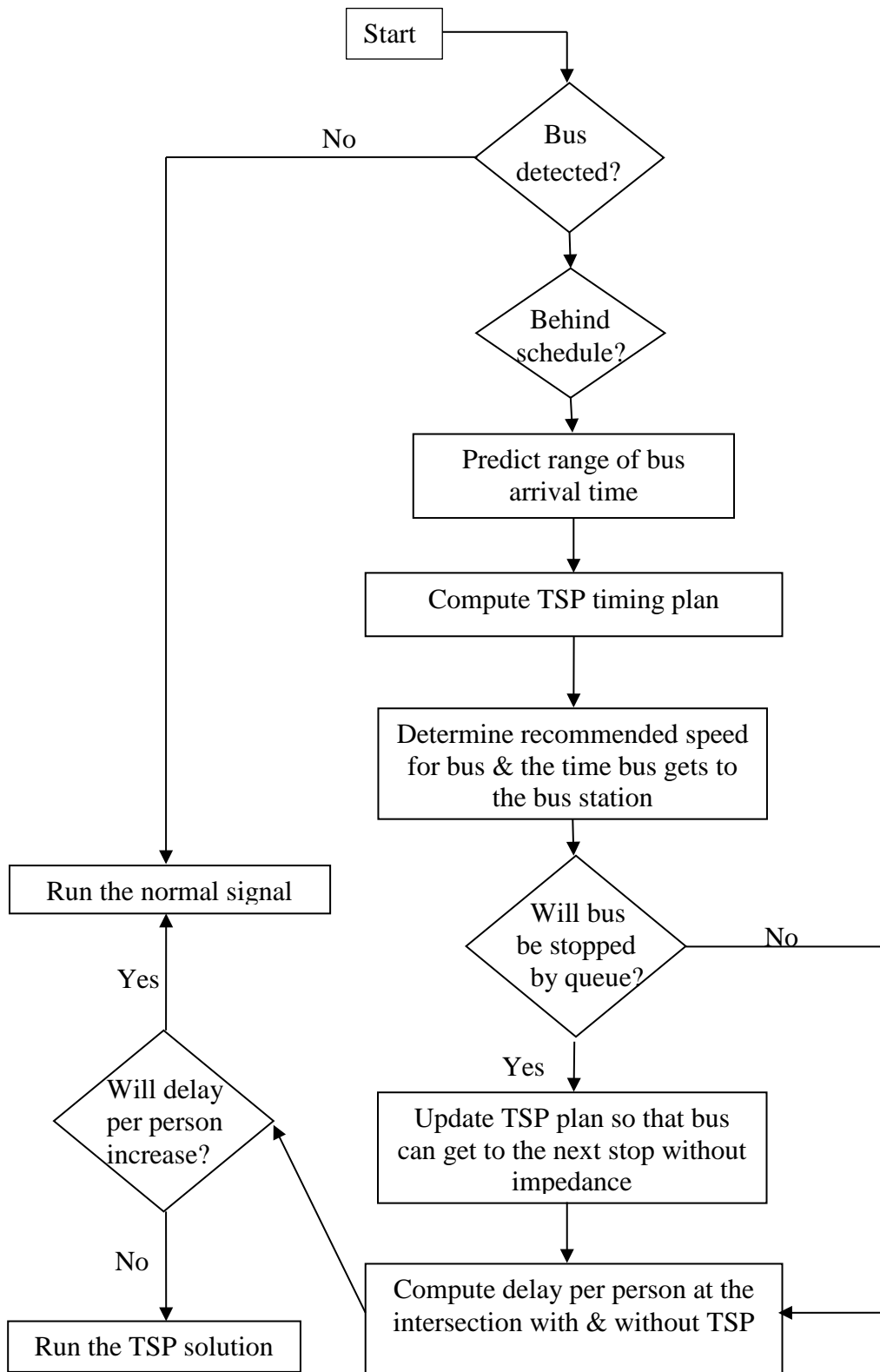


Figure 1 One Bus Scenario with Near-side Bus Stop

3. Logic assessment and implementation component, in which the TSP timing plan will be compared against the normal signal time (winner overwrites the other) and the recommended bus speed will be transmitted to the coming bus.

3.1. Arrival time prediction component

One of the great advantages of integrating TSP into a CV system is having more information with better quality. Most importantly, the passenger counts on buses and potential passenger counts at the bus stops could be obtained. Utilizing this information, dwell time at the bus stops can be predicted more accurately.

Another feature of CVs of which this study takes advantage is the two-way communication between roadside equipment (RSE) and traffic users, which in this case is the bus. A CV-equipped bus communicates with the traffic signal controller 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 fixed number; instead, it is a range of time. The range of arrival time is given so that the bus can adjust its travel at various speeds to cooperate with TSP strategy.

With the proposed logic, the arrival time is calculated using a simple equation derived from physics. The queue in front of the bus will be cleared before bus arrival at the stop bar. Thus, the movement of the bus with near-side bus stop will be: (i) slowing down as it approaches at the bus stop, (ii) dwelling at the bus stop for a known period of time (e.g., 30 seconds), (iii) departing the bus stop and speeding up until it reaches the recommended/desired speed, and (iv) passing the intersection. For a far-side bus stop, there will be no deceleration and acceleration at the bus stop. In this step, upper and lower boundaries of arrival time at the bus stop and at the intersection are calculated to generate an expected range of arrival time.

$$T_{BusArrival} = T_c + T_{dec} + T_{acc} + T_{dwell}$$

Where:

T_c : Travel time at constant speed

T_{dec} : Travel time that bus spends decelerating

T_{acc} : Travel time that bus spends accelerating

T_{dwell} : Time bus stopped at the bus stop

3.2. TSP timing plan and bus speed calculation component

The TSP timing plan is calculated based on the goal that TSP green is inserted to exactly where it is needed for the duration it is needed. The cycle length will be the same even when the TSP green is inserted, because the TSP green time is spliced from the original green time of the direction in which the bus travels. So strictly speaking, the extra TSP green time is “moved” rather than “inserted” or “added.” TSP green time is designed such that the bus will catch up with the end of the queue right at the stop bar of the intersection. The advantage of this approach is twofold:

1. Queue is cleared before the bus arrives at the intersection.
2. The inserted green time taken from the certain direction is 100% used in clearing traffic for that direction. Therefore, theoretically speaking, not a single second is wasted during the TSP.

The calculation of the real-time queue length estimation is based on the model developed by Liu [19], which is an extension of shock wave theory.

The range of predicted bus arrival time was passed on from the last step for TSP timing plan calculation. Therefore, the computation finds a range of TSP green start time and end time. While there will be numerous TSP timing plans depending on when the bus arrives, the following rules were used in calculating the TSP timing plan:

1. A TSP green time is preferred to start at the end of phase rather than to cut into the middle of a phase (for better safety and drivers’ expectation).
2. If a TSP green has to start in the middle of a phase, it is preferred that the bus travels at its normal speed.
3. Minimum green time is required for both the TSP green time and the original timing plan.

Based on these rules, the algorithm would find optimal TSP start and end times from the time range that TSP can possibly start and end. Once the timing plan is generated, the recommended bus speed could then be computed so that bus will travel through the intersection right after the queue in front is cleared and before the TSP green phase ends.

Then, for the scenario with a near-side bus stop, there will be an extra step to update the timing plan in case of extraordinarily high volume. Since a bus stop is located on a bus’ way to the intersection, it is possible that the queue in front would block the bus from loading and unloading. Then the previously predicted arrival time would no longer be accurate. In that case, the bus would miss the inserted TSP green. This situation cannot be anticipated until the speed of the bus is found. Therefore, after the recommended speed of the bus is computed, the logic is designed to double check if queue spillback happens

with the initial TSP timing plan. In case queue spillback does happen, the TSP timing plan would be adjusted so that the bus can get to the station without impedance. However, the bus will have to wait for the normal green time to traverse through the intersection after it finishes loading and unloading.

3.3. Logic assessment and implementation component

After a TSP timing plan is determined, the algorithm would compare the “with TSP” scenario against the “normal timing” scenario. Since the number of passengers on board is likely to be known under the CV environment, a person delay performance measure is to be used. The person delay will be calculated for three consecutive signal cycles starting from the TSP implemented cycle. In this study, a TSP timing plan would be implemented only when its corresponding person delay is less than the “no TSP” scenario.

During the 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 in case the bus is not expected to make it to the intersection. The TSP green time would be extended up to 5 seconds to accommodate the random delay.

4 Evaluations

Both analytical tests and simulation evaluations were performed for the proposed TSP as well as for conventional TSP and no TSP cases. The test network is a calibrated model of the intersection at Emmet Street and Barracks Road in Charlottesville, Va., as shown in Figure 2. Vehicle volumes and turning movements are real morning peak-hour data collected from the site. In order to verify that the findings from the experiment were consistent with various congestion levels, a sensitivity analysis was also conducted. Four scenarios were tested: $v/c=0.5$, $v/c=0.7$, $v/c=0.9$, and $v/c=1.0$. Although there were currently no buses passing through the intersection, the research assumed a bus was traveling NB on Emmet Street with a mid-block bus stop located 750 ft upstream of the intersection. The speed limit on Emmet Street is 40 mph; therefore, buses are allowed to travel within the speed range between 30 mph and 45 mph. The TSP logic is activated when buses pass 0.5 mile upstream of the intersection.

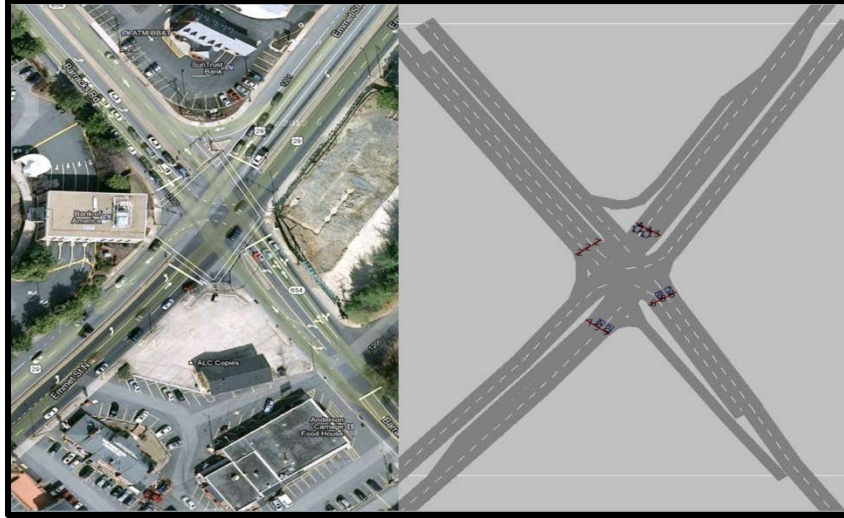


Figure 2 Study Site—Emmet Street and Barracks Road Intersection, Charlottesville, Va.

Both analytical tests and simulation evaluations compared three scenarios: without TSP (NTSP), conventional TSP (CTSP), and TSP with Connected Vehicle. The conventional TSP logic compared here is TSP with AVL and an on-board passenger counting system. In other words, CTSP is the state-of-the-art TSP plus a more accurate bus arrival time forecasting 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. It is designed that CTSP will grant 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 could not make it through the intersection within that 10 second period, CTSP will augment the previous 10 seconds with up to 5 additional seconds to accommodate the late arrival.

4.1. Analytical test

The cycle length at the intersection was 160 seconds. Assuming a TSP can be activated at any given second, there are 160 possible situations. Travel times for a bus and for all traffic users are calculated for these 160 situations. Figure 3 shows bus travel times associated with various buses activating TSP over the cycle length at the intersection. The blue bars are bus travel time without TSP and red bars are travel time with TSPCV. It is observed that on part of the chart two scenarios overlap with each other. This is when a bus would travel through the intersection within the original green time without any impedance. Therefore, it is reasonable to see that maximum time savings occurs right after the end of the original green time and that savings decrease with time.

Another interesting observation is that bus travel time with TSPCV is not a fixed value; rather, it fluctuates with time. This is due to the rule specifying that TSP is preferred to

start from the end of the phase rather than to cut into the middle of a phase or the minimum green time requirement. In these cases, the bus would have to travel faster or slower than its normal speed. As a result, travel time varies, but still, transit buses are not stopped at the intersection.

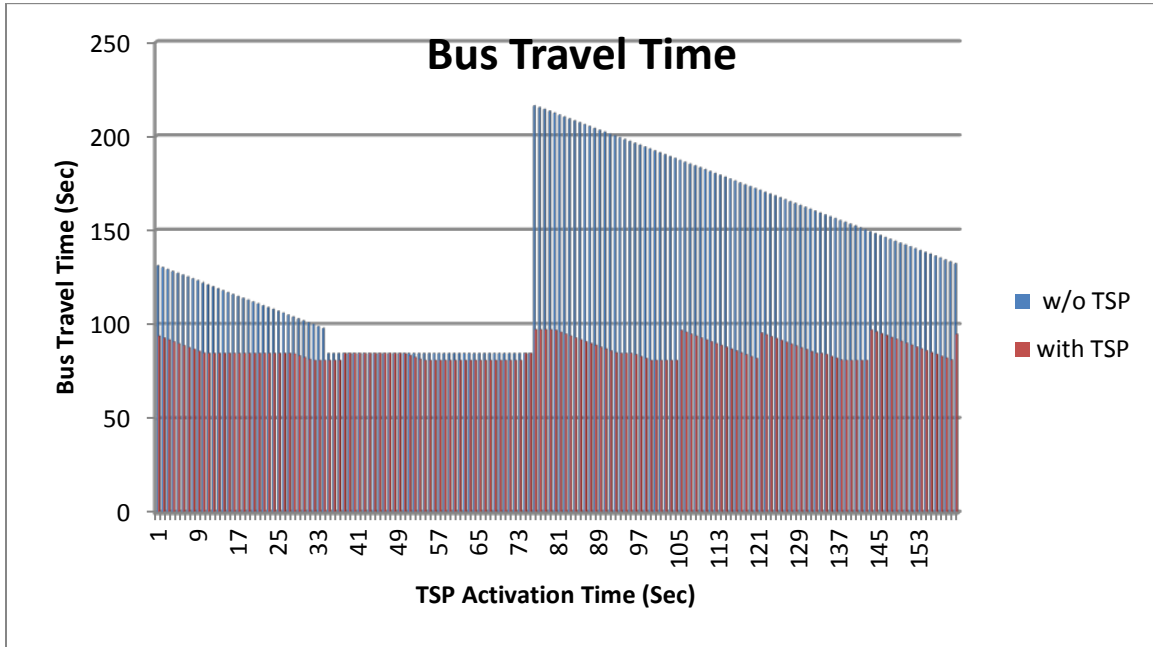


Figure 3 Bus Travel Time (Without TSP Compared to TSPCV)

While the conventional TSP is not shown in Figure 3 to keep it clean and more comprehensible, the pattern can be easily anticipated. Since the logic of conventional TSP is to extend green for an extra a few seconds to let buses arriving right after the original green pass the intersection, the travel times of buses that arrive right after the dent (between 75 and 85 seconds in Figure 3) would be as low as that of TSPCV condition (red bars). Hence, it can be expected that the travel time pattern of CTSP would be very similar to that of the without-TSP scenario, with the couple highest blue columns behind the dent dropping to the red columns' height. The number of lowered bars would depend on how many seconds the TSP is allowed to extend the green time. But no matter how many seconds CTSP is extended, the delay time savings of conventional TSP would be less than that of TSPCV.

Table 2 shows a comparison of delay among three scenarios: without TSP, conventional TSP, and TSP with Connected Vehicle. The person delay is the average delay of all traffic users over three cycle lengths and then averaged over all 160 situations. The bus delay is the average bus waiting time of all 160 situations. In summary, the proposed TSP logic, TSPCV, would save 89.7% on bus delay and reduce total delay by 5.6%. In the same conditions the conventional TSP would only save 12.6% on bus delay and not

reduce total delay. Intuitively, one may expect TSP to cause extra delay to the overall traffic, but this may not always be true. Because of the TSP green time, vehicles on the major street are being released at a higher frequency. As a result, the delay polygon would be smoothed out and never reach the old maximum. Thus, total delay would actually decrease, given the volume is not too high. In addition, considering the higher passenger density on the bus, the time savings from bus riders would have a tendency to reduce the overall delay.

Table 2 Analytical Delay Comparison for One-Bus Scenario

	NTSP	CTSP	TSPCV	N/TSPCV	N/C	C/TSPCV
per person delay (sec)	49.5	49.5	46.7	-5.6%	-0.0%	-5.6%
Bus delay (sec)	57.7	50.4	5.9	-89.7%	-12.6%	-88.3%

4.2. Simulation Evaluation in VISSIM

The microscopic simulation software package VISSIM [20] was used to evaluate the proposed TSP logic under the Connected Vehicle environment. A COM interface was used to assess information that would be available within the Connected Vehicle environment. The evaluation was performed under the assumption that only transit buses were connected to the traffic signal controller and that other traffic users did not have CV equipment. In other words, there was 0% CV market penetration except for buses. Therefore, the data extracted via COM interface [21] would only be the speed and position of the bus, number of passengers on board, number of potential passenger at the bus stop, and 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 EXCEL VBA.

As noted, the test network was a calibrated model of the intersection at Emmet Street and Barracks Road in Charlottesville, Va. Vehicle volumes and turning movements are actual morning peak-hour data collected from the site. Bus dwell time at the stop was 30 seconds on average, with a standard deviation of 2 seconds. A transit bus was designed to arrive every 494 seconds. Given that the cycle length was 160 seconds at the intersection; the interval of bus arrival was about 3 cycles. During the evaluation, the team discovered that the simulation evaluation of CTSP could be easily biased. In order to include as many arrival scenarios as possible, the headway between buses should not be an exact multiple of signal cycles. Otherwise, all buses would arrive at the same specific time relative to the signal cycle. Therefore, there should be a small offset added to the arrival interval to include various arrival scenarios. However, if this offset is less than the TSP green extension time, and because the TSP extension causes the original green phase to

shift in the same direction as the bus arrival time, as long as one bus gets TSP, all following buses would be included in the green phase. Therefore, this research purposefully designed the offset to be 14 seconds so that a sequence of buses would arrive at various times relative to signal cycles without causing the domino effect; hence the simulation result would be less biased.

The simulation-based evaluations also compared three scenarios: without TSP, with conventional TSP, and TSP with Connected Vehicle. Each scenario ran at least five times with different random speeds. It was ensured that the results show statistical significance with a 95% confidence level and 3% tolerance error. Table 3 shows the minimum sample size calculated to make statistically significant comparisons. The sample size computation formula documented in *Traffic and Highway Engineering*, by Garber and Hoel [23], was used. Clearly, five runs were sufficient in this case.

Table 3 Minimum Sample Size to Compare Two Means

	NTSP	CTSP	TSPCV
Sample size	1	1	3

The simulation-based results shown in Table 4 support the results from the analytical tests. Delay per person was approximately on the same level for all three scenarios and so was the bus delay. Although the delay of all traffic users for conventional TSP is slightly lower than the analytical result, statistical tests show that the three scenarios do not have statistically significant difference on delay of all traffic users. Therefore, the simulation results are consistent with those of the analytical model in terms of person delay. For bus delay, CTSP seems to perform better than expected while TSPCV performs a bit worse than expected. Closer investigation shows that this phenomenon is caused by the bias of CTSP simulation evaluation. Although the bus arrival time has been designed to shift 14 seconds every time a new bus comes to minimize the bias, this bias cannot be eliminated. Because the CTSP green shifts the green cycle 10-15 seconds in the same direction as bus arrival time, their synchronization increases with the number of buses helped by CTSP. But this would not be the case in the real world, as bus arrival time and green cycles do not shift in the same direction. As for TSPCV, the lower than expected performance is caused by a couple of buses that do not make it through the intersection within TSP green time due to randomness of traffic and dwell time at the bus station.

Table 4 Simulation Delay Comparison for One-Bus Scenario

	NTSP	CTSP	TSPCV	N/TSPCV	N/C	C/TSPCV
Delay per person (sec)	42.8	39.2	40.3	-5.9%	-8.4%	2.6%
Bus Delay (sec)	45.4	36.3	18.1	-60.1%	-20.1%	-50.0%

The TSPCV shows better performance over the conventional TSP in terms of bus travel time savings. It reduces the bus delay by 50.0% compared to conventional TSP and 60.1% compared to NTSP condition.

This research also compared the standard deviation of bus travel times as a measurement to represent the reliability of bus service. Table 5 demonstrates that TSPCV improved the reliability of the bus service, while CTSP was actually less reliable than no-TSP condition. However, the statistical tests show that the reliability difference between NTSP and CTSP is not statistically significant.

Table 5 Standard Deviation of Bus Travel Time

	NTSP	CTSP	TSPCV
STDDEV	31	32	26

4.3. 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. Since the field collected volume data were at v/c ratio 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 6 and Table 7.

Table 6 Sensitivity Study of Congestion Level from Analytical Model

	v/c ratio	NTSP	CTSP	TSPCV	N/TSPCV	C/TSPCV
Bus Delay (Sec)	0.5	57.7	50.3	5.3	-90.8%	-89.5%
	0.7	57.7	50.3	5.3	-90.8%	-89.5%
	0.9	57.7	50.4	5.9	-89.7%	-88.3%
	1.0	57.7	51.1	27.1	-53.0%	-46.8%
Delay per person (Sec)	0.5	46.8	46.8	44.1	-5.6%	-5.6%
	0.7	46.8	46.8	44.1	-5.6%	-5.6%
	0.9	49.5	49.5	46.7	-5.6%	-5.6%
	1.0	51.1	51.1	48.3	-5.6%	-5.5%

Table 7 Sensitivity Study of Congestion Level from VISSIM Simulations

MOE	v/c ratio	NTSP	CTSP	TSPCV	N/TSPCV	C/TSPCV
Bus Delay (Sec)	0.5	39.1	27.5	5.6	-85.7%	-79.7%
	0.7	40.6	29.2	4.8	-88.3%	-83.7%
	0.9	45.4	36.3	18.1	-60.1%	-50.0%
	1.0	48.7	34.0	30.9	-36.5%	-9.2%
Delay per person (Sec)	0.5	36.1	33.0	30.9	-14.3%	-6.2%
	0.7	37.6	34.7	33.2	-11.6%	-4.3%
	0.9	42.8	39.2	40.3	-5.9%	2.6%
	1.0	52.0	44.5	45.7	-12.0%	2.8%

Both analytical and simulation evaluation results show similar trends with respect to how TSPCV performed under various congestion levels. In terms of bus delay at the intersection, TSPCV always reduced bus delay compared to conventional TSP and NTSP conditions. It should be considered that the analytical evaluation is intended to obtain upper ceiling benefits, while the simulation evaluation is performed to assess expected performance under real-world implementation.

When the congestion level was low, TSPCV helped reduce bus delays up to about 90% compared to NTSP under VISSIM simulations. As the congestion level rose, the benefit of TSPCV decreased, while no extra delay was caused. This is because the algorithm was designed to be conditional on person delay. When the volume becomes closer to the capacity, a smaller portion of the green time is granted to TSPCV 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. It is interesting to see that even when the v/c ratio equals 0.9, the benefit of TSPCV is still significant and drops dramatically when v/c becomes 1.0. However, even when v/c=1.0, TSPCV is still superior to conventional TSP.

As noted, per person delay at the intersection is a measurement that reflects adverse effects caused by TSP. When examining the results, both CTSP and TSPCV did not cause additional person delay at various v/c ratios. For low v/c ratio scenarios (v/c<0.9), TSPCV person delays are lower than those of CTSP. As the congestion level increases, the difference of person delay between TSPCV and CTSP decreases and eventually becomes statistically insignificant.

5 Conclusions

To address challenges identified in the current TSP strategies, a next-generation TSP logic based on Connected Vehicle technology was proposed. This new TSP takes advantage of the two-way communication and additional and more accurate information provided by Connected Vehicle technology. Based on the simulation results, it can be concluded that the proposed TSP provides buses with more accuracy and better effectiveness. Furthermore, it accommodates a higher percentage of transit buses than conventional TSP does. Its performance is compared against conventional TSP and no-TSP conditions under various congestion levels. The results show that the TSPCV would greatly reduce bus delay at signalized intersections without causing negative effects on side streets.

The performance of TSPCV was evaluated under various congestion conditions, including near capacity volume condition. The results confirm the anticipated findings. Since the algorithm was designed to be conditional on person delay, as the volume became closer to the capacity, less and less TSPCV were granted. As a result, the benefit of TSPCV decreased, while adverse effects on side streets remained under a certain level. Hence, TSPCV would work well even at intersections with near capacity volume at the peak hours. During the off-peak hours, as congestion level is low, most buses would be granted TSP and save travel time. When volume becomes closer to capacity, fewer buses would receive TSP green. Although the benefit would be small during peak hours, no adverse effects on side streets are expected. Hence, it will no longer be a must for VDOT to perform study on LOS and/or V/C ratio for potential TSP intersections before installation.

The evaluation of this study is based on the mid-block near-side bus stop condition. In the past, research often found it preferred to have TSP with far-side bus stops. This is because the tremendous randomness of dwell time would greatly compromise the performance of CTSP. However, with Connected Vehicle technology, information such as potential passengers at the bus stop would be readily available. This extra information reduces the randomness of dwell time. As a result, whether the bus station is far-side or near-side may become a less influential fact. Future research is recommended about evaluation of the performance of TSPCV with far-side bus stops.

As more streetcars are being deployed, it is important to mention here that this algorithm would fit streetcars as well. As a matter of fact, it would work even better if streetcars have separated right of way, since there is no queue to clear in order to let the streetcar through.

The last important point to make is that TSPCV is one of the few ITS applications that would generate benefits even at early stages of Connected Vehicle technology deployment. The quantitative evaluation performed in this research is based on the assumption that only buses are equipped with Connected Vehicle technology (i.e., DSRC) devices. This feature also brings out another character of TSPCV, that its deployment cost is moderate compared to other Connected Vehicle applications: the application only needs equipment upgrades on buses and traffic signal controllers. Thus, TSPCV could be a good starting point to promote Connected Vehicle technology.

6 Discussion of Virginia Case and Recommendations for VDOT

As noted, a past study investigated the performance of conventional TSP on the US 1 corridor in Northern Virginia (Arlington) area. The field operational study reported that TSP operated buses improved 3-6% travel time, while the simulation results indicated that TSP did not make statistically significant changes in the system-wide travel times. A discussion with the City of Arlington traffic engineer confirmed that TSP is not currently being operated, as they do not see large benefits. A further investigation on the US 1 corridor traffic signal system and the study report indicated that there are two possible reasons why TSP did not perform well. One reason was that only 20 intersections were equipped with TSP among 27 traffic signalized intersections – this means that TSP-equipped buses do not have a continuous progression along the corridor. The other reason was that only green extension was implemented to accommodate TSP-operated buses – this means no truncation of green times from cross streets and no insertion to accommodate the buses.

Based on the findings from this project, the following recommendations were made for Virginia DOT:

- Virginia DOT should consider an additional simulation-based study to revisit Arlington TSP that can take advantage of additional strategies such as the green insertion evaluated in this project. In addition, Virginia DOT should consider deploying TSP to the entire corridor instead of the current five signalized intersections.
- Given that the proposed TSPCV significantly outperforms CTSP and that the proposed TSP can be deployed at a relatively low market penetration rate of Connected Vehicle technology, Virginia DOT should consider TSPCV as one of the transit-oriented applications for Active Transportation Management Strategies in Northern Virginia.

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