Transportation Research Part C 55 (2015) 393–408

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Coordinated transit signal priority supporting transit progression under Connected Vehicle Technology

Jia Hu [a,*], Byungkyu Brian Park [a,1], Young-Jae Lee [b,2]

[a] Department of Civil and Environmental Engineering, University of Virginia, P.O. Box 400742, Charlottesville, VA 22904-4742, United States
[b] Department of Transportation and Urban Infrastructure Studies, Morgan State University, 1700 E. Cold Spring Lane, Baltimore, MD 21251, United States

ARTICLE INFO

Article history:
Received 16 October 2014
Accepted 15 December 2014
Available online 28 January 2015

Keywords:
Conditional transit signal priority
Bus progression
Connected Vehicle
Green re-allocation
Binary Mixed Integer Linear Program

ABSTRACT

In this paper, a person-delay-based optimization method is proposed for an intelligent TSP logic that enables bus/signal cooperation and coordination among consecutive signals under the Connected Vehicle 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 downstream intersections. The problem is formulated as a Binary Mixed Integer Linear Program (BMILP) which is solved by standard branch-and-bound method. 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 grant of TSP causes no extra total person delay.

The logic developed in this research is evaluated using both analytical and microscopic traffic simulation approaches. Both analytical tests and simulation evaluations compared four scenarios: without TSP (NTSP), conventional TSP (CTSP), TSP with Connected Vehicle (TSPCV), and Coordinated TSP with Connected Vehicle (TSPCV-C). The measures of effectiveness used include bus delay and total travel time of all travelers. The performance of TSPCV-C is compared against conventional TSP (CTSP) under four congestion levels and five intersection spacing cases. The results show that the TSPCV-C greatly reduces bus delay at signalized intersection for all congestion levels and spacing cases considered. Although the TSPCV is not as efficient as TSPCV-C, it still demonstrates sizable improvement over CTSP. An analysis on the intersection spacing cases reveals that, as long as the intersections are not too closely spaced, TSPCV can produce a delay reduction up to 59%. Nevertheless, the mechanism of TSPCV-C is recommended for intersections that are spaced less than 0.5 mile away. Simulation based evaluation results show that the TSPCV-C logic reduces the bus delay between 55% and 75% compared to the conventional TSP. The range of improvement corresponding to the four different v/c ratios tested, which are 0.5, 0.7, 0.9 and 1.0, respectively. No statistically significant negative effects are observed except when the v/c ratio equals 1.0.

* Corresponding author. Tel.: +1 919 744 9842; fax: +1 (434) 982 2951.
E-mail addresses: jh8dn@virginia.edu (J. Hu), bpark@virginia.edu (B.B. Park), YoungJae.Lee@morgan.edu (Y.-J. Lee).
[1] Tel.: +1 (434) 924 6347; fax: +1 (434) 982 2951.
[2] Tel.: +1 (443) 885 1872; fax: +1 (443) 885 8218.

http://dx.doi.org/10.1016/j.trc.2014.12.005
0968-090X/

1. Introduction

Transit Signal Priority (TSP), or commonly referred to as bus priority, is a collection of techniques that provide preference to transit buses at the signalized intersections. By adjusting the traffic signal plan according to bus arrivals, the delay that transit buses experience at intersections is reduced. Therefore, transit service quality is improved and bus ridership increases. The technology has been applied in most major cities around the world, including Seattle, Portland, Los Angeles, and Chicago as one the most important approaches to promote public transportation system (Liao et al., 2007).

The first study on TSP dates back to 1979 (Salter and Shahi, 1979) where Salter and Shahi demonstrated that giving priority to buses increased the delay of private vehicles as a price of reducing bus delay. Since then, a number of researches are conducted proposing new mechanisms that overcome the problems of previous designs or evaluating existing TSP systems (Jacobson and Sheffi, 1981; Khasnabis et al., 1991; Chang and Messer, 1985; Garrow et al., 1997; Muthuswamy et al., 2007; Al-Sahili and Taylor, 1996; Pratt et al., 2000). These are the conventional TSP (CTSP) which usually only provides simple strategies like extension to or early start of the originally planned green time. The strategies that conventional TSP adopted are usually called ‘‘green extension’’ and ‘‘red truncation’’ (Lee et al., 2005). The problem with ‘‘green extension’’ and ‘‘red truncation’’ is that it sacrifices the capacity of the competing travel direction. As a result, the progression on the competing movements is disturbed. During peak period when the TSP is mostly needed, it could take hours for the competing movement to regain its progression (Shalaby et al., 2006). Furthermore, the capacity transferred to the TSP travel direction is inefficient and barely taken advantage of. Since the queue on the TSP direction is fully discharged during normal green time, one can expect that, during the extra green time, only a limited number of vehicles make through the intersection while a long queue is delaying on the competing movement. On top of these problems, conventional TSP strategies can only cover a very small portion of the bus fleet. Chatila and Swenson suggested setting the maximum green extension time to 1/5 of the cycle length (Chatila and Swenson, 2001). Given this, only up to 20% of buses could receive benefit from TSP.

To address the shortcomings of conventional TSP technology, research efforts have been dedicated to finding more advanced TSP logic. A number of new TSP strategies have been added into the TSP logic library. Apart from the basic TSP strategies which are ‘‘green extension,’’ ‘‘red truncation’’ and ‘‘phase skipping’’ (Lee et al., 2005), Balke et al. proposed possible ‘‘green time insertion’’ at all phase transitions (Balke, 2000), cycle extension is proposed and found to be beneficial during rush hours (Ekeila et al., 2009), compensation has been introduced to limit the adverse effects on the side streets by cutting or skipping the time from the non-bus phase, and finally combining TSP consideration into adaptive signal control (Liao et al., 2007; Chang et al., 1996). Although these advanced TSP strategies differ significantly from each other at the first glance, fundamentally what they really did was increasing the portion of buses that could receive TSP while, at the same time, reducing the sacrifice of the competing movements. This idea could be further advanced. There are many other aspects that existing advanced TSP logic could make improvements. For instance, the duration of TSP green should reflect traffic condition and bus status (Lee et al., 2005; Balke, 2000; Ekeila et al., 2009). Otherwise, TSP green time is not fully utilized which leads to unnecessary extra delay on other traffic users. In fact, some of the existing advanced TSP system assume exclusive bus lane (Ma et al., 2013). It means the queuing effect in front of the bus was neglected. This fact limited significantly the application of those advanced TSP systems, since the majority of the urban streets are not designed with exclusive bus lanes.

Part of the reason why existing TSP logic libraries were not fully responsive to traffic condition and bus status was because that information was not readily available. However, with the new emerging ‘‘Connected Vehicle’’ (CV) technology, additional measurements and more functions become available, including two-way communications between the bus and the traffic signal controller, accurate bus location detection and prediction, and passenger count. Therefore, the authors proposed a next generation TSP logic based on Connected Vehicle Technology (TSPCV) Hu et al., 2014 which raises the portion of TSP buses to the maximum and reduces the sacrifice of the competing movements to the minimum. The key features of the previously developed TSP logic are green time re-allocation and bus-signal coordination. The mechanism of green time re-allocation divides and reassigns part of the original green time as TSP green instead of adding extra green time. Therefore, whenever a TSP request is made, there is an associated TSP timing plan. Even if the original bus arrival time does not allow TSP reallocation (minimum green for competing movements), the bus could adjust its speed to avoid that unfavorable time window and then receive TSP green. This coordination between bus and signal also allows the TSP green to start when minimum extra delay will be caused to other traffic users. The duration of the TSP green is designed to clear the queue in front of the bus right before it arrives at the intersection. Hence, superior to other TSP strategies, reallocated TSP green is not only useful for the bus, but also taken advantage by the private vehicles. Every single second is not wasted and utilized to discharge queues. This feature further reduces the adverse effect possibly caused by implementing TSP. Simulation-based evaluation results show that the TSPCV logic reduces bus delay up to 84% compared to conventional TSP.

All the advanced TSP systems were developed under the context of one isolated intersection (Balke, 2000; Ekeila et al., 2009; Dion and Hellinga, 2002; Ma et al., 2014). In fact, even for the conventional TSP, the bus progression along a corridor is overlooked. There have been a few limited studies on this topic. The idea was first pointed out by Skabardonis that the coordination between adjacent intersections is important for TSP (Skabardonis, 2000). He proposed that the decision to grant TSP at one signal should consider whether this effort will be wasted at the downstream intersection. Although Skabardonis did not personally evaluate his proposal, the importance of this suggestion was proven quantitatively by the following studies (Ma et al., 2013, 2010; Ngan et al., 2004). Ngan demonstrated that bus delay increases by 6% without the coordination between adjacent intersections. Six percent may seem marginal at first glance, but if compared to the average delay saving

(10–20%) observed by various conventional TSP studies (Liao et al., 2007; Muthuswamy et al., 2007; Al-Sahili and Taylor, 1996; Balke, 2000). Almost one third of the benefit is sacrificed. While Ma's studies (Ma et al., 2010; Ma and Bai, 2008) show that, suppose TSP is simply not granted to buses that could not make through the downstream intersection, bus delay does not increase significantly while other traffic user's delay could be significantly reduced.

Enabling coordination among traffic signals along a corridor has even more meanings for a TSPCV system. One limitation of the previously developed TSPCV mechanism is that its performance would be affected greatly by spacing to downstream intersection. The TSPCV requires a certain distance for bus to adjust its speed to ensure its maximum performance so that the bus is capable of being granted with TSP no matter when the TSP is requested and that the start time of the TSP causes the least adverse effect. The previous study used 0.5 mile speed-adjusting distance which is the average intersection spacing in the United States. It appears to be a sufficient distance. However, not all intersections are 0.5 mile away from each other. There is possibility that a bus received TSP at the upstream intersection is stopped by traffic signal at the downstream intersection when two intersections are too closely located. It could either because the TSP cannot start as needed due to reasons like minimum green time requirement or because all the candidate TSP start time leads to substantial adverse effect. 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 is too closely spaced.

Another goal of this research is to improve the generalization of the TSPCV logic. The previously developed TSPCV logic was designed for a specific intersection in Charlottesville, VA. In order to make the logic applicable to any intersections, the problem is formulated as a Binary Mixed Integer Linear Programs (BMILP) which is solvable by any standard branch-and-bound routine.

1.1. Research objective

Therefore, the purpose of this research is to further advance the TSPCV logic into a Coordinated TSPCV (TSPCV-C) which will have the following features:

1. Adopts TSP green re-allocation strategy.
2. Enables bus-signal cooperation.
3. Grants conditional TSP.
4. Realizes coordination among traffic signals.
5. Formulates and solves BMILP formulation applicable to any intersection.

The remainder of this paper is organized as follows. Section 2 describes the key features of the enhanced TSPCV-C. Section 3 provides step-by-step description of the TSPCV-C logic. Section 4 demonstrates the problem formulation. Section 5 presents analytical and simulated test results and findings. And finally, Section 6 identifies the conclusions and contributions.

2. TSPCV-C logic highlights

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

2.1. 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 fulfill its objective function. In this case, the decision variables include signal plan for each intersection and recommended bus speed leading towards 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.

2.2. Transit-signal cooperation

The cooperation between transit buses and traffic signal is required and enabled. When a bus approaching an intersection sends a priority request, not only the traffic controller tries to accommodate the buses, but also the bus needs to travel at a reasonable speed to increase the portion of buses that can be granted with TSP. The speed should fall into a range predefined by users. As shown in Fig. 1, the prediction regarding bus arrival is a time range, instead of a specific time stamp. The bus speed is recommended based on remaining/expected queue, road geometry and normal signal timing plan.

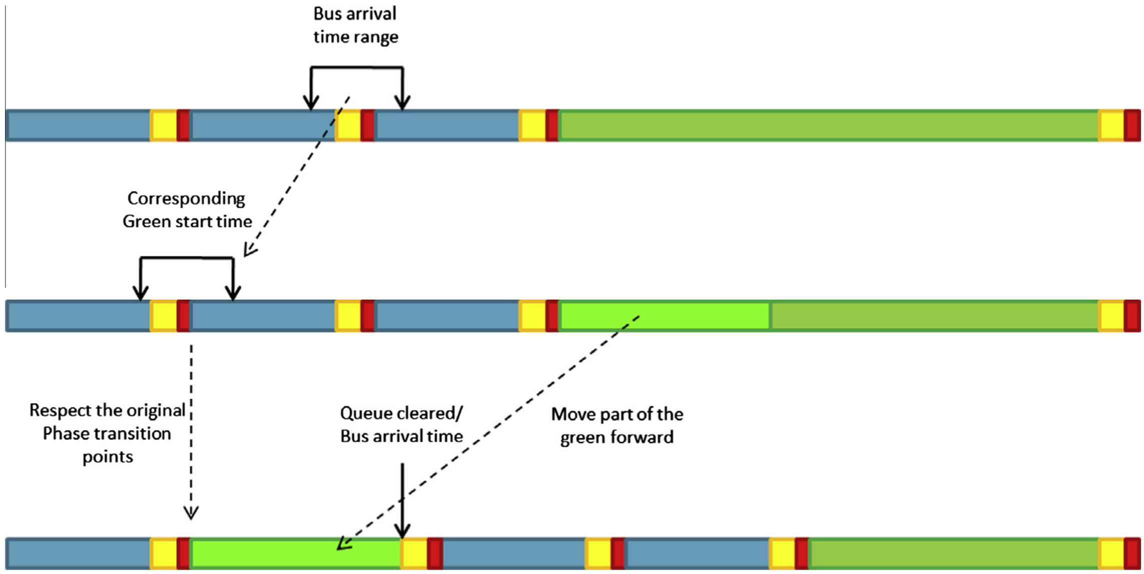

Fig. 1. Illustration of green reallocation.

2.3. Coordination among intersections

The problem is formulated so that all the closely located intersections are considered together as a whole system. When the bus could not receive TSP at one 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 too closely located. Hence, the bus progression is maintained and the delay savings gained from upstream intersections are preserved along a corridor.

2.4. Green re-allocation

As shown in Fig. 1, the TSP logic adopts the strategy of 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 compensates part of it to when green time is mostly needed by a transit bus. It is noted that the cycle length will be the same even when the TSP green is inserted, because the TSP green time is spliced from the green time of the direction of the bus. So strictly speaking, the extra TSP green time is "moved" rather than "inserted" or "added." The inserted green time taken from the certain direction is 100% used to clear the traffic for that direction. This mechanism makes sure that all the TSP green time is fully used. It is either discharging remaining queue or letting go the bus. Therefore, theoretically speaking, not a single second is wasted during the TSP. Compared to the conventional TSP, unnecessary TSP green time is reduced to the minimum.

2.5. Conditional TSP grant

TSP green time is granted conditionally based on two criteria which are schedule adherence and delay per person. The mechanism checks: I. whether the bus is behind schedule; II, whether the implementation of this TSP increase total delay per person at all intersections of interest. Only if both criteria are satisfied, the TSP is granted to the bus.

3. TSPCV-C logic architecture description

Here provides a step-by-step description of the TSPCV-C logic. Fig. 2 displays the architecture of the TSPCV-C in a flow chart. The logic is composed of three major components:

3.1. Bus detection component

This is the first step of the TSPCV-C mechanism which is activated when a bus passes an activation point. The activation point is either at an upstream intersection or an 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 with TSP. The state examined in this design is schedule adherence. The system proceeds to the next step only if the bus is found behind its schedule. Otherwise, the TSP process is terminated.

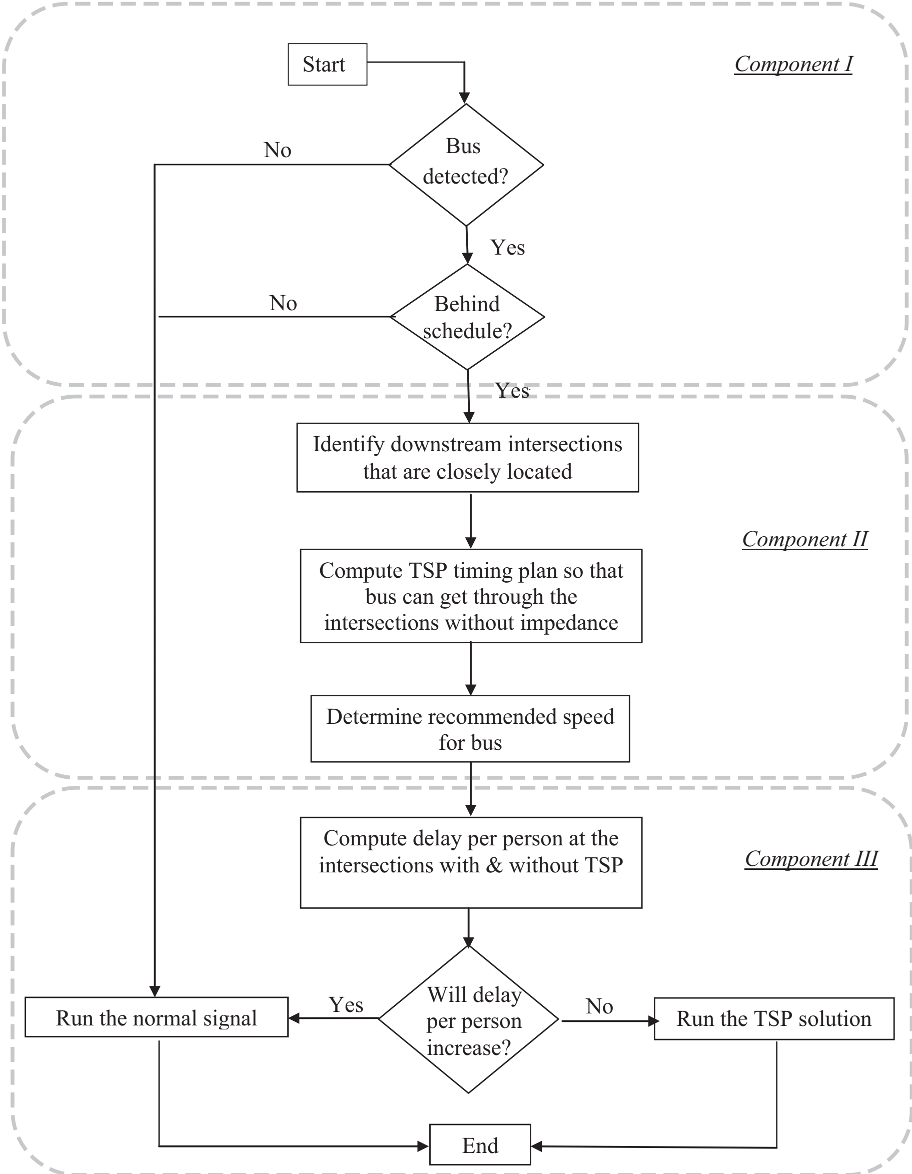

Fig. 2. The structure of TSPCV-C.

3.2. 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 needs to be first determined. All the intersections closely located immediately downstream of the activation point are identified. An 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 falls within the system scope. These variables are the input for the Binary Mixed Integer Linear Programs (BMILP) formulated in the following section. By solving the BMILP problem using standard branch-and-bound routine, the following output is found: link specific advisory bus speed leading towards each intersection and signal timing plan for each intersection inside the system scope.

3.3. Logic assessment and implementation component

In this step, 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.

After a TSP timing plan is determined, the algorithm will 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, the person delay performance measure is to be used. The person delay is calculated for a predefined duration of time starting from the TSP implemented cycle. In this research, a TSP timing plan will be only implemented when its corresponding person delay is less than the "no TSP" 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 in case a bus is not expected to make it through the intersection. The TSP green time would be extended up to 5 s to accommodate the random delay.

4. Problem formulation

4.1. Assumptions

The proposed model made the following assumptions:

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

4.2. Notation

Table 1 lists the indices and parameters utilized hereafter.

4.3. 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) generalize it for multiple buses
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

4.4. 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 person delay can be expressed as follows:

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

4.4.1. 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 Fig. 3. The effect of residual queue is considered. The delay calculation is based on the real-time queue length estimation model developed by Liu (Liu et al., 2009) which is an extension of the shock wave theory.

As shown in Fig. 3, 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. Fig. 3 describes the case that 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 the front queuing vehicle. The magnitude of delay is solved using trigonometry:

Table 1
Symbols and parameters.

a	Numbering for intersection legs. It indicates the leg TSP bus is traveling on
b	Numbering for intersection legs defined locally with respect to leg "a" along clockwise direction. It indicates the leg 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 travelling towards 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 travelling towards 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" along clockwise direction
N_c	Total number of signal cycles considered. It is an user-defined value
N_I	Total number of intersections
N_k	Sequence of signal cycle when TSP green starts
N^A_k	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^t_k	Number of vehicles arrive 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 (second)
s_k	Saturation flow rate at the intersection k
t	Time stamp in second
t_{qk}	Queue dissipating time at the intersection $k-1$
T^A_{abk}	Time when the TSP mechanism is activated at the intersection k. It is associated with the bus coming from leg m and travelling towards 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)

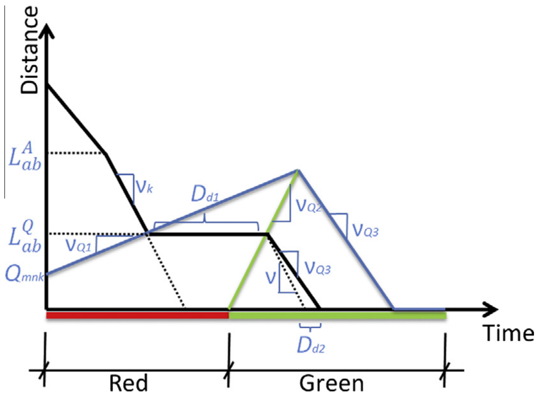

Fig. 3. Bus delay computation.

$$D_{b1} = \frac{v_{Q2} * (1 - \Psi_{abk}) * C_k + Q_{mnk}}{v_{Q2}} + \frac{(L^Q_{ab} - Q_{mnk}) * (v_{Q2} - v_{Q1})}{v_{Q1} * v_{Q2}}, \quad \forall m = a;\ n = b;\ k = 1, \ldots, N_I;\ a \in [1, \ldots, N_L];\ b \in [1, \ldots, N_L - 1] \tag{2}$$

$$D_{b2} = \frac{L^Q_{ab} * (v_k - v_{Q3})}{v_k * v_{Q3}}, \quad \forall a \in [1, \ldots, N_L];\ b \in [1, \ldots, N_L - 1];\ k = 1, \ldots, N_I; \tag{3}$$

L^Q_{ab} is the distance between the bus and the front stop line when the bus stops for the front queue. It is acquired by solving the following equation set. In the equation set, the first equation describes the trajectory of the end of the accumulating queue, while the second equation represents the trajectory of the coming bus.

$$\begin{cases} L^Q_{ab} = v_{Q1} * t + Q_{mnk} \\ L^Q_{ab} = -v_k * t + L^A_{ab} + v * T^A_{ab}, \quad \forall m = a;\ n = b;\ k = 1, \ldots, N_I;\ a \in [1, \ldots, N_L];\ b \in [1, \ldots, N_L - 1] \end{cases} \tag{4}$$

Thus, the total delay of bus is given by substituting Eq. (4) into the Eqs. (2) and (3):

$$D_b = \frac{v_{Q2} * (1 - \Psi_{abk}) * C_k + Q_{mnk}}{v_{Q2}} + \frac{(v_{Q1} * L^A_{ab} + v_{Q1} * v_k * T^A_{ab} - v_{Q1} * Q_{mnk}) * (v_{Q2} - v_{Q1})}{v_{Q1} * v_{Q2} * (v_{Q1} + v_k)} + \frac{(v_{Q1} * L^A_{ab} + v_{Q1} * v_k * T^A_{ab} + v_k * Q_{mnk}) * (v_k - v_{Q3})}{v_k * v_{Q3} * (v_{Q1} + v_k)}, \quad \forall m = a;\ n = b;\ k = 1, \ldots, N_I;\ a \in [1, \ldots, N_L];\ b \in [1, \ldots, N_L - 1] \tag{5}$$

Details of how v_{Q1}, v_{Q2} and v_{Q3} are computed are provided in the literature (Liu et al., 2009).

4.4.2. 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 (Liu et al., 2009). For other approaches that are downstream of another intersection, platoon dispersion model is applied (Mathew et al., 2013). In other words, when the upstream intersection is discharging the queue ($t < t_{qk}$), vehicle arrival rate at time t at the downstream intersection can be expressed as,

$$Q^t_k = s_{k-1}(1 - (1 - F)^t), \quad \forall k = 2, \ldots, N_I \tag{6}$$

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

$$Q^t_k = s_{k-1}(1 - (1 - F)^{t_{qk}}) \times (1 - F)^{t - t_{qk}}, \quad \forall k = 2, \ldots, N_I \tag{7}$$

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

4.4.3. Constraints

(1) *Queue clearance constraint:* when a bus is granted with TSP, this bus should arrive after its front queue is fully discharged. As shown in Fig. 4, the TSP green should start before the bus arrival. Hence, the bus meets with the rear end of the front queue at the stop bar. This can be expressed as:

$$(\Theta_{abk} + \Psi_{abk}) * C_k - \frac{L^A_{abk}}{v_k} - T^A_{abk} + (N_k - N^A_k) * C_k = 0, \quad \forall a \in [1, \ldots, N_L];\ b \in [1, \ldots, N_L - 1];\ k = 1, \ldots, N_I \tag{8}$$

(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, this constraint can be expressed as:

$$T^A_{ab(k+1)} = T^A_{abk} + \frac{L^A_{abk}}{v_k}, \quad \forall a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L-1];\; k = 1,\ldots,N_I \tag{9}$$

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

$$L^A_{abk} = min(L^A, L_k), \quad \forall a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L-1];\; k = 1,\ldots,N_I \tag{10}$$

(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:

$$\sum_{n=1}^{N_L-1} (\Delta_{mnk} + \delta_{mnk}) \leqslant 1, \quad \forall m = 1,\ldots,N_L;\; n = 1,\ldots,N_L-1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I \tag{11}$$

(5) *Bus speed constraint:* to limit the interference 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:

$$80\% * V_k \leqslant v_k \leqslant 110\% * V_k, \quad \forall k = 1,\ldots,N_I \tag{12}$$

(6) *Assigned TSP constraint:* it ensures that the permission of relocating TSP green is consistent with the actual start time of TSP green. In other words, 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 right after the end of the green time for movement from leg m to leg n. It is specified by the following equations, $\mathcal{M}$ is an arbitrary large positive number:

$$(\Omega_{mnk} * C_k) * \Delta_{mnk} < \Theta_{abk} * C_k < \Omega_{mnk} * C_k + G_{mnk} + \mathcal{M} * (1 - \Delta_{mnk}), \quad \forall m = 1,\ldots,N_L;\; n = 1,\ldots,N_L-1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L-1] \tag{13}$$

$$(\Omega_{mnk} * C_k + G_{mnk}) * \delta_{mnk} \leqslant \Theta_{abk} * C_k \leqslant \Omega_{mnk} * C_k + G_{mnk} + \mathcal{M} * (1 - \delta_{mnk}), \quad \forall m = 1,\ldots,N_L;\; n = 1,\ldots,N_L-1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L-1] \tag{14}$$

(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.

$$G_{mnk} = G'_{mnk} + \Delta_{mnk} * G''_{mnk}, \quad \forall m = 1,\ldots,N_L;\; n = 1,\ldots,N_L-1;\; k = 1,\ldots,N_I \tag{15}$$

$$G''_{mnk} = \Delta_{mnk} * (G_{mnk} - (\Theta_{abk} - \Omega_{mnk}) * C_k + YR), \quad \forall m = 1,\ldots,N_L;\; n = 1,\ldots,N_L-1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L-1] \tag{16}$$

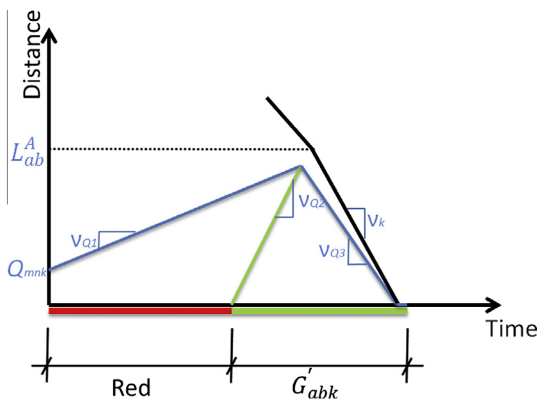

Fig. 4. Illustration of the queue clearance constraint.

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

$$G_{abk} = \Psi_{abk} * C_k + G''_{abk} + \left[\sum_{m=1}^{N_L}\sum_{n=1}^{N_L-1}(2 * \Delta_{mnk}) + \sum_{m=1}^{N_L}\sum_{n=1}^{N_L-1}(\delta_{mnk})\right] * YR, \quad \forall m = 1,\ldots,N_L;$$
$$n = 1,\ldots,N_L - 1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L - 1] \tag{17}$$

(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.

$$G_{mnk} \geqslant G_{min}, \quad \forall m = 1,\ldots,N_L;\; n = 1,\ldots,N_L - 1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L - 1] \tag{18}$$

$$G'_{mnk} \geqslant G_{min}, \quad \forall m = 1,\ldots,N_L;\; n = 1,\ldots,N_L - 1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L - z] \tag{19}$$

$$G''_{mnk} = \Delta_{mnk} * (G_{mnk} - (\Theta_{abk} - \Omega_{mnk}) * C_k + YR) \geqslant \Delta_{mnk} * G_{min}, \quad \forall m = 1,\ldots,N_L;$$
$$n = 1,\ldots,N_L - 1;\; m \neq a;\; n \neq b;\; k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L - 1] \tag{20}$$

$$G'_{abk} = \Psi_{abk} * C_k \geqslant G_{min}, \quad \forall k = 1,\ldots,N_I;\; a \in [1,\ldots,N_L];\; b \in [1,\ldots,N_L - 1] \tag{21}$$

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

5. Evaluations

5.1. 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 Fig. 5, are the joints of Route 50 with Sullyfield Cir and Centreville. The current intersection spacing is 0.14 miles. The site was chosen because the signal timing is coordinated and has been calibrated shortly before the volume data was collected (Park et al., 1856).

5.2. Methodology

Two levels of evaluation are performed. The first is the analytical evaluation and the second is the microscopic simulation-based evaluation. The analytical evaluation is a deterministic calculation that quantifies the performance of the proposed TSP logic on a theoretical level. In this evaluation, all possible TSP activation scenarios are considered. Considering a TSP request is made at any point in second over the cycle length of an intersection, an unbiased performance measure is acquired by averaging the performance of all possible TSP activation scenarios. However, this kind of evaluation could not consider the stochastic nature of the traffic. On the other hand, simulation-based evaluation considers variability due

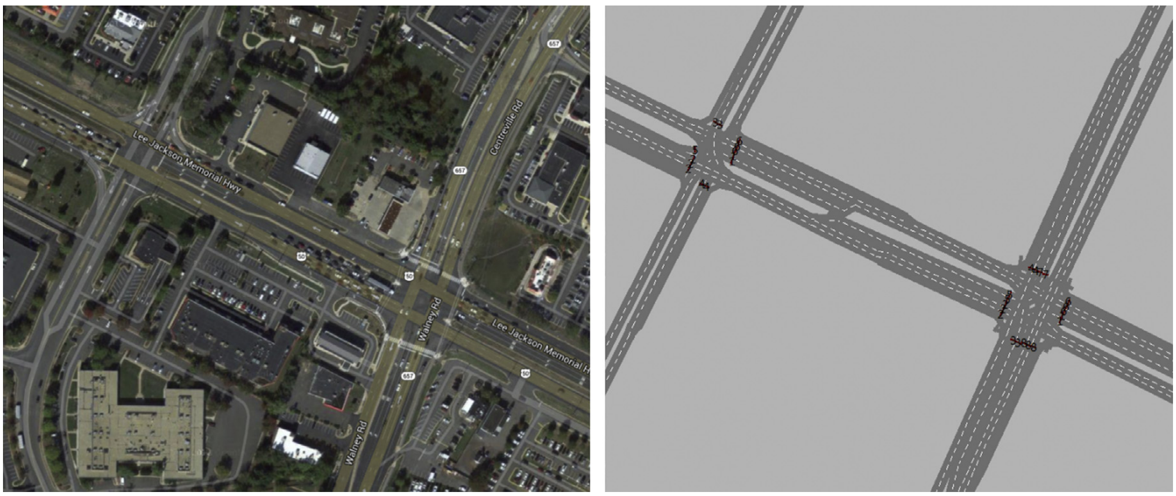

Fig. 5. Study site.

to vehicle interactions and inter-arrival times (Stevanovic et al., 2008). In this sense, simulation evaluation is a more plausible performance assessment.

Four different control strategies are being compared:

- *TSPCV-C.* It is the proposed control strategy with coordination among intersections that are closely located. It also has all the features that TSPCV has.
- *TSPCV.* It is the previously developed intelligent transit signal priority logic. No coordination. The TSP system of a specific intersection activates when the bus passes the immediate upstream intersection.
- *Conventional TSP (CTSP).* The conventional TSP logic compared here is TSP with an 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. The CTSP will grant 10-s extra green time to buses which arrive within 10 s of the end of normal green time. In case the bus could not make through the intersection within that 10 s, CTSP will add to the previous 10 s with up to 5 s to accommodate the late arrival. The logic follows the real implementation in the Northern Virginia (Rakha et al., 2006).
- *No TSP (NTSP).* This control runs the background signal timing plan, without taking any control action responding to bus appearance.

As the study site has been identified, some inputs of the model are specified here:

Signal timing plan is adopted from the site which has been updated shortly before the volume data was collected (Park et al., 1856). It is actuated and coordinated. The cycle length on the corridor is 120 s.

- Vehicle volumes and turning movements are actual peak-hour data collected from the site.
- To consider the effect of bus stop, it is assumed that a bus is traveling EB 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 are allowed to travel within the speed range between 35 mph and 50 mph (i.e., between 20% below and 10% above speed limit).

$$80\% * V_k \leqslant v_k \leqslant 110\% * V_k, \quad \forall k = 1, \ldots, N_I \tag{23}$$

- The TSP logic is activated when buses pass 0.5 mile upstream of the first intersection.

$$L^A_{abk} = \min(0.5, L_k), \quad \forall a \in [1, \ldots, N_L];\ b \in [1, \ldots, N_L - 1];\ k = 1, \ldots, N_I \tag{24}$$

- As aforementioned, a duration of time needs to be predefined for person delay calculation. In this case study, a duration of 3 signal cycles is adopted. It is noted that the three cycles are used to be long enough to capture residual effects caused by TSP and be short enough to prevent including another TSP request, given three cycles of 120-s cycle is about the minimum bus headway.

Several assumptions are made for the buses. The values are adopted from an NCHRP research regarding bus rapid transit (Cost/Benefit Analysis of Converting a Lane for Bus Rapid Transit: Phase II Evaluation and NCHRP Research Results Digest, 2011):

- Bus occupancy is 40 passengers.
- Private vehicle occupancy is 1.2 passengers.
- Dwell time at bus stops is 30 s with 2 s standard deviation. Consider that the CV technology is capable of providing accurate dwell time prediction; the variation is set to be moderately low.
- Bus headway is 6 min.

Therefore, the objective function is now specified as following:

$$\text{Min} \sum_{k=1}^{2} \left[\sum_{cycle=1}^{cycle=3} \sum_{T=1}^{120} \sum_{i} Occ_i + D_b * Occ_b \right] \tag{25}$$

The Measures of Effectiveness (MOE) 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 the adverse effect is caused.

Finally, all the differences have been checked for statistical significance. The purpose is to ensure that all the improvements or adverse effects claimed in the result session are statistically significant. Paired two tailed T-test was utilized, since data in comparison was collected from the same site, and the confidence level tested was 95%.

5.3. Analytical test

The analytical test is a deterministic calculation that quantifies the performance of the proposed TSP logic on the theoretical level. Here are all the factors considered. Volume is the average flow rate collected from the study site during peak hour, which is near capacity situation. Signal timing plan is adopted from the current timing plan in the field. Saturation flow rate is borrowed from the default value in Synchro which is 1900 veh/h/ln. Queue length at the stop bar is estimated based on the constant arrival rate assumption. All possible TSP activation scenarios are considered. The cycle length at the intersection is 120 s. Assuming a TSP can be activated at any given second, there are 120 possible situations. The stop delay for bus is calculated by averaging these 120 situations. The program is coded in VBa and run on an i5-2400 3.10 GHz processor with 8 GB RAM. The computation time for all 120 situations takes less than 20 s. All three treatments have been computed and compared to NTSP condition. The delay comparisons are presented in Figs. 6 and 7.

The current spacing between the two intersections is 0.14 miles. Under such condition, TSPCV presents a little improvement over CTSP with a reduction around 7%, while TSPCV-C overcomes the effect of short intersection spacing and demonstrates much greater benefit of 55% delay reduction. It is intuitive since the small spacing of the two intersections significantly reduces the flexibility of the TSPCV and thus the portion of buses that is able to receive TSPCV from both intersections largely decreases. However, one can expect that, as the spacing increases, the flexibility of TSPCV will also increase and bring up the associated bus delay reduction.

Therefore, the research took one step ahead and performed a sensitivity analysis on the intersection spacing based on deterministic computation. Again, the results are presented in Figs. 6 and 7. The results are intuitive to show that the performance of CTSP is not affected by intersection spacing, since a fixed proportion of buses receive CTSP treatment. The benefit of TSPCV is positively correlated with the intersection spacing. Although TSPCV shows small benefit over CTSP under the 0.14-mile-spacing condition, its advantage over CTSP becomes more obvious as the spacing increases 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 similar benefit as 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 over 0.24 mile. The phenomenon demonstrates that the TSPCV-C is not completely immune to spacing change. Nevertheless, TSPCV-C always demonstrates superior improvement than the other two treatments, no matter what size of the spacing is.

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 is also less in total delay compared to TSPCV and CTSP.

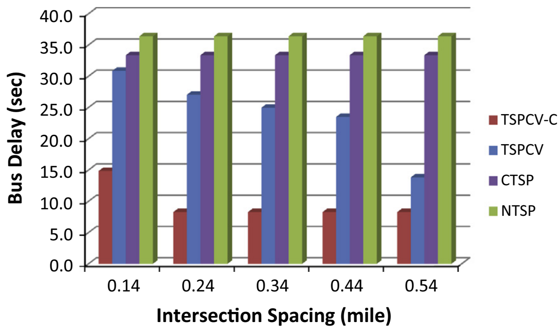

Fig. 6. Bus delay under various intersection spacing.

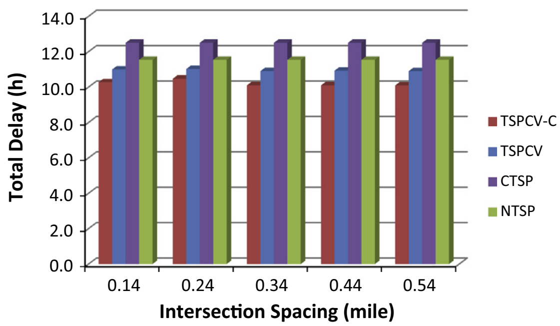

Fig. 7. Total delay under various intersection spacing.

5.4. Simulation-based evaluation in VISSIM

While the analytical test results show significant benefits under the proposed TSPCV-C logic, it does not consider any variability due to vehicle interactions and inter-arrival times. A microscopic traffic simulator can assess the performance under more plausible conditions. The microscopic simulation software package VISSIM (PTV, 2008a) is used to evaluate the proposed TSP logic under a CV environment. A COM interface is used to assess information that would be available within a CV environment (PTV, 2008b). The evaluation is performed under the assumption that only transit buses are connected to the traffic signal controller and other traffic users do not have CV devices. In other words, 0% CV market penetration except for buses. The end of the queue is estimated based on incoming vehicles and outgoing vehicles at the intersection. Detailed algorithm can be found in the model developed by Liu (Liu et al., 2009) which is an extension of the shock wave theory. The input to this algorithm is the average flow rates from all travel directions. Therefore, the data extracted via COM interface would include speed and position of bus, number of passengers on board, number of potential passengers at the bus stop, number of vehicles passing the intersection and volume from all four approaches. Besides, the COM interface is used to change the signal timing plan during the simulation. All programs are coded in Microsoft EXCEL VBA.

As noted, the test network is a calibrated model of 2 consecutive intersections on Route 50 in Fairfax, Virginia. Vehicle volumes and turning movements are actual peak-hour data collected from the site. Bus dwelling time at the stop is 30 s average with a standard deviation of 2 s. A transit bus is designed to arrive every 375 s. Given the cycle length is 120 s at the intersection; the interval of bus arrival is exactly 3 cycles plus 15 s. This research purposefully designed the offset to be 15 s so that buses within one single simulation run will arrive at different times relative to signal cycles; hence the simulation results would be 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 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, 2013), which is:

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

where

Z: Number of standard deviations away from the mean corresponding to the required confidence level in a normal distribution. In this research, confidence level is set to be 95%.

Ss: Sample standard deviation.

Xs: Sample mean.

E: Tolerable error. In this research, $E = 10\%$.

The results from the simulation based evaluation are shown in Table 2. 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 NTSP condition and *T*-test was performed to validate the differences from a statistical perspective. As two intersections are closely located (0.14 miles), TSPCV and CTSP showed minor improvement over NTSP condition while TSPCV-C significantly saved bus delay by 37%. Since the delay savings generated by TSPCV and CTSP are not statistically significant, only TSPCV-C presented benefit for bus traveling through closely spaced intersections under near capacity volume.

Generally speaking, the simulation based results support the findings from the analytical analysis. Although the percentage delay-saving observed from the simulation is a little less than that from the analytical test, the magnitude of delay saving 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 simulation is larger than that of the analytical test. 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 2. It is discovered that TSPCV-C and TSPCV caused a minor adverse effect on other traffic users. It is likely due to the delay estimation module embedded in the TSPCV-C logic could not accurately predict the effect of the queue-spill-back condition, and the peak-hour data collected from the field is around the capacity. Hence, some TSP requests are granted regardless of the fact that extra delay would be caused. However, the effect is minimal (less than 1% increase in travel time). When translated into delay increase, TSPCV-C caused about 1 s delay per person.

Table 2
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

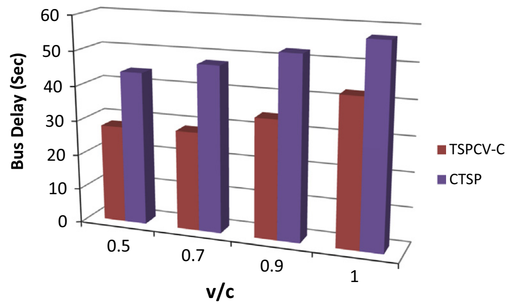

Fig. 8. Bus delay under various congestion levels.

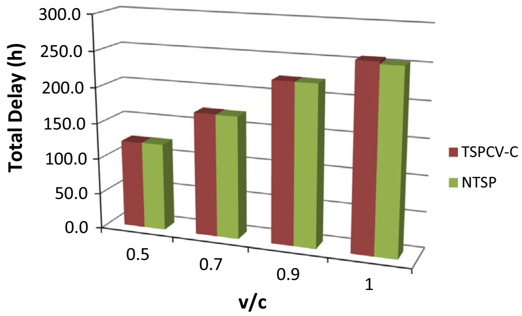

Fig. 9. Total delay under various congestion levels.

5.4.1. Sensitivity analysis on congestion levels

In order to verify that the findings from the experiment are consistent with various congestion levels, a sensitivity analysis is conducted. Because TSPCV cannot perform well under such close intersection spacing, the sensitivity study on congestion levels is not conducted for TSPCV. Since the field collected volume data is at v/c ratio of 1.0, three other scenarios are tested: v/c = 0.5, v/c = 0.7 and v/c = 0.9. The results have been presented in the Figs. 8 and 9.

When the congestion level is low, TSPCV-C reduces bus delays significantly under all levels of v/c ratios. The most delay saving (about 68%) is observed when v/c ratio equals to 0.7. The least delay is reduced (about 35%) when v/c ratio equals to 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 person delay. When the volume becomes closer to the capacity, an increasing portion of the bus fleet will not be granted with TSPCV to prevent TSP from causing extra delay on other travelers. As a result, the benefit would drop correspondingly, while adverse effects on side streets would still be kept under a certain level. But when v/c ratio drops below 0.7, most of the buses are granted with TSP, the performance of TSPCV is no long restricted by congestion level, but bounded by other facts, like the minimum green time requirement. Hence, the negative correlation levels off between bus delay and v/c ratio.

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

6. Conclusions and future research

In this research, a person-delay-based optimization method is proposed for an intelligent TSP logic that enables bus/signal cooperation and coordination among consecutive signals under the Connected Vehicle 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 would not be wasted at the downstream intersections. The problem is formulated as a Binary Mixed Integer Linear Programs (BMILP) which is solved by 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 grant of TSP causes no extra total delay. The evaluation on TSPCV-C shows:

- TSPCV-C greatly reduces bus delay up to 75% compared to CTSP. Its performance is superior to any other TSP logic (TSPCV or CTSP) no matter what size of the intersection spacing is. 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, it could 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 mile, two logics show similar performance. Therefore, it is recommended to set 0.5 mile as a threshold of activating TSPCV-C logic. In other words, the coordination among consecutive intersections is necessary when they are located less than half mile away.
- TSPCV-C logic is beneficial under all levels of v/c ratio. When 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 person delay. When the volume becomes closer to the capacity, a decreasing portion of the bus fleet will be granted with TSPCV to prevent TSP from causing extra delay on other travelers. When v/c drops below 0.7, the performance of TSPCV-C reaches its optimum and delay saving starts to level off.
- The effect on other traffic users of TSPCV-C was evaluated under various congestion conditions, including near capacity volume condition. The results show that, for congestion levels below capacity, TSPCV-C causes no adverse effect. Although little adverse effects on side streets are expected when the volume reaches capacity, the delay increase is minor and less than 1 s per person. Hence, the adverse effect is negligible. It saves cost for local agencies and DOTs to not performing a study of LOS and/or V/C ratio for potential TSP intersections before installing TSPCV-C.

This research evaluated the performance of the proposed TSP logic under the 0% market penetration condition except for buses. The purpose is to show the bottom line improvement. Future research could consider investigating the improvement of TSPCV-C generated with higher CV technology coverage. In addition, the next phase of this research could proceed to consider multiple buses and multiple corridors, in other words, a TSP logic that accommodates conflicting TSP requests on a transportation network. This ultimate TSP logic can be embedded with the city traffic control system and would be able to optimize the transit system performance on an area basis. This research adopted person delay as one of the conditional criteria, other measurements can be tested in future research, for example, fuel consumption, emissions, etc. Finally, future research should consider alternative solution approaches so that the computation time would be reasonable for real-time implementation even for a large number of intersections.

Acknowledgements

This research project was supported by the Connected Vehicle/Infrastructure University Transportation Center and the Global Research Laboratory Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2013K1A1A2A02078326).

References

Al-Sahili, K., Taylor, W., 1996. Evaluation of bus priority signal strategies in Ann Arbor∗ Michigan. Transport. Res. Rec.: J. Transport. Res. Board 1554 (1), 74–79.
Balke, K.N., Dudek, C.L., Urbanik, T., 2000. Development and evaluation of intelligent bus priority concept. Transp. Res. Rec. 1727, 12–19.
Chang, E., Messer, C.J., 1985. Minimum delay optimization of a maximum bandwidth solution to arterial signal timing (Abridgment). Transp. Res. Rec. 1005, 89–95.
Chang, G., Vasudevan, M., Su, C., 1996. Modeling and evaluation of adaptive bus-preemption control with and without automatic vehicle location systems. Transport. Res. Part A: Policy Pract. 30 (4), 251–268.
Chatila, H., Swenson, M., 2001. Transit Signal Priority Along State Route 522. ITE Quad Conference.
Cost/Benefit Analysis of Converting a Lane for Bus Rapid Transit: Phase II Evaluation and Methodology, 2011. NCHRP Research Results Digest, No. 352, p. 28.
Dion, F., Hellinga, B., 2002. A rule-based real-time traffic responsive signal control system with transit priority: application to an isolated intersection. Transport. Res. Part B: Methodol. 36 (4), 325–343.
Ekeila, W., Sayed, T., El Esawey, M., 2009. Development of a Dynamic Transit Signal Priority Strategy, p. 20.
Garrow, M., Machemehl, R., 1997. Development and Evaluation of Transit Signal Priority Strategies.
Hu, J., Park "Brian", B., Parkany Emily, A., 2014. Transit Signal Priority with Connected Vehicle Technology, 2014, p. 20.
Jacobson, J., Sheffi, Y., 1981. Analytical model of traffic delays under bus signal preemption: theory and application. Transport. Res. Part B: Methodol. 15B (2), 127–138.
Khasnabis, S., Reddy, G., Chaudry, B., 1991. Signal preemption as a priority treatment tool for transit demand management. Vehicle Navigat. Inform. Syst. 2, 1093–1111.
Lee, J., Shalaby, A., Greenough, J., Bowie, M., Hung, S., 2005. Advanced transit signal priority control with online microsimulation-based transit prediction model. Transport. Res. Rec.: J. Transport. Res. Board, No. 1925, 185–194.
Liao, C.G., Davis, A., 2007. Simulation study of bus signal priority strategy: taking advantage of global positioning system, automated vehicle location system, and wireless communications. Transport. Res. Rec.: J. Transport. Res. Board, No. 2034, 82–91.
Liu, H.X., Wu, X., Ma, W., Hu, H., 2009. Real-time queue length estimation for congested signalized intersections. Transport. Res. Part C: Emerg. Technol. 17 (4), 412–427.
Ma, W., Bai, Y., 2008. Serve Sequence Optimization Approach for Multiple Bus Priority Requests Based on Decision Tree, pp. 605–615.
Ma, W., Yang, X., Liu, Y., 2010. Development and evaluation of a coordinated and conditional bus priority approach. Transport. Res. Rec.: J. Transport. Res. Board, No. 2145, 49–58.
Ma, W., Ni, W., Head, L., Zhao, J., 2013. Effective coordinated optimization model for transit priority control under arterial progression. Transport. Res. Rec.: J. Transport. Res. Board, No. 2356, 71–83.
Ma, W., Head, K.L., Feng, Y., 2014. Integrated optimization of transit priority operation at isolated intersections: a person-capacity-based approach. Transport. Res. Part C: Emerg. Technol. 40, 49–62.

Mathew, J., Thomas, H., Sharma, A., Devi, L., Rilett, L., 2013. Studying platoon dispersion characteristics under heterogeneous traffic in India. Proc. – Soc. Behav. Sci. 104, 422–429.

Muthuswamy, S., McShane, W., Daniel, J., 2007. Evaluation of transit signal priority and optimal signal timing plans in transit and traffic operations. Transport. Res. Rec.: J. Transport. Res. Board 2034 (1), 92–102.

Ngan, V., Sayed, T., Abdelfatah, A., 2004. Impacts of various parameters on transit signal priority effectiveness. J. Public Transport. 7 (3), 71–93.

Park, B., Schneeberger, J., Microscopic, D., 1856. Simulation model calibration and validation: case study of VISSIM simulation model for a coordinated actuated signal system. Transp. Res. Rec. 2003, 185–192.

Pratt, R.H.K., Turnbull, F., Evans, J., EB. McCollom, E.F., Spielberg, Vaca, E., Kuzmyak Richard, J., 2000. Traveler Response to Transportation System Changes: Interim Handbook. TCRP Web Document, No. 12, pp. v.p.

PTV, 2008a. VISSIM 5.10 User Manual, July 2008.

PTV, 2008b. VISSIM 5.10-03 COM Interface Manual, September 2008.

Rakha, H., Ahmed, Ahn, K., 2006. Transit Signal Priority Project – Phase II: Field and Simulation Evaluation Results.

Salter, R.J., Shahi, J., 1979. Prediction of effects of bus-priority schemes by using computer simulation techniques. Transp. Res. Rec. 718, 1–5.

Shalaby, A., Lee, S.J., Greenough, J., Bowie, M.D., 2006. Development, evaluation, and selection of advanced transit signal priority concept directions. J. Public Transport. 9 (5), 97–120.

Skabardonis, A., 2000. Control strategies for transit priority. Transp. Res. Rec. 1727, 20–26.

Stevanovic, J., Stevanovic, A., Martin, P.T., Bauer, T., 2008. Stochastic optimization of traffic control and transit priority settings in VISSIM. Transport. Res. Part C: Emerg. Technol. 16 (3), 332–349.

VDOT, T.E.D., 2013. Traffic Operations Analysis Tool Guidebook. <http://www.virginiadot.org/business/resources/traffic_engineering/VDOT_Traffic_Operations_Analysis_Tool_GuidebookV1.1-August2013.pdf> (accessed 15.12.13).