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Transit signal priority accommodating conflicting requests under Connected Vehicles technology

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ABSTRACT

In this research, a person-delay-based optimization method is proposed for an intelligent Transit Signal Priority (TSP) logic that resolves multiple conflicting TSP requests at an isolated intersection. This TSP with Connected Vehicles accommodating Conflicting Requests (TSPCV-CR) overcomes the challenge bore by the conventional "first come first serve" strategy and presents significant improvement on bus service performance. The feature of TSPCV-CR includes green time re-allocation, simultaneous multiple buses accommodation, and signal-transit coordination. These features help maximize the transit TSP service rate and minimize adverse effect on competing travel directions. The TSPCV-CR 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 optimization is formulated as a Binary Mixed Integer Linear Program (BMILP) which is solved by standard branch-and-bound routine. Minimizing per person delay is the objective of the optimization model.

The logic developed in this research is evaluated using both analytical and microscopic traffic simulation approaches. Both analytical tests and simulation evaluations compared three scenarios: without TSP (NTSP), conventional TSP (CTSP), and TSP with Connected Vehicles that resolves Conflicting Requests (TSPCV-CR). The measures of effectiveness used include bus delay and total travel time of all travelers. The performance of TSPCV-CR is compared against conventional TSP (CTSP) under four congestion levels and three different conflicting scenarios. The results show that the TSPCV-CR greatly reduces bus delay at signalized intersection for all congestion levels and conflicting scenarios considered. Simulation based evaluation results show that the TSPCV-CR logic reduces average bus delay between 5% and 48% 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.

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1. Introduction

Transit Signal Priority (TSP) is a traffic signal control technique that reduces transit buses' delay at the signalized intersections by adjusting signal timing plan according to bus arrivals. This technique has been widely applied to improve transit

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service quality and increase bus ridership. It has become one of the most important treatments of public transportation system in major cities, such as Seattle, USA, Los Angeles, USA, Beijing, China and Tokyo, Japan (Liao and Davis, 2007).

Conventional TSP is not perfect as it has potential adverse effect on other traffic users. It has been dragging the promotion of TSP. This shortcoming was first revealed by Salter and Shahi (1979) that the conventional TSP causes significant delay on competing travel directions and breaks traffic progression. The compromised progression could take hours to recover during peak hours (Shalaby et al., 2006). Since then, various new mechanisms have been proposed trying to overcome the adverse effect (Jacobson and Sheffi, 1981; Khasnabis et al., 1991; Chang and Messer, 1985; Garrow and Machemehl, 1997; Muthuswamy et al., 2007; Al-Sahili and Taylor, 1996; Pratt et al., 2000; He et al., 2014). Nevertheless, they all kept the same conventional signal strategies which are "green extension" and "red truncation" (Lee et al., 2005). This feature greatly impacts the effectiveness of their upgrades, since these conventional strategies by nature sacrifice the capacity of the competing travel direction.

Furthermore, the benefit of the conventional TSP is not usually noticeable by human drivers. It is because the conventional TSP only provides preference to a small percentage of the bus fleet. Only the buses that arrive during the green extension window could be accommodated. Even if the maximum green extension time (1/5 of cycle length (Chatila and Swenson, 2001)) is adopted, theoretically only up to 20% of buses could experience the travel time savings.

To address the shortcomings of conventional TSP, various new TSP strategies have been invented. For instance, "green time insertion" at all phase transitions (Balke et al., 2000), cycle extension during rush hours (Ekeila et al., 2009), TSP green time compensation, phase skipping, and TSP enabled adaptive signal control (Liao and Davis, 2007; Chang et al., 1996). Fundamentally, these newly developed TSP strategies have the same objective which is increasing the portion of buses that could receive TSP while, at the same time, reducing the sacrifice of the competing movement groups. This objective was advanced to its limit by the authors of this paper. A next generation TSP strategy was proposed using Connected Vehicles technology (TSPCV) (Hu et al., 2014) which increased the portion of TSP buses receiving the priority to the maximum and reduced the sacrifice of the competing movements to the minimum. The key features of the TSPCV are green time re-allocation and bus-signal coordination. Green time re-allocation divides and reassigns original green time as TSP green instead of adding extra green time. Therefore, no sacrifice is needed from the competing travel direction. The relocated TSP green time could start at any time corresponding to buses' arrivals. When green time re-allocation is not feasible due to minimum green time requirement, buses adjust their speed to avoid infeasible time window to coordinate with signal and receive TSP. As a result, portion of TSP buses is raised up to approximately 100%. This coordination between transit and signal control also allows TSP green to start when minimum progression interference is caused to the competing traffic direction. Therefore, the sacrifice from the competing street is reduced to the minimum. Evaluation results showed that the TSPCV reduces bus delay up to 84% compared to conventional TSP.

Like many other advanced TSP strategies (Liao and Davis, 2007; Balke et al., 2000; Chang et al., 1996; Ekeila et al., 2009), the TSPCV was developed for single bus scenario only. In case that multiple conflicting TSP requests were received, the system was designed to serve the first request only. However, it was discovered that the current "first come, first serve" way of solving conflicting priority requests not only does no benefit but also deteriorates the TSP system. A 13% extra bus delay was observed with first-come-first-serve strategy compared to no-TSP option (Zlatkovic et al., 2012). Therefore, it is important to upgrade the previously developed TSPCV strategy (Hu et al., 2014b) to be capable of accommodating multiple conflicting TSP requests.

Studies have been conducted to investigate the problem of resolving conflicting TSP requests. Ma et al. (2013) and Ma and Bai (2008) developed two methods accommodating multiple TSP requests. The first is a passive bus priority for exclusive bus lane that maximizes person capacity (Ma et al., 2014), and the other uses decision tree method to decide serving sequence (Ma and Bai, 2008). He et al. presented a heuristic algorithm which reduces up to 50% of the bus delay compared to the "first come first serve" policy (He et al., 2011). Zlatkovic et al. proposed a rule-based logic which always provides priority first to the direction with the green phase on (Zlatkovic et al., 2012). This algorithm shows a benefit of more than 30% reduction on bus delay.

The TSPCV strategy requires its own enhancement to accommodate conflicting TSP requests. Firstly, the aforementioned conflicting TSP resolving logic (Ma et al., 2014; Ma and Bai, 2008; He et al., 2011; Zlatkovic et al., 2012) were developed for the basic two conventional TSP strategies: "green extension" and "red truncation" (Lee et al., 2005). They are not applicable towards advanced TSP strategies like the green re-allocation. Secondly, and more importantly, with the transit-signal coordination feature, TSPCV could guide multiple buses to be discharged within one single TSP green time. This is a feature that could double benefit and has never been investigated before. Hence, the development of an enhanced TSPCV logic is essential and is a goal of this research.

This research also aims 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 isolated 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 an upgraded version which will have the following features:

1. Adopts TSP green re-allocation strategy
2. Enables bus-signal cooperation
3. Grants conditional TSP
4. Resolves multiple conflicting TSP requests
5. Formulates and solves BMILP formulation applicable to any intersection

This TSP logic utilizing Connected Vehicles and handling multiple transit requests is dubbed as TSPCV-CR.

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

2. TSPCV-CR logic highlights

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

2.1. Green re-allocation

As shown in Fig. 1,[1] the TSP logic adopts the green time reallocation strategy. In other words, instead of adding additional green time to the original timing plan, the proposed TSP logic splits the original green time and distributes part of it to when green time is needed by the approaching transit bus. Therefore, green re-allocation is more flexible and could accommodate higher portion of buses compared to the conventional green extension. The cycle length is always the same even when the TSP green is re-allocated. So strictly speaking, the extra TSP green time is "moved" rather than "inserted" or "added." The TSP green time is 100% used to either discharging remaining queue or servicing the bus. Hence, the green re-allocation mechanism theoretically does not waste a single second except for an extra amble and red clearance time. Compared to the conventional TSP, where most of the TSP green time is wasted on waiting for bus arrival, unnecessary TSP green time is reduced to the minimum. Detailed information of green re-allocation is provided in the previous research of the authors in this paper (Hu et al., 2015, 2014).

2.2. Transit-signal cooperation

The cooperation between transit buses and traffic signal is enabled. When a bus sends a priority request, not only the traffic controller alters its timing plan to accommodate the buses, but also the bus adjusts its speed to match the granted green window. This mechanism increases the portion of buses that can be served by TSP. The adjusted bus speed should fall into a range predefined by users. As shown in Fig. 1, the predicted bus arrival time is not a specific time, but a time range. The bus speed is recommended based on remaining/expected queue, road geometry, original signal timing plan and the information of other approaching buses.

2.3. Simultaneous TSP accommodation

The TSPCV-CR is capable of providing TSP to multiple buses within one single TSP green time. This mechanism is activated when two conditions are met at the same time: (i) the arrival times of these buses are in the same traffic signal cycle and (ii) the movements of these buses do not conflict with each other. The mechanism is visualized in Fig. 2. The mechanism further increases bus delay savings and reduces adverse effect on other traffic, as the bus served per TSP interference ratio is as least doubled.

2.4. 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 and (ii) whether the implementation of this TSPCV-CR increase total delay per person for all approaching travelers. Only if both criteria are satisfied, the TSPCV-CR is granted to the bus.

2.5. Buffer green time

A possible buffer green time is given to a bus in case a bus cannot travel through the intersection as guided due to unexpected delay. This TSP green time extension is no longer than 5 s.

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[1] For interpretation of color in Figs. 1 and 4, the reader is referred to the web version of this article.

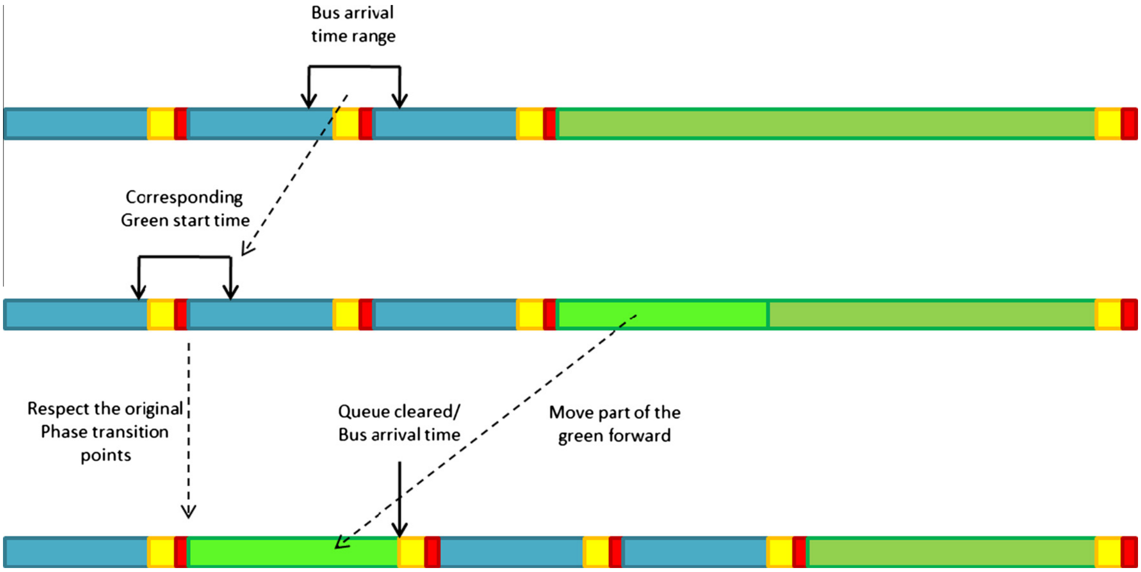

Fig. 1. Illustration of green reallocation (Hu et al., 2015).

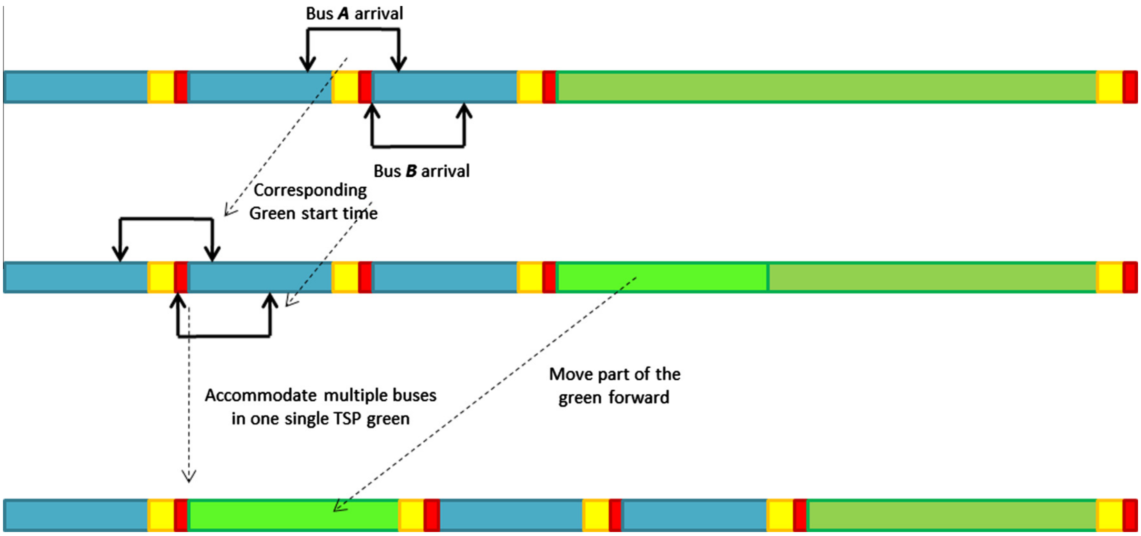

Fig. 2. Illustration of simultaneous TSP accommodation.

3. Logic architecture description

Here provides a step-by-step description of the TSPCV-CR logic. Fig. 3 displays the architecture of the TSPCV-CR in a flow chart. The logic is composed of three major components:

3.1. Bus detection component

As noted, this is the first step of the TSPCV-CR mechanism. When a TSP request is received, the system checks for two criteria before proceeding to the TSPCV-CR logic. The first criterion checks whether the bus is behind the schedule and the second one verifies whether this TSP request conflicts with any previously accepted request. Conflicting TSP requests are defined as multiple TSP green times requested within one signal cycle. If the first criterion is not met, then the TSP process is terminated. If the second criterion is not fulfilled, then the logic falls back to the previously developed single-bus TSPCV logic. The system proceeds to the next step only if both criteria are satisfied.

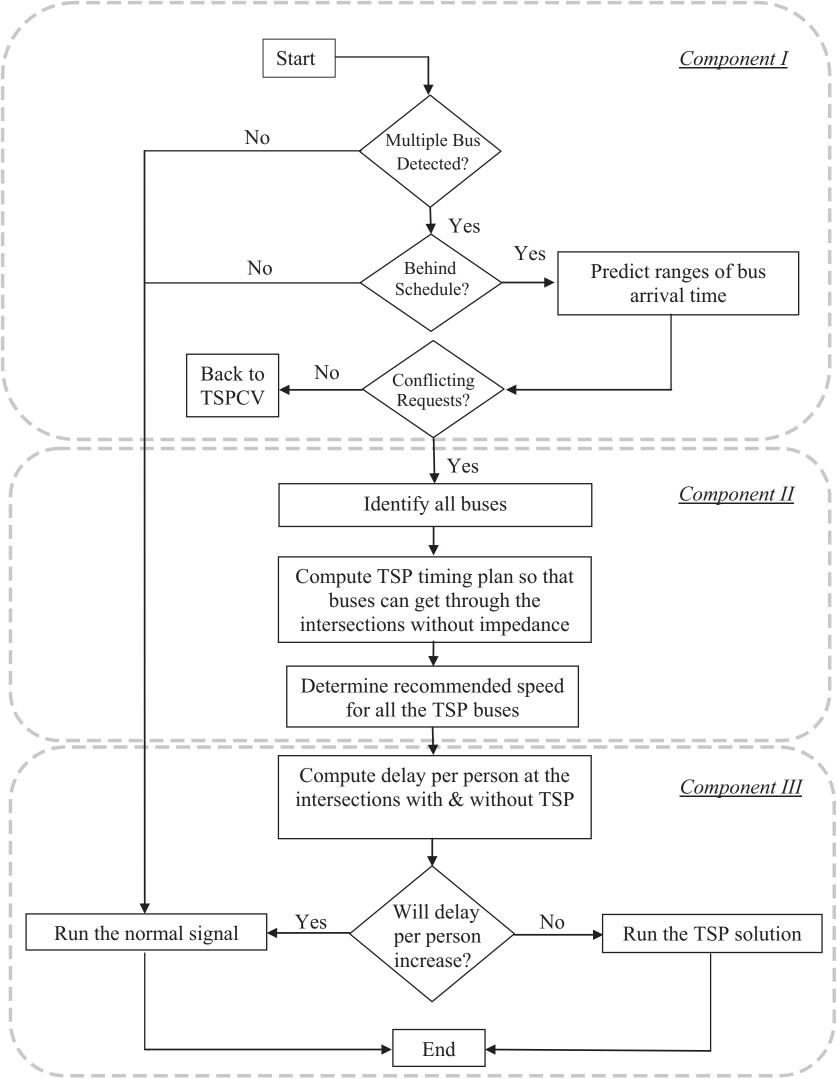

Fig. 3. The structure of TSPCV-M.

3.2. TSP timing plan and bus speed calculation component

In this step, the Binary Mixed Integer Linear Programs (BMILP) optimization problem is solved. Detailed information about the BMILP formulation is presented in the Section 4. The optimization model generates two outputs: an updated signal timing plan that has minimum impact on all approaching travelers; and recommended speeds for all the buses that are being served. By generating these outputs, the logic automatically solves two underlying problems: bus serving sequence determination; and simultaneously-served bus group choosing. Not all buses are necessarily granted with TSP. In order to ensure the robustness of the proposed logic, maximum number of TSP phase is two. Hence, for cases where three or more conflicting requests are detected, the system will try to accommodate all requested simultaneously within the two TSP phases. If simultaneous accommodation is not feasible, the two requests that reduce the most total person delay will be granted with TSP. Other requests will be denied.

3.3. Logic assessment and implementation component

In this step, the TSP timing plan is compared against the normal traffic signal timing plan (winner overwrites the other) and the recommended bus speeds are transmitted to the buses approaching at the intersection.

After a TSP timing plan is determined, the algorithm compares the “with TSP” scenario against the “normal timing” (no TSP) scenario. Since the number of passengers on board is likely to be known under the Connected Vehicles (CV) environment, person delay performance measure is used. The person delay is calculated for a number of consecutive signal cycles starting from the TSP implemented cycle. The number of signal cycles considered is a user pre-defined parameter. A TSP timing plan is only implemented when its corresponding total person delay is less than the "no TSP" scenario.

During the implementation, two major steps are conducted. First, instructions are sent to the approaching buses about the recommended desired speeds. Second, the signal time is altered to accommodate TSP green. A possible buffer green time is given to a bus in case a bus cannot travel through the intersection as guided due to unexpected delay. This TSP green time extension is no longer than 5 s.

4. Problem formulation

4.1. Assumptions

The proposed model made the following assumptions:

- Traffic signal cycle length is fixed.
    - This assumption could be relaxed by removing the constraint #6. As a result, $G''_{a_k b_k k}$ become an additional decision variable.
- The sequence of signal phases is definite.
    - This assumption could be relaxed by adding a set of binary decision variables indicating whether two signal phases are next to each other.
- Maximum number of TSP green inserted is two per signal cycle
    - This assumption could be relaxed by changing the constant on the right side of the Eq. (12).
- General traffic is assumed to enter the road network at a constant rate.

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	
v_k	recommended speed (integer) for bus k (mph)
$\Theta_{a_k b_k k}$	start of TSP green signal k for movement from leg a to leg b (fraction of cycle length)
$\Psi_{a_k b_k k}$	TSP green signal k ratio for movement from leg a to leg b (fraction of cycle length)
Two variables are binary variables	
$\Delta_{m_k n_k k}$	permission of reallocating TSP green k into the phase for movement from leg m to leg n
$\delta_{m_k n_k k}$	permission of reallocating TSP green k right after the phase for movement from leg m to leg n

4.4. Objective function

The optimization algorithm is designed to find a set of decision variables that minimize the total travel time of all approaching travelers. The objective function can be expressed as follows:

$$\text{Min} \sum_{cycle=1}^{cycle=N_c} \sum_{t=1}^{C} \sum_{i} Occ_i + \sum_{k=1}^{N_B} (D_b * Occ_b) \tag{1}$$

4.5. Bus travel time computation

The bus travel time TT_b is demonstrated in Fig. 4. As shown in the figure, 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. The figure describes the case that bus is impeded by the queue and then discharged with other vehicles.

As demonstrated, the travel time TT_b consists of three parts. Part 1, TT_{b1}, is the travel time that bus cruise through intersection at the desired speed. Part 2, TT_{b2}, is the extra time the bus spends waiting in the queue. Part 3, TT_{b3}, is the travel time due to slower speed when following the front queuing vehicle. The effect of residual queue is considered. The travel time 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. The magnitude of travel time 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	Signal timing cycle length (s)
D_b	Delay of bus
D_v	Delay of private vehicles
$G_{a_k b_k k}$	Duration of the original green time for movement that TSP bus k makes (from leg a to leg b)
$G'_{a_k b_k k}$	Duration of the TSP green time for movement that TSP bus k makes (from leg a to leg b)
$G''_{a_k b_k k}$	Duration of the revised green time for movement that TSP bus k makes (from leg a to leg b) which starts after TSP green k
G_{min}	Minimum green time requirement
$G_{m_k n_k k}$	Duration of the original green time for movement from leg m to leg n for the bus k
$G'_{m_k n_k k}$	Duration of the revised green time for movement from leg m to leg n which starts before TSP green k
$G''_{m_k n_k k}$	Duration of the revised green time for movement from leg m to leg n which starts after TSP green k
k	Numbering for TSP buses
k'	Numbering for TSP buses, $k' \neq k$
$L^Q_{a_k b_k k}$	Distance between the bus k and the front stop line when the bus stops for the front queue. It is associated with the bus coming from leg a and traveling towards leg b
$L^A_{a_k b_k k}$	Distance between the bus k and the front stop line when the TSP mechanism is activated. It is associated with the bus coming from leg a and traveling towards leg b. It has a predefined value: L^A
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_B	Total number of buses
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
$Q_{m_k n_k k}$	Residual queue for movement from leg m to leg n at the intersection k
$R_{m_k n_k k}$	Red time in one cycle for movement from leg m to leg n at the intersection k (s)
s_k	Saturation flow rate for the movement that bus k is traveling on
t	Time stamp in second
$T^A_{a_k b_k k}$	Time when the TSP mechanism is activated for the bus k. It is associated with the bus coming from leg m and traveling towards leg n
v_k	Recommended speed for bus k (mph)
V_k	Speed limit on link bus k is traveling on (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
$\Delta_{m_k n_k k}$	Permission of reallocating TSP green k into the middle the phase for movement from leg m to leg n
$\delta_{m_k n_k k}$	Permission of reallocating TSP green k at the end of the phase for movement from leg m to leg n
$\Theta_{a_k b_k k}$	Start of TSP green signal for bus k for movement from leg a to leg b (fraction of cycle length)
$\Psi_{a_k b_k k}$	TSP green signal ratio for bus k for movement from leg a to leg b
$\Omega_{m_k n_k k}$	Start of the original green signal for movement from leg m to leg n associated with the bus k (fraction of cycle length)

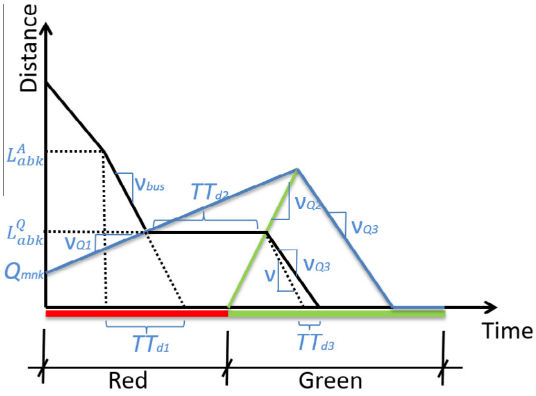

Fig. 4. Bus travel time computation.

$$TT_{b1} = \frac{L^A_{a_k b_k k}}{v_{bus}}, \quad \forall k = 1,\ldots,N_B; \quad a_k \in [1,\ldots,N_L]; \quad b_k \in [1,\ldots,N_L - 1] \tag{2}$$

$$\begin{aligned} TT_{b2} &= \frac{v_{Q2} * (1 - \Psi_{a_k b_k k}) * C + Q_{m_k n_k k}}{v_{Q2}} + \frac{\left(L^Q_{a_k b_k k} - Q_{m_k n_k k}\right) * (v_{Q2} - v_{Q1})}{v_{Q1} * v_{Q2}}, \\ &\forall m_k = a_k; \quad n_k = b_k; \quad k = 1,\ldots,N_B; \quad a_k \in [1,\ldots,N_L]; \quad b_k \in [1,\ldots,N_L - 1] \end{aligned} \tag{3}$$

$$TT_{b3} = \frac{L^Q_{a_k b_k k} * (v_{bus} - v_{Q3})}{v_{bus} * v_{Q3}}, \quad \forall a_k \in [1,\ldots,N_L]; \quad b_k \in [1,\ldots,N_L - 1]; \quad k = 1,\ldots,N_B; \tag{4}$$

$L^Q_{a_k b_k k}$ 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 approaching bus.

$$\begin{cases} L^Q_{a_k b_k k} = v_{Q1} * t + Q_{m_k n_k k} \\ L^Q_{a_k b_k k} = -v_{bus} * t + L^A_{a_k b_k k} + v_{bus} * T^A_{a_k b_k k} \end{cases}, \quad \forall m_k = a_k; \quad n_k = b_k; k = 1,\ldots,N_B; \quad a_k \in [1,\ldots,N_L]; \quad b_k \in [1,\ldots,N_L - 1] \tag{5}$$

Thus, the total travel of bus is given by substituting Eq. (5) into Eqs. (2)–(4):

$$\begin{aligned} TT_b &= TT_{b1} + TT_{b2} + TT_{b3} \\ &= \frac{L^A_{a_k b_k k}}{v_{bus}} + \frac{v_{Q2} * (1 - \Psi_{a_k b_k k}) * C + Q_{m_k n_k k}}{v_{Q2}} + \frac{\left(v_{Q1} * L^A_{a_k b_k k} + v_{Q1} * v_{bus} * T^A_{a_k b_k k} - v_{Q1} * Q_{m_k n_k k}\right) * (v_{Q2} - v_{Q1})}{v_{Q1} * v_{Q2} * (v_{Q1} + v_{bus})} \\ &+ \frac{\left(v_{Q1} * L^A_{a_k b_k k} + v_{Q1} * v_{bus} * T^A_{a_k b_k k} + v_{bus} * Q_{m_k n_k k}\right) * (v_{bus} - v_{Q3})}{v_{bus} * v_{Q3} * (v_{Q1} + v_{bus})}, \quad \forall m_k = a_k; \quad n_k = b_k; k = 1,\ldots,N_B; \\ &a_k \in [1,\ldots,N_L]; \quad b_k \in [1,\ldots,N_L - 1] \end{aligned} \tag{6}$$

Details of how v_{Q1}, v_{Q2} and v_{Q3} are computed are provided in the literature (Liu et al., 2009). The delay of bus is the difference of TT_b between with TSP and without TSP.

4.6. Travel time of general traffic users

General traffic is assumed to enter the road network at a constant rate. Again, the delay calculation is based on the real-time queue length estimation model developed by Liu et al. (2009). The total person delay is computed by integrating the number of passengers waiting at the intersection over time.

4.7. Constraints

(1) Queue clearance constraint: the queue standing in the way of the bus should be discharged before the bus' arrival. As shown in Fig. 5, the bus catches up with the rear end of the front queue right at the stop line of the intersection. To be noted, when oversaturated, constraint (1) would become infeasible. However, this would not generate any error. The scenario falls into the condition where the granted TSP would not reduce delay at the intersection. In that case, according to the "conditional granting" nature of the proposed logic, no TSP would be granted. Therefore, the fact that constraint (1) becomes infeasible is consistent with the proposed logic. This can be expressed as:

$$(\Theta_{a_k b_k k} + \Psi_{a_k b_k k}) * C - \frac{L^A_{a_k b_k k}}{v_k} - T^A_{a_k b_k k} + \left(N_k - N^A_k\right) * C = 0, \quad \forall a_k \in [1,\ldots,N_L]; \quad b_k \in [1,\ldots,N_L - 1]; \quad k = 1,\ldots,N_B \tag{7}$$

(2) Multiple accommodation constraint: when multiple buses arrive within one phase, and their movements are not conflicting with each other, the TSP mechanism allows these buses to be accommodated within one TSP green time. This constraint can be expressed as:

$$\begin{aligned} &\left\{ \begin{aligned} &\left(\Delta_{a_k b_k k} * \Delta_{a_k b_k k'} + \delta_{a_k b_k k} * \delta_{a_k b_k k'}\right) * \left[\Theta_{a_k b_k k} - \min\left(\Theta_{a_k b_k k'}\right) + \Psi_{a_k b_k k}\right] \\ &\quad + \left(1 - \Delta_{a_k b_k k} * \Delta_{a_k b_k k'} - \delta_{a_k b_k k} * \delta_{a_k b_k k'}\right) * (\Theta_{a_k b_k k} + \Psi_{a_k b_k k}) \end{aligned} \right\} * C * s_k \geqslant Q_{a_k b_k k}, \quad \forall a_k \in [1,\ldots,N_L]; \\ &b_k \in [1,\ldots,N_L - 1]; \quad k = 1,\ldots,N_B; \quad k' = 1,\ldots,N_B; k' \neq k \end{aligned} \tag{8}$$

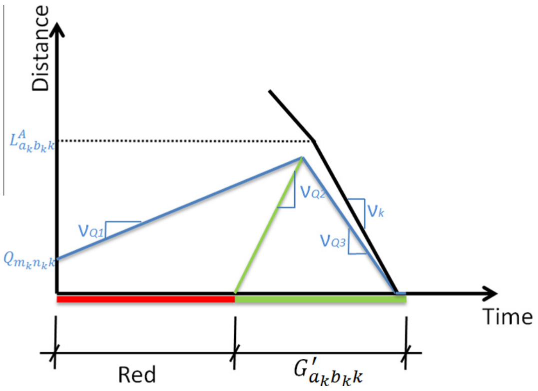

Fig. 5. Illustration of the queue clearance constraint.

(3) TSP start time constraint: it provides the range for the decision variable Θ_{abk}. In the equations, Δ_{mnk} and δ_{mnk} are both binary indicators. When $\Delta_{mnk} = 1$, the TSP start time falls in the middle of the green time for movement from leg m to leg n. When $\delta_{mnk} = 1$, then TSP green starts at 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:

$$(\Omega_{m_k n_k k} * C) * \Delta_{m_k n_k k} < \Theta_{a_k b_k k} * C < \Omega_{m_k n_k k} * C + G_{m_k n_k k} + \mathcal{M} * (1 - \Delta_{m_k n_k k}), \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m_k \neq a_k; \quad n_k \neq b_k; \quad k = 1, \ldots, N_B; \quad a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{9}$$

$$(\Omega_{m_k n_k k} * C + G_{m_k n_k k}) * \delta_{m_k n_k k} \leqslant \Theta_{a_k b_k k} * C \leqslant \Omega_{m_k n_k k} * C + G_{m_k n_k k} + \mathcal{M} * (1 - \delta_{m_k n_k k}), \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m_k \neq a_k; \quad n_k \neq b_k; \quad k = 1, \ldots, N_B; \quad a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{10}$$

(4) Maximum TSP constraint: This constraint limits the total number TSP green inserted for practical implementation purpose. No more than two TSP green times are granted per signal cycle. No more than one TSP green time is granted within each timing phase. This constraint also ensures that no more than one TSP is permitted for each bus, which can be specified as:

$$\Delta_{m_k n_k k} * \Delta_{m_{k'} n_{k'} k'} * (\Theta_{a_k b_k k} - \Theta_{a_{k'} b_{k'} k'}) = 0, \quad \forall\, m_k = 1, \ldots, \quad N_L; \quad n_k = 1, \ldots, \quad N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \ldots, \quad N_B; k' = 1, \ldots, N_B; \quad k' \neq k \tag{11}$$

$$\delta_{m_k n_k k} * \delta_{m_{k'} n_{k'} k'} = 0, \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m \neq a; \quad n \neq b; \quad k = 1, \ldots, N_B; \quad k' = 1, \ldots, N_B; \quad k' \neq k \tag{12}$$

$$\sum_{n_k=1}^{N_L-1} \sum_{m_k=1}^{N_L} (\Delta_{m_k n_k k} + \delta_{m_k n_k k}) \leqslant 2, \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m \neq a; \quad n \neq b; k = 1, \ldots, N_B \tag{13}$$

$$\sum_{k=1}^{N_B} (\Delta_{m_k n_k k} + \delta_{m_k n_k k}) \leqslant 1, \quad \forall\, m_k = 1, \ldots, \quad N_L; \quad n_k = 1, \ldots, \quad N_L - 1; \quad m \neq a; \quad n \neq b; k = 1, \ldots, \quad N_B \tag{14}$$

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

$$80\% * V_k \leqslant v_k \leqslant 110\% * V_k, \quad \forall k = 1, \ldots, N_B \tag{15}$$

(6) Green relocation constraint: the total duration of green time for each movement does not change after TSP green is granted. This constraint automatically ensures that cycle length does not change after the reallocation of TSP green.

$$G_{m_k n_k k} = G'_{m_k n_k k} + \Delta_{m_k n_k k} * G''_{m_k n_k k}, \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad k = 1, \ldots, N_B \tag{16}$$

$$G''_{m_k n_k k} = \Delta_{m_k n_k k} * (G_{m_k n_k k} - (\Theta_{a_k b_k k} - \Omega_{m_k n_k k}) * C + YR), \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m_k \neq a_k; \quad n_k \neq b_k; k = 1, \ldots, N_B; \quad a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{17}$$

It should be noted that by dividing part of the original green time for bus TSP green, extra change interval time (i.e., yellow and red clearance times) 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:

$$G_{a_k b_k k} = \mathit{\Psi}_{a_k b_k k} * C + G''_{a_k b_k k} + \left[\sum_{m=1}^{N_L} \sum_{n=1}^{N_L - 1} (2 * \Delta_{m_k n_k k}) + \sum_{m=1}^{N_L} \sum_{n=1}^{N_L - 1} (\delta_{m_k n_k k}) \right] * YR, \quad \forall m_k = 1, \ldots, N_L;$$
$$n_k = 1, \ldots, N_L - 1; \quad m_k \neq a; \quad n_k \neq b; k = 1, \ldots, N_B; \quad a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{18}$$

(7) Minimum green requirement: the duration of green time for all movements including reallocated TSP green should follow the minimum green requirement.

$$G_{m_k n_k k} \geqslant G_{min}, \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m_k \neq a; \quad n_k \neq b; \quad k = 1, \ldots, N_B;$$
$$a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{19}$$

$$G'_{m_k n_k k} \geqslant G_{min}, \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m_k \neq a; \quad n_k \neq b; \quad k = 1, \ldots, N_B;$$
$$a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{20}$$

$$G''_{m_k n_k k} = \Delta_{m_k n_k k} * (G_{m_k n_k k} - (\mathit{\Theta}_{a_k b_k k} - \mathit{\Omega}_{m_k n_k k}) * C + YR) \geqslant \Delta_{m_k n_k k} * G_{min}, \quad \forall m_k = 1, \ldots, N_L;$$
$$n_k = 1, \ldots, N_L - 1; \quad m_k \neq a; \quad n_k \neq b; \quad k = 1, \ldots, N_B; \quad a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{21}$$

$$G'_{a_k b_k k} = \mathit{\Psi}_{a_k b_k k} * C \geqslant G_{min}, \quad \forall k = 1, \ldots, N_B; \quad a_k \in [1, \ldots, N_L]; \quad b_k \in [1, \ldots, N_L - 1] \tag{22}$$

$$G''_{a_k b_k k} \geqslant G_{min}, \quad \forall m_k = 1, \ldots, N_L; \quad n_k = 1, \ldots, N_L - 1; \quad m_k \neq a; \quad n_k \neq b; k = 1, \ldots, N_B; \quad a_k \in [1, \ldots, N_L];$$
$$b_k \in [1, \ldots, N_L - 1] \tag{23}$$

4.8. Branch and bound based solving process

To solve the aforementioned problem for optimal vehicle speed control and optimal signal timing plan, a numerical solution is presented here. The main idea is to recursively split searching space into smaller spaces and eliminate candidate spaces that can be proven not containing optimal solution. The procedure is summarized in the following:

1. Set the objective function $= \mathcal{M}$. It represents the best solution found $\widehat{T}$.
2. Start the loop:
    a. Use the bound on advisory speed v_k to find feasible space for $\Delta_{m_k n_k k}$ and $\delta_{m_k n_k k}$
    b. Branch on feasible $\Delta_{m_k n_k k}$ and $\delta_{m_k n_k k}$, for each $\Delta_{m_k n_k k}$ and $\delta_{m_k n_k k}$,
        i. Use associated green phase time duration to find feasible space for speed v_k
        ii. Branch on feasible speed v_k for each $\Delta_{m_k n_k k}$ and $\delta_{m_k n_k k}$ and compute candidate total cost T, for ith speed $v_k(i)$
            1. If $T(i) < \widehat{T}$, do nothing, this is not the optimal solution
            2. Else, store associated v_k, $\Delta_{m_k n_k k}$ and $\delta_{m_k n_k k}$, set $\widehat{T} = T(i)$
3. Output variables and $\widehat{T}$.

5. Evaluations

5.1. Study site

The test network is a VISSIM model based on the intersection at Emmet St. and Barracks Rd. in Charlottesville, VA, as shown in Fig. 6. The model had been calibrated (Hu et al., 2014b) to match the real world. It was achieved by adjusting the car following model parameters to reach a realistic saturation flow rate at the intersection. The model was also visually examined by the authors of this paper to ensure the validity of the simulation.

5.2. Methodology

Two levels of evaluation are performed. The first is analytical evaluation and the second is 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 and conflicting scenarios are considered. An unbiased performance measure is then acquired by averaging the delay change of all possible TSP activation scenarios. However, this kind of evaluation could not consider the stochastic nature of the traffic. Hence, a microscopic traffic simulation-based evaluation is conducted to consider variability due to vehicle interactions and inter-arrival times (Stevanovic et al., 2008). Nevertheless, consider the massive number of all TSP activation scenarios, simulation-based evaluation could only test a small portion of it. Therefore, both evaluations are presented to demonstrate a complete picture.

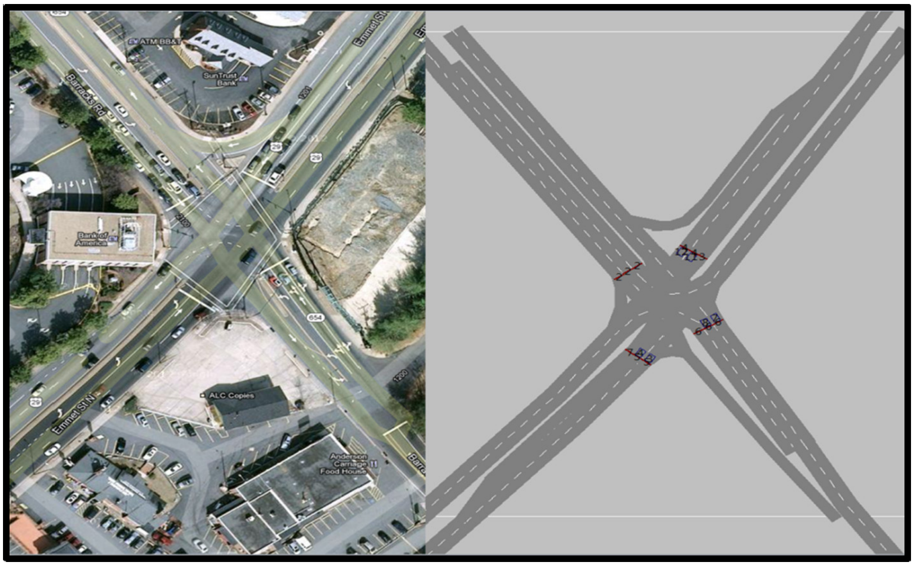

Fig. 6. Study site—Emmet St. and Barracks Rd. intersection, Charlottesville.

Three different control logic cases were compared:

- *TSPCV-CR*. It is the proposed control strategy with the capability of bus serving sequence determination and simultaneous multiple buses accommodation.
- *Conventional TSP (CTSP)*. The conventional TSP logic compared here is the first-come-first serve TSP. It is not only because the first-come-first-serve (FCFS) TSP is the current common practice, but also because all the aforementioned research use the FCFS TSP as the control group. By comparing to the same benchmark, the advantage of TSPCV-CR is clearly presented. 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 simpler (i.e., green extension only) with no cooperative interactions between the bus and the traffic signal controller. The CTSP grants 10-s extra green time to buses which arrive within 10 s of the end of normal green time. When multiple TSP requests are made within one signal cycle, only one request is accommodated by the CTSP. The logic follows the real implementation in the Northern Virginia (Rakha and Ahn, 2006).
- *No TSP (NTSP)*. This signal controller runs the background signal timing plan, without taking any action responding to bus' appearance.

Three different scenarios are investigated for all three control strategies:

- Two conflicting requests from opposite directions
- Two conflicting requests from competing perpendicular directions
- Three conflicting requests from three directions (microscopic simulation only)

Confliction from more than three directions is not tested, since there is very low possibility of occurrence.
The settings of the evaluations are specified here:

- Signal timing plan is adopted from the site. The cycle length at the intersection is 160 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 each approach is with a mid-block bus stop located 750 feet upstream of the intersection.
- The speed limit is 45 mph on all approaches. 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).

$$80\% * 45 \leqslant v_k \leqslant 110\% * 45, \quad \forall\, k = 1,\ldots, \quad N_B \tag{24}$$

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

$$L^A_{a_k b_k k} = \min(0.5, L_k), \quad \forall\, a \in [1,\ldots,N_L]; \quad b \in [1,\ldots,N_L - 1]; k = 1,\ldots, \quad N_B \tag{25}$$

- As aforementioned, time duration needs to be predefined for total person delay calculation. In this case study, a duration of 3 signal cycles is adopted. It is noted that three cycles are adequate to capture residual effects caused by TSP and to prevent including another TSP request, given three cycles of 160-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 (NCHRP, 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. This is borrowed from the NCHRP report. It was suggested that with the Automated Passenger Counting (APC) system, the number of passengers boarding and debarking can be estimated more accurately. As a result, the variation is set to be moderately low.
- Bus headway is 494 s (microscopic simulation).

Therefore, the objective function is now specified as following:

$$\text{Min} \sum_{cycle=1}^{cycle=3} \sum_{T=1}^{160} \left[\sum_{i} Occ_i + \sum_{k=1}^{N_B} (D_b * Occ_b) \right] \tag{26}$$

The Measures of Effectiveness (MOE) used are bus delay, person-based delay and total travel time of all travelers. Bus delay quantifies the effectiveness of various TSP treatments while the person-based delay and total travel time demonstrates whether the adverse effect is caused.

Finally, all the differences shown in the following tables have been checked for statistical significance. The differences that are NOT statistically significant are underlined and in italics. All other changes were determined to be statistically significant at $\alpha = 0.05$.

5.3. Analytical test

The analytical test is a deterministic simulation that quantifies the performance of the proposed TSPCV-CR logic on a theoretical level. The analytical evaluation is needed on top of the microscopic simulation is because simulation has its limitation in this specific case. In this case, both how far away the conflicted requests are made and how those requests fall into signal cycle affect performance of the proposed logic. As a result, the scenarios are too many to be evaluated by microscopic simulation. Take 2-bus conflict as an example, assuming signal cycle length is 160 s, there are $160 \times 160 = 25{,}600$ possible TSP activation situations. This is too much work for simulation running. Therefore, the microscopic simulation could only sample a small portion of those 25,600 situations and may have its own bias. This is the reason why the analytical evaluation is presented as all the situations can be tested with the analytical approach. Here are all the factors considered:

- Volume is the flow rate collected from the study site during peak hour, which is near capacity situation ($v/c = 0.9$).
- 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 160 s. Assuming a TSP can be activated at any given second, there are $160 \times 160 = 25{,}600$ possible TSP activation situations. Stop delay for bus and all other traffic users is calculated by averaging results from these 160×160 situations.

The program was coded in VBA and run on an i5-2400 3.10 GHz processor with 8 GB RAM. The computation time for each conflicting scenario is less than 1 s. All three control strategies have been computed and pairwise comparison was conducted. The delay comparisons are presented in Table 2 and visualized in Fig. 7.

Table 2 presents the performance of TSPCV-CR accommodating 2 different kinds of conflicting TSP requests: two buses coming from opposite directions (Opp) and buses coming from perpendicular directions (Perp). Both per person delay of all traffic users and bus delay are compared. The bus delay presented is the summation of both buses. It is discovered that TSPCV-CR is superior to CTSP regardless of conflicting conditions. While CTSP showed comparable benefits over two conflicting scenarios, TSPCV-CR demonstrated more advantages when buses are coming from opposite directions. Not only the bus delay is reduced more, delay per person is also minimized in a greater magnitude. This observation is intuitive because two opposite traveling buses can be accommodated in a single TSP green. As a result, more bus passengers are provided with preference at the same time while fewer disturbances are caused to other travelers. To further prove this hypothesis, Table 3 is computed and is visualized in Figs. 8 and 9.

Table 3 presents the number of TSPCV-CR granted sorted by TSP type out of the $160 * 160$ different conflicting conditions. The cases where buses arrive during original green is not included in the statistics. The first column is the number of TSP granted only to the bus traveling on the main street. The second column represents the number of TSP granted only to the minor street bus. The third column shows the number of cases that both buses receive TSP. As shown in Table 2, the likelihood of double accommodation for opposite traveling buses is 20% which is about 4 times higher than that of the

Table 2
Analytical assessment on various TSP treatments.

	NTSP	CTSP	TSPCV-CR	N/TSPCV-CR (%)	C/TSPCV-CR (%)
Delay per person (Opp) (s)	49.5	49.2	44.3	10.5	9.8
Delay per person (Perp) (s)	49.5	49.2	46.0	7.2	6.5
Bus delay (Opp) (s)	105.4	99.2	51.8	50.9	47.8
Bus delay (Perp) (s)	117.2	109.4	65.4	44.2	40.3

Note: Here “Opp” represents “opposite direction” and “Perp” represents “perpendicular direction”.

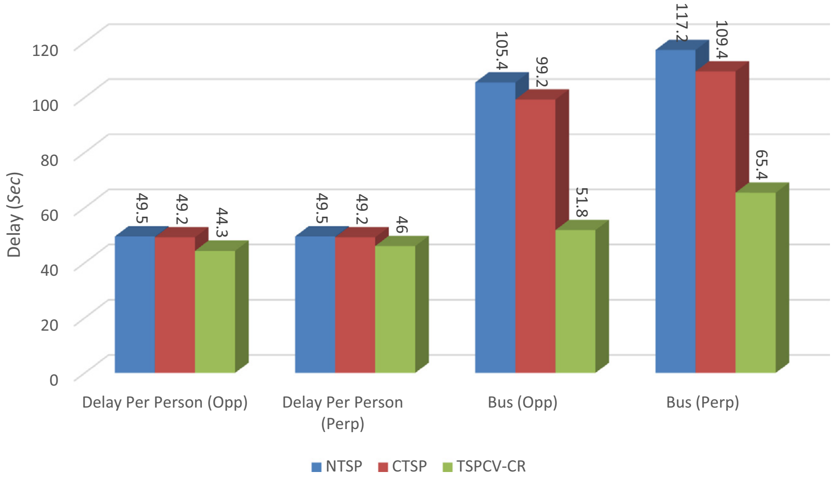

Fig. 7. Analytical assessment on various TSP treatments.

Table 3
TSP Granting Condition.

Perpendicular	Main St	Minor St	Both buses	None
Count	13,800	10,828	972	0
Opposite	Main St 1	Main St 2	Both buses	None
Count	11,032	9460	5108	0

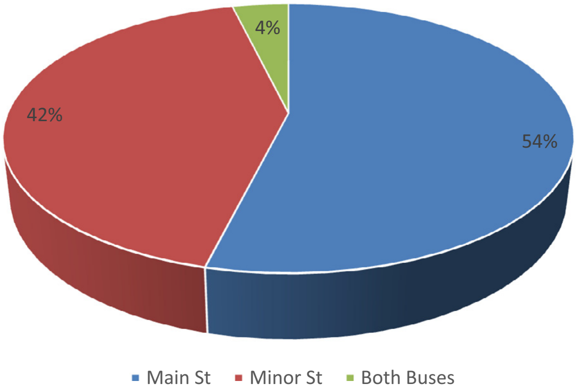

Fig. 8. TSP granting condition – perpendicular direction conflict.

perpendicular traveling buses. This is the reason why TSPCV-CR has an advantage when buses are coming from opposite directions. In addition, the results also reveal that the TSPCV-CR logic prefers buses traveling on the direction with a higher volume level. As a larger portion of buses on the main street are granted with TSP than that of the buses on the minor street. Given that the volume is slightly higher on the main street direction 1 than the main street direction 2, the percentages

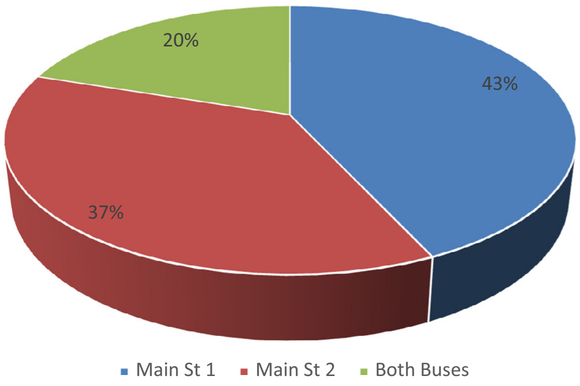

Fig. 9. TSP granting condition – opposite direction conflict.

associated demonstrate the same relationship. It is intuitive because the TSP green not only provides preference to the buses, but also discharge the vehicles that are traveling with the bus. The higher the volume is, the greater the benefit would be for the other traffic users' experience. Hence this TSP plan would be more likely to be executed.

5.4. Simulation-based evaluation in VISSIM

While the analytical test results show significant benefits, it does not consider any variability due to vehicle interactions and inter-arrival times. A microscopic traffic simulator can assess the performance of the proposed TSP under more plausible conditions. The microscopic simulation software package VISSIM (PTV, 2008a,b) is used to evaluate the proposed TSP logic under a Connected Vehicles (CV) environment. A COM interface is used to access information that is available within a Connected Vehicles environment (PTV, 2008a,b). The evaluation is performed under the assumption that only transit buses are connected to traffic signal controllers and other vehicles do not have CV equipment. In other words, 0% CV market penetration except for buses. Therefore, the data extracted via COM interface is only speed and position of bus, number of passengers on board, number of potential passenger at the bus stop, number of vehicles passing the intersection and volume from all four approaches. The COM interface is also used to change traffic signal timing plan during the simulation. All programs are coded in Microsoft EXCEL VBA.

The simulation test network has been calibrated to match the real world. Measurement utilized is saturation flow rate. In order to reduce the saturation flow rate to a realistic range, the default settings of Wiedemann 74 car following model have been adjusted. Average standstill distance is raised to 7.5, additive part to 3 and multiplicative part to 4. After these adjustments, saturation flow rate is reduced to an average of 1838 veh/h/ln. It is in a reasonable range as it is in between the HCM, 2010 value (1800 veh/h/ln) (HCM, 2010) and the default value in Synchro (1900 veh/h/ln).

At least 10 simulation runs were performed for each scenario and the MOEs for each scenario were averaged from the output of all simulation runs. Minimum sample size requirement was checked to make sure that sufficient number of simulation runs was achieved to ensure statistically significance. Minimum sample size was calculated using the formula recommended by the Virginia Department of Transportation (VDOT, 2013), which is:

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

where

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

Ss: Sample standard deviation.

Xs: Sample mean.

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

5.4.1. Conflicting requests from opposite directions

As noted, the test network is a calibrated model of the intersection at Emmet St. and Barracks Rd. in Charlottesville, VA. A pair of transit buses is designed to arrive every 494 s. Given the cycle length is 160 s at the intersection; the interval of bus arrival is exactly 3 cycles plus 14 s. Also, the headway between the two buses within a pair increases by 14 s every time another pair of buses is generated. This research purposefully designed the offset and headway so that buses within one single simulation run would arrive at different times relative to the traffic signal cycles; hence the simulation result would be less biased.

The results from the microscopic traffic simulation based evaluation are shown in Table 4 and visualized in Fig. 10. Bus delay and total travel time of all vehicles were summarized and averaged from all simulation runs. The proposed TSP treatment was compared with NTSP and CTSP conditions and *T*-tests were performed to validate that all the differences are statistically significant. All the differences presented have been confirmed significant. In summary, the simulation based results support the findings from the analytical analysis. Compared to the other conflicting scenarios, most significant improvements are observed in opposite conflicting condition. The delay of all buses is reduced by 44% compared to CTSP and 50% compared to NTSP. Delay of all traffic users is slightly minimized as well. An unbalance of improvement is observed between the two bus lines. As aforementioned, it is because the traffic volume traveling in the same direction with the second bus line is less. As a result, the algorithm tends to provide more preference for the bus direction with more traffic to discharge. The other reason is that a larger portion of buses on line 2 arrives during the green phase. Hence, the room for improvement is relative small compared to line 1. The benefit observed from microscopic simulation is slightly less than that from the analytical test. Nevertheless, no bus is found failed to take advantage of the TSP granted. The difference is caused by buffer green time. When bus requires buffer green time to pass, although it traverses through during TSP green phase, it is still a longer delay than analytical test expectation.

5.4.2. Conflicting requests from perpendicular directions

The setting of simulation of this scenario is similar to the opposite direction scenario, except that the buses come from perpendicular directions in this scenario. Again the offset and headway were purposefully designed so that buses within one single simulation run would arrive at different times relative to the traffic signal cycles. Hence the simulation result would be less biased.

The results from the microscopic simulation based evaluation are shown in Table 5 and visualized in Fig. 11. Bus delay and total travel time of all vehicles are summarized and averaged from all simulation runs. The proposed TSP treatment is compared with NTSP and CTSP conditions and the *T*-tests were performed. In summary, the simulation based results support the findings from the analytical analysis. The delay of all buses is reduced by 31% compared to CTSP and 35% compared to NTSP. Regardless of the fact that the delay of all traffic users increases slightly, the differences are proven to be statistically insignificant. Buses on the minor street are showing larger improvement than the buses on the principal street. One major reason is that a larger room of improvement exists for the minor street buses. Therefore, when being granted with TSP, minor street buses tend to generate more delay savings. Hence, despite that less portion of minor street buses receive TSP, more benefit is observed. The other reason why main street bus is showing less benefit is because one main street bus failed to pass through intersection during TSP green phase. It is due to under-estimation of queue length and bus station dwell time. When estimation bias is too significant, even 5 s green buffer time could not help. It is further discovered that the travel direction with higher volume is more likely to experience TSP failure. This is because higher volume direction is with longer green phase which allows longer TSP green phase and potentially leads to greater bias in queue length estimation.

5.4.3. Conflicting requests from three directions

The same bus schedule generated in the previous two scenarios is adopted. The consideration again is to ensure that buses within one single simulation run would arrive at different times relative to the traffic signal cycles; hence the simulation result would be less biased. When three conflicting requests is detected

The results from the microscopic simulation based evaluation are shown in Table 6 and visualized in Fig. 12. The magnitude of improvement is not as significant as the two-conflicting-requests conditions. It is because the TSPCV-CR only allows a maximum of two TSP grants at a time. As a result, when more than two TSP requests are made, at least one bus does not receive TSP treatment. Although this fact reduces the size of improvement, the results are still showing 18% reduction in bus delay compared to CTSP and 21% benefit compared to NTSP. Again no adverse effect on other traffic users is caused by TSPCV-CR. Nevertheless, the TSPCV-CR does show advantage over CTSP on total travel time of all traffic users.

5.4.4. 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 comparing TSPCV-CR against CTSP. Since the field collected volume data is at v/c ratio 0.9, three other scenarios are tested: $v/c = 0.5$, $v/c = 0.7$ and $v/c = 1.0$. The results have been presented in Tables 7–12.

All three scenarios show similar trends with respect to how TSPCV-CR performs under various congestion levels. When the congestion level is low, TSPCV-CR helps reduce bus delays up to about 44% compared to CTSP. As the congestion level increases, the benefit of TSPCV-CR decreases, while no extra delay is caused. This is because the algorithm is designed to be conditional on person delay. When the volume level becomes closer to the capacity, less portion of the green time would be granted to TSPCV-CR 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. It is interesting to find that even when v/c ratio equals to 0.9, the benefit of TSPCV-CR is still significant and drops dramatically when v/c increases to 1.0. However, even when $v/c = 1.0$, TSPCV is still superior to conventional TSP. Furthermore, the TSPCV-CR logic only shows unbalanced preference on buses under near capacity conditions. When v/c level is low, the improvements observed by different bus line are similar. As the congestion level increases, the difference in delay savings increases with it. When buses approach from perpendicular directions, the logic sacrifices one bus line in order to achieve an overall delay reduction.

As shown in Tables 7 and 8, the greatest delay reduction is observed when conflicting TSP requests come from opposite directions. The performance of TSPCV-CR reacts to congestion level change the same fashion as described above. Statistically significant total travel time reduction is observed under all congestion levels tested.

Table 4
Two conflicting requests from opposite directions.

	NTSP	CTSP	TSPCV-CR	N/TSPCV-CR (%)	C/TSPCV-CR (%)
Bus 1 delay (s)	46.6	38.3	16.4	64.9	57.3
Bus 2 delay (s)	34.4	34.2	24.2	29.5	29.1
Total bus delay (s)	81.0	72.5	40.6	49.8	44.0
Total travel time (h)	170.5	170.1	161.1	–5.5	–5.3

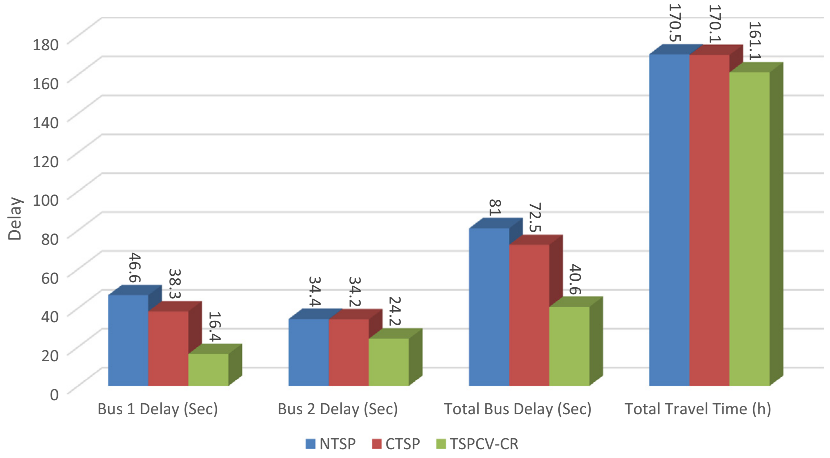

Fig. 10. Two conflicting requests from opposite directions.

Table 5
Two conflicting requests from perpendicular directions.

	NTSP	CTSP	TSPCV-CR	N/TSPCV-CR (%)	C/TSPCV-CR (%)
Main St bus delay (s)	53.4	52.7	42.0	21.5	20.4
Minor St bus delay (s)	73.2	66.9	40.6	44.6	39.4
Total bus delay (s)	126.6	119.6	82.5	34.8	31.0
Total travel time (h)	148.1	147.4	153.2	3.4	4.0

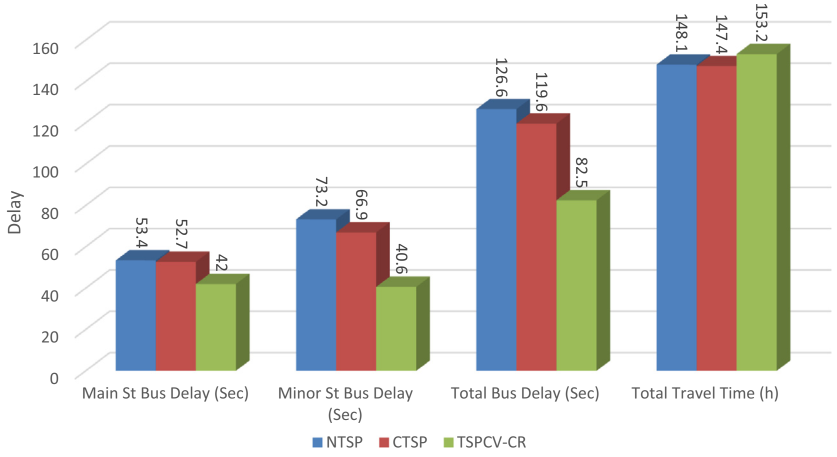

Fig. 11. Two conflicting requests from perpendicular directions.

Tables 9 and 10 demonstrate how bus delay savings and total travel time change with congestion levels when conflicting TSP requests come from perpendicular directions. The performance of TSPCV-CR mostly reacts to congestion level change the same fashion as described above. When the volume is at the capacity, the logic sacrifices the bus line on the main street to

Table 6
Conflicting requests from three directions.

	TSPCV-CR	CTSP	NTSP	TSPCV-CR/CTSP (%)	TSPCV-CR/NTSP (%)
Main St bus 1 delay (s)	41.7	46.1	49.9	9.5	16.5
Main St bus 2 delay (s)	32.5	34.5	34.7	5.9	6.5
Minor St bus delay (s)	50.6	70.8	72.9	28.5	30.6
Total bus delay (s)	124.8	151.3	157.5	17.6	20.8
Total travel time (h)	169.1	171.5	170.4	−1.4	−0.8

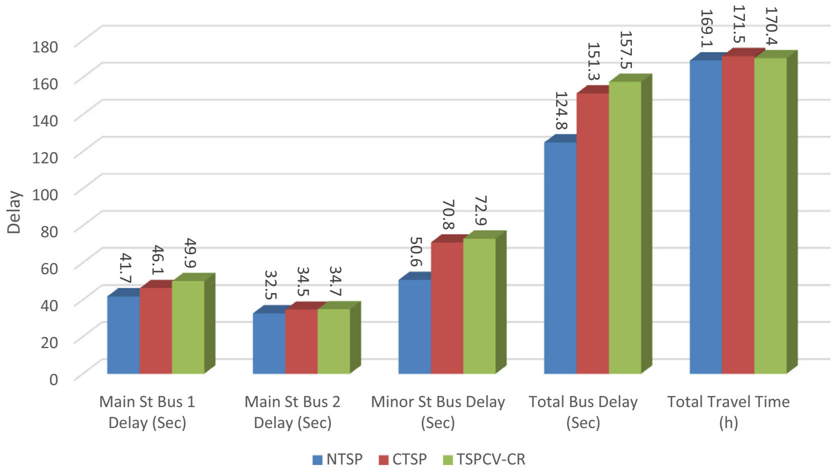

Fig. 12. Conflicting requests from three directions.

Table 7
Sensitive analysis for conflicting requests from opposite directions (bus delay).

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

Table 8
Sensitive analysis for conflicting requests from opposite directions (total delay).

v/c	TSPCV-CR (h)	NTSP (h)	Diff (%)	*T*-test
0.5	91.7	93.8	2.3	6.80E−07
0.7	122.8	128.5	4.4	7.81E−05
0.9	161.1	170.5	5.8	1.84E−07
1.0	197.3	204.1	3.3	3.00E−02

achieve overall bus delay improvement. This is because minor street bus has a larger room for delay saving. When congested, both travel direction could provide constant discharge flow. Consequently, TSP preference would shift from the major street to the minor street which saves more delay both on bus and on other motorists. It is discovered that TSPCV-CR reduces delay for other traffic users when $v/c = 0.5$. No statistically significant adverse effect is observed under all other congestion levels.

Tables 11 and 12 demonstrate how bus delay savings and total travel time change with congestion levels under three conflicting TSP request scenarios. The performance of TSPCV-CR mostly reacts to congestion level change the same fashion as described above. When the volume is at the capacity, the logic sacrifices the bus line 1 on the main street to achieve overall bus delay improvement. No statistically significant adverse effect is observed under all congestion levels.

Table 9
Sensitive analysis for conflicting requests from perpendicular directions (bus delay).

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

Table 10
Sensitive analysis for conflicting requests from perpendicular directions (total delay).

$v/c =$	TSPCV-CR (h)	NTSP (h)	Diff (%)	*T*-test
0.5	92.9	96.0	3.3	0.0001
0.7	132.3	132.2	*−0.1*	0.8938
0.9	153.2	148.1	*−3.4*	0.0821
1.0	206.6	206.7	*0.1*	0.9849

Table 11
Sensitive analysis for conflicting requests from three directions (bus delay).

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

Table 12
Sensitive analysis for conflicting requests from three directions (total delay).

$v/c =$	TSPCV-CR (h)	NTSP (h)	Diff (%)	*T*-test
0.5	84.2	87.3	3.5	0.046
0.7	116.2	120.3	3.4	0.020
0.9	169.1	170.4	*0.7*	0.088
1.0	188.4	188.2	*−0.1*	0.642

6. Conclusions and future research

In this research, a person-delay-based optimization method is proposed for an intelligent TSP logic that handles multiple conflicting TSP requests at an isolated intersection. This TSP with Connected Vehicles accommodating Conflicting Requests (TSPCV-CR) overcomes the challenge born by the conventional "first come first serve" strategy and presents significant improvement on bus service performance. The feature of TSPCV-CR includes green re-allocation, simultaneous multiple buses accommodation, and signal-transit coordination. There features help maximize the transit TSP service rate and minimize adverse effect on competing travel directions. The TSPCV-CR 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 optimization is formulated as a Binary Mixed Integer Linear Program (BMILP) which is solved by standard branch-and-bound routine. Minimizing per person delay is the objective of the optimization model. The evaluation on TSPCV-CR based on a microscopic traffic simulation shows:

- The TSPCV-CR is superior to the conventional first-come-first-serve TSP. It reduces the single bus delay up to 57%.
- The TSPCV-CR logic is beneficial under all levels of v/c ratios. It reduces average bus delay between 5% and 48%. The range of improvement corresponding to four different degrees of saturation tested, which are 0.5, 0.7, 0.9 and 1.0.
- No adverse effect was observed under all congestion levels. Hence, the TSPCV-CR minimizes installation and maintenance cost in the sense that it might require for local agencies and DOTs to perform a minimum validation test for potential TSP intersections before installation.
- The TSPCV-CR shows more benefits when buses' movements do not conflict with each other. This is intuitive because these non-conflicting buses can potentially be accommodated in a single TSP green. As a result, more bus passengers are provided with preference while fewer disturbances are caused to other travelers.
- The TSPCV-CR provides more preference to buses traveling on the direction with a higher volume (major street) under most traffic conditions, but switches its preference to the minor street under near capacity condition.
- The TSPCV-CR sometimes sacrifices the mobility of one bus line in order to achieve an overall delay reduction.
- Bus could possibly not be successful to take advantage of the TSP granted due to estimation bias in queue length and bus dwell time. Travel direction with higher volume is more vulnerable to failure.
- The computation time is less than 1 s. Given the program was coded in VBA and run on an i5-2400 3.10 GHz processor with 8 GB RAM. This application can be potentially used in real time.

The proposed design is evaluated under the assumptions adopted from NCHRP documents. Although the assumptions appear to be reasonable, it is interesting to conduct a sensitivity study on various uncertainties, for example, dwell time variation, bus occupancy variation, etc. It can be expected that various variation would lead to different TSP success rate and benefit. The result would serve as a benchmark for future implementation of this technology.

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