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# Transit signal priority in a connected vehicle environment: User throughput and schedule delay optimization approach *

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*Abstract*— **Transit signal priority (TSP) is a common strategy to improve bus right-of-way at signalized intersections. However, TSP systems have several challenges, such as negative externalities for non-transit users, and handling conflicting priority requests. Considering recent advances in connected vehicle technology, we propose a user-based signal priority strategy (UST) to facilitate bus movement at intersections while minimizing adverse effects to non-transit users. Additionally, we extend UST by minimizing bus scheduled delay (UST-SD) to compensate bus delay that is caused by network congestion. We compare UST and UST-SD with a conventional TSP ring barrier controller (RBC) at an isolated signalized intersection in a microscopic simulation environment. The findings show that the proposed strategy improves user and vehicle performance measures while providing priority for buses.**

## I. INTRODUCTION

Transit signal priority (TSP) is a signal timing strategy facilitating movement of public transit vehicles at signalized intersections. TSP implementation brings various improvements, such as increasing bus schedule reliability, reducing transit travel time and delay, reducing emissions, and increasing public transit attractiveness for users [1]. In contrast to TSP benefits, there are several typical shortcomings, especially if both green extension and red truncation are used. These shortcomings include increasing total network delay, inability to handle conflicting priority requests, and negative externalities for non-transit users [2]. Additionally, red truncation may negatively affect safety, by increasing dilemma zone, which may increase accident risk [3].

Recently, CV technology has provided various opportunities to implement TSP in traffic management strategies[4]. Hu et al. proposed next generation logic based on CV (TSPCV) for the first time [5]. This strategy has been developed based on two-way communications between the bus and the traffic signal controller to provide priority for buses while reducing total person delay. TSPCV can reduce bus delay up to 84% compared with conventional TSP. Hu et al. extended TSPCV to coordinated TSPCV (TSPCV-C) by considering coordination between traffic signals among the corridor [6]. According the simulation-based evaluation, TSPCV-C can reduce bus delay between 55% and 75% in comparison with conventional TSP. Hu et al.also developed a TSP strategy with connected vehicles that resolves conflicting requests [7]. Wu et al. presented an integrated optimization of bus holding times at bus stops, signal timings, and bus speeds to provide priority to buses at isolated intersections [8]. Results indicate that the average bus delay has been reduced up to 24.2% by minimizing the average vehicle delays, while ensuring that the bus clears the intersection without stopping at a red light. In order to address the limitation of the effective range of vehicle to infrastructure communications, a peer to peer priority signal control has been suggested using a mixed integer linear programming [9]. Yang et al. developed a multimodal TSP model by considering near-side and far-side bus stops and bus schedule delay to minimize bus and car delay [10]. In a recent study, effect of TSP on moving bottleneck has been investigated by Wu et al. at the signalized intersection in connected auto and bus environment [11]. Additionally, a real-time TSP has been proposed by considering the migration states of coordinated phases and queuing states of non-transit vehicles for the single-ring sequential phasing [12]. A cooperative TSP using vehicle to vehicle and vehicle to infrastructure communication has been also developed and investigated which could reduce 61% reduction of transit delay in the network compared to the base scenario [13]. Considering car and bus occupancy in signal timing optimization has been proposed in TSP literature such as [14], [10]. In most studies, passenger occupancy has been implemented as a weight factor in optimization for providing transit priority considering various delay models for cars and buses. Zeng et al. considered each vehicle occupancy minimizing total person delay while the delay model was identical for cars and buses [15]. Nevertheless, maximizing overall user throughput has not been the objective of signal timing optimization in any studies. Concept of person capacity or throughput has been investigated only by Ma et al. for the design of lane markings, exclusive bus lanes, and passive bus priority signal settings [16]. Moreover, previous studies do not extensively explore the trade-off between user throughput and bus delay. Additionally, none of the previous studies has considered performance measures of other vehicle types based on number of users on-board while employing TSP strategies. Therefore the objective of this study is to implement a TSP signal by considering different vehicle types based on number of users on-board and minimizing bus schedule delay.

The remainder of the paper is organized as follows. In the next section, we describe proposed user-based strategy in the methodology section, followed by simulation setup description. Latter part of the paper includes various simulation results that are thoroughly discussed. The last section reports paper conclusions.

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## II. CONTROL STRATEGY FORMULATION

The user-based signal timing (UST) consists of three main components: 1) user throughput calculation, 2) bus schedule-delay calculation, and 3) signal timing optimization. As UST is designed to operate in a fully-connected environment, we assume that vehicle data, such as speed, location, length, and number users, are always available. Most of the required data, such as vehicle speed and position, can be provided by current CV technology, which has been described in previous studies involving signal timing optimization [17]. On the other hand, collecting the exact number of users in each vehicle is yet to be fully developed. However, users of buses can be counted by automatic passenger counting systems which are currently implemented in various transit systems [18]. In the proposed strategy, we assume that V2X technology provides also the number of users in each vehicle approaching the intersection. We use exact number of users for two purposes. First, number of users are used to solve conflicting request of buses. Second, we consider passenger cars based on number of users in model and evaluation. In addition, we also take into account bus schedule delay in order to deal with interaction of priority request, as well as to compensate for any delay experienced before entering the detection area. A summary of the notation used in UST is presented in Table I. The remainder of this section elaborates on the main components of the UST strategy.

### A. User-throughput calculation

In order to calculate user-throughput, we employ an queue length estimation and stop-bar passage time method which have been developed in our recent work [19]. Firstly, we estimate initial queue length in each lane. Then, we calculate stop-bar passage time for each of detected vehicles (The detailed description and formulations of these two steps are available in [19].) After calculating stop-bar passage time for each vehicle ($T_{ij}^n$) based on previous step, we compare calculated stop-bar passage time for each detected vehicle and corresponding green time. This comparison determines if a vehicle can be served in cycle time or not as follows.

$$G_i = \sum_{i=1}^{i} g_i + (i-1)Y \tag{1}$$

$$p_{ij}^n = \begin{cases} 1, & \text{if } T_{ij}^n < G_i \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Then, we calculate total number of users on-board of all passing vehicle which shows user-throughput for a cycle. At the end, the queue length is updated based on number of vehicles which cannot pass the stop-bar in current cycle. A Summary of user-throughput calculation is presented in Figure 1.

### B. Bus schedule delay

We describe here the method developed to calculate bus schedule delay, assuming that there is a bus stop after intersection. We define bus schedule delay as the difference between scheduled time of bus arrival to the bus stop and its actual time of arrival. In particular, a bus can be ahead of schedule, on time, or late based on its fixed schedule. The bus schedule delay includes three type of delay: schedule delay before entering the detection area ($\hat{D}_{ij}^n$), delay accumulated between the time a bus entered the and when it is detected ($\tilde{D}_{ij}^n$), and delay between the detection time and the arrival to the bus stop ($\bar{D}_{ij}^n$). The sum of these three delays determine the final bus schedule delay at the bus stop. We assume that ideal bus arrival time to edge of detection area is calculated based on schedule and moving with desired speed.

TABLE I: Notations

| Notation | Definition |
|---|---|
| $i$ | signal phase index ($i$=1,2,..,$I$) |
| $j$ | ring index ($j$=1,2,..,$J$) |
| $n$ | vehicle index ($n$=1,2,..,$N_{ij}$) |
| $m$ | last served vehicle index ($m$=1,2,..,$M_{ij}$) |
| $\Delta_{ij}^n$ | distance between head of bus and bus stop [m] |
| $\chi_{ij}^n$ | distance between start of detection area and head of bus is detected [m] |
| $c_{ij}$ | time from starting of cycle to starting of phase $i$ in ring $j$ [s] |
| $C$ | cycle time [s] |
| $d_s$ | distance between stop bar and bus stop [m] |
| $D_{ij}^n$ | schedule delay of bus $n$ in assigned lane for phase $i$ of ring $j$ [m] |
| $\hat{D}_{ij}^n$ | schedule delay of bus $n$ before entering the detection area $n$ in assigned lane for phase $i$ of ring $j$ [m] |
| $\tilde{D}_{ij}^n$ | delay of bus $n$ between when the bus entered into the detection area and when the bus is detected in assigned lane for phase $i$ of ring $j$ [m] |
| $\bar{D}_{ij}^n$ | delay of bus $n$ between the detection time and arrival and the bus stop $n$ for phase $i$ of ring $j$ [m] |
| $g_{i,\min}$ | minimum green time of phase $i$ [s] |
| $g_{i,\max}$ | maximum green time of phase $i$ [s] |
| $G_i$ | end of green time for phase $i$ [s] |
| $g_i$ | green time of phase $i$ in ring $j$ [s] |
| $H$ | time headway between vehicles and time gap between starting of green and stop-bar passage of first vehicle [s] |
| $p_{ij}^n$ | binary parameter indicating if vehicle $n$ is served in current cycle or not |
| $S$ | safety distance between stopped vehicles [m] |
| $T_{ij}^n$ | time between starting of cycle and when vehicle $n$ in phase $i$ of ring $j$, passes the stop-bar [s] |
| $u_{ij}^n$ | number of users for vehicle $n$ in assigned lane for phase $i$ of ring $j$ |
| $v_d$ | desired speed of vehicles in phase $i$ of ring $j$ [m/s] |
| $Y$ | amber and all red time duration [s] |

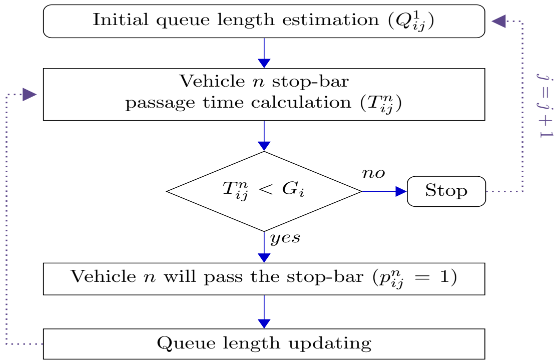


Fig. 1: Summary of user-throughput calculation

Accordingly, the difference between scheduled arrival time and actual arrival time determines bus scheduled delay before entering the detection area. Thus, $\hat{D}^n_{ij}$ can be considered either as an input to the controller or it can be calculated by the controller based on received data. In order to compute $\tilde{D}^n_{ij}$, let $\tau^n_{ij}$ denotes the bus time elapsed in the detection area, while $\chi^n_{ij}$ denotes the distance between the edge of the detection area and the head of bus when the bus is detected (**??**). The ideal elapsed time of a bus can be calculated by dividing $\chi^n_{ij}$ by its desired speed. Therefore, we calculate $\tilde{D}^n_{ij}$ as the difference between $\tau^n_{ij}$ and the ideal elapsed time (4). Finally, $\bar{D}^n_{ij}$ is calculated based on the difference between the ideal and actual travel time of bus between its detection point and the bus stop. Under the assumption that a bus moves at its desired speed after passing the stop-bar, the travel time of bus between the point where it is detected and the bus stop equals to the sum of $T^n_{ij}$ and the travel time assuming desired speed from stop-bar to bus stop (5). Moreover, in case a bus cannot pass the intersection during the current cycle, it will wait in queue, further increasing its delay. To deal with this case, we assume that a bus waits at least an entire cycle and then is able to pass the intersection during next cycle, considering a best-case scenario, as follows. Let $m$ denotes the index of the last vehicle arriving to intersection before the bus and $n$ index of bus. Thus, $m - n$ indicates the number of vehicles are ahead of the bus in the queue at the next cycle. We assume that bus stop-bar passage time in this case equals to sum of cycle time and queue discharging time in next cycle time, where the queue discharging is calculated similarly to Case 2 in [19]. Note that, despite maximizing user throughput provides priority for buses due to higher number of users, minimizing bus schedule delay can also address the challenge of conflicting transit priority requests. Note that we assume that vehicles are processed starting from the vehicle closest to the stop-bar up to the last vehicle that can pass the stop-bar in the current cycle; index $n = 1$ indicates the closest vehicle to stop-bar in each lane. The bus schedule delay formulation is detailed as follows, while parameters mentioned in calculations are illustrated in Figure 2:

$$D^n_{ij} = \hat{D}^n_{ij} + \tilde{D}^n_{ij} + \bar{D}^n_{ij} \qquad \forall i \in Bus \tag{3}$$

$$\tilde{D}^n_{ij} = \tau^n_{ij} - \frac{\chi^n_{ij}}{v_d} \qquad \forall i \in Bus \tag{4}$$

$$\bar{D}^n_{ij} = \begin{cases} T^n_{ij} + \frac{d_s - \Delta^n_{ij}}{v_d}, & \text{if } p^n_{ij} = 1 \\ C + (n-m)H + \frac{d_s - \Delta^n_{ij}}{v_d}, & \text{if } p^n_{ij} = 0 \end{cases} \tag{5}$$

### C. Optimization problem definition

The objective function considered in the optimization problem consist of two parts. The role of first part is to maximize user throughput while the second part aims at minimizing bus schedule delay. Although maximizing user throughput prioritizes buses due to higher number of users on-board, the second part accounts for bus schedule delay with a quadratic term, acting as a penalty for both ahead of schedule buses as well delayed buses. The output of optimization is the set of green times in a fixed sequence and cycle time signal controller. The constraints of optimization problem are fixed cycle time and maximum and minimum of green time (7, 8 and 9). UST objective function and constraints are expressed as:

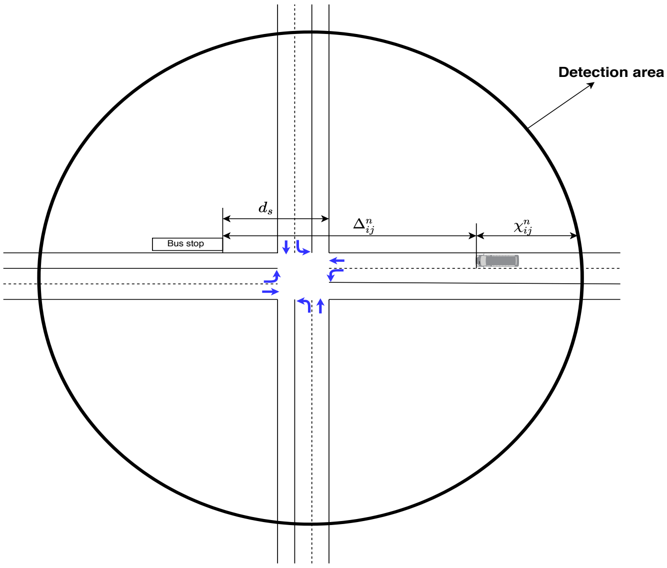


Fig. 2: Representation of bus schedule delay algorithm elements

$$\max \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{n=1}^{N_{ij}} p^n_{ij} u^n_{ij} + \min \lambda \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{n=1}^{N_{ij}} (D^n_{ij})^2 \tag{6}$$

subject to:

$$\sum_{i=1}^{I} g_i + (I-1)Y = C \tag{7}$$

$$g_i \geqslant g_{i,\min} \quad \forall i \tag{8}$$

$$g_i \leqslant g_{i,\max} \quad \forall i \tag{9}$$

The developed optimization problem is a mixed-integer nonlinear program (MINLP). Possibility of different user and vehicle arrival patterns leads to a complex problem characterized by a huge feasible solution region. Consequently, solving the UST optimization by analytical methods leads to considerable high computation time - if we assume the problem is solvable - which is not acceptable in real time problem. As UST can estimate user-throughput in a given set of green times, genetic algorithm (GA) method can find the optimal solution by testing different set of green times. To achieve this, we use a GA MATLAB library to solve the optimization problem [20]. We assign green time of each phase to a gene within a chromosome. Then, fitness function of GA is (6).

## III. SIMULATION SETUP

A four-leg intersection with through and left turn lanes is used as a test case as presented in , is considered as test platform. Phase sequence settings are assumed according to NEMA Standard ring-and-barrier [21] Fig. 3 shows test intersection and phases settings. We use VISSIM microscopic simulation software for evaluation [22], and MATLAB to solve optimization problem, connecting them via COM interface. After simulation warm up time (10 min), vehicle data are collected. The collected vehicle data include: speed, length, position, time in detection area, and number of users. We assume that all vehicles with speed lower than 1 km/h are in queue due to 100% penetration rate of CVs. In order to implement bus schedule delay optimization, we include two bus stops located 400 m downstream the intersection in major approaches. Note that we consider negative delay in order to cover the condition that bus is ahead of schedule when enters to detection area. The simulation duration is one hour and the optimization process is repeated for each cycle, until the end of simulation time.

Five levels of volume to capacity (v/c) ratio are considered to cover under-saturated, saturated, and over-saturated traffic conditions (v/c ratio = 0.3-1.1). The capacity of the intersection is assumed to be 1800 veh/hr. We define a traffic volume in minor streets that is half of major streets, while traffic volume of left turn approaches are a quarter of through approaches. We assign bus traffic only to straight approach of major streets. The bus flow is considered 12 veh/hr, i.e., corresponding to 5 min headway. The passenger car flow is categorized based on number of users on board of each vehicle, defining share of cars with one user (U1), cars with two user (U2), cars with three users (U3), and cars with four users (U4), 50%, 30%, 15% and 5% respectively. Additionally, bus occupancy is assumed to be a random normal distributed number with $\mu = 20$ and $\sigma = 2$. In this study, we assume that $\hat{D}_{ij}^{n}$ is random number by normal distribution. For each bus, a random number varies between -1 to 5 min with $\mu = 2$ and $\sigma = 2.47$ is assigned as $\hat{D}_{ij}^{n}$. We run the simulation in 10 random seeds.

As previously stated, we select GA to solve the optimization problem using the library [20]. In order to increase accuracy and reduce the risk of falling in local optimum, we run GA for 10 separate random instances for each of the random seeds, and then the optimum green time is selected as the best solution for each random seed. We consider GA setting parameters as follows: population size=40, generation number=30, crossover probability=0.9, and mutation probability=0.25. The calculation time to run one GA instance for this problem is approximately 6 s using a laptop computer with a i5-7300, 2.6-GHz central processing unit. Since GA instances can be run in a parallel fashion, total calculation time is not affected by running multiple instances.

In order to evaluate UST, we run the simulations for three different controllers, namely UST without considering bus schedule delay ($\lambda = 0$ in Equation 6), UST considering bus schedule delay ($\lambda > 0$ in Equation 6), and ring barrier controller TSP (RBC) as a controller providing conventional TSP, for base comparison [23]. Optimal signal settings for RBC are same is computed using VISTRO [24].

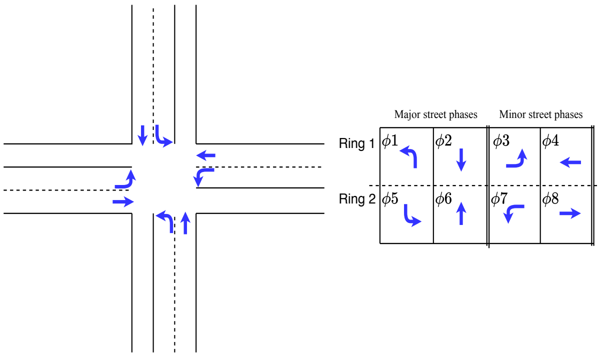


Fig. 3: Test intersection and phases settings

## IV. RESULTS

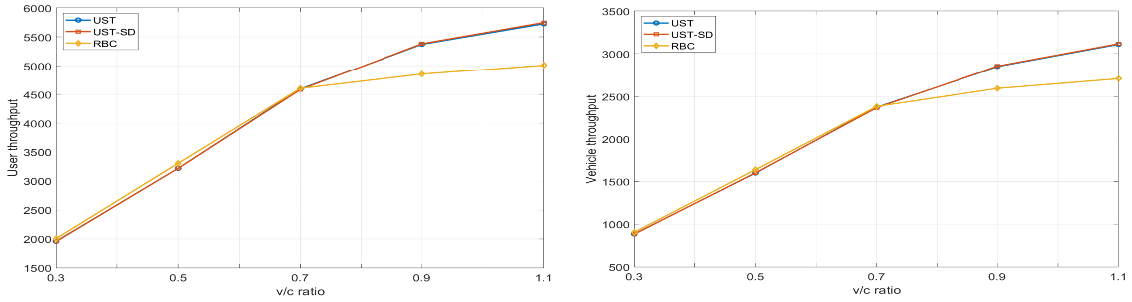
In this section, we evaluate via simulation the performance of the developed strategy. We compare, using various performance measures, three different controllers: UST, UST considering bus schedule delay (UST-SD), and conventional RBC. Note that for running UST-SD, we calibrated $\lambda$ via trial-and-error for each v/c ratio. We present user-related and vehicle-related performance measures, in term of throughput and average delay, as well as bus throughput and average bus scheduled delay, for the three aforementioned control strategies. Finally, we also show experienced delays for all vehicle types.

### A. *User and vehicle average performance measures*

Figure 4 shows average throughput and delay for all users and vehicles in the simulated intersection. The throughput analysis shows significantly better performance of UST and UST-SD compared with RBC in high traffic flow condition, where resulting user throughput is more than 600 users higher (Figure 4.a). Note that, for the same scenario, vehicle throughput is also more than 500 vehicles higher using UST and UST-SD with respect to RBC (Figure 4.b). Inspecting Figure 4.c, one may observe that the average user delay with UST and UST-SD is considerable lower than RBC, while similar result can be seen in vehicle delay based on Figure 4.d. The benefit of UST and UST-SD is clear when v/c ratios is greater than 0.5. Whereas, since implementation of TSP within the RBC strategy aims at serving arriving buses in major streets, user and vehicle throughput are slightly higher compared with UST and UST-SD in lower v/c ratio (¡0.5). However, delay is smaller for UST and UST-SD compared with RBC in all traffic condition.

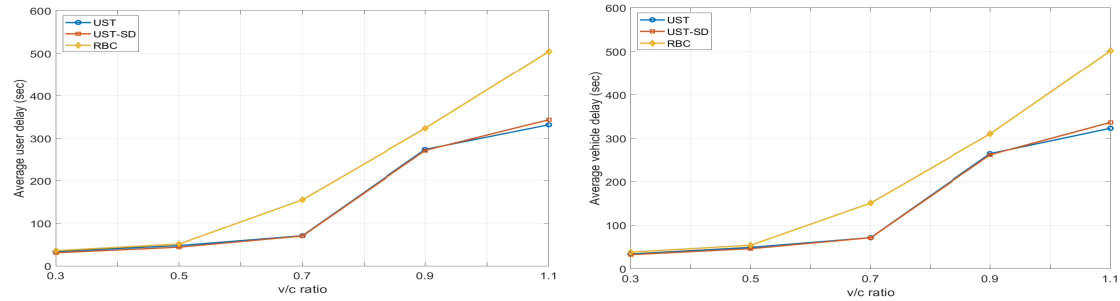
### B. *Bus performance measures*

We show here bus performance measures related to the effectiveness of UST and UST-SD in providing priority of public transit. Figure 5 shows bus average throughput and schedule delay. According to Figure 5.a, bus throughput is higher for RBC only in low v/c ratios, since the controller provides "hard" priority for buses. Whereas, in higher v/c ratios, efficiency of RBC decreases substantially, since its behaviour leads to increasing queue length, which, in turn, does



(a) User throughput

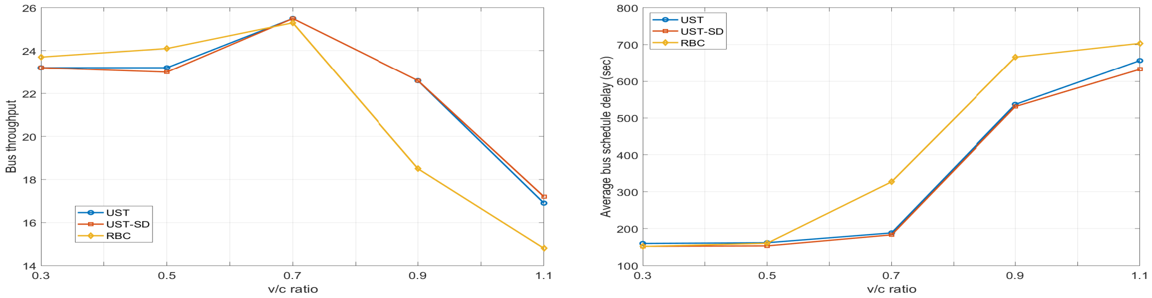
(b) Vehicle throughput



(c) Average user delay

(d) Average vehicle delay

Fig. 4: Average user and vehicle performance measures



(a) Bus throughput

(b) Average bus schedule delay

Fig. 5: Average bus performance measures

not allow the bus to be detected, loosing its prioritization capabilities. In contrast, both UST and UST-SD maximize total user throughput of intersection which leads to better traffic condition and shorter queue length in major streets. Moreover, buses can be detected in all the detection area, providing also priority. Additionally, only in very low v/c ratio RBC leads to lower schedule delay compared with UST, while UST-SD produces lowest schedule delay for buses in all simulated traffic condition (Figure 5.b).

### C. *Vehicles delay measurement based on number of users*

As previously mentioned, we consider four different types of passenger cars based on number of users in simulation. Table II shows average delay of all vehicle types in five traffic conditions and with three different controllers. It can be seen that UST and UST-SD strategies also minimize passenger car and bus delay based on number of users compared with RBC. For instance, U4 has the lowest delay compared with other cars in lower v/c ratios (0.3 and 0.5) employing UST-SD; while the lowest delay for U4 in near saturated and over saturated conditions is seen using UST controller. Whereas, utilizing RBC as controller, the vehicle type with lowest delay appears to be randomly assigned for any v/c ratio. Overview of vehicle results reveals that UST and UST-SD firstly minimize bus delay over passenger cars and then minimize delay of passenger cars with higher occupancy over low occupancy cars.

## V. CONCLUSIONS

In this paper, we employed a proposed novel user-based traffic control strategy designed for a connected vehicle environment, UST, demonstrating that it is capable of prioritizing bus movement at intersection while not increasing other vehicle delay, which is a major issue of conventional TSP systems. In order to account for bus schedule delay, we also

TABLE II: Average delay of all vehicle types (sec)

| v/c ratio | Vehicle type | Control type | | |
|---|---|---|---|---|
| | | UST | UST-SD | RBC |
| 0.3 | U1 | 33.86 | 32.38 | 37.03 |
| | U2 | 33.84 | 32.33 | 40.2 |
| | U3 | 34.51 | 33.83 | 40.99 |
| | U4 | 33.44 | 30.50 | 37.72 |
| | Bus | **32.85** | **25.15** | **24.92** |
| 0.5 | U1 | 49.46 | 46.95 | 54.66 |
| | U2 | 48.88 | 45.52 | 54.66 |
| | U3 | 50.19 | 46.90 | 57.20 |
| | U4 | 44.61 | 42.64 | 49.80 |
| | Bus | **41.36** | **32.36** | **39.20** |
| 0.7 | U1 | 71.22 | 71.66 | 151.18 |
| | U2 | 70.95 | 70.50 | 152.68 |
| | U3 | 72.19 | 72.04 | **146.03** |
| | U4 | 72.15 | 72.38 | 146.50 |
| | Bus | **67.26** | **62.01** | 204. 45 |
| 0.9 | U1 | 265.85 | 263.10 | 311.51 |
| | U2 | 265.17 | 262.46 | 312.65 |
| | U3 | 253.92 | **251.61** | **291.81** |
| | U4 | **251.94** | 252.16 | 295.55 |
| | Bus | 417.65 | 413.16 | 545.41 |
| 1.1 | U1 | 324.74 | 337.7 | 503.88 |
| | U2 | 323.77 | 338.26 | 502.51 |
| | U3 | 311.08 | 325.50 | 493.94 |
| | U4 | **305.58** | **321.36** | **484.15** |
| | Bus | 539.48 | 513.33 | 589.31 |

The bold number shows lowest delay on each controller type and underlined number represents lowest delay of each vehicle type among three controllers.

extended UST to UST-SD, in order to minimize bus schedule delay. Both UST and UST-SD prioritizes passenger cars based on the number of users on-board which is not achieved by conventional controllers, such as RBC. As showed in this research, we proposed a method to solve TSP conflicting requests by considering schedule delay and number of bus riders. Additionally, this method can improve high occupancy vehicle mobility at the intersection by considering the exact number of users in an optimization framework. These findings reveal the importance of using additional information that may be provided by CVs, such as in-vehicle user counts, to operate more sustainable and user-centred transportation systems. Besides, combination of user-based signal timing strategy with other high occupancy vehicles supportive policies such as high occupancy vehicle lane can facilitate ride sharing and public transit simultaneously.

In addition to considering number of bus users and schedule delay as criteria to deal with conflicting priority requests, there are several other directions for further research. First, one may consider effect of bus stop capacity, queue length, and real-time user demand at the bus stops. Second stream of research can be interaction of emergency priority requests and TSP. For such investigation, conflicting between preemption request for emergency vehicles and priority request for transits should be taken into account. Lastly, evaluation of UST on a corridor and network level is also an important direction for further research.

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