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# A Transit Signal Priority Strategy With Right-Turn Lane Sharing

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**ABSTRACT** Transit signal priority (TSP) has become an increasingly popular way to tackle bus operation issues. Many efforts have been conducted to design TSP strategies, yet challenges still exist in real-life applications due to the difficulty in realizing the control logics and the limitation of road infrastructures. This paper proposes a novel TSP strategy considering lane sharing and real-time bus arrival time prediction. First, a right-turn lane sharing method is presented, it shares the right-of-way of a dedicated right-turn lane with through buses at the approaches of a signalized intersection. Next, a control logic based on phase insertion is proposed, and the new signal plan for next signal cycle is generated by judging the requirement of an exclusive bus phase based on predicted bus arrivals. Finally, the Kalman filter is used to establish a bus arrival time prediction model by using RFID and GPS data. The proposed method was implemented on an arterial road of real-life traffic network in Kunshan, China. Test results show that the proposed TSP strategy can achieve satisfactory performances. Bus delay decreases significantly compared to the general traffic delay, especially in peak hours. Further investigation shows that the findings of sensitivity analysis can provide beneficial guidance for practical applications.

**INDEX TERMS** Public transit system, transit signal priority, lane sharing, RFID, Kalman filter.

## I. INTRODUCTION

Public transit system plays an essential role in intelligent transportation systems and has been widely used around the world due to its high occupancy and reliability. However, the efficiency of public transit is vastly affected by road traffic conditions because transit vehicles (e.g., buses) need to share right-of-way with general traffic (e.g., private cars). As a promising way to improve transit efficiency, transit signal priority (TSP) provides preference to transit vehicles at the signalized intersections by adjusting signal plans according to bus arrivals. Properly designed TSP strategies will significantly reduce delay and improve schedule adherence of transit systems [1], [2]. Therefore, TSP has become one of the increasingly popular options to tackle bus operation issues, yet still remains challenges for transportation engineers and agencies.

Existing TSP strategies can be clarified into three categories: passive, active, and adaptive TSP. Passive TSP was firstly proposed in 1979 [3], it operates continuously

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regardless of whether a transit vehicle is present or not without transit detection [4]. However, passive priority may be unreliable and inefficient under the conditions of low-frequency transit, unpredictable bus arrival time, and heavy traffic volumes. Comparatively, active TSP offers priority treatment to a specific transit vehicle based on vehicle detection technologies such as an Automatic Vehicle Location (AVL) system [5]. Generally, a series of rules involving the measurement of schedule adherence or transit vehicle occupancy are pre-set to determine whether or not a priority request should be satisfied [6]. Adaptive TSP provides priority to transit vehicles by overriding normal signal timings with adjusted timings [7], [8]. The objective of adaptive priority is to optimize given performance criteria regarding bus delay or overall network efficiency. The control strategies/phase plans are continuously adjusted and a green phase is allowed for detected vehicles that meet the priority conditions based on a set of control logics [9]. In addition, in order to make the TSP have better effect and reduce the impacts from general traffic, transit vehicles should be given an exclusive or intermittent right-of-way at the intersections. Consequently, the TSPs are usually implemented combining

with a special designed lane including dedicated bus lane (DBL) [10], and intermittent bus lane (IBL) [11], [12]. For instance, a project of IBL with a dynamic priority lane for trams in Melbourne showed that the average speed of trams has increased about 10% in morning rush hours [13].

TSP strategies, especially the active and adaptive TSPs, are realized based on a series of TSP logics. The commonly used TSP logics are as follows. (1) Green extension [14]: the extension of a current green phase for the approaching transit vehicle. (2) Red truncation (or early green) [15]: earlier finish/start of the red/green time phase for transit vehicles. The weakness of “green extension” and “red truncation” is that it sacrifices the capacity of the competing travel direction, on which an unexpected long queue will be delayed during peak hours. (3) Phase skipping [16]: the time from the non-bus phase is skipped for providing TSP. (4) phase insertion [17]: a priority phase is inserted within the normal phase sequence and also, the signal cycle is extended. (5) Phase rotation [18]: the order of the normal signal phases is rotated. (6) Actuated transit phase [9]: an exclusive transit phase is added to the normal phase sequence only when a transit vehicle is detected. Basically, the last four TSP logics seems different from each other but the common objective of them is to increase the portion of transit vehicle that could receive TSP while reducing the extra delay of other vehicles. Since these TSP logics have to change the number or order of the normal phase sequences, their negative effects on general traffic and bus service must be carefully evaluated using the simulation-based approaches [19], [20].

The effectiveness of TSP strategies relies on the accurate prediction of bus arrival times at the stop line [1]. Over the past decades, a variety of models have been proposed for predicting bus arrival time. Historical average models calculate the historical average travel time of a bus as the predicted travel time based on the assumption that the real-time data have the similar pattern with historical data [21]. The models will derive inaccurate prediction due to unexpected variations of traffic conditions. Patnaik et al. proposed several regression models to estimate bus arrival time using automatic passenger counters (APC) data, the linear relationship between bus travel time and a set of independent variables such as dwell time, number of stops, and travel distance was established [22]. Similarly, a nonparametric regression, the k-nearest neighbor (kNN) model, was employed by Chang et al. [23], results show that it outperformed the linear regression methods because of the absence of estimating parameters. With its dynamic feature to update the estimation of state variable, a Kalman filter model was used to predict bus arrival time in real time based on AVL-APC data [24]. In recent years, artificial intelligence (AI) models got more attentions since that an explicit function or independence among input variables are not required. Two artificial neural network (ANN) models were proposed to predict real-time bus arrivals, results reveal that time-varying characteristic of traffic flow can be captured by the model [25]. By a combing use of support vector machine (SVM) and ANN, Yu et al.

predicted the bus arrival times at the same bus stop with multiple routes [26]. Subsequently, a random forest model was designed and achieved satisfactory results [27]. However, the AI models need a large amount of data for model training.

Even though many efforts have been made to develop the TSP strategies and some of them can achieve satisfactory performance in simulated traffic scenarios [15]–[18], some shortcomings still remain so that hinder the applications of TSP strategies in real-life road networks. First, many TSP strategies are strictly limited to current situation of road infrastructures [11]–[13]. Before applications, special designs or reconstructions such as road widening, re-channelization at intersections must be conducted, whereas the reconstructions are of high cost and sometimes unfeasible in urban areas, especially in downtown areas. In practice, lots of bus priorities are implemented at new constructed roads rather than the downtown areas where the traffic condition is more congested. Second, most of TSP logics (e.g., green extension, phase skipping) need to modify the executing signal plans in the current signal cycle. However, this modification involves an adjustment to the internal logic of signal controller, which is merely achieved by traffic agencies except the manufacturer of signal controller because no such kind of API functions are provided (The existing APIs could only read and write the timing plan of next signal cycle). Third, there still exists much room for improving the accuracy and reliability of bus arrival time prediction, especially in the big data era, emerging sensing technologies (e.g., RFID) have bring us a good chance for real-time bus arrivals prediction based on multi-sources data.

In term of these, this paper proposes a novel TSP strategy that provides priorities to transit vehicles with right-turn lane sharing and an exclusive bus phase. The objectives of this paper are: (1) to propose a strategy for transit signal priority with right-turn lane sharing; (2) to design a control logic for new timing plan generation; (3) to formulate a Kalman filter model for bus arrival time prediction. Building upon previous studies, our contributions include: (1) an easy-to-implement lane sharing approach is proposed for sharing the right-of-way of a dedicated right-turn lane with buses; (2) a phase insertion-based control logic is designed to actively judge the requirement of an exclusive bus phase; (3) the bus arrival time(s) are predicted in real-time using multi-sources bus detection data (e.g., GPS, RFID), and the bus-specific control delay is considered. The paper is organized as follows, the methodology is presented in the next section, followed by the implementation and results analysis, and finally conclusions are drawn.

## II. METHODOLOGY

This section presents the proposed method for transit signal priority strategy. First, the concept of right-turn lane sharing and its applicable conditions are introduced, and then the control logic is designed. Finally, a bus arrival time prediction model is proposed based on the Kalman filter technique. The details of the proposed method are as follows.

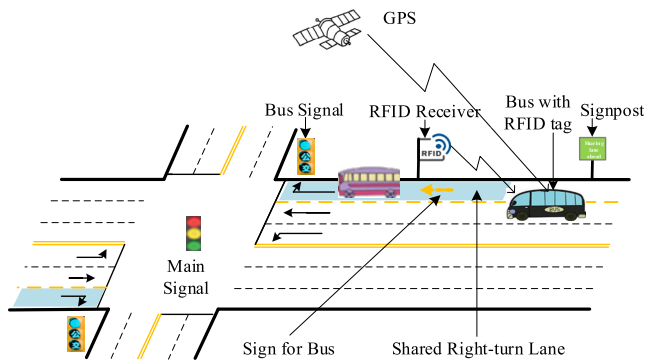


FIGURE 1. Illustration of right-turn lane sharing.

### A. RIGHT-TURN LANE SHARING

Giving buses a dedicated right-of-way is an efficient way to achieve bus priority. However, it is hard to set or add a dedicated bus lane at intersections with limited space for reconstruction. This paper proposes a novel lane-sharing method that shares the right-of-way of an exclusive right-turn lane with through buses (the buses go through the intersection). Figure 1 shows the details of right-turn lane sharing. The key features for right-turn lane sharing are described as follows.

(1) *Lane configurations.* Regardless of the number of lanes at an intersection entrance, we must ensure that a dedicated right-turn lane exists, and it will be set as a shared lane (the light blue lane in Figure 1). To provide guidance to road users, a special road sign (e.g., yellow arrows) should be painted on the shared lane, and the lane line between the shared right-turn lane and its adjacent lane is designed to be a yellow dash line wider than normal lines. The queuing length of through vehicles may have side effects on the buses intend to enter the shared right-turn lane, to avoid this problem buses must enter the shared right-turn lane before arriving at the end of the queue of through vehicles. Hence, a signpost is installed on the roadside about 100 meters ahead of the intersection, in order to inform the bus drivers the approaching intersection has a shared right-turn lane.

(2) *Infrastructures.* Some devices and traffic sensors should be installed to support the right-turn lane sharing. The main traffic signal is essential for controlling the movements of social vehicles and pedestrians. To give priority to buses, a bus signal is installed beside or above the right-turn lane, before the stop line. For bus arrivals detection, an RFID receiver is installed on the roadside 20 meters away from the stop line, and an RFID tag is stuck to the front windshield of each bus. In addition, the GPS equipment are employed to capture bus trajectories and their speeds. The RFID and GPS equipment are indispensable for supporting the proposed TSP strategy. Furthermore, other sensors (e.g., APCs) are not essential but also could be used to improve the performance of the proposed method. For example, buses can be given different weights based on the bus occupancy detected by APCs.

(3) *How to share?* First, the right-turn phasing must be controlled in a permissive manner to ensure that the right turn vehicles can make a permissive right turn at any time, thus will not line up so that blocking the buses. Second, buses can pass through the intersection directly when the traffic light of main signal is green. But when the main traffic light is red, the through buses are suggested to drive into the right-turn lane. Finally, buses have right to go through from the shared right-turn lane in next green phase which maybe an exclusive bus phase (when a bus phase is executed) or a normal green phase of main signal (when a bus phase is not required).

Therefore, the priority for buses comes from two aspects. One is from the right-turn lane sharing. With the shared right-of-way, the through buses no longer need to wait in line with general vehicles in the through lanes. Even if there is no bus-specific signal, buses can also go through using the right-turn lane with less queue dissipation time when the main signal is green. The other priority is from the exclusive bus phase. In this phase, only buses has the right to pass while other vehicles must wait behind the stop lines.

### B. CONTROL LOGIC DESCRIPTION

The basic idea of the proposed TSP is to insert an exclusive bus phase into the normal signal in next signal cycle, then the buses waiting in line in the red phase of current signal cycle will pass through the approach earlier than general vehicles when next timing plan begins. Thus, a prerequisite for the control logic is that in the normal signal, a green phase for through traffic must be followed by a red phase. Figure 2 depicts the control logic in a flowchart, the logic is composed of three major components. It is noted that although the three components are conducted in current signal cycle, the objective of the control logic is to generate a new timing plan for next signal cycle, therefore, the executing signal plan in current signal cycle is not affected by the control logic and thus does not need to be modified.

#### 1) BUS ARRIVAL ESTIMATION

In this component, the number of buses that will arrive at approaches is estimated based on bus detection information. Let  $t_B$  donates the length of the exclusive bus phase,  $R$ ,  $G$  are the length of red phase and green phase, respectively.  $R$  includes the yellow change interval. The estimation process is conducted before the end time ( $t_0$ ) of current signal cycle. To clearly state the process of bus arrival estimation, it is assumed that a bus phase exists in next signal cycle (see in Figure 3). Then, time interval ( $\Omega$ ) for bus arrival prediction can be written as

$$\Omega = [t_0 - R, t_0] \cup [t_0 + G, t_0 + G + t_B] \quad (1)$$

In the interval  $[t_0 - R, t_0]$ , buses are arrived in the red phase of current signal cycle, herein they can be directly detected by the RFID receiver. Since the receiver is away from the stop line, the bus arrival time (to the stop line) should be adjusted by adding a lead time ( $\tau$ ). Let  $t_{detect}$  denotes the time when

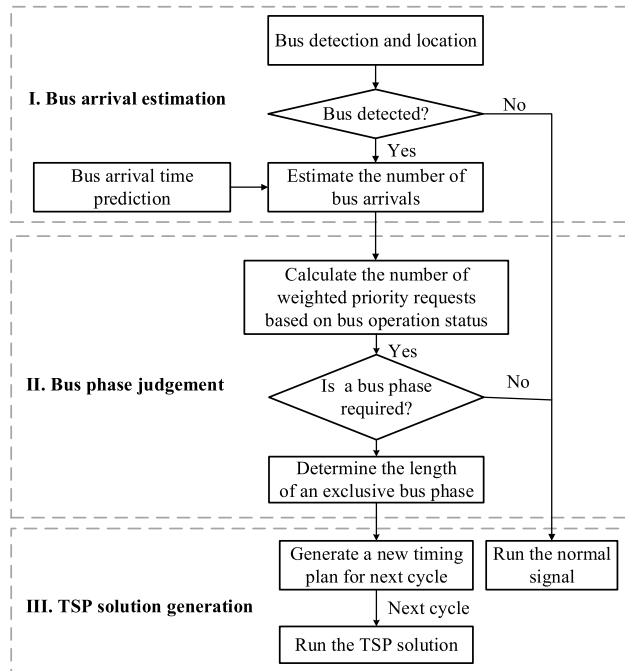


FIGURE 2. The control logic of proposed TSP.

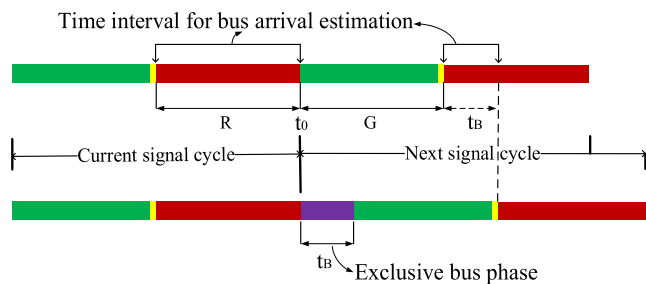


FIGURE 3. Illustration of the new timing plan generation.

a bus was detected, then the bus arrival time ( $t_{arrival}$ ) can be estimated as

$$t_{arrival} = t_{detect} + \tau = t_{detect} + L/v_0 \quad (2)$$

where  $\tau$  and  $L$  are the travel time and distance from the bus detection location to the stop line,  $v_0$  is the average speed of a bus approaching the intersection.

For the buses that will arrive in the interval  $[t_0 + G, t_0 + G + t_B]$ , when no bus phase exist next signal cycle (the upper bar in Figure 3), the buses will arrive at the beginning of the red phase. Comparatively, if a bus phase is given in next signal cycle, these buses will arrive in the green phase, thus they can pass through the intersection without waiting. The bus arrivals can be estimated using a bus arrival time prediction model, the details of the model will be proposed in the next subsection. Based on the estimated bus arrival time, the number of buses that will arrive during time interval  $\Omega$  is finally obtained.

## 2) BUS PHASE JUDGEMENT

The main tasks of this component are to judge whether a bus phase is required and to determine the length of the bus phase. The weighted priority request ( $WPR$ ) is calculated based on the number of bus arrivals and bus operation status (e.g., bus schedule adherence, or occupancy).

$$WPR = \sum_{i=1}^N r_i \quad (3)$$

where  $N$  is the number of predicted bus arrivals,  $r_i \in [0, 1]$  is the weight of the  $i$ th bus. The weights are determined based on bus status, a bus with a higher occupancy or behind schedule could be assigned a larger weight.

A priority request threshold ( $\delta$ ) is used to judge whether a bus phase is required in the next signal cycle. Let  $N_1$  and  $N_2$  denote the number of bus arrivals in the interval  $[t_0 - R, t_0]$  and  $[t_0 + G, t_0 + G + t_B]$ , respectively, then the total number of bus arrivals ( $N$ ) is the sum of  $N_1$  and  $N_2$ . The judgement statements can be summarized as follows:

(1). If  $WPR \geq \delta$ ;

A bus phase is required. For the buses arrive in the red phase of current signal cycle, the bus phase can provide them priorities, thus they can pass through the intersection earlier than general vehicles. In the interval  $[t_0 + G, t_0 + G + t_B]$ , buses will arrive before the end of the green phase if a bus phase is inserted in next signal cycle, so that these buses no longer needs to wait for next green phase.

(2). If  $WPR < \delta$ ;

No bus phase is required, and run the normal signal in next cycle.

The length of bus phase ( $t_B$ ) should satisfy two constrains: (i)  $t_B \geq G^{min}$  ( $G^{min}$  is the minimum green length); (ii)  $C + t_B \leq t^{maxCyc}$  ( $t^{maxCyc}$  is the maximum allowable signal cycle length,  $C$  is the cycle length of normal signal). In order to maintain the stability of traffic signals,  $t_B$  is usually pre-selected from a set of calibrated discrete values (e.g., 11, 13 seconds) according to the priority request-related criteria.

It is noted that for ensuring the utilization efficiency of the bus phase, it is recommended to implement the TSP at two opposite approaches of an intersection (seen in Figure 1). At this time,  $N$  is the sum of bus arrivals predicted in both the two opposite directions. When a bus phase is executed, the buses at both approaches obtain priorities.

## 3) TSP SOLUTION GENERATION

When a bus phase is judged to be required, a new timing plan for the next signal cycle will be generated before the end of current signal cycle (time point  $t_0$ ). As shown in Figure 3, the upper part of the figure shows the normal signals are executed in both the current and next signal cycle, while a bus phase is inserted in front of the green phase of the normal signal in next signal cycle. Then, the new timing plan is sent to signal controller and will be executed in next signal cycle.

**C. BUS ARRIVAL TIME PREDICTION**

The Kalman filter technique is used to develop a bus arrival time prediction model due to the capability of online updating the state variables. Unlike the method proposed by Chen *et al.* [24], the signal status and delay at signal intersections are considered as important variables in the prediction model.

For each bus trip, a Kalman filter is established to predict the arrival time to the stop lines of downstream intersections where the TSP is conducted. Figure 4 depicts the procedure of the prediction model. Suppose that there are  $M$  signal intersections along a specific bus route. Let  $I_k$  denotes the  $k$ th intersection,  $k \in [1, M]$ . The origin of the bus route is viewed as  $I_1$ ,  $s_k$  is the travel time from the origin to the current intersection  $I_k$ , and  $T_{k,k+1}$  is the travel time from the approach of intersection  $I_k$  to intersection  $I_{k+1}$ . Then, the travel time from the origin to  $I_{k+1}$  can be calculated as

$$s_{k+1} = s_k + T_{k,k+1} \tag{4}$$

Let  $t_{k,j}$  denotes the travel time from  $I_k$  to a given downstream intersection  $I_j$ ,  $j \in [k + 1, M]$ , the travel time from  $I_{k+1}$  to  $I_j$  can be described as

$$t_{k+1,j} = t_{k,j} - T_{k,k+1} \tag{5}$$

On urban arterials, the travel time  $T_{k,k+1}$  is highly related to the signal status at intersection  $I_k$ . If a bus arrives at the intersection in a red phase, intersection delay will account for a large proportion of its travel time. Obviously, compared the buses arrive in green phase with those arrive in red phase, bus delays at a specific intersection have two dissimilar patterns. Let  $D_k$  denotes the delay at intersection  $I_k$  at the moment when a bus arrived, it is also called bus-specific delay. Then,  $T_{k,k+1}$  can be written as

$$T_{k,k+1} = D_k + T'_{k,k+1} \tag{6}$$

where  $T'_{k,k+1}$  is the travel time from the outgoing approach (exit) of intersection  $I_k$  to the approach of intersection  $I_{k+1}$ . It depends on the traffic flow conditions and the length of road segment, thus  $T'_{k,k+1}$  are easily to be obtained as historical average values. Basically,  $D_k$  is determined for each bus based on the signal status when the bus arrives at  $I_k$ .

For the downstream intersection  $I_j$ , let  $x_{k,j} = (t_{k,j}, s_k)^T$  denote a state variable, the state equation of the Kalman filter can be formulated as

$$x_{k+1,j} = \emptyset_k x_{k,j} + u_k + w_{k,j} \tag{7}$$

If  $z_k$  denotes the observed travel time from the origin to intersection  $I_k$ , then theoretically  $z_k = s_k$ . The measurement equation can be written as

$$z_k = H_k x_{k,j} + v_{k,j} \tag{8}$$

where

$$\emptyset_k = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad H_k = [0, 1], \quad u_k = \begin{pmatrix} -1 \\ 1 \end{pmatrix} (D_k + T'_{k,k+1})$$

$w_{k,j}$  and  $v_{k,j}$  are white noises associated with the transition process and measurement, respectively. They are assumed to have zero mean and variances of  $Q_{k,j}$  and  $R_{k,j}$ , respectively.

Equation 7 describes the update process in which a bus travels from one intersection to its downstream intersection, and the state variable is predicted based on its current state. Equation 8 provides a feedback process in which the newly measured travel time ( $z_k$ ) is used to adjust the predicted travel time (to downstream intersections). The model can be solved using the time-update recursions [28] as follows.

*Step 1:* Initialization. Set  $k = 1, j = 2, s_1 = 0$ .

*Step 2:* Set  $\hat{x}_{k,j} = (\hat{t}_{k,j}, \hat{s}_k)^T$

Initialize covariance  $P_{k,j}, Q_{k,j}, R_{k,j}$ .

*Step 3:* Prior estimate of state vector

$$\hat{x}_{k+1|k,j} = \emptyset_k \hat{x}_{k,j} + u_k \tag{9}$$

*Step 4:* Prior estimate of state error covariance

$$P_{k+1|k,j} = \emptyset_k P_{k,j} \emptyset_k^T + Q_{k,j} \tag{10}$$

*Step 5:* Calculate measurement noise

$$v_{k+1,j} = z_{k+1} - H_{k+1} \hat{x}_{k+1|k,j} \tag{11}$$

*Step 6:* Compute Kalman gain

$$K_{k+1,j} = P_{k+1|k,j} H_{k+1}^T (H_{k+1} P_{k+1|k,j} H_{k+1}^T + R_{k+1,j})^{-1} \tag{12}$$

*Step 7:* Posterior estimate of state vector

$$\hat{x}_{k+1,j} = \hat{x}_{k+1|k,j} + K_{k+1,j} v_{k+1,j} \tag{13}$$

*Step 8:* Posterior estimate of state error covariance

$$P_{k+1,j} = (I - K_{k+1,j} H_{k+1}) P_{k+1|k,j} \tag{14}$$

If  $j < M$ , go to Step 9; else if  $j = M$ , go to Step 10.

*Step 9:* Next  $j. j = j + 1$ , go to Step 2.

*Step 10:* Next  $k. k = k + 1, j = k + 1$ ,

Stop if  $k + 1 = M$  ( $I_{k+1}$  is the last intersection along the bus route); otherwise, go to Step 2.

It is noted that the initial state variable  $\hat{x}_{1,j}$  and the variable  $u_k$  are both derived from historical travel time information. In step 5, the measurement  $z_{k+1}$  is collected by RFIDs. When a bus arrives at intersection  $I_k$ , the Kalman filter is conducted and the travel time from  $I_{k+1}$  to its downstream intersections are predicted. Then, the arrival time at the downstream intersection  $I_j$  can be calculated as  $(t_{k+1,j} + s_{k+1})$ .

If  $(t_{k+1,j} + s_{k+1}) \in \Omega$ , the bus is considered to require a priority in intersection  $I_j$ . Therefore, based on the predicted bus arrival time, the number of buses that will arrive at downstream intersections in next signal cycle are finally estimated.

**III. IMPLEMENTATION AND RESULTS ANALYSIS**

**A. DATA DESCRIPTION**

To validate the proposed method, an arterial (6.17 kilometers in length) in the downtown area of Kunshan, China was selected as a testbed. 12 signalized intersections are

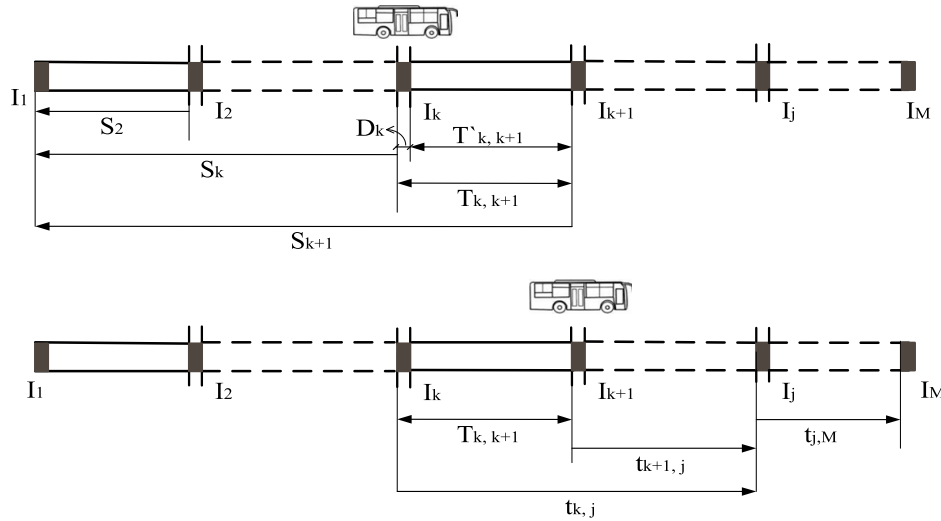


FIGURE 4. Illustration of bus arrival time prediction.

located on this arterial. The proposed TSP strategy was implemented in both the southbound (SB) and northbound (NB) approaches of these intersections. In each approach, a shared right-turn lane is set, and an RFID device as well as a bus signal are installed. Figure 5 shows the study area and the locations of the test intersections, and a photograph shot in actual traffic scene (at intersection I<sub>7</sub>) is attached on the left side.

The raw dataset was collected from August 5th, 2019 to September 1st, 2019 (4 weeks data) by RFIDs and embedded GPS devices. The fields of data include device ID, date, time, license number, and bus location. The historical bus travel times were estimated by fusing RFID and GPS data using the Dempster-Shafer model [29]. The signal timings of these intersections were obtained from the traffic signal control system of Kunshan. For comparison, the travel times of general traffic were derived from the vehicle trajectories reconstructed using the ALPR (automatic license plate recognition) data [30].

**B. BUS ARRIVAL TIME PREDICTION**

The bus routes that pass through all the 12 intersections were used to evaluate the performance of bus arrival time prediction. The Kalman filter was calibrated using three weeks data (from August 5th, 2019 to August 25th, 2019), and the last week data were used as a validation dataset. Considering the time-varying characteristic of traffic flow, the model was calibrated using the data of morning peak, midday non-peak, and afternoon peak, respectively.

An individual bus trip was selected to analyze the procedure of arrival time prediction. The bus trip was started from the origin (I<sub>1</sub>) at 6:55:00 on August 26 and arrived at intersection I<sub>12</sub> at 7:17:15. The prediction results are illustrated on a time-space diagram in Figure 6. The red line depicts the actual bus arrival time from the origin to each



FIGURE 5. Study area and intersections.

downstream intersection. Each line of other colors represents the bus arrival times (from origin to downstream intersections) predicted when the bus arrived at a certain intersection. For example, the light blue line that begins from I<sub>2</sub> depicts the trajectory that predicted at I<sub>1</sub>. One can observe that as a bus proceeds along the route towards I<sub>12</sub>, the predicted

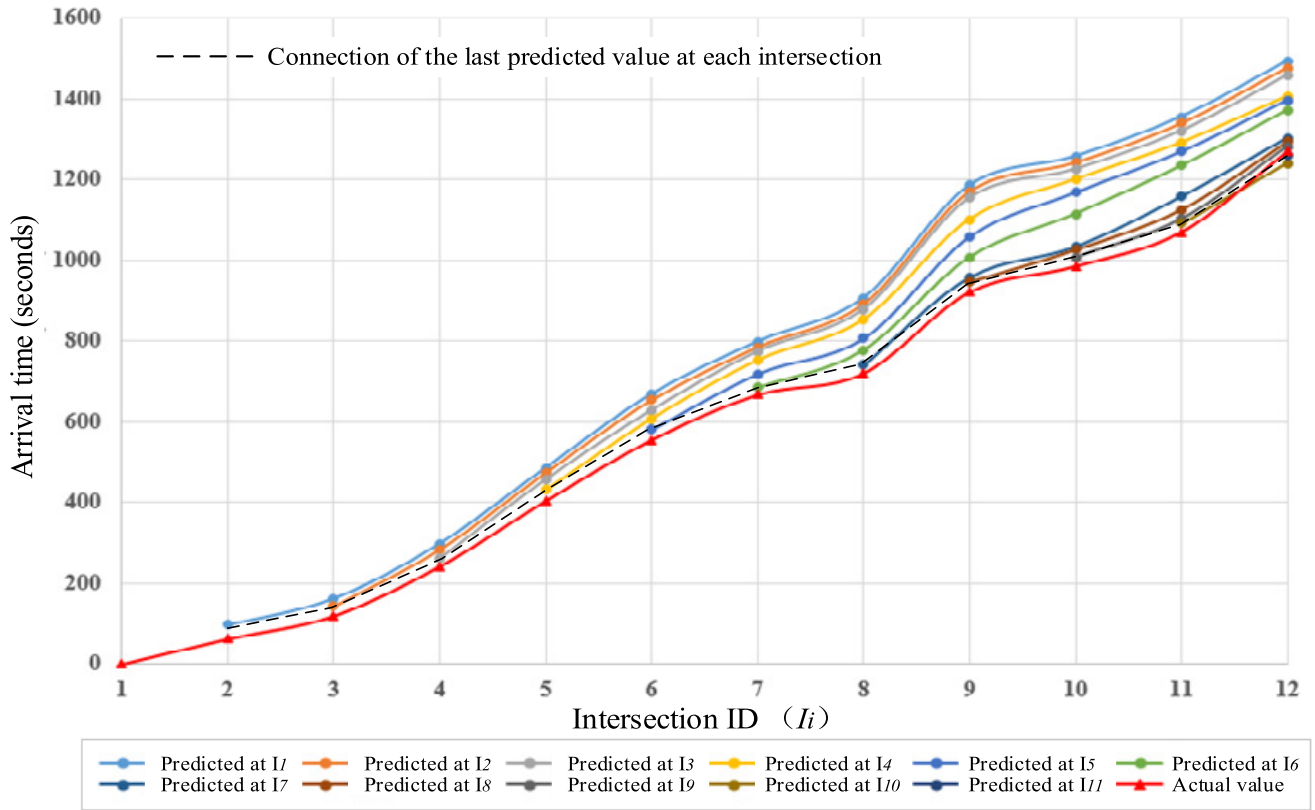


FIGURE 6. The predicted time-space diagram.

trajectories are getting much closer to the actual trajectory (red line), indicating that the bus arrival times predicted in  $I_k$  are more accurate than those predicted in  $I_{k+1}$ . The reason is that new measurements at each intersection have been employed to adjust the predicted arrival time. For a specific intersection  $I_k$ , the last predicted value (that predicted at  $I_{k-1}$ ) is the most accurate one, thus it could be viewed as the predicted bus arrival time from the origin to this intersection. These points of all intersections are connected together by a dash line which describes the predicted trajectory of the bus. As seen in Figure 3, the dash line is much closer to the actual trajectory. Additionally, due to the initial state variable ( $\hat{x}_{1,j}$ ) is larger than the actual travel time at the starting time (6:55:00), thus most of the predicted arrival times are larger than the actual values. Regardless of this, the prediction errors are getting much smaller as the bus proceeds.

The performance of the proposed method is compared with a traditional Kalman filter proposed by Chen *et al.* [24] that does not consider the traffic signal status and bus-specific delay. The root mean square error (RMSE) and mean average percentage error (MAPE) are computed as measures. The two indices can be obtained as follows.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (15)$$

$$MAPE = \frac{1}{n} \sum_{i=1}^n \frac{|y_i - \hat{y}_i|}{\hat{y}_i} \times 100\% \quad (16)$$

where  $y_i$  is the actual travel time of sample  $i$ ,  $\hat{y}_i$  is the predicted travel time of sample  $i$ ,  $n$  is the number of sampled bus trips.

The MAPE and RMSE for each route segment  $k$  (i.e., the road segment from intersection  $I_k$  to  $I_{k+1}$ ) are calculated based on the predicted results of 300 bus trips. Their distribution are shown in Figure 7, from which one can found that both the two indices of the proposed method are smaller than those of traditional method, indicating that the proposed method outperforms the traditional method. Specifically, the RMSEs of the proposed model range from 18 to 34 seconds. Also, most of the MAPEs of the proposed model are less than 20%. The maximum RMSE is 34 seconds at segment 8, but the MAPE of which is only 14.5% since the actual travel time of this segment is very large (more than 270 seconds). In one word, the proposed model can achieve accurate prediction results, thus it is feasible to provide the number of bus arrivals for bus signal priority.

It is noted that although the proposed model is evaluated based on the buses passing through all test intersections, the estimated travel time also could be used to predict the arrival time of the bus that passes some of these intersections. For instance, if a bus enters the test arterial from  $I_4$  and exits from  $I_6$ , its arrival time at  $I_6$  can be predicted using the

TABLE 1. Performance results at morning peak.

Intersection ID	Number of bus phase executed	Northbound approach				Southbound approach			
		Number of priority requests	Bus delay (sec)	General traffic delay (sec)	Delay difference* (sec)	Number of priority requests	Bus delay (sec)	General traffic delay (sec)	Delay difference* (sec)
I1	31	84	22.4	51.6	29.2	46	26.7	60.4	33.7
I2	28	35	24.0	56.0	32.0	74	31.2	69.7	38.5
I3	33	29	13.4	39.6	26.2	82	19.8	52.7	32.9
I4	29	40	16.3	43.5	27.1	71	27.3	69.9	42.6
I5	26	69	30.2	67.8	37.6	30	26.8	63.6	36.8
I6	17	21	22.1	39.4	17.3	18	21.2	37.7	16.5
I7	23	32	37.0	73.4	36.4	49	32.8	62.6	29.8
I8	19	38	39.8	72.0	32.2	34	31.9	56.3	24.4
I9	18	27	38.8	68.9	30.1	24	40.0	71.0	30.9
I10	15	33	37.1	57.2	20.1	18	27.9	47.0	19.1
I11	13	15	28.4	45.2	16.8	23	21.5	39.3	17.8
I12	14	22	36.5	57.2	20.7	16	28.3	50.6	22.3

\*Delay difference is the difference between general traffic delay and bus delay.

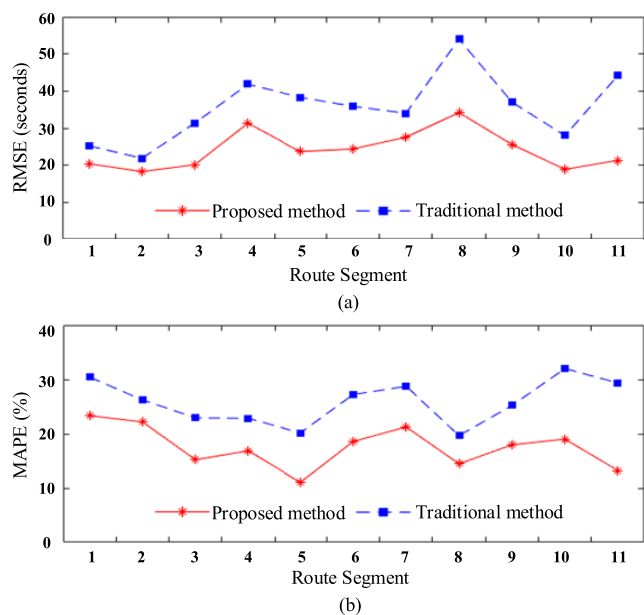


FIGURE 7. Accuracy of bus arrival time prediction.

estimated travel time from I<sub>4</sub> to I<sub>6</sub>. Therefore, the bus arrival time at all the intersections can be predicted no matter how many intersections a bus has passed.

C. PERFORMANCE EVALUATION

The proposed TSP strategy was implemented in the selected intersections. The threshold  $\delta$  was calibrated to be 2, and the length of bus phase was set to be 11 seconds. Since the number of passengers on the buses cannot be collected in

the testbed, all priority requests were given the same weight ( $r_i = 1$ ). Table 1 shows the results at morning peak (7:00 – 9:00) on August 26th, 2019. Intersection delays of bus vehicles and general traffic (derived from the traffic surveillance system of Kunshan) are compared to show the advantages of the proposed method.

The “number of executed bus phase” refers to the number (or times) the exclusive bus phases are determined to be executed in the timing plans during the test periods. As shown in Table 1, the bus phase was executed 31 times at I<sub>1</sub> but only 13 times at I<sub>11</sub>, implying that the bus priority requests are heterogeneous across the study area. Comparison shows that all bus delays are smaller than the corresponding general traffic delays at both the southbound and northbound approaches, thus buses can pass through the intersections more quickly than general traffic. Meanwhile, the differences between bus delays and general traffic delays vary from 16.5 to 42.6 seconds. The maximum value happens at the southbound approach of I<sub>4</sub> because of the heaviest traffic flow at this approach. It implies that the TSP strategy can achieve better performance at the approach with heavy traffic. Moreover, most of general traffic delays are larger than 55 seconds (the level of service (LOS) of these intersections is LOS E based on the HCM 2010 criteria [31]), indicating that these intersections are under unstable flow conditions.

However, most of the corresponding bus delays are less than 35 seconds (LOS C), demonstrating the efficiency of buses is significantly improved.

The arterial travel time of bus and general traffic at times of day (6:30-22:00) are presented in Figure 8. The dash blue line presents references bus travel time, in which dwell time



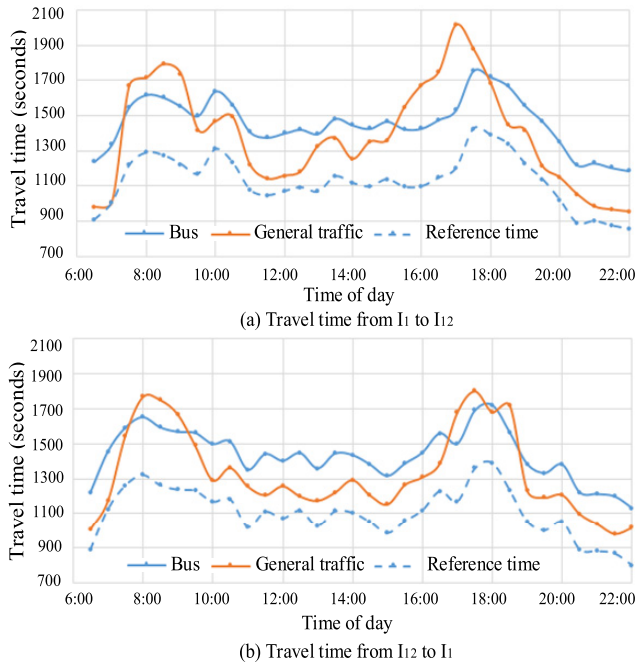


FIGURE 8. Arterial travel time comparison.

at bus stops along the test arterial is excluded. As seen from the figure, both the travel times of bus and general traffic are bimodal and have higher values during morning and afternoon peak, but the range of bus travel time (569 seconds in Figure 7(a)) is smaller than that of general traffic (1062 seconds). This implies that the volatility of bus travel time is reduced by the proposed TSP, and the heavy or congested traffic conditions in peak hours have less impact on buses than general traffic. One can also observe that buses take less time (about 300 seconds at 8:30 from I<sub>1</sub> to I<sub>12</sub>) to pass through the arterial than social vehicles in peak hours, while bus travel times are larger than those of general traffic in other time periods. The reasons are as follows. First, the waiting time and queue dissipating time of buses in signalized intersections are decreased by the exclusive bus signal and the shared right-turn lane, and this time reduction becomes more significant in peak hours when intersections are under congested conditions. Second, there are 11 bus stops on the test arterial, the dwell time at each bus stop is about 30-40 seconds, the dwell time accounts for a vital proportion in the bus travel time. The dwell time is excluded when calculating the reference travel time, it is observed that the reference times are less than the travel times of general traffic in the whole day. Therefore, the application of proposed TSP can efficiently reduce the bus travel time, especially in peak hours, and also makes the bus travel time less fluctuated with the change of traffic conditions.

**D. SENSITIVITY ANALYSIS**

There are two important variables: the priority request threshold ( $\delta$ ) and the length of bus phase ( $t_b$ ) that affect the

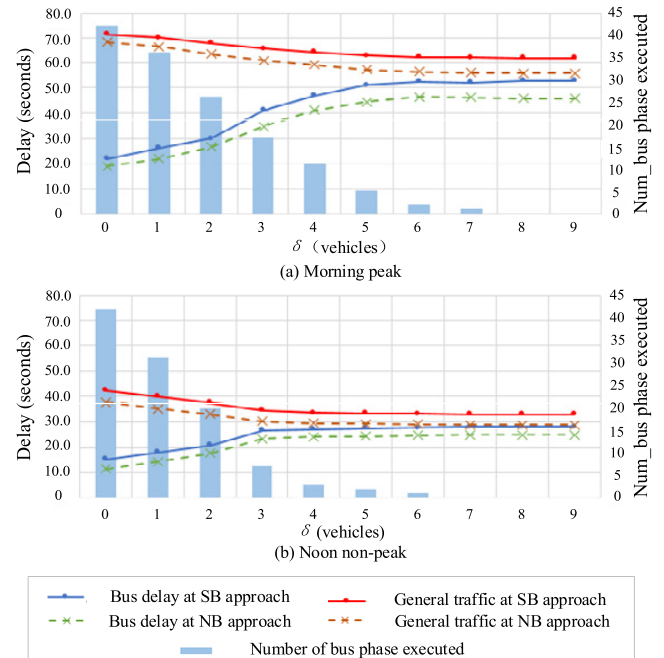


FIGURE 9. Impact of different  $\delta$  values (at intersection I5).

performance of the proposed TSP. Thus, a sensitivity analysis is conducted to investigate their impacts under various traffic conditions.

The sensitivity analysis of the priority request threshold is conducted at intersection I<sub>5</sub> during the morning peak and noon non-peak. The threshold ( $\delta$ ) is set to be from zero to 9, the zero value means the bus phase is executed in all signal cycles even though no bus arrives. Figure 9 shows the impact of different  $\delta$  values. One can find that the number of executed bus phase (presented by the blue bars) reduced from 42 to zero with the increase of the  $\delta$  values, indicating that the bus phase is hard to be triggered by the larger thresholds, it will not be executed when the threshold is larger than 7. Second, bus delays are more significantly affected by the changes of the threshold than general traffic delays. At the southbound approach, the bus delay increases from 22 to 53 seconds at morning peak, however, the general traffic delay slightly decreases about 11 seconds. The delays remain unchanged when the threshold is larger than 5 at morning peak (4 at non-peak) because the bus phase is merely executed. Typically, bus delays suddenly enlarged at the morning peak when the threshold changes from 2 to 3, meanwhile, the general traffic delay is less than 70 seconds when  $\delta$  is larger than one, and thus it is reasonable to set the threshold to be 2. However, the value of one seems to be a more suitable threshold for the non-peak. Finally, bus delays are always smaller than general traffic delays even though  $\delta$  is equal to 9, implying that the performance of bus operation can be improved by the shared right-turn lane even though no bus signal is executed. Also, the differences between the delays of bus and general traffic in morning peak are larger than those in

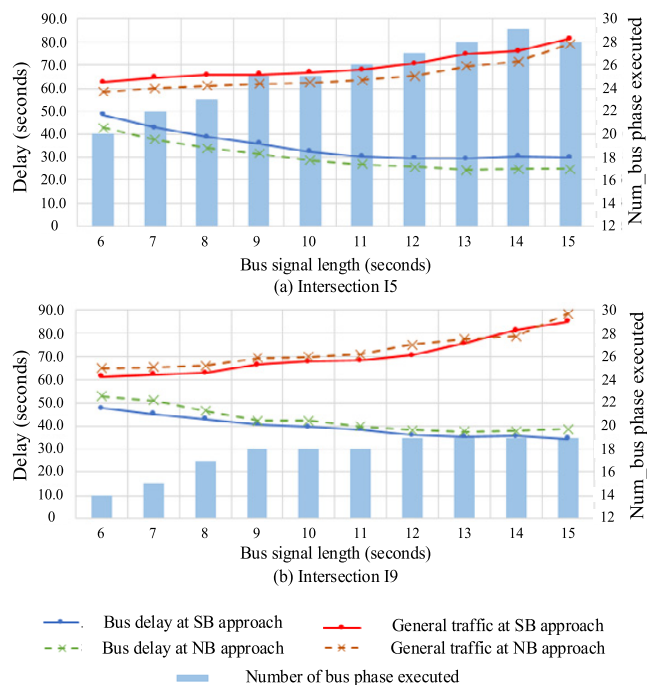


FIGURE 10. Impact of bus signal length (at morning peak).

noon non-peak. It illustrates the proposed TSP strategy has a better performance under heavier traffic conditions, thus it is feasible to improve the efficiency of public transit, especially in the congested intersections. In addition, the delays at the northbound approach are smaller than the southbound because the northbound approach has lower traffic volumes.

The impact of the length of bus phase was investigated at intersection I<sub>5</sub> and I<sub>7</sub>, both the two intersections have heavy traffic flows at morning peak, but the bus volume at I<sub>5</sub> is higher than that at I<sub>7</sub>. The minimum allowable green time of the signal controllers in the testbed is 6 seconds. The test results are shown in Figure 10. It is observed that the number of executed bus phase slowly increases with the rise of bus signal length ( $t_B$ ). Specifically, almost no more bus phase is executed when  $t_B$  is larger than 11 seconds, illustrating that the growth in the number of predicted bus arrivals result from the increasing duration of time interval  $\Omega$  is limited. Second, general traffic delay slightly rises when  $t_B$  changes from 6 to 11 seconds, while it increases significantly when  $t_B$  becomes much larger. This phenomenon is more obvious at I<sub>9</sub>, the general traffic delay at where becomes larger than 80 seconds. The reason lies in that the green splits for straight vehicles reduced when a long bus signal was executed, leading to a saturated traffic state at the intersection. Comparatively, the bus delay can be effectively reduced by the increasing length of bus signal. However, it barely reduces when  $t_B$  is larger than 11 seconds. Therefore, the bus signal length is set to be 11 seconds in our study.

Based on the above analysis, we can put forward some suggestions for practical applications of the proposed TSP. First, both the values of  $\delta$  and  $t_B$  have big impacts on the

performance of the TSP strategy, they must be carefully calibrated before implementation. Second, the  $\delta$  value should be studied under different traffic conditions, a higher value is recommended for peak hours. Last, the bus signal length relies on the traffic states and normal signal timings of the specific intersections, it must be long enough for reducing the bus delay but keeping general traffic delay in an acceptable range.

#### IV. CONCLUSION

This paper proposes a novel transit signal priority strategy with right-turn lane sharing. The proposed method consists of three components. First, the concept of right-turn lane sharing and its applicable conditions are illustrated. Next, the control logic of an active TSP strategy is designed based on bus phase insertion. The details of bus arrival estimation and bus phase judgement are presented. Last, a bus arrival time prediction model based on the Kalman filter is proposed so as to support the estimation of bus arrivals. The proposed method was evaluated on an arterial in Kunshan, China. Test results showed that the proposed method can perform well in real-life traffic scenarios. Also, the impacts of the priority request threshold and bus phase length were explored and some suggestions for practical applications were provided.

Further tasks can be focused on the following aspects. First, the length of bus phase is empirically pre-determined in the proposed method, optimization models could be built to adjust the length of bus phase in real-time. Second, it is interesting to explore the use of bus operation status (e.g. occupancy, schedule adherence) to assign different weights to priority requests. Third, as the proposed TSP logic only can be applied to the intersections where one or two opposing approaches have bus signals, it must be improved so that it could be employed at intersections with more than two priority directions. Last, multiple data sources could be used to enhance the estimation accuracy of the proposed bus arrival time prediction model.

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