KSCE Journal of Civil Engineering (0000) 00(0):1-9

DOI 10.1007/s12205-015-1516-4

Transportation Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Signal Optimization and Coordination for Bus Progression Based on MAXBAND

Guangyuan Dai*, Hao Wang, and Wei Wang*****

Received September 2, 2014/Revised February 9, 2015/Accepted March 22, 2015/Published Online April 20, 2015

Abstract

A new bandwidth-based approach for bus lane systems is proposed to optimize and coordinate signals and achieve bus progression along urban streets. Elements of the bus systems, such as bus speed, locations of bus stops, and dwell time, were considered to be relevant variables in the proposed approach, which is based on the classic MAXBAND program. First, to establish the bus progression model, intersections along the main street are categorized based on the locations of the bus stops. Second, mixed integer linear programming is employed to construct models that adhere to the following two basic principles: (a) optimizing the bandwidth for each group of intersections and (b) connecting the central lines of green bands for adjacent groups. A software package is then utilized to obtain the global optimal solutions for the model, and a time-space diagram can be created based on the results. Finally, a case study is presented to illustrate the application of the proposed approach. The results show that the proposed approach generates significant improvements in not only the operational performance of the bus lane system but also the average performances of all passengers in the entire traffic system.

Keywords: *signal optimization, bus progression, MAXBAND, intersection categorization, bandwidth optimization, bus line*

1. Introduction

Because of its incomparable advantages, public transportation has assumed an important role in improving traffic conditions. As a key component of public transportation, bus systems have been promoted extensively throughout the world. In China, the infrastructure for urban bus systems remains an issue of concern for the government. However, a lack of signal optimization and coordination along streets generates considerable unexpected delays and a large number of stops for buses on streets with bus lanes.

Several researchers have conducted relevant studies on bandwidth optimization for traffic progression and adaptivE Transit Signal Priority (TSP) optimization. Half-time synchronization (Morgan, Little 1964; Little 1966) was developed to assign maximal equal bandwidths for both directions of a street. Subsequently, a computer program named MAXBAND was designed (Little *et al.* 1981). For two-phase, fixed-time signals, Baass (1983) used WAVE1 and WAVE2 to generate curves that show the continuous relationship between a uniform progression speed and the corresponding maximal bandwidth for an extensive range of speeds and cycles. Messer *et al.* (1973, 1991, and 1996) attempted to optimize multi-phase signals to obtain maximized bandwidths. Gartner *et al.* (1990, 1991, and 1996) proposed a MULTI-BAND approach that considers the actual traffic volumes and flow capacities on each link and generates a variable bandwidth progression in which an individually weighted bandwidth is obtained for each directional street section. Recently, Tian and Urbanik (2007) introduced a system partition technique for bandwidth-oriented signal timing.

Another important area for bus progression is the study of signal control for bus priority. A traffic control strategy was explicitly designed (Janos, Furth, 2002). Link and Shalaby (2003) developed a next-generation transit signal priority strategy that adaptively controls the transit operations of high-frequency routes using traffic signals. Rakha and Zhang (2004) performed a systematic simulation evaluation of the impact of a Transit Signal Priority (TSP) system on the operations of a single signalized intersection within a coordinated arterial system. Liu *et al.* (2004) developed a dynamic signal timing optimization model that reallocates green times among the phases. Mirchandani and Hickman (2010) proposed a macroscopic model that integrates bus signal priority with bus rescheduling. Skabardonis and Christofa (2011) considered the additional delays caused by residual queues and presented a

*Ph.D. Student, Jiangsu Key Laboratory of Urban ITS, Southeast University, Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, Nanjing 210096, China (E-mail: 230119463@seu.edu.cn)

**Associate Professor, Jiangsu Key Laboratory of Urban ITS, Southeast University, Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, Nanjing 210096, China (Corresponding Author, E-mail: haowang@seu.edu.cn)

***Professor, Jiangsu Key Laboratory of Urban ITS, Southeast University, Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, Nanjing 210096, China (E-mail: wangwei@seu.edu.cn)

technique for estimating the impact of TSP. Li *et al.* (2011) presented an adaptive TSP optimization model that minimizes the weighted sum of the transit vehicle delay and other traffic delays.

Regardless of the bus speed, dwell time, and locations of bus stops, bandwidth-based approaches such as MAXBAND have failed to consider the characteristics of the bus lane system as key factors. In addition, adaptive TSP optimization primarily focuses on isolated actuated signalized intersections.

Bandwidth-based approaches are primarily designed for fixed-time signalized intersections, which are prevalent in China. Using classic MAXBAND to implement bus-relevant improvements, this paper proposes a new bus progression model to optimize and coordinate traffic signals along urban streets, which can potentially improve the operational performance of the bus lane system without significantly impacting commuters in standard vehicle lanes. In this paper, exclusive bus lanes are necessary to allow buses to travel without interference from general vehicles.

The remainder of this paper is organized as follows. Section 2 introduces the progression model and the algorithm of the proposed approach. In Section 3, a case study is presented to compare the proposed approach with MAXBAND. Finally, a number of important conclusions and suggestions for future studies are summarized.

2. The Proposed Approach

The proposed approach consists of the following steps: categorize intersections into different groups, analyze the relationships among intersections in the same group, analyze the relationships among intersections in adjacent groups, analyze the phase order patterns, construct the progression model, and present the algorithm of the model.

2.1 Intersection Categorization

For the intersection categorization, we assumed that the number of outbound bus stops is equal to the number of inbound bus stops. Additionally, the outbound bus stop and its corresponding inbound bus stop should be located on opposite sides of the same link. For example, the j-th outbound bus stop N_j and the j-th inbound bus stop $\overline{N}_j$ should both be located on the same link between adjacent intersections S_i and S_{i+1}. The intersections can then be categorized into different groups by the locations of either the outbound bus stops or the inbound bus stops, e.g., intersection S_i is the last intersection of group O_{j-1}, whereas intersection S_{i+1} is the first intersection of group O_j. The result of intersection categorization based on the locations of the outbound bus stops is identical to the result of intersection categorization based on the locations of the inbound bus stops. Bus stops are not included in any intersection groups; they are simply boundaries between two adjacent intersection groups. Intersection categorization allows the signalized intersections to be assigned to different groups, where the number of signalized intersections in each group is small. The bandwidths in each group can then be expanded, and the center lines of the bandwidths of two adjacent intersection groups can be connected. The relationships between intersections and bus stops are shown in Fig. 1. A main street has n signalized intersections and $2n_b$ bus stops.

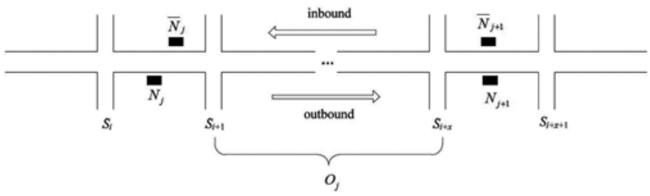


Fig. 1. Relationships between Intersections and Bus Stops

Let S_i = i-th signalized intersection, i = 1,…, n; N_j = j-th outbound bus stop, j = 1,…, n_b; $\overline{N}_j$ = inbound corresponding bus stop, j = 1,…, n_b; and O_j= j-th intersection group between bus stops N_j and N_{j+1} , where j = 1, … , n_b-1.

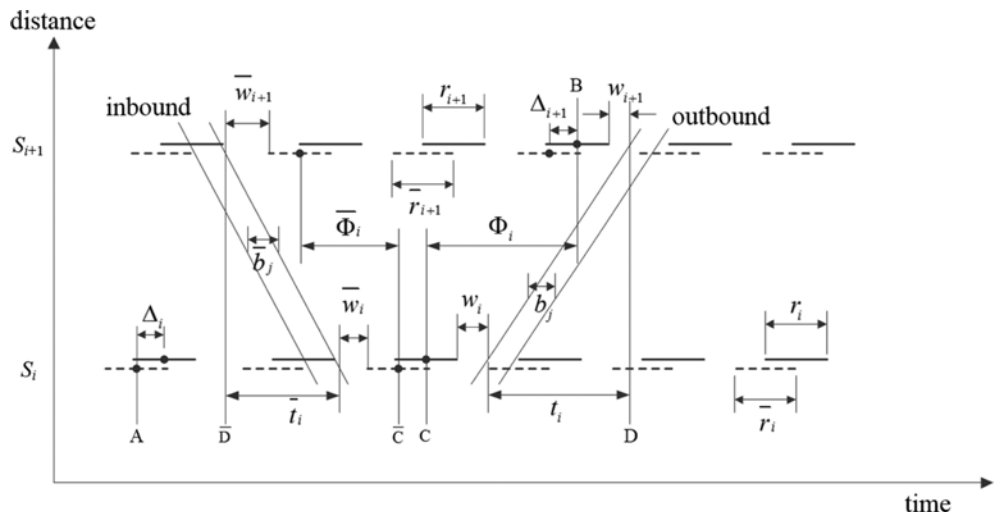


Fig. 2. Relationships in the Same Group

In Fig. 1, intersections $S_{i+1}, \ldots, S_{i+x}$ are located between bus stops N_j and N_{j+1}; thus, they are categorized into group O_j. S_i is assigned to group O_{j-1}, whereas S_{i+x+1} is assigned to group Q_{j+1}. In addition, k_j is defined as the ratio of the total inbound volumes to the total outbound volumes in group O_j, whereas the total inbound (outbound) volumes in group O_j refer to the sum of all the inbound (outbound) volumes of the intersections in group O_j. Two subscripts are used in this paper: i and j. The variables subscripted with i are related to the intersection S_i, whereas the variables subscripted with j are related to the intersection group O_j.

2.2 Constraints in the Same Group

Based on MAXBAND, the relationships between adjacent intersections in the same group O_j are shown in Fig. 2. All the time variables are expressed in units of cycle time, and the cycle times of all the intersections in the same group are uniform. In this paper, the constraints in the same group are similar to the constraints of the adjacent intersections in MAXBAND. However, the bus speed is designed as the band speed, which is not the case in MAXBAND.

Let $b_j(\bar{b}_j)$ = outbound (inbound) bandwidth in group O_j (cycles); $r_i(\bar{r}_i)$ = outbound (inbound) red time at S_i (cycles); and $w_i(\bar{w}_i)$ = time from the right (left) side of $r_i(\bar{r}_i)$ at S_i to the left (right) edge of $b_j(\bar{b}_j)$ (cycles). Δ_i = offset between the outbound and inbound red time at S_i = time from the center of to the nearest center of r_i. This value is positive if the center of r_i is located to the right of the center of $\bar{r}_i$ (cycles). $\Phi_i(\bar{\Phi}_i)$ = offset between the outbound (inbound) red times at S_i and S_{i+1} = time from the center of $r_i(\bar{r}_i)$ at S_i to the center of a particular $r_{i+1}(\bar{r}_{i+1})$ at S_{i+1}. The two red times are selected such that each red time is located immediately to the left (right) of the same $b_j(\bar{b}_j)$. This value is positive if S_{i+1}'s center of $r_{i+1}(\bar{r}_{i+1})$ is located to the right (left) of S_i's center of $r_{i+1}(\bar{r}_{i+1})$ (cycles). $t_i(\bar{t}_i)$ = travel time from S_i to S_{i+1} outbound (S_{i+1} to S_i inbound). The travel time can be derived from the distance and the bus speed between S_i and S_{i+1} (cycles).

The following equations can be derived from Fig. 2:

$$\Delta_i + m_A + \Phi_i = \Delta_{i+1} + m_B - \bar{\Phi}_i \tag{1}$$

$$\Phi_i + \bar{\Phi}_i + \Delta_i - \Delta_{i+1} = m_i \tag{2}$$

$$\Phi_i + \frac{r_{i+1}}{2} + w_{i+1} = \frac{r_i}{2} + w_i + t_i \tag{3}$$

$$\Phi_i = \frac{r_i}{2} - \frac{r_{i+1}}{2} + w_i - w_{i+1} + t_i \tag{4}$$

$$\bar{\Phi}_i + \frac{\bar{r}_{i+1}}{2} + \bar{w}_{i+1} = \frac{\bar{r}_i}{2} + \bar{w}_i + \bar{t}_i \tag{5}$$

$$\bar{\Phi}_i = \frac{\bar{r}_i}{2} - \frac{\bar{r}_{i+1}}{2} + \bar{w}_i - \bar{w}_{i+1} + \bar{t}_i \tag{6}$$

where $m_i = m_A + \mathrm{m}_B$ and m_A, m_B and m_i are integers that represent integer multiples of the uniform cycle time. m_i is defined as an integer variable related to S_i and S_{i+1}. Substituting (4) and (6) into (2), the integer variable constraint equation is derived as follows:

$$\frac{r_i + \bar{r}_i}{2} - \frac{r_{i+1} + \bar{r}_{i+1}}{2} + (w_i + \bar{w}_i) - (w_{i+1} + \bar{w}_{i+1}) + (t_i + \bar{t}_i) + (\Delta_i - \Delta_{i+1}) = m_i \tag{7}$$

To ensure that the bandwidth cannot exceed the green time, the following expressions can be derived.

$$w_i + b_j \le 1 - r_i \tag{8}$$

$$\bar{w}_i + \bar{b}_j \le 1 - \bar{r}_i \tag{9}$$

To ensure that the ratio of the inbound bandwidth to the outbound bandwidth reflects the ratio of the total inbound

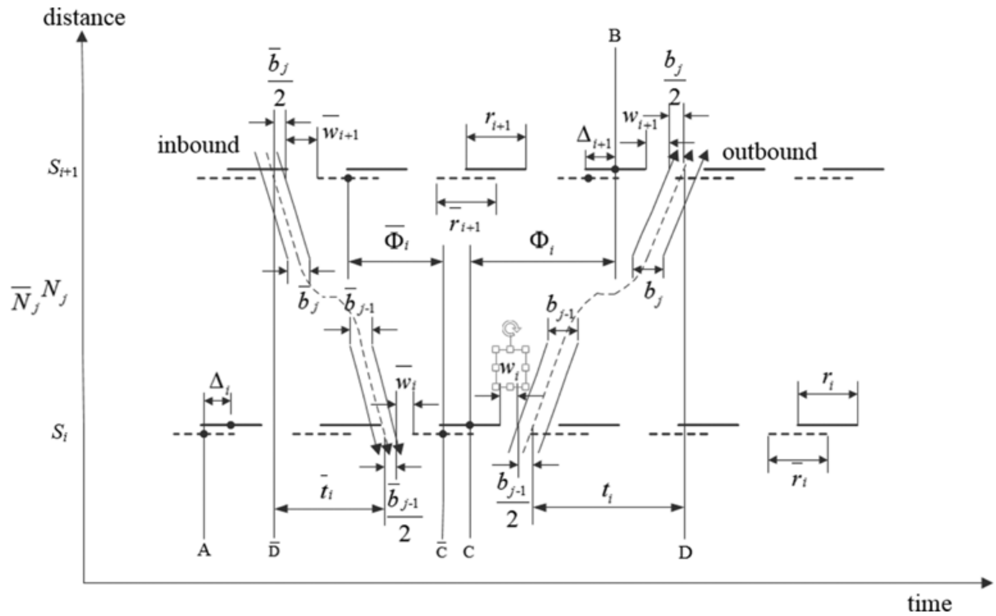


Fig. 3. Relationships in Adjacent Groups

volumes to the total outbound volumes in the same group, the following continuous variable constraint can be derived:

$$(1-k_j)k_j b_j \le (1-k_j)\bar{b}_j, \quad \text{for group } O_j \tag{10}$$

If $k_j = 1$, then $(1-k_j)k_j b_j \le (1-k_j)\bar{b}_j$ is transferred to $b_j = \bar{b}_j$. The bus speed is the expectation value of the relevant data, which can be obtained from the GPS on each bus.

2.3 Constraints in Adjacent Groups

The constraints within a given group were described above. Based on these constraints, the green band for buses within each intersection group can be obtained. However, it is more important to join green bands in adjacent groups to generate a system green band for buses. Bus stops have frequently been disregarded in other band-based approaches; in this paper, bus stops are considered to be a bus-relevant improvement over the classic MAXBAND. The relationships between adjacent intersections in adjacent groups O_{j-1} and O_j are shown in Fig. 3.

In addition to the previously defined variables, two additional pairs of bandwidths and travel times are defined. Let $b_{j-1}(\bar{b}_{j-1})$ = outbound (inbound) bandwidth in group O_{j-1} (cycles) and $t_i(\bar{t}_i)$ = travel time from S_i to S_{i+1} outbound (S_{i+1} to S_i inbound). The travel time can be derived from the distance, bus speed, acceleration speed of the bus, deceleration speed of the bus between S_i and S_{i+1}, and dwell times at S_i and S_{i+1} (cycles).

As previously shown,

$$\Phi_i + \bar{\Phi}_i + \Delta_i - \Delta_{i+1} = m_i \tag{11}$$

where m_i is an integer variable related to S_i and S_{i+1}.

Green bands in adjacent groups are joined by the central lines. Therefore,

$$\Phi_i + \frac{r_{i+1}}{2} + w_{i+1} + \frac{b_{j+1}}{2} = \frac{r_i}{2} + w_i + t_i + \frac{b_j}{2} \tag{12}$$

$$\Phi_i = \frac{b_j}{2} - \frac{b_{j+1}}{2} + \frac{r_i}{2} - \frac{r_{i+1}}{2} + w_i - w_{i+1} + t_i \tag{13}$$

$$\bar{\Phi}_i + \frac{\bar{r}_{i+1}}{2} + \bar{w}_{i+1} + \frac{\bar{b}_{j+1}}{2} = \frac{\bar{r}_i}{2} + \bar{w}_i + \bar{t}_i + \frac{\bar{b}_j}{2} \tag{14}$$

$$\bar{\Phi}_i = \frac{\bar{b}_j}{2} - \frac{\bar{b}_{j+1}}{2} + \frac{\bar{r}_i}{2} - \frac{\bar{r}_{i+1}}{2} + \bar{w}_i - \bar{w}_{i+1} + \bar{t}_i \tag{15}$$

Substituting (13) and (15) into (10), the integer variable constraint equation is derived as follows:

$$\begin{aligned}&\frac{b_j+\bar{b}_j}{2} - \frac{b_{j+1}+\bar{b}_{j+1}}{2} + \frac{r_i+\bar{r}_i}{2} - \frac{r_{i+1}+\bar{r}_{i+1}}{2} + (w_i+\bar{w}_i)\\ &\quad -(w_{i+1}+\bar{w}_{i+1}) + (t_i+\bar{t}_i) + (\Delta_i - \Delta_{i+1}) = m_i\end{aligned} \tag{16}$$

Similarly, the continuous variable constraint inequalities are expressed as follows:

$$w_i + b_j \le 1 - r_i \tag{17}$$

$$\bar{w}_i + \bar{b}_j \le 1 - \bar{r}_i \tag{18}$$

Note that the $t_i(\bar{t}_i)$ between adjacent intersections in adjacent groups is primarily influenced by the dwell time at the bus stops. Considering that the dwell time is slightly stochastic, the expectation value of the dwell time is used in the modeling of the bus travel times. The dwell times are also available from the GPS data for each bus.

2.4 Patterns of Phase Order

Band-based approaches primarily focus on the green band of the main (arterial) street and ignore the exact phase patterns for the streets that intersect the main street. This tendency can be attributed to the fact that the time assigned to either the main street or the cross streets is fixed, and the exact phase patterns for the cross streets do not affect the bandwidth of the main street.

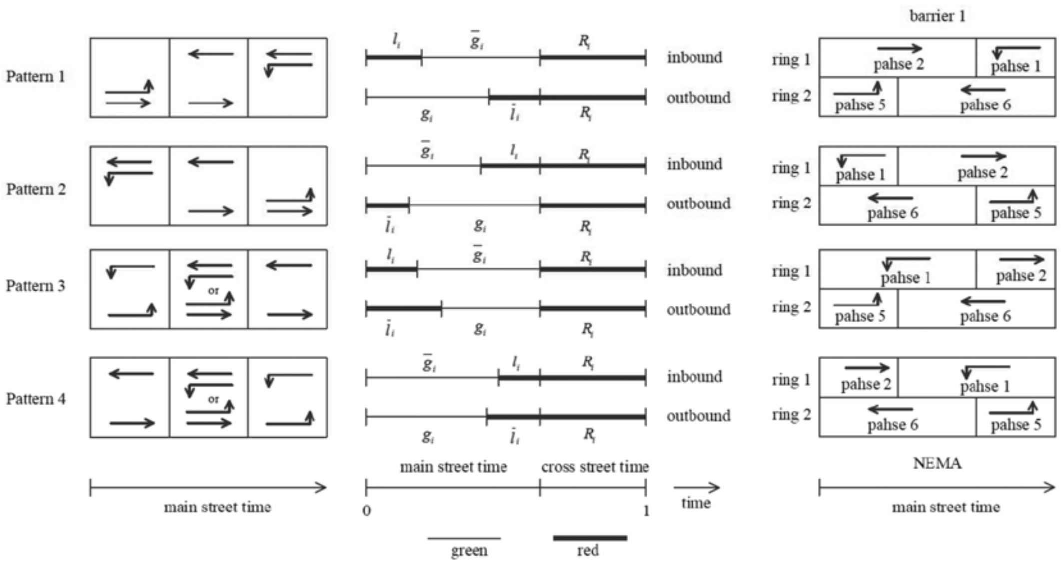


Fig. 4. Patterns of Left-turn Phases

The green time for the right-turn movement of the main street is usually equivalent to the green time for the through movement of the main street. In this paper, the green time for the through movement of the main street is serviced for both the through and right-turn movements of the main street. In addition, the left-turn phases can be categorized into different patterns by creating lead or lag left-turn phases. Fig. 4 shows four left-turn phase patterns according to Little *et al.* (1981), where the patterns of the phases in Fig. 4 are simplified and generated from NEMA standard 8 phases, and the relationships between the two are displayed in the figure. These relationships are shown in Fig. 4.

Let $g_i(\bar{g}_i)$ = outbound (inbound) green time for the through (through and right-turn) movement at S_i of the main street (cycles); $l_i(\bar{l}_i)$ = outbound (inbound) green time for the left-turn movement at S_i of the main street (cycles); and R_i = time for all the movements at S_i of the cross streets (cycles).

The 0-1 variables δ_i and $\bar{\delta}_i$ are introduced. Δ_i can then be expressed as follows:

$$\Delta_i = \frac{(2\delta_i - 1)*l_i - (2\bar{\delta}_i - 1)*\bar{l}_i}{2} \tag{19}$$

All the intersections in this paper are fixed-time controlled. For each signalized intersection, splits in the proposed approach are determined by the demands of vehicles and pedestrians in advance, and the ratios of all the phase splits to the cycle length remain constant. The pedestrian phases consist of two components: phases of crossing the main street and phases of crossing the cross streets. In this paper, all the intersections are fixed-time controlled; therefore, all the pedestrian phases are identical to the corresponding vehicle phases, and no "push button control" exists for the pedestrian phases. The pedestrian phases of crossing the cross streets are identical to the phases of the through movements in both directions along the main street, and the phases of the through movements along the main street are already considered in the proposed approach. Meanwhile, the pedestrian phases of crossing the main street are identical to the phases of the through movements in both directions along the cross streets. Because the exact phase patterns of the cross streets have no influence on the bandwidth along the main street, the pedestrian phases of crossing the main street are also ignored.

2.5 Mathematical Model

The main street features n intersections and $2n_b$ bus stops. Intersections are categorized into n_b-1 groups. Thus, a mixed integer linear programming problem can be constructed as follows. The objective function can be expressed as:

$$\max = \frac{\sum_{j=1}^{n_b-1}(b_j + k_j\bar{b}_j)}{n_b - 1}$$

and expressions (7)~(10), (16)~(19) are the constraints. In addition, $b_j, \bar{b}_j \geq 0$, $j = 1, \ldots, n_b - 1$ and $w_i, \bar{w}_j \geq 0$, $i = 1, \ldots, n$.

To solve the previously described mixed integer linear programming problem, LINGO 11 is used to obtain the global optimal solution for this model.

3. A Case Study

A case study is presented in this section to introduce an application of the proposed approach to the design of the progression of a main street in Changzhou, China. A comparison of the classic MAXBAND and the proposed approach is also presented to demonstrate the performance of the proposed approach.

3.1 Case Description

In this case study, the main street that was selected is a part of Tongjiang Street in Changzhou, China. Tongjiang Street includes eight fixed-time, signal-controlled intersections. Bus lanes are located in the center of this main street, occupying the two center lanes in both directions. Four pairs of designated bus stops are located along the center of the main street near the bus lanes. Define the southbound direction as the outbound direction and the northbound direction as the inbound direction.

To apply the proposed approach, the cycle times of all the signals must be unified and are set to 150 s based on the traffic volumes. $g_i(\bar{g}_i)$, $r_i(\bar{r}_i)$, $l_i(\bar{l}_i)$, and R_i of all the signals are based on the Webster function in the case study and are expressed in units of cycle time. These variables are presented in Table 1.

3.2 Optimization with Classic MAXBAND and the Proposed Approach

In the proposed approach, the intersections in the study case are categorized into three groups based on the locations of the bus stops. The values of k_j can then be calculated. The results are listed in Table 2.

In the classic MAXBAND, k is a global variable defined as the ratio of the total inbound volume to the total outbound volume on the main street, where k = 0.86 in this case.

Table 1. Relevant Variables for All Signals in the Case Study

S_i	g_i	$\bar{g}_i$	l_i	$\bar{l}_i$	r_i	$\bar{r}_i$
S_1	0.36	0.36	0.23	0.23	0.64	0.64
S_2	0.38	0.38	0.23	0.23	0.62	0.62
S_3	0.43	0.43	0.15	0.15	0.57	0.57
S_4	0.26	0.26	0.24	0.24	0.74	0.74
S_5	0.42	0.42	0.25	0.25	0.58	0.58
S_6	0.45	0.45	0.19	0.19	0.55	0.55
S_7	0.63	0.63	0.19	0.19	0.37	0.37
S_8	0.49	0.49	0.19	0.19	0.51	0.51

Table 2. Groups of Intersections for the Proposed Approach

O_j	S_i	k_j
O_1	S_1, S_2, S_3	$k_1 = 1.01$
O_2	S_4, S_5	$k_2 = 0.83$
O_3	S_6, S_7, S_8	$k_3 = 0.72$

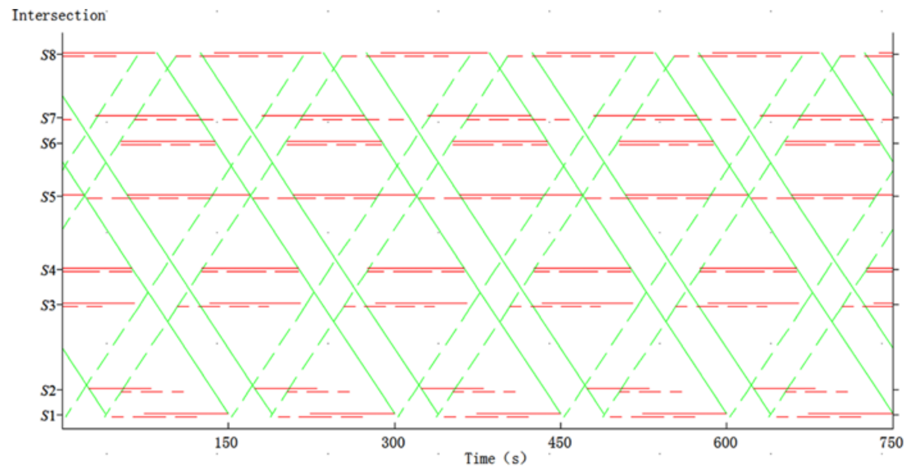
Table 3. Travel Times for the Two Approaches

Approach		MAXBAND	The proposed approach
t_i	1	0.25	0.38
	2	0.10	0.15
	3	0.21	0.46
	4	0.29	0.44
	5	0.14	0.39
	6	0.34	0.51
	7	0.10	0.15
$\bar{t}_i$	1	0.25	0.38
	2	0.10	0.15
	3	0.21	0.46
	4	0.29	0.44
	5	0.14	0.39
	6	0.34	0.51
	7	0.10	0.15

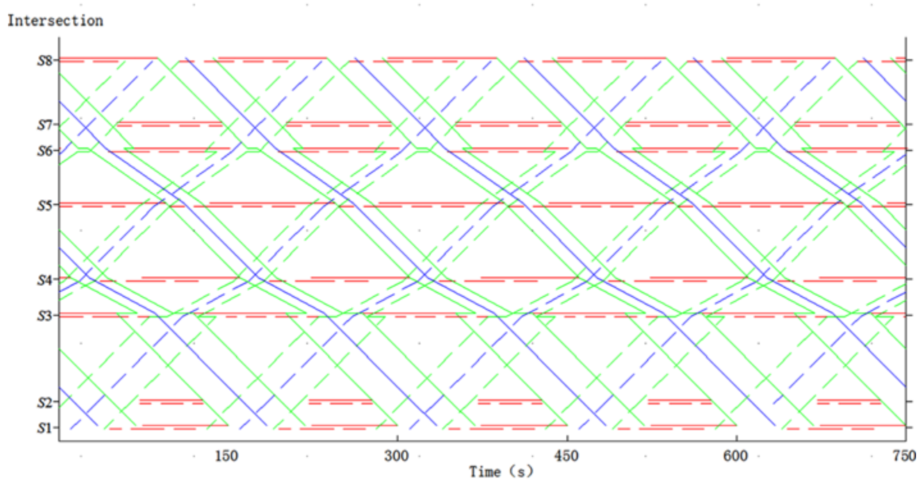
Table 4. Bandwidths of MAXBAND and the Proposed Approach

Bandwidth	Group	MAXBAND	The proposed approach
b_j	1	39s	49s
	2		32s
	3		68s
$\bar{b}_j$	1	35s	48s
	2		27s
	3		59s

The travel times between adjacent intersections for the two approaches are derived in Table 3 and are also expressed in units of cycle time. In the classic MAXBAND, the travel times between adjacent intersections are defined as the distance between adjacent intersections divided by the average car speed. In the proposed approach, the travel times between adjacent intersections in the same group are defined as the distance between adjacent intersections divided by the average bus speed. As the average car speed is higher than the average bus speed, the travel times of the classic MAXBAND are shorter than the travel times of the proposed approach. In addition, in the proposed approach, the travel times between adjacent intersections in adjacent groups



(a)



(b)

Fig. 5. Time-space Diagrams: (a) MAXBAND, (b) Proposed Approach

are longer because bus stops exist between those adjacent intersections and require extra time, for example, in the form of dwell time or acceleration and deceleration times.

The bandwidths of the classic MAXBAND and the proposed approach are shown in Table 4.

Furthermore, we define the intersection S_1 as the reference intersection and the offset between the other intersection and S_1 as the time from the starting time of the outbound red of S_1 to the starting time of the outbound red of the other intersection. Therefore, the offset of S_1 is 0 s, and the offsets of the other intersections are set to 60 s, 75 s, 142 s, 82 s, 128 s, 80 s, and 83 s in sequence. Regarding the adjustment of the bus system schedule, we should adjust the frequency of each bus route to ensure that the outbound bus arrives at intersection S_1 within the outbound bandwidth, whereas the inbound bus should arrive at intersection S_8 within the inbound bandwidth. Defining the starting time of the outbound red of S_1 to be 0 s, the outbound bus should arrive at intersection S_1 between (96±150*M) s and (145±150*M) s, whereas the inbound bus should arrive at intersection S_8 between (140±150*M) s and (199±150*M) s, where M is an integer variable.

Two time-space diagrams are shown in Fig. 5 and are based on the classic MAXBAND and the proposed approach.

In these two figures, solid and dashed lines represent outbound and inbound elements, respectively. The color red represents the red time, and the color green represents the bandwidth. The blue line in Fig. 5(b) denotes the central line of the bandwidth. As shown in Table 4, the proposed approach generates a wider link bandwidth than does the classic MAXBAND method, which is also shown in Fig. 5(b) and Fig. 5(a). This occurs because the global bandwidth in the classic MAXBAND may be confined by two critical factors: the red time for a specific intersection and the number of intersections. In the proposed approach, the intersections are categorized into groups based on the bus stop locations. As a result, the number of intersections in each group is reduced. The specific intersection that confines the global bandwidth is assigned to a specific group and only affects the bandwidth of this group, not those of other groups. However, because the proposed approach is designed for buses, the band speed is slower than the band speed in the classic MAXBAND method, as shown in Fig. 5.

3.3. Simulation Evaluation

To evaluate the proposed approach, the optimized solutions

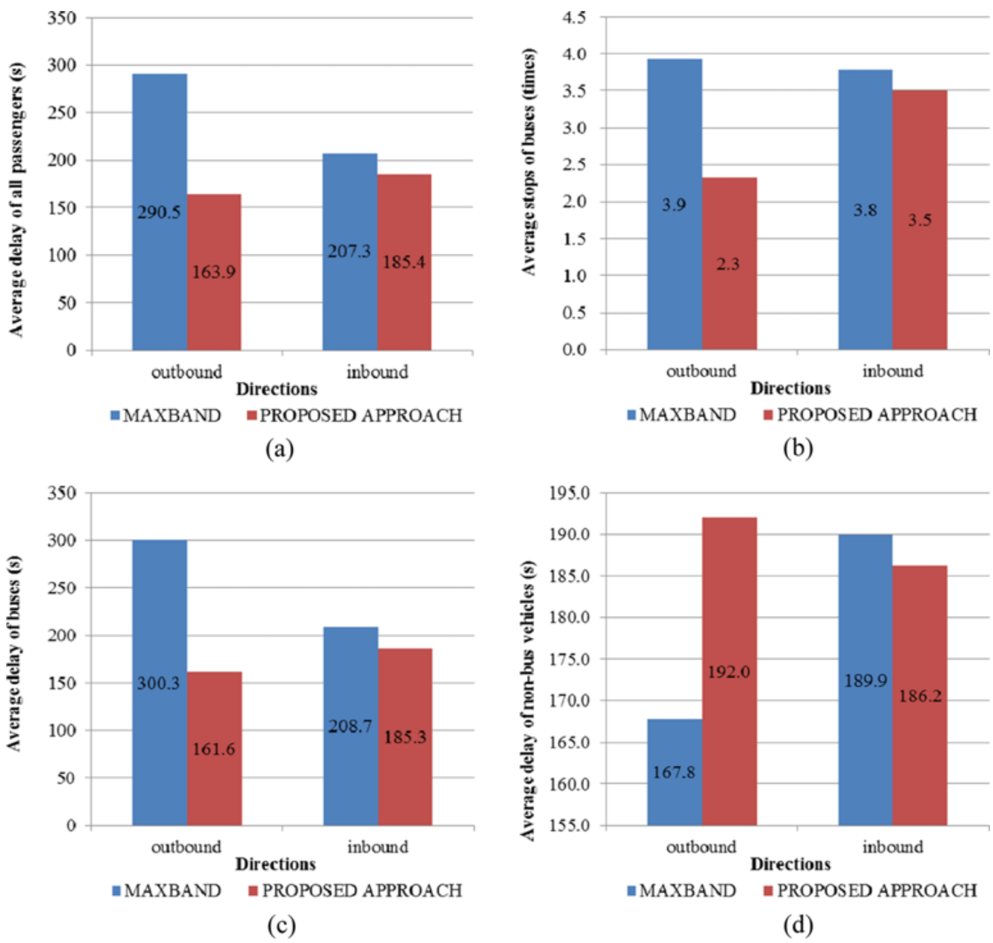


Fig. 6. Results of Simulations: (a) Average Delay for All Passengers, (b) Average Stops for Buses, (c) Average Delay for Buses, (d) Average Delay foR Non-bus Vehicles

obtained using the classic MAXBAND and the proposed approach were simulated using VISSIM. Based on the observations made during the morning peak hours, the bus occupancy is determined to be 60 passengers/bus, whereas the car occupancy is determined to be 2 passengers/car. The results are shown below.

In practice, the average delay for passengers is an important index when evaluating an entire traffic system. The average delay for passengers using both the proposed approach and the classic MAXBAND can be obtained by simulation. The results, which are shown in Fig. 6(a), show an improvement using the proposed approach. The delay for passengers in both directions decreases significantly (44% outbound and 11% inbound). At high occupancy, improvements in the bus systems may generate visible benefits for the passengers of the entire traffic system.

Because the proposed approach is designed for bus progression, a significant improvement in bus operational performance should be achieved. The average numbers of stops for buses travelling along the main street are shown in Fig. 6(b). A significant improvement in the bus operational performance is observed, with a reduction in the number of stops in both directions, especially outbound stops, which decrease by 41%. Fig. 6(c) shows the average delay for buses travelling along the main street. Similar to the bus stops, a significant improvement is achieved, with a 46% reduction in outbound delay and a 12% reduction in inbound delay for buses.

Although the entire traffic system and the bus systems benefit from the proposed approach, the influence on cars (non-bus vehicles) should also be considered. Fig. 6(d) shows the average delay for non-bus vehicles travelling along the main street. The results reveal a 14% increase in outbound delay and a 2% decrease in inbound delay for non-bus vehicles. The delay for general traffic is slightly longer than that obtained using the MAXBAND method, while the average delay for the passengers of the traffic system as a whole is significantly reduced. However, the influence is slight and seemingly arbitrary.

4. Conclusions

Considering the distinctive characteristics of the bus lane system, a signal optimization and coordination approach designed for bus progression is proposed in this paper to model and solve a bandwidth-based bus progression problem. This approach is a new attempt to make buses the key objects of design and considers bus elements, such as dwell time and location of bus stops, to construct a bandwidth-based model. Using compiled programming in LINGO, a global optimal solution can be found. Finally, the proposed approach and the classic MAXBAND were evaluated in a case study using VISSIM. The major conclusions are listed below.

1. Intersection categorization is a key method in the proposed approach. The proposed approach can widen the bandwidth by categorizing intersections along the main street by locations of bus stops. In this way, without affecting the whole system, intersections that may confine the whole bandwidth in the MAXBAND method only affect one or more intersection groups in the proposed approach. In the case study, the classic MAXBAND has fixed bandwidths of 39 s and 35 s for the two directions, whereas the proposed approach generated maximum bandwidths of 68 s and 59 s. Even the shortest bandwidths in the proposed approach were greater than the shortest bandwidths using the classic MAXBAND. Different outbound and inbound volume ratios for different intersection groups were employed as constraints to design variable bandwidths in different intersection groups in the proposed approach; thus, the bandwidths could be applied to different intersection groups.
2. The proposed approach considers bus elements, making the band progression more suitable for bus systems, with little effect on other vehicles. In the case study, with a significant reduction in stops and delays (maxima of 41% and 46%, respectively) for buses along the main street, the delay for non-bus vehicles fluctuated randomly (increasing by 14% and decreasing by 2%). However, the entire traffic system would benefit significantly from this approach (the delay decreased by a maximum of 44%).
3. The algorithm for the bus progression model employs mixed integer linear programming. By compiling the programming in the relevant language in LINGO, a global optimal solution can be achieved in a few seconds as long as the solver is implemented, regardless of the number of intersections and groups.

Generally, compared with cars, bus systems can serve more passengers during peak hours; therefore, bus speeds are used to optimize the bus progression in this paper, and the entire traffic system can benefit from the proposed approach. However, in some instances, the entire traffic system may benefit from MAXBAND with car speeds. Let $E = \alpha Q_g R_g F_g - Q_b F_b$, where α is the weight factor and $\alpha > 0$, E is the decision index, Q_g is the volume of cars (cars/hour), Q_b is the frequency of the bus system (buses/hour), and F_g and F_b are the occupancies of cars (passengers/car) and buses (passengers/bus). If $\alpha > 1$, cars are favored by passengers; otherwise, buses are favored. If E > 0, cars can serve more passengers, and car speeds (MAXBAND) should be used for the optimization. Otherwise, buses can serve more passengers, and it is best to perform the optimization using bus speeds (proposed approach).

We should mention that the proposed approach suffers from a number of limitations. First, the main street must have bus lanes. To categorize the intersections, the number of bus stops in both directions should be equal, and the locations of specific pairs of bus stops should be along the same link between two adjacent intersections. The schedule and frequency of each bus route should be properly adjusted and managed to support the new signal-setting method. To this end, a control center must be constructed.

The dwell time in the proposed approach is used as the expectation value of the survey data. Additional studies should focus on the dwell time uncertainty.

Acknowledgements

The authors appreciate the comprehensive data supplied by their colleagues at the School of Transportation. The authors are also grateful to the anonymous referees for suggestions on how to improve the paper. This research is supported by the National High Technology Research and Development Program of China (2014AA110303) and the Scientific Research Foundation of the Graduate School of Southeast University (3221004942).

References

Baass, K. G. (1983). "Another look at bandwidth maximization." *In Transportation Research Record: Journal of the Transportation Research Board, No.905, Transportation Research Board of the National Academies, Washington, D.C.,* pp. 38-47.

Chang, E. C. P. and Messer, C. J. (1991). "Arterial signal timing optimization using PASSER II-90-Program user's manual." *Publication FHWA/TX-90/467-2F. FHWA, U.S. Department of Transportation.*

Chaudhary, N. A. and Messer, C. J. (1996). "PASSER IV-96, version 2.1, User/Reference manual." *Publication FHWA/TX-97/1477-1. FHWA, U.S. Department of Transportation.*

Gartner, N. H., Assmann, S. F., Lasaga, F., and Hous, D. (1991). "A multi-band approach to arterial traffic signal optimization." *Transportation Research Part B*, Vol. 25, No. 1, pp. 55-74, DOI: 10.1016/0191-2615(91)90013-9.

Gartner, N. H., Assmann, S. F., Lasaga, F., and Hous, D. (1990). "MULTIBAND: A variable bandwidth arterial progression scheme." *In Transportation Research Record: Journal of the Transportation Research Board, No.1287, Transportation Research Board of the National Academies, Washington, D.C.*, pp. 212-222.

Janos, M. and Furth, P. G. (2002). "Bus priority with highly interruptible traffic signals: Simulation of san juan's avenida ponce de leon." *In Transportation Research Record: Journal of the Transportation Research Board, No.1811, Transportation Research Board of the National Academies, Washington, D.C.,* pp. 157-165, DOI: 10.3141/1811-19.

Li, M., Yin, Y. F., Zhou, K., and Zhang, W. B. (2011). "Modeling and implementation of adaptive transit signal priority on actuated control systems." *Computer-Aided Civil and Infrastructure Engineering*, Vol. 26, No. 4, pp. 270-284, DOI: 10.1111/j.1467-8667.2010.00677.x.

Link, K. and Shalaby, A. (2003). "Automated transit headway control via adaptive signal priority." *Journal of Advanced Transportation*, Vol. 38, No. 1, pp. 45-67, DOI: 10.1002/atr.5670380105.

Little, J. D. C. (1966). "The synchronization of traffic signals by mixed-integer linear programming." *Operations Research,* Vol. 14, No. 4, pp. 568-594, DOI: 10.1287/opre.14.4.568.

Little, J. D. C., Kelson, M. D., and Gartner, N. H. (1981). "MAXBAND: A versatile program for setting signals on arteries and triangular networks." *In Transportation Research Record: Journal of the Transportation Research Board, No.795, Transportation Research Board of the National Academies, Washington, D.C.*, pp. 40-46.

Liu, H., Li, M., and Skabardonis, A. (2004). "Development and application of a simulation tool for transit signal priority." *Presented at 83rd Annual Meeting of the Transportation Research Board, Washington, D.C.*

Messer, C. J., Whitson, R. H., Dudek, C., and Romano, E. (1973). "A variable-sequence multiphase progression optimization program." *In Transportation Research Record: Journal of the Transportation Research Board, No. 445, Transportation Research Board of the National Academies, Washington, D.C.*, pp. 24-33.

Mirchandani, P., Li, J., and Hickman, M. (2010). "A macroscopic model for integrating bus signal priority with vehicle rescheduling." *Public Transport*, Vol. 2, No. 3, pp. 159-172, DOI: 10.1007/s12469-010-0028-3.

Morgan, J. T. and Little, J. D. C. (1964). "Synchronizing traffic signals for maximal bandwidth." *Operations Research*, Vol. 12, No. 6, pp. 896-912, DOI: 10.1287/opre.12.6.896.

Rakha, H. and Zhang, Y. (2004). "Sensitivity analysis of transit signal priority impacts on operation of a signalized intersection." *Journal of Transportation Engineering*, Vol. 130, No. 6, pp. 796-804, DOI: 10.1061/(ASCE)0733-947X(2004)130:6(796).

Skabardonis, A. and Christofa, E. (2011). "Impact of transit signal priority on level of service at signalized intersections." *Procedia - Social and Behavioral Sciences*, Vol. 16, pp. 612-619, DOI: 10.1016/j.sbspro.2011.04.481.