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Signal coordination model for local arterial with heavy bus flows

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ABSTRACT

Conventional Transit Signal Priority (TSP) controls often reach the limitation for arterials accommodating heavy bus flows since the priority function can significantly increase delay at minor streets. Under such conditions, a proper signal progression plan that accounts for the benefits of buses may offer the potential to improve the reliability of bus operations and increase the bus ridership. This study proposes a bus-based progression model to reduce the delay of buses on local arterials. Given the cycle length and green splits at each intersection, the bus-based progression model, grounded on the same notion as conventional signal progression methods, considers the operational characteristics of transit vehicles, such as the impact of bus dwell time and the capacity constraints at bus stops. Also, to deal with the stochastic nature of dwell time, this study introduces additional constraints to maximize the percentage of buses which can stay within the green band after leaving bus stops. Taking an arterial with five intersections and three two-way bus stops as an example, this study applies VISSIM as an unbiased tool for model evaluation. The simulation results demonstrate that the proposed model can significantly reduce bus passenger delays and the average person delays for the entire arterial, compared with the conventional progression models.

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bus progression; bus stops; effective bandwidth; stochastic dwell time

Introduction

Over the past decades, Transit Signal Priority (TSP) control has been recognized as a promising method to reduce bus travel time in urban networks (Smith, 1968). In response to the presence of buses, a TSP control system will grant extra green time to the approaching transit vehicles and many research publications (Yagar & Han, 1994; Chang, Vasudevan, & Su, 1996; Ling & Shalaby, 2004; Hounsell & Wu, 1995; Yao et al., 2009; Ma, Liu, & Yang, 2013; Lin, Yang, Zou, Jia, & Pan, 2013; Hu, Park, & Lee, 2015; Ghanim & Abu-Lebdeh, 2015) have demonstrated the effectiveness of TSP in reducing the bus delays. However, those existing studies also showed the negative impact to side streets when granting TSP to major approaches. Hence, to promote the application of TSP on local arterial with heavy bus flows, one critical issue to be studied is how to reduce the frequency of activating TSP at signalized intersections. For example, Li et al. (2011) minimized the sun of bus delay and other traffic delay with the consideration of safety and other operational constraints. Lin et al. (2013) proposed a conditional TSP strategy ensuring that the delays for all passengers are not increased. Yet these strategies may become less efficient when the number of requests is large.

In review of the literature, passive control strategy may serve as a potentially effective way to deal with arterials accommodating heavy bus flows. Different from active TSP control, passive control techniques do not explicitly recognize the actual presence of buses, but pre-determine the signal timings to yield benefits to transit vehicles. In 1997, Urbanik et al. (1977) concluded several typical passive control strategies, including shortening the cycle length, splitting phase, area-wide signal timing plan, and metering vehicle. Using TRAF-NETSIM simulation, Garrow and Machemehl (1998) tested the effectiveness of shortening cycle length and splitting phase at both isolated intersections and local arterials. Skabardonis (2000) formulated the passive TSP by modifying the objective function of TRANSYT-7F to provide more green time to bus movements. Ma and Yang (2007) presented a passive TSP control on an area-wide timing plan that reassigns the spatial and temporal resources to optimize the bus frequency. However, the existing passive control strategies may fall short of facilitating the movement of bus flows along multiple successive intersections.

Taking London as an example, Hounsell, Shrestha, Head, Palmer, and Bowen (2008) has shown that a pre-timed signal control with bus progression design can

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clearly outperform the other strategies in terms of reducing bus travel times. Over the past decades, providing signal progression for local arterial has long been considered as one of the most promising methods in facilitating the movement of passenger cars. The study by Morgan and Little (1964) is the pioneer work that first intend to maximize signal green bandwidth for two-way through traffic. Then, a set of enhanced versions, such as a MAXBAND model (Little, 1966; Little, Kelson, & Gartner, 1981) has been developed to account for left-turn movements and impact of queue length at intersections. Ground on the same logic, another advanced model, named MULTIBAND, was developed by Gartner, Assmann, Lasaga, and Hou (1991) to design different bandwidths at links with different volumes. An efficient solution heuristic for MULTIBAND model is also reported in the literature (Gartner and Stamatiadis, 2002). To consider the different traffic flow patterns, Li (2014) proposed a robust signal coordination model, and Yang, Cheng, and Chang (2015) formulated three multi-path signal progression models.

Following the principle of signal progression but with the focus of bus vehicles, Ma and Yang (2007) developed a passive signal priority approach for bus rapid transit system by analyzing the traffic signal status upon bus arrival to an intersection. In TRANSYT optimization package (Wallace et al., 2003), transit vehicles are assumed to be traveling on exclusive lanes when designing signal progression. Lin et al. (2013) proposed a bus-based progression model to account for the bus dwell time at bus stops. With the comparison to signal plans generated by the MULTIBAND model (Gartner, Assman, Lasaga, & Hou, 1991), Lin et al. (2013) has demonstrated the effectiveness of the bus progression model in reducing bus delays. However, the strong assumptions, such as deterministic bus dwell time, have limited the potential application of this model. Dai, Wang, and Wang (2015) accounted the benefit of both the bus systems and general vehicles by analyzing the relationships between these bands for these two modes. The dwell times of buses are minimized conditioning on pre-determined lower and upper bound of bands for bus band and general vehicle band. Dai, Wang, and Wang (2016) categorized intersections into groups based on the location of bus stops and generated progression bands for buses with expected dwell time. In practice, an efficient bus progression model shall fully consider the operational features and physical constraints of transit vehicles at local arterials. In response to such needs, this study proposes an efficient transit progression model with the following key features: (1) using each bus stop as a control point to design the green band for buses, (2) taking the bus stop capacity as a primary control constraint, and (3) accounting for bus dwell time variance at bus stops.

The remaining of this paper is organized as follows: the section "Problem nature" will introduce several critical issues that need to be considered when addressing the vital subject. The model formulations will be described in the section "Model formulations". A case study is then shown in the section "Numerical examples" to evaluate the proposed model. Conclusions and future research will be reported in the last section.

Problem nature

As reported in the literature, the core logic of signal progression design is to maximize the green bandwidth for traffic flows. Then, vehicles staying in the green band can pass the arterial segment without stops. Examples of existing algorithms for the design of signal progression for passenger cars include MAXBAND (Little et al., 1981) and MULTIBAND (Gartner, Assmann, Lasaga, & Hou, 1991). Different from the design of progression for passenger cars, a transit vehicle may need to dwell at a bus stop for a short time when travelling between intersections. Hence, a green band designed for transit vehicles shall fully reflect the impact of its dwell time, as shown in Figure 1. For convenience of discussion, this study has defined such a bus band as the bus band and its width is called as bus bandwidth in the text.

Notably, bus dwell time is dependent of the varying of passenger demands at bus stops. As shown in most field data (see Figure 2), the bus dwell time is not a constant, but is stochastic in nature. Hence, failing to fully account for such uncertainty, a transit vehicle may not stay within the pre-set green band after departing from bus stops.

For both the operational and safety concerns, another critical issue to be addressed in design of bus progression system is the storage capacity at bus stops. Figure 3 presents an arterial segment with one far-side bus stop.

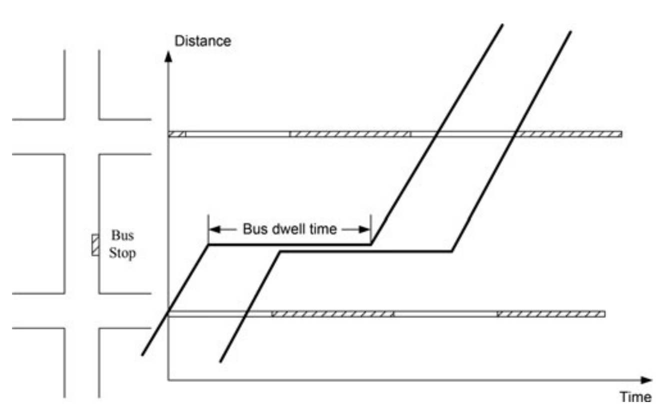
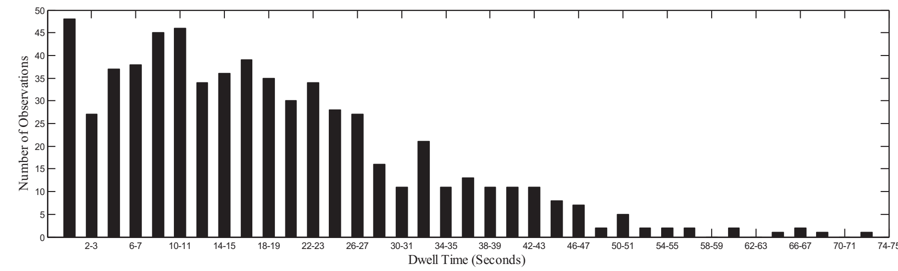
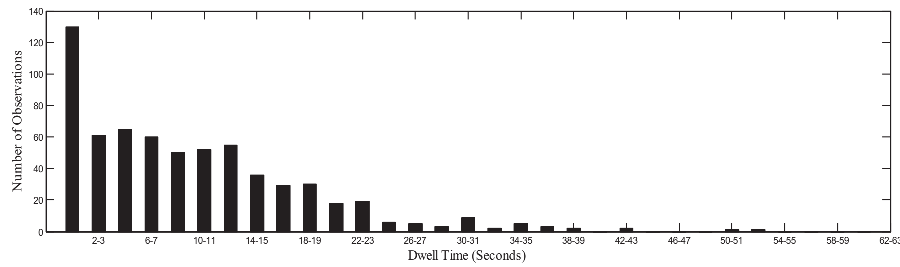


Figure 1. Green band for bus vehicles.



(A) Bus dwell time at stop-3 of Jiefang Rd, Jinan, China



(B) Bus dwell time at stop-4 of Jiefang Rd, Jinan, China

Figure 2. Distribution of bus dwell time collected between 11 January 2014 and 11 July 2014.

When the number of arriving buses within a short time period exceeds the storage capacity of a bus stop, the queuing buses may spillback to the nearby intersection and thus block the traffic flows at that intersection. Hence, to prevent the occurrence of such queue spillback, one shall pre-determine an upper bound for bus bandwidth so as to limit the number of buses concurrently arriving at the same stops.

In brief, an efficient bus progression model shall account for both bus dwell time uncertainty and limitation of bus stop capacities. To overcome these two critical issues, this study introduces a variable-band progression model which takes each bus stop as a control point. As shown in Figure 4, by specifying different upstream and downstream green bandwidths for a bus stop, one can design a robust bus progression plan that accounts for the stochastic nature of bus dwell time. For example, a larger downstream green band can increase its probability to receive buses leaving bus stops. Also, to prevent the bus queue spillover, a pre-determined upper bound can be applied to constrain the bandwidths at each link.

Model formulations

For convenience of discussion, key parameters and variables are listed in Figure 4 and Table 1.

Control objective

To accomplish the research objectives, this study has developed a bus progression model that takes the pre-set cycle length, green splits, bus stop capacities, and mean bus dwell time as its major inputs. The proposed model is formulated with a mixed-integer-linear programming method, which optimizes the signal offsets to yield the maximal bus bandwidths. Notably, the bus bandwidths before and after the bus stop can be different. Following the same notion as in conventional signal progression models, one can formulate the objective function as follows:

$$\text{Max} \quad \sum_i \varphi_i b_i + \sum_i \overline{\varphi}_i \overline{b}_i, \tag{1}$$

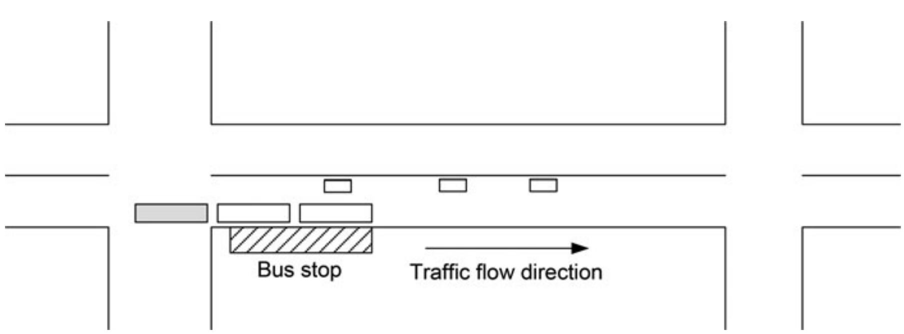


Figure 3. Bus queue spillover at the far-side bus stops.

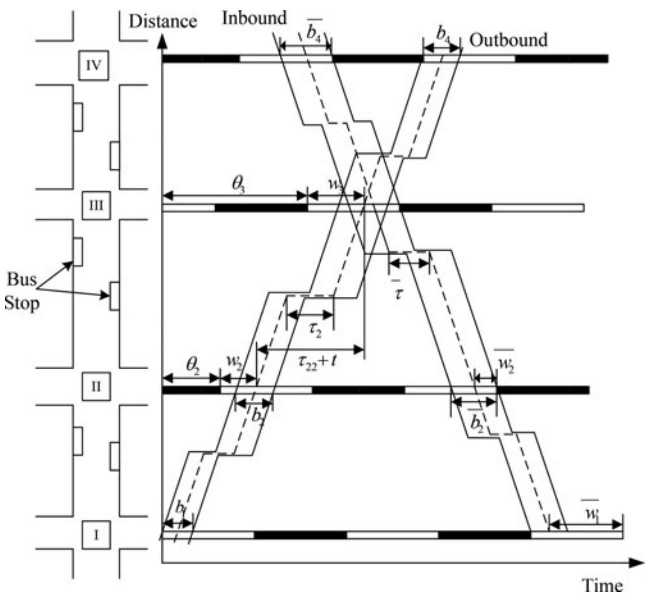


Figure 4. Variable green band using bus stop as control point.

where $b_i(\overline{b}_i)$ denotes the outbound (inbound) bus bandwidth at intersection i and $\varphi_i(\overline{\varphi}_i)$ is the corresponding weighting factor. Let $n_i(\overline{n}_i)$ denote the expected number of outbound (inbound) buses passing intersection i during the synchronized phase in 1 h. Then, the weighting factor can be calculated as follows:

$$\varphi_i = \frac{n_i}{\sum_j \frac{n_j}{n}} \quad \forall i, \tag{2}$$

$$\overline{\varphi}_i = \frac{\overline{n}_i}{\sum_j \frac{\overline{n}_j}{n}} \quad \forall i. \tag{3}$$

Table 1. Key notations in this study.

Variables	Descriptions
I	The set of intersections
n	Total number of intersections
I' ($\overline{I}'$)	The set of intersections which are at upstream (downstream) of outbound (inbound) bus stops
K	The set of bus stops
$g_i(\overline{g}_i)$	The outbound (inbound) green ratio at intersection i
r_i	The time difference from the start of outbound green to the end of inbound green at intersection i
$t_i(\overline{t}_i)$	Average outbound (inbound) travel time from intersection i (i+1) to intersection i+1 (i)
$w_i(\overline{w}_i)$	The time period between the start (end) of green to the center of the band at intersection i for an outbound(inbound) intersection
$b_i(\overline{b}_i)$	outbound (inbound) bandwidth at intersection i
θ_i	the signal offset at intersection i
$\tau_i(\overline{\tau}_i)$	average dwell time of buses at the outbound (inbound) bus stop after intersection i(i+1)
$\sigma_i(\overline{\sigma}_i)$	standard deviation of dwell time at the outbound (inbound) bus stop after intersection i(i+1)
C	a cycle, it equals to 1 in the model
$\varphi_i(\overline{\varphi}_i)$	weight factor for the outbound (inbound) bandwidth at intersection i
α, β, p	control parameters

Bandwidth constraints

To facilitate the optimization model, one shall first introduce the interference constraints as follows:

$$w_i - 0.5b_i \geq 0 \quad w_i + 0.5b_i \leq g_i \quad \forall i, \tag{4}$$

$$\overline{w}_i - 0.5\overline{b}_i \geq 0 \quad \overline{w}_i + 0.5\overline{b}_i \leq g_i \quad \forall i, \tag{5}$$

where Eqs. (4) and (5) can ensure that the green bandwidth does not exceed the available green time.

The second set of constraints, progression constraints, are specified to ensure that the signals do not stop the bus flows moving during the green bands. Each constraint functions to limit the differences between centers of the inbound or outbound bands for each pair of neighboring intersections. Also note that only the average bus dwell time are accounted here.

Taking any pair of neighboring intersections, shown in Figure 4, as an example, the progression constraints for the links with bus stops can be expressed as follows:

$$\theta_i + w_i + t_i + \tau_i = \theta_{i+1} + w_{i+1} + n_{i+1}C \quad \forall i \in I\prime, \tag{6}$$

$$-\theta_i + r_i + \overline{w}_i + \overline{t}_i + \overline{\tau}_i = -\theta_{i+1} + r_{i+1} + \overline{w}_{i+1} + \overline{n}_{i+1}C \quad \forall i \in \overline{I}'. \tag{7}$$

The progression constraints for the links without bus stops can be shown with similar expressions:

$$\theta_i + w_i + t_i = \theta_{i+1} + w_{i+1} + n_{i+1}C \quad \forall i \in I - I', \tag{8}$$

$$-\theta_i + r_i + \overline{w}_i + \overline{t}_i = -\theta_{i+1} + r_{i+1} + \overline{w}_{i+1} + \overline{n}_{i+1}C \quad \forall i \in I - \overline{I}'. \tag{9}$$

Note that on arterials having far-side bus stops, the bus queue length may exceed a stop's capacity and spill over to the nearby intersections if a serial of buses arrive sequentially over a short interval. Hence, to prevent such queue spillover, one shall set an upper bound to limit the bus green bandwidths. Assuming that the multi-route bus arriving frequency to each stop follows a Poisson distribution, the probability of k buses being in the outbound green band i can be expressed as follows:

$$f(k) = \frac{(\lambda b_i)^k \times e^{-\lambda b_i}}{k!}, \tag{10}$$

where λ denotes the bus arrival rate. Then, the upper bound of a bus bandwidth can be computed with the following equation:

$$b_i^{\max} = arc \max_{b_i} \left\{ \sum_{k=0}^{C_s} \frac{(\lambda b_i)^k \times e^{-\lambda b_i}}{k} \geq p \right\}, \tag{11}$$

where C_s denotes the capacity of the bus stop and p is the parameter of confidence level (e.g., 0.9).

However, due to the inequality nature of interference constraints shown in Eqs. (4) and (5), directly adding an upper bound $b_i^{\max}(\overline{b}_i^{\max})$ for $b_i(\overline{b}_i)$ may force the solution algorithm to simply reduce the value of $b_i(\overline{b}_i)$ without reaching the optimal value for the control variables (i.e., offsets).

Therefore, to ensure that the upper bound constraint for the green bandwidth can function effectively, one shall set additional constraints in the outbound direction with a set of new decision variables $x_i(\overline{x}_{i+1})$

$$w_i - 0.5 \times b_i^{\max} \le M \times x_i \quad \forall i \in I', \tag{12}$$

$$w_i + 0.5 \times b_i^{\max} \ge g_i - M \times (1 - x_i) \quad \forall i \in I', \tag{13}$$

where M is a large positive number that dominates all decision variables and parameters. Hence, only one of Eqs. (12) and (13) can be effective in the bus progression model. For example, when x_i equals "1," Eq. (12) will be ineffective and Eq. (13) shall become

$$w_i + 0.5 \times b_i^{\max} \ge g_i \quad \forall i \in I'. \tag{14}$$

Then, Eqs. (14) and (4) will function together to ensure the length, from the center of a bus band to the end of a green phase, is less than a half of the bandwidth's upper bound. In other words, a half of the bus bandwidth will be less than a half of its upper bound.

If x_k equals "0," Eq. (13) is ineffective and Eq. (12) becomes

$$w_i \le 0.5 \times b_i^{\max} \quad \forall i \in I', \tag{15}$$

And, Eq. (15) ensures that the length, from the start of green phase to the center of a bus band, is less than the half of its upper bound, which can also force the bus bandwidth to be less than its upper bound.

Similarly, for the bus band in the inbound direction, one can derive the following constraints:

$$\overline{w}_{i+1} - 0.5 \times \overline{b}_i^{\max} \le M \times \overline{x}_{i+1} \quad \forall i \in \overline{I}', \tag{16}$$

$$\overline{w}_{i+1} + 0.5 \times \overline{b}_i^{\max} \ge g_{i+1} - M \times (1 - \overline{x}_{i+1}) \quad \forall i \in \overline{I}', \tag{17}$$

where $\overline{b}_k^{\max}$ denotes the upper bound for the bandwidth of $\overline{b}_k$.

One remaining issue is to account for the impact of bus dwell uncertainties at bus stops on the progression design. As discussed previously, taking bus stops as the control points, the bandwidth for buses to enter the stops may differ from the one for the departure. Hence, some constraints are needed to ensure that the band at the downstream of a bus stop can accommodate the number of buses coming from the upstream band. As shown in Figure 5, to keep vehicles (within band αb_i) entering from the upstream green band to stay within the downstream

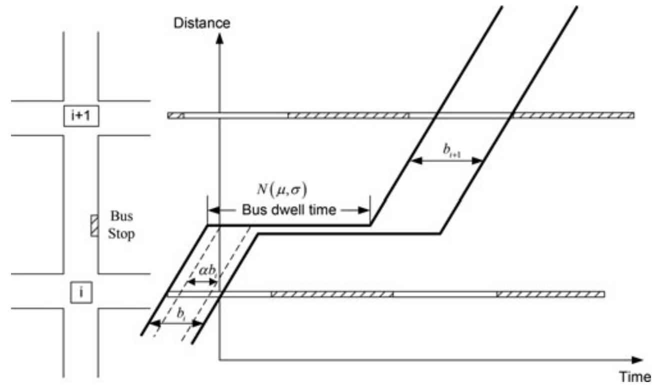


Figure 5. Impact of bus dwell time uncertainties.

green band b_{i+1}, the following constraints shall be satisfied:

$$(\mu - \varepsilon) > \frac{1}{2}\alpha b_i + \mu - \frac{1}{2} b_{i+1}, \tag{18}$$

$$\alpha b_i + (\mu + \varepsilon) < \frac{1}{2}\alpha b_i + \mu + \frac{1}{2} b_{i+1}, \tag{19}$$

where μ denotes the mean bus dwell time and ε denotes its uncertainty; α is a conservative parameter, which represents the portion of effective bandwidth for the upstream bus band. Assuming bus dwell time follows normal distribution $N(\mu, \sigma)$, the effective bandwidth is defined as the portion of upstream green band which guarantees those buses in progression can still stay within the green band after dwelling at bus stops if their stochastic dwell time lies in $[\mu - \sigma, \mu + \sigma]$. Based on the principle of normal distribution, the exact probability of buses within effective band can catch the downstream band is 68%.

By integrating these four constraints, one can reach the following relations:

$$b_{i+1} \ge \alpha b_i + |2\varepsilon|. \tag{20}$$

In Eq. (20), $|2\varepsilon|$ represents the tolerance of the dwell time uncertainty. It should be a function of the standard deviation of the dwell time. By defining $\rho\sigma = |2\varepsilon|$, one can get following constraints:

$$b_{i+1} \ge \alpha \cdot b_i + \beta \cdot \sigma_i \quad \forall i \in I' \tag{21}$$

where β is a control parameter which indicates the preferred confidence level.

Similarly, for the inbound direction, the constraints should be

$$\overline{b}_i \ge \alpha \cdot \overline{b}_{i+1} + \beta \cdot \overline{\sigma}_i \quad \forall i \in \overline{I}'. \tag{22}$$

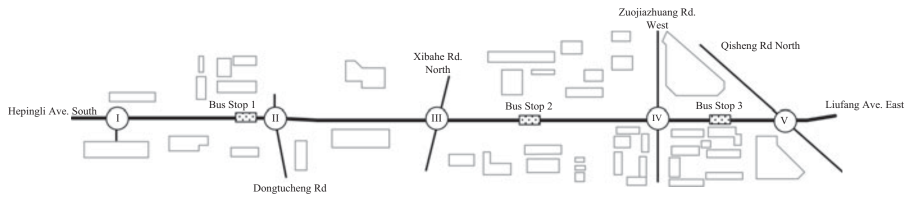


Figure 6. Summary of case study information.

In brief, the optimization model could be summarized as follows:

$$\begin{aligned} & Max \quad \sum_i \varphi_i b_i + \sum_i \overline{\varphi}_i \overline{b}_i \\ \text{s.t.} \quad & \text{Eqs. } (4)-(9) \\ & \text{Eqs. } (12)-(13) \\ & \text{Eqs. } (16)-(17) \\ & \text{Eqs. } (21)-(22) \\ & b_i,\ w_i,\ \overline{b}_i,\ \overline{w}_i \geq 0 \\ & n_i,\ \overline{n}_i \text{ are integer variables} \\ & x_i,\ \overline{x}_i \text{ are binary variables.} \end{aligned}$$

Note that the proposed model is formulated with the mixed-integer-linear-programming formulations, which can be solved with existing algorithms, such as Branch-and-Band technique, due to its limited number of decision variables.

Numerical examples

Case design

To illustrate the applicability and efficiency of the proposed system, this study takes an arterial segment, Liufang Ave. North, in Beijing for case study. As shown in Figure 6, the experimental system for performance evaluation consists of five intersections, four two-lane connecting links, and three two-way bus stops. Some key geometric features are introduced in Table 2.

The key traffic pattern and key parameters used in the analysis are listed below:

- The common cycle length of the five intersections is 150 sec.
- The outbound and inbound bus flows share the same signal phase, and their green times at intersections are 99, 77, 66, 75, and 60 sec, respectively.

Table 2. Geometry features of the studied segment.

Link	Number of lanes	Link length (ft)	Bus travel time	With bus stop?
I↔II	2	906	20	Yes
II↔III	2	948	21	No
III↔IV	2	1250	28	Yes
IV↔V	2	725	16	Yes

- The dwell time at all three bus stops are assumed to follow the following normal distributions: bus stop 1: N(30,9); bus stop 2: N(27,7); bus stop 3: (24,6).
- The bus stop capacity is two buses at each direction, and the confidence parameter p equals 0.95; then the maximal bus bandwidth could be computed as 50 sec using Eq. (11).
- The bus volume is 60 veh/h for outbound and 50 veh/h for inbound direction, the passenger car volume are 600 veh/h and 500 veh/h, respectively.
- The two control parameters in Eqs. (18), (19), α and β, are set to be 0.5 and 1.0, respectively.
- The loading factors for buses and passenger cars are set to be 20 and 1.2 persons, respectively.

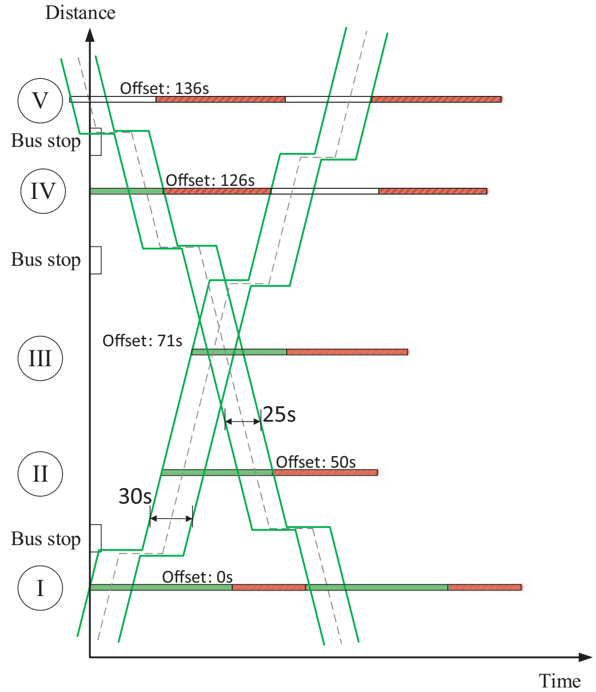
Experimental analysis

To evaluate the effectiveness of the bus progression model, this study conducts the comparisons for the following three models:

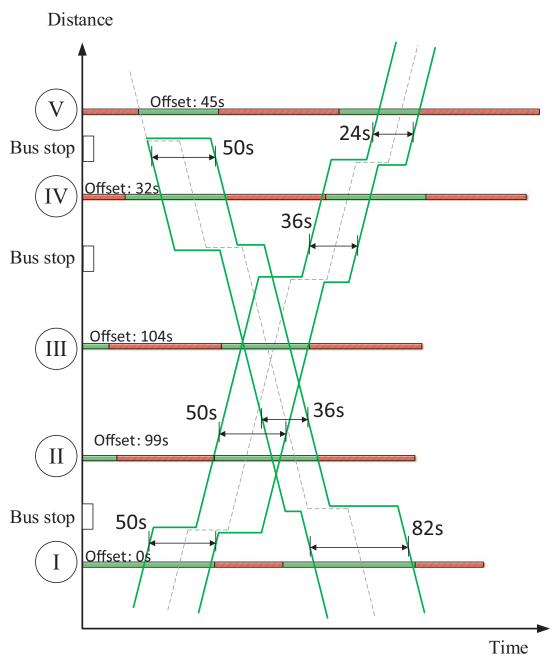
Model-1: MAXBAND model that only offers the green bands to passenger cars.
Model-2: a bus-based progression model that is a directly extension of MAXBAND by adding average bus dwell time to the link travel times (Lin et al., 2013).
Model-3: the proposed model for variable bus bands that accounts for both the bus dwell time uncertainties and the capacity constraints at bus stops.

By applying these three models to the target arterial segment, the resulting progression plans are presented in Figure 7. Also, note that the progression plan obtained from Model-1 is not shown here because buses cannot receive a non-zero green band in that case.

From Figure 7(A), one can observe that the bus bands at both the outbound and inbound directions remain unchanged along the five intersections. At each intersection, the green band is shifted to the right side for a short time, which represents the impact caused by the average bus dwell time. Also, the ratio between outbound and inbound bandwidth is close to that between their volumes, due to the directional factor in the model. Taking bus stops as control points to change the bandwidths, the proposed model generated a set of variable



(A) Model-2: bus-based progression model



(B) Model-3: the proposed model

Figure 7. Signal plans generated with different models.

bus bands. As shown in Figure 7(B), the green bands for buses have acceptable bandwidths in both directions. Though, the inbound band near intersection V has been reduced to zero due to the limited green time for buses at that intersection, some buses are still benefited from the available green bands to travel over the downstream intersections.

Simulation evaluation

Based on the comparisons, it is evident that the proposed model can clearly outperform the other two models in terms of providing effective green bands for bus flows. To further illustrate the applicability and efficiency of the proposed bus progression model, this study has employed VISSIM as an unbiased tool for performance evaluation. Recognizing that a simulated system is meaningful only if it can faithfully reflect actual traffic patterns, this study has performed the calibration by minimizing the difference between simulated and filed collected volumes during the two-hour simulation process. The calibrated parameters are summarized in Table 3.

Several measures of effectiveness are selected for model assessment: average bus delay, average number of stops per bus, average passenger car delay, and average person delay. Given the loading factors and vehicle flows for buses and passenger cars, the average person delay is computed using the following equation:

$$d_p = \frac{\rho_c \cdot q_c \cdot d_c + \rho_b \cdot q_b \cdot d_b}{\rho_c \cdot q_c + \rho_b \cdot q_b} \tag{20}$$

where d_p, d_c, and d_b denote the average person delay, average bus delay, average passenger car delay, respectively; ρ_c and ρ_b are the loading factors of passenger cars and buses; q_c and q_b are the flow rates of passenger cars and buses at the target arterial.

Based on the definition given in Eq. (20), Figure 8 presents the results from different models, including average bus delay, average number of stops per bus, average passenger car delay, and average person delay. Several key findings are summarized below

1. As shown in Figure 8(A), the two-bus progression models (i.e., Model-2 and Model-3) can offer some operational benefits to bus vehicles at the target arterial, evidenced by the reduction in average bus delay and number of stops. However, they can also cause an increase in the average passenger car delay (see Figure 8(C)).
2. The proposed model (Model-3) can outperform the Model-2 in terms of reducing the average bus delay (6.43%) and average person delay (3.43%) while does not significantly impact average passenger car delay. This is due to that Model-2 has ignored the stochastic nature of bus dwell time at bus stops, thus allowing only a small portion of its

Table 3. Calibrated VISSIM parameters.

Parameters	Value
Average stand still distance (Urban)	3.22 ft
Maximum deceleration (Lane change)	– 14.99 ft/s^2
Accepted deceleration (Lane change)	– 6.00 ft/s^2
Maximum deceleration for cooperative braking	– 14.99 ft/s^2

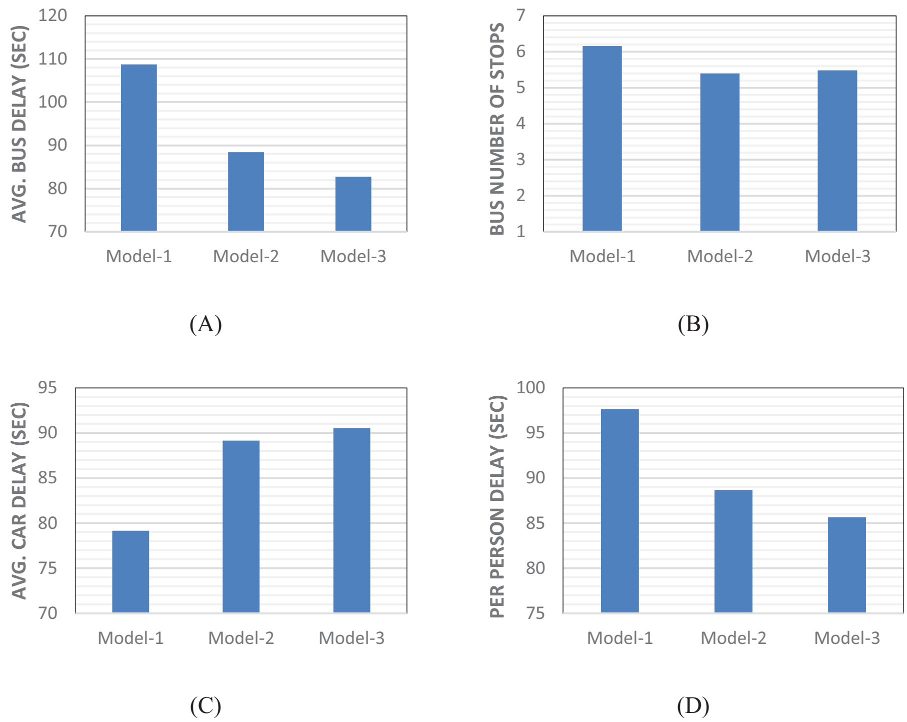


Figure 8. Performance comparison among three models.

band for bus progression. Also, further comparisons between Model-1 and Model-2 reveal that Model-2 results in a 12.65% higher average car delay, and an 18.72% reduction in the average bus delay.

3. Compared with Model-2, the proposed Model-3 can reduce the average bus delay by 6.43%. However, the increased average passenger car delay by Model-3 is not significant. Hence, passenger cars can still receive the operational benefit, under a bus progression system. This is due to the fact that the proposed bus progression model has produced a relatively large green band between bus stops, which can concurrently facilitate the passenger cars to pass intersections.

Note that the loading factor of passenger cars and buses are assumed to be 1.2 and 20 persons, respectively. And the results shown in Figure 8(D) reveal that the Model-3 can yield a 12.30% reduction in average person delay, compared to Model-1. However, based on its definition shown in Eq. (20), one can observe that the average person delay is sensitive to the ratio of the two loading factors. Now to test the benefits of Model-3 over Model-1 with respect to different values of the ratio (ρ_b/ρ_c), Figure 9 shows its reduction of average person delay under different scenarios. Based on the results, one can conclude that the target arterial can benefit from the proposed bus progression model in terms of reducing the of average person delay when the ratio (ρ_b/ρ_c) is larger than five.

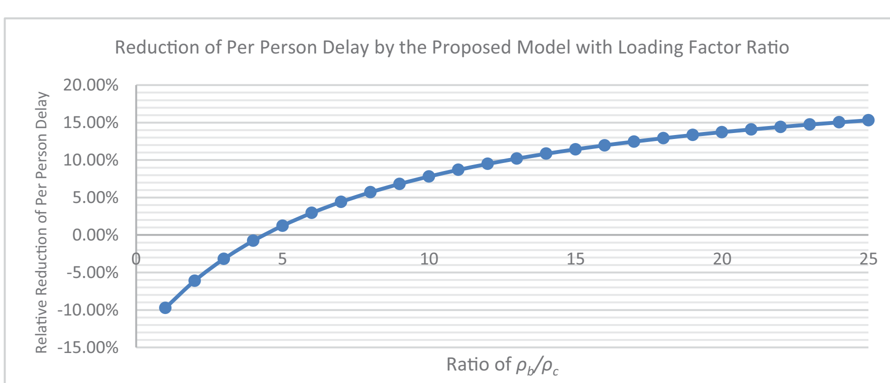


Figure 9. The reduction of average person delay by Model-3 compared to Model-1.

Table 4. The summary of model performance under different scenarios.

		Case (with different passenger car volumes, unit: veh/h)				
Performance index	Model	I:500/400	II:600/500	III:700/600	IV:800/700	V:900/800
Average bus delay (sec)	Model-1	109.761	108.775	110.641	111.968	110.389
	Model-2	87.078	88.412	90.59	89.458	97.208
	Model-3	80.261	82.725	84.422	87.31	95.375
Average car delay (sec)	Model-1	72.352	79.14	87.216	95.001	103.805
	Model-2	83.763	89.148	94.929	100.368	108.822
	Model-3	87.993	90.513	95.607	103.242	115.842
Average person delay (sec)	Model-1	97.4434	97.66188	100.9221	104.3329	107.2212
	Model-2	85.98648	88.688	92.21713	94.3675	102.7959
	Model-3	82.8069	85.6455	88.61638	94.4794	105.2223

Besides the loading rates, some other factors, such as the ratio of bus and passenger car volumes, will collectively impact the effectiveness of the proposed bus progression model. Hence, how to select the proper model for progression design under a given traffic conditions is a vital operational issue. To analyze the models' performance under different ratios of bus and car volumes, this study further investigates several cases by changing the passenger car volumes, and the corresponding results are summarized in Table 4. Values after the case numbers represent the passenger car volumes for the outbound/inbound direction.

The results in Table 4 show that the proposed model (Model-3) can clearly outperform the other two models in reducing average bus delay, but at the cost of average passenger car delays. In addition, the investigation of average person delay in each case reveals that Model-3, a bus-band based progression model, can reduce the average person delay at the target arterial. However, with the passenger car volumes evolving to the saturation level (e.g., in case IV), the benefits of Model-3 may be diminishing. Hence, one can conclude that the proposed bus progression model is applicable only when the passenger car volumes has not caused the traffic to a saturation level.

Sensitivity analysis

To accounts for the stochastic nature of bus dwell time, this study has introduced two control parameters, α and β, to represent the relations between bus bandwidths at the upstream and downstream of bus stops. To investigate the efficiency of the proposed model with respect to dwell time uncertainty, this section has performed a sensitivity analysis for different values of α and β. Two MOEs are selected for evaluation, i.e., the average bus delay and average number of stops for buses.

As shown in Figure 10, under different sets of parameters α and β, both average bus delay and average bus number of stops vary within a small range. This indicates that the model is quite robust when these two

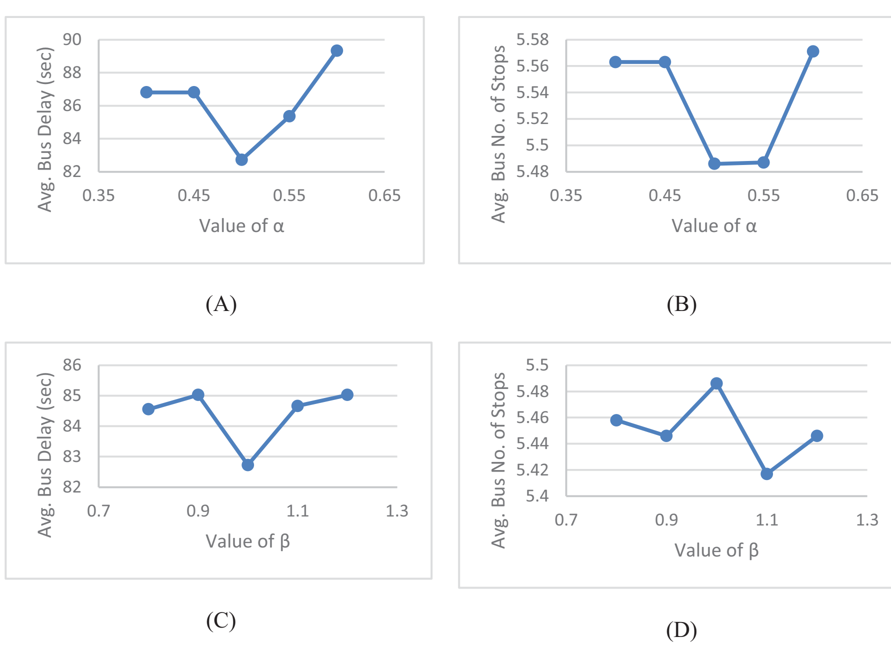


Figure 10. Sensitivity analysis of control parameters α and β.

parameters are changed within a certain range. However, no clear relations between the selected MOEs and the two parameters could be observed in this sensitivity analysis. Hence, how to select the optimal values of α and β so as to maximize the operational efficiency of the proposed bus progression model shall be another research subject.

Conclusions

The active TSP control may reach its limitation when the arterial needs to accommodate a large volume of transit vehicles. However, the passive strategy, if properly incorporated with bus flow properties, can be effective to improve the reliability of bus operations. To minimize the potential impacts on the side-street traffic flows, this study proposes a bus progression model to promote the efficiency of transit operations. Given the cycle length and green splits at each intersection, the bus-based progression model takes the bus stops as the control points and provide variable bus green band along the arterial. To deal with the stochastic nature of bus dwell time, this study has introduced two control parameters to capture the relations between the bus bandwidths at the upstream and downstream of bus stops. Taking an arterial with five intersections and three bus stops as an example, the study has employed VISSIM as an unbiased tool for model evaluation. The simulation results indicate that the proposed model can significantly reduce the bus passenger delay and average person delay of the entire network, compared to the conventional progression models. Notably, since this proposed method is focusing on producing the offsets for bus progression, it may inevitably impact the automobile flows. Therefore, the proposed model is more applicable for arterials with a relatively high bus volume.

Our further research directions includes: (1) exploring a stochastic analysis method to identify the optimal set of control parameters α and β so as to maximize the operational benefits of the proposed bus progression model, (2) developing a benefit-cost analysis tool to assist traffic engineers in making a decision between passenger-car-based and bus-based progression models, and (3) designing a user-friendly interface to facilitate the application of the proposed model.

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