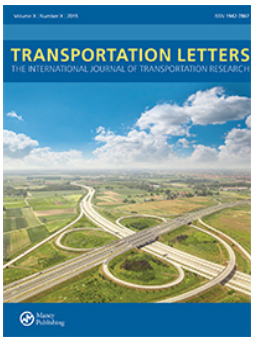

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Passive transit signal priority for high transit demand: model formulation and strategy selection

Yongjie Lin[a], Xianfeng Yang[b] and Nan Zou[c]

[a]School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, China; [b]Department of Civil, Construction and Environmental Engineering, San Diego State University, San Diego, CA, USA; [c]School of Control Science and Engineering, Shandong University, Jinan, China

ABSTRACT
With the increasing of transit vehicles in urban networks, traditional active transit signal priority (TSP) control may fall short of efficiency and bring negative impacts to non-priority approaches due to overusing priority grants. To reduce the frequency of activating TSP under high bus volumes, this study presents a new model, named INTEBAND, to facilitate the platooning of both passenger-cars and buses along arterials. The model integrates the conventional signal progression model with bus progression model to balance the travel delay of car-users and bus-passengers. Taking Jingshi road in Jinan for example, this study employs VISSIM for model evaluations. Further sensitivity analysis reveals that INTEBAND could clearly outperform the two conventional models in reducing network person delay when the ratio of bus-passengers and car-users exceeds a threshold of 1.5. Moreover, a multi-classifier model based on simulation results is to conveniently answer when INTEBAND can yield more benefit than conventional progression models.

KEYWORDS
Passive transit signal priority; BUSBAND; INTEBAND; model selection

Introduction

Over the past decades, Transit Signal Priority (TSP) control has been widely recognized as a promising method to improve regularity and punctuality of transit services. Active priority control, which is widely used at low bus flow intersections, could grant control priority based on the bus location, schedule adherence, and traffic conditions (Lin et al. 2014). Differing from unconditional active priority strategies (Yagar and Han 1994), some studies focused on implementing conditional ones to improve bus punctuality according to the target bus's performance with respect to its schedule (Hounsell et al. 2000, 2008; Ling and Shalaby 2004). Alternatively, other researches were conducted to minimize the total delay of detected buses (Head, Gettman, and Wei 2006; Ma, Yang, and Liu 2010; Ma et al. 2013). Along the same line, some researchers extended the objectives to reduce the total vehicle delay of buses and passenger cars (Mirchandani et al. 2001; Li et al. 2011). Chang, Vasudevan, and Su (1996), Christofa and Skabardonis (2011), and Wu et al. (2012) selected the total person delay of buses and passenger cars as the control objective to grant bus priority. Altun and Furth (2009) presented a conditional TSP control with bus-holding at stations to grant the priority to late buses, and Mirchandani, Li, and Hickman (2010) proposed a macroscopic model that integrates bus signal priority with bus rescheduling. Hounsell and Shrestha (2012) presented a new approach to grant a bus priority if its forward headway is longer than the backward headway. And then, we extended their logic to determine the optimal priority duration when the system receives multiple bus priority requests from different routes (Lin et al. 2013). Recently, Zeng et al. (2014) proposed a real-time TSP control at the isolated intersection with considering stochastic bus arrival time. He, Head, and Ding (2014) developed a new paradigm to simultaneously implement coordinated-actuated signal control and multi-modal priority control for handling multiple requests from priority eligible vehicles in Connected Vehicle Systems. Hu, Park, and Lee (2015) presented a person-delay-based optimization algorithm by splitting the green time of bus approach under the Connected Vehicle environment, and then extended it for multiple conflicting priority requests (Hu, Park, and Lee 2016).

Contrast to the active control aforementioned, passive TSP control does not explicitly recognize the real-time bus presence, but predetermine the signal plans based

CONTACT Xianfeng Yang xyang@mail.sdsu.edu

on the estimated number of cars and buses. For example, when bus headway is less than 1 min, the passive TSP with arterial coordination has been reported to outperform other strategies in London (Hounsell and Wu 1995). A typical passive TSP control includes shortening cycle length, splitting phase, area-wide signal timing plan, and metering vehicle (Urbanik, Holder, and Fitzgerald 1977). Garrow and Machemehl (1998) used TRAF-Netsim simulation to test extensively the effectiveness of shortening cycle length and splitting phase at an isolated intersection and an arterial, respectively. Their results showed that the former approach could improve the overall performance of the entire arterial with some impacts on general traffic, but the latter might provide much more efficiency and less impact to the isolated intersection. Both of methods, however, also inevitably increase lost time and shorten the green time for pedestrians. Skabardonis (2000) formulated the passive TSP by modifying the objective function of TRANSYT-7F to provide more green time for bus movements, in which bus delay and the number of bus stops are regarded as one part of the objective function. A similar method has also been implemented in Real-time, Hierarchical, Optimized, Distributed, and Effective System (RHODES) (Mirchandani et al. 2001). Following the similar logic, Ma and Yang (2007) presented a passive TSP control on a network signal design with considering the relationship of bus frequency, cycle length, and the number of signal phases.

In summary, active TSP control strategies are more applicable under low bus flow conditions. When the bus flow increases, an active TSP may need to be activated more frequently, which would inevitably increases person delay and reduces vehicle throughput on the non-priority approaches. Moreover, it may also deteriorate the arterial coordination plan since it will discharge other traffic into downstream intersections when granting priority to buses. Hence, a more practical control logic under such condition is to firstly design a passive signal coordination plan for the majority of bus vehicles, and then employ the active control to serve the remaining ones. If a passive plan is properly designed, it could significantly reduce the frequency of calling active TSP function so as to decrease the negative impact on crossing streets. Despite those well-recognized signal progression models, such as MAXBAND (Little, Kelson, and Gartner 1981), MULTIBAND (Gartner et al. 1991), and REALBAND (Dell'Olmo and Mirchandani 1995), have been widely implemented in practice, bus vehicles could not benefit from the preset car-preference band due to their dwelling time at bus stations. To this end, others researches were conducted to design green band based on bus trajectories, named BUSBAND, which considered bus dwell time and travel time between two adjacent intersections (Pangilinan and Carnarius 2011; Cheng, Yang, and Chang 2015; Dai, Wang, and Wang 2015). Their experimental results showed bus progression may reduce bus travel time. However, due to the different trajectory of cars and buses, such BUSBAND model may significantly increase the delay of passenger cars. Therefore, it is necessary to design a multi-modal model which can concurrently satisfy the progression need of both cars and buses.

In response to such a need, this study aims to design an integrated progression model which is capable of facilitating the movements of both buses and cars along the arterial. This paper is organized as follows: the next section reviewed the existing MULTIBAND and BUSBAND methods. Section 'INTEBAND control' presents the formulation of the integrated progression model. Section 'Model evaluation' demonstrates model application and evaluation on a field network. Section 'Control strategy selection' develops a simulation-based strategy choice model to select the best progression strategy, given network configuration and traffic pattern. Section 'Conclusions' summarizes the conclusions and future research directions.

BUSBAND control

As shown in Figure 1(A), MULTIBAND has been proved as one of the most efficient strategies for arterial signal coordination designs. Grounded on its core logic, a modified version, named BUSBAND, is developed to account for the bus dwell time. As shown in Figure 1(B), due to the bus stop ('S') between intersections i and $i+1$, buses have to dwell for a while before reaching the downstream signal, which can result in a shift of green band at the bus station location.

Similar to the MULTIBAND model, one can formulate the BUSBAND model with mixed-integer-linear programing technique and the corresponding constraints and objective function are introduced as follows.

Interference constraints

The interference constraints are to ensure that the computed progressive bands can fully use the available green time during each control cycle. As shown in Figure 1(B), one can obtain such constraints as follows:

$$0.5b_i^B \le w_i^B \le 1 - r_i - 0.5b_i^B \tag{1-a}$$

$$0.5b_i^B \le w_{i+1}^B \le 1 - r_{i+1} - 0.5b_i^B \tag{1-b}$$

$$0.5\bar{b}_i^B \le \bar{w}_i^B \le 1 - r_i - 0.5\bar{b}_i^B \tag{1-c}$$

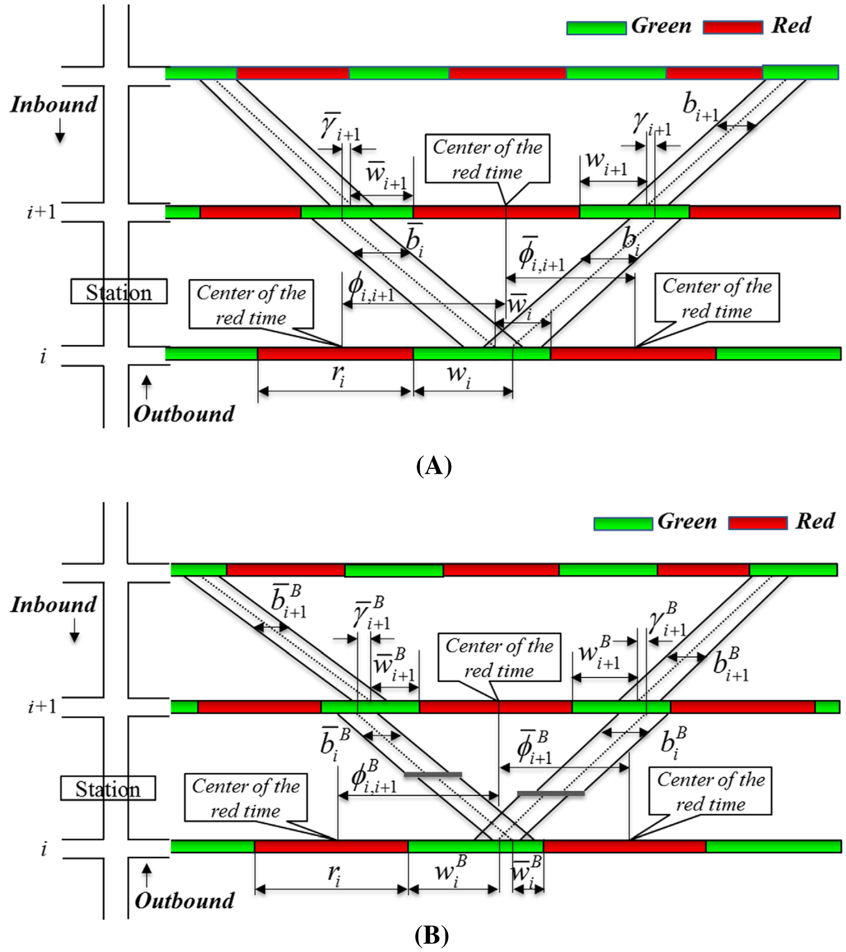

Figure 1. Time-space diagram for uniform bandwidth optimization. (A) MULTIBAND control, (B) BUSBAND control.

$$0.5\bar{b}_i^B \le \bar{w}_{i+1}^B \le 1 - r_{i+1} - 0.5\bar{b}_i^B \tag{1-d}$$

where b_i^B and $\bar{b}_i^B$ are the outbound and inbound bus bandwidth between intersection i and $i+1$ (cycles); w_i^B denotes the time duration from the left edge of the green signal to the center of the outbound green band, called shift time from green start to band center (cycles); $\bar{w}_i^B$ is the time duration from the center of the inbound green band to the right edge of the green signal (cycles); r_i represents the red duration at intersection i (cycles). Notably, all variables in this model are non-negative.

Loop integer constraints

Given the common signal cycle length, it is noticeable that the total bus travel time on a link with bus stations shall be the summation of link travel time and bus dwell time. Therefore, the internode offset between two adjacent intersections can be formulated as below:

$$\phi_{i,i+1}^B = \frac{r_i}{2} + w_i^B + t_{i,i+1}^B + dt_{i,i+1}^B - \gamma_{i+1}^B - w_{i+1}^B - \frac{r_{i+1}}{2} \tag{2-a}$$

$$\bar{\phi}_{i,i+1}^B = \frac{r_i}{2} + \bar{w}_i^B + \bar{t}_{i,i+1}^B + \bar{d}t_{i,i+1}^B - \bar{\gamma}_i^B - \bar{w}_{i+1}^B - \frac{r_{i+1}}{2} \tag{2-b}$$

where $\phi_{i,i+1}^B(\bar{\phi}_{i,i+1}^B)$ denote the duration from the center of the red phase at intersection i to the center of red phase at intersection $i+1$ for outbound (inbound) flows (cycles); $t_{i,i+1}^B$ ($\bar{t}_{i,i+1}^B$) are the bus running time from intersection i to $i+1$ in the outbound (inbound) direction (cycles); $dt_{i,i+1}^B$ ($\overline{dt}_{i,i+1}^B$) is bus dwell time which is estimated from historical data (cycles). When no bus station locates between two intersections, $dt_{i,i+1}^B$ and $\overline{dt}_{i,i+1}^B$ should be set to zero. γ_{i+1}^B ($\bar{\gamma}_i^B$) represents initial queue clearance time for bus vehicles in the outbound (inbound) direction (cycles). Also, based on the definition of the internode offset in Figure 1(B), one can express the loop integer constraint as follows:

$$m_{i,i+1}^B = \phi_{i,i+1}^B + \bar{\phi}_{i,i+1}^B \tag{3}$$

where $m_{i,i+1}^B$ is the corresponding integer variable (i.e. number of cycles).

Objective function

The BUSBAND model aims to maximize the total weighted bandwidth of bus flows at both directions, which has the following expression:

$$\max \sum_{i=1}^{N-1} (v_i^B b_i^B + \bar{v}_i^B \bar{b}_i^B) \tag{4}$$

where v_i^B and $\bar{v}_i^B$ are bus arrival rates at intersection i in the inbound and outbound direction, respectively.

INTEBAND control

Since BUSBAND is designed to facilitate the progression of buses only, it may not be able to benefit passenger vehicles that have shorter travel time than buses. Hence, such control may not be sufficiently effective unless bus volume is much higher than passenger cars. To overcome the limitation of BUSBAND, this study presents a new strategy, named INTEBAND, by integrating BUSBAND and MULTIBAND models to create a compromised progression plan. To do so, the offset of BUSBAND and MULTIBAND must be rigorously equal and the relationship of offset between two models can be formulated as follows:

$$\begin{aligned}\theta_{i,i+1} &= mod(w_i + t_{i,i+1} - w_{i+1} - \gamma_{i+1}) \\ &= mod(w_i^B + t_{i,i+1}^B + dt_{i,i+1}^B - w_{i+1}^B - \gamma_{i+1}^B)\end{aligned} \tag{5}$$

where $\theta_{i,i+1}$ represents the relative offset between intersection i and $i + 1$ (cycles); the function mod(•) denotes an non-linear operator used to take the decimal part of the number in the bracket; γ_{i+1} denotes initial queue clearance time for passenger cars in the outbound direction (cycles). To ensure the linearity of the optimization model, one can use a set of integer variables p_i to convert Equation (5) as below:

$$\begin{aligned}&(w_i + t_{i,i+1} - w_{i+1} - \gamma_{i+1}) \\ &- (w_i^B + t_{i,i+1}^B + dt_{i,i+1}^B - w_{i+1}^B - \gamma_{i+1}^B) = p_i\end{aligned} \tag{6}$$

where p_i is an integer variable which represents a number of signal cycles. By introducing Equation (6), the proposed model can guarantee that the offset difference between BUSBAND and MULTIBAND must be a certain times of cycle length.

The objective function of INTEBAND control is to maximize the weighted summation of passenger-car and bus bandwidths in terms of traffic volumes:

$$\max \sum_{i=1}^{N-1} [N_{car} v_i b_i + N_{car} \bar{v}_i \bar{b}_i + N_{bus} v_i^B b_i^B + N_{bus} \bar{v}_i^B \bar{b}_i^B] \tag{7}$$

where b_i and $\bar{b}_i$ represent the bandwidth of passenger-car bands in the inbound and outbound direction (cycles), respectively; N is the number of intersections; v_i and $\bar{v}_i$ denote the passenger-car arrival rates in the inbound and outbound direction, respectively; N_{car} and N_{bus} are the number of persons in passenger-cars and bus vehicles, respectively. Besides Equations (1–3) and Equation (6), other constraints of INTEBAND can be formulated as follows:

$$0.5b_i \le w_i \le 1 - r_i - 0.5b_i \tag{8-a}$$

$$0.5\bar{b}_i \le \bar{w}_i \le 1 - r_i - 0.5\bar{b}_i \tag{8-b}$$

$$0.5b_i \le w_{i+1} \le 1 - r_{i+1} - 0.5b_i \tag{8-c}$$

$$0.5\bar{b}_i \le \bar{w}_{i+1} \le 1 - r_{i+1} - 0.5\bar{b}_i \tag{8-d}$$

$$\begin{aligned}&r_i - r_{i+1} + w_i - w_{i+1} + \bar{w}_i - \bar{w}_{i+1} + t_{i,i+1} + \bar{t}_{i,i+1} - \gamma_{i+1} \\ &- \bar{\gamma}_i - m_{i,i+1} = 0\end{aligned} \tag{8-e}$$

where $m_{i,i+1}$ is the corresponding loop integer variable for MULTIBAND, as defined in Equation (3); $\bar{\gamma}_i$ denotes initial queue clearance time for passenger cars in inbound direction (cycles). Notably, the green split and signal cycle length are not optimized in the proposed INTEBAND model.

Model evaluation

Case study design

To illustrate the applicability and efficiency of the proposed models, this study employs VISSIM micro-traffic simulation model as the unbiased tool for model evaluations. Also, this study selects an arterial of Jingshi Road between Shanda Road and Shungeng Road in Jinan city, China as the field site for demonstrations. The simulation network in VISSIM has been calibrated based on the field collected data, including traffic volume, turning flow percentage, and average link travel speed. In addition, the baseline signal timings in the simulation network follows the observed field plans. Some other key network parameters are listed below:

- The target arterial is about 2.7 km with four-lane, two-way roadway of having one bus exclusive lane in each direction;
- There are six intersections and two bus stations along the arterial;
- Along the eastbound direction, the spacing between adjacent intersections are about 660, 420, 710, 530, and 420 m;

- N_{car} and N_{bus} are set to be 1 and 30 during peak hours, respectively;
- The passenger-car volume is set to be 2000 vehs/h at each direction, and bus volume is about 100 vehs/h;
- The bus dwell time follows a normal distribution of N(30, 9); and
- The simulation duration is set to be one hour and average over three replications with different random seeds.

To evaluate the overall control efficiency, the following performance indexes depending on the number of stops and average travel delay are selected as the MOEs:

$$PI^B = D^B + \lambda S^B \tag{9-a}$$

$$PI^C = D^C + \lambda S^C \tag{9-b}$$

$$PI = \frac{N_{car}v_{car}(D^C + \lambda S^C) + N_{bus}v_{bus}(D^B + \lambda S^B)}{N_{car}v_{car} + N_{bus}v_{bus}} \tag{9-c}$$

where PI^B and PI^C are the equivalent passenger-car user and bus passenger delay of the entire network (s); PI represents the comprehensive person delay of the entire network, including passenger-car users and bus passengers (s); D^C and D^B denote the average vehicle delay of cars and buses (s); S^C and S^B represent the average number of stops for cars and buses, respectively; λ is a weight factor, called stop penalty, and it is set to 4 (Huddart and Turner 1969). In this study, four types of signal progression strategies are tested for comparisons: MAXBAND (Little, Kelson, and Gartner 1981), MULTIBAND (Gartner et al. 1991), BUSBAND and the proposed INTEBAND. Those previous two ones are designed based on passenger-car trajectory. The simulation results under different controls are shown in Figure 2.

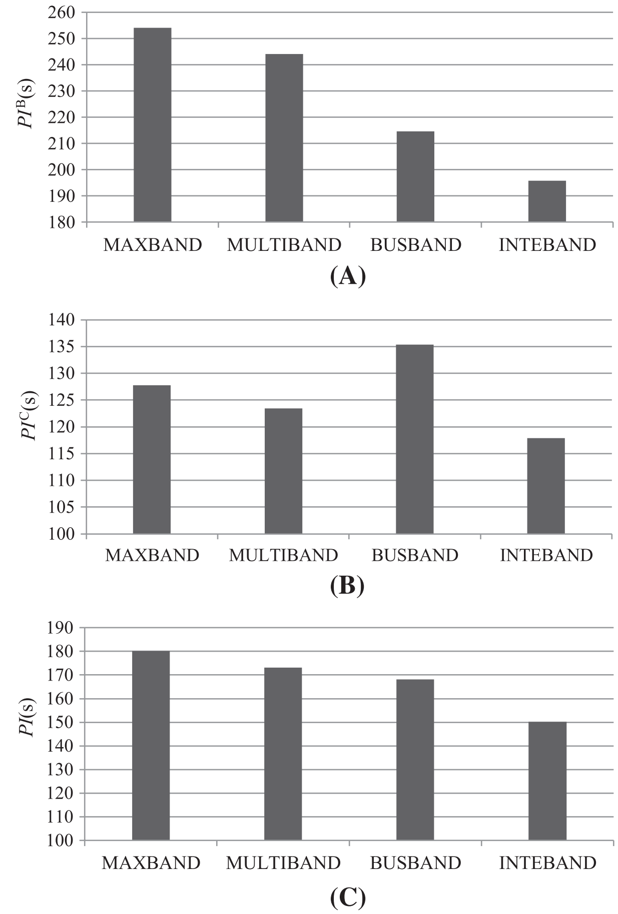

Figure 2. MOEs of the entire network under four controls. (A) Equivalent bus passenger delay, (B) Equivalent passenger-car user delay, (C) Equivalent comprehensive person delay.

According to the simulation results in Figure 2, it is noticeable that BUSBAND model can lead to the highest PI^C for passenger-car users. Compared with the MULTIBAND model, it has been increased by 12s/person in terms of PI^C. In contrast, the BUSBAND model can clearly outperform both MAXBAND and MULTIBAND model in terms of bus passenger delay reduction. Another interesting finding is that INTEBAND may even yield lower bus delay compared with BUSBAND. This is due to the fact that BUSBAND simply assume bus dwell time as a constant in its loop integer constraints. However, in this numerical example, the variation of dwell time cannot be fully accounted by that linear constraint and the BUSBAND model falls short of efficiency. Therefore, to further assess the performance of BUSBAND and INTEBAND in reducing bus passenger delays, a more comprehensive sensitivity analysis is required.

Compared with the other three models, the INTEBAND can yield the lowest network PI^B, PI^C, and PI. Despite MAXBAND and MULTIBAND are designed for passenger-car flows, the INTEBAND still produce lower car user's delay under this scenario. The main reason is that the fluctuation of vehicle speed on the link prevents some vehicles from catching the green band, and meanwhile the objective function of maximizing green bandwidth is not equivalent to the minimizing of total travel delay. Simulation results also indicate the initial queue in each cycle severely affected the benefits of MULTIBAND with the increasing traffic demand.

Based on these simulation experiments, one may observe a tradeoff of progression efficiency between passenger cars and buses, and those single mode control strategies, such as MULTIBAND or BUSBAND, may lead to a great delay increase to the other mode of vehicles. Among the tested four models, the INTEBAND model

Table 1. Demand patterns for sensitivity analysis.

Variables	Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5
Passenger-car demand per hour	2600	2600	2600	2000	1500
# of passenger-car users per hour ($N_{car}=1$)	2600	2600	2600	2000	1500
Bus volume per hour	60	75	100	100	100
# of bus passengers per hour ($N_{bus}=30$)	1800	2250	3000	3000	3000
Demand ratio between bus passengers and passen-ger-car users	0.7	0.875	1.15	1.5	2

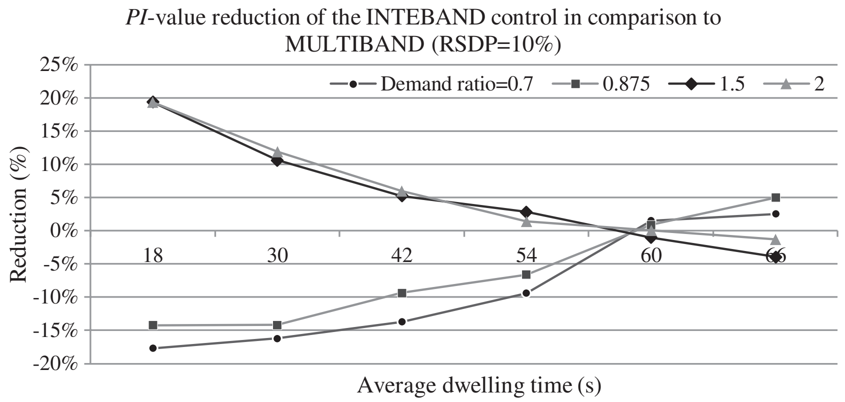

Figure 3. *PI*-value reduction of the INTEBAND control in comparison to MULTIBAND under various ADT.

can concurrently balance the benefits of buses and passenger-cars, and bring the best network performance.

Sensitivity analysis

Bus dwell time estimation is a complex problem which can be directly impacted by many operational factors at bus stations, such as station location, the number of bus stations, station type, station capacity, and passenger demands. Therefore, to explore the applicable conditions of the proposed INTEBAND, this study firstly performs sensitivity analysis with respect to four different key factors: average dwelling time (ADT), the relative standard deviation percentage of dwelling time which is equal to the ratio between standard deviation of dwelling time and the average dwelling time (RSDP), bus station coverage rate (BSCR), and demand ratio of bus passengers to passenger-car users (DR). Particularly, for convenience of discussion, this paper defines the bus station coverage rate as the ratio of the total length of links with bus stops to the target arterial length.

To further compare INTEBAND with MULTIBAND, this study defines the comprehensive person delay reduction percentage as follows:

$$R = \frac{PI_1 - PI_2}{PI_1} \times 100\% \tag{10}$$

where PI_1 and PI_2 denote the equivalent comprehensive person delay of MULTIBAND and INTEBAND in Equation (9-c). When the reduction is greater than zero, the INTEBAND can provide more benefit to all persons than MULTIBAND. The details of those tested demand patterns are listed in Table 1.

Bus dwell time

In INTEBAND model, bus dwell time can directly affect its operational effectiveness due to the different travel behaviors of buses and cars. As shown in Figure 1(B), one can observe that the coordination of buses and cars would be much more difficult with the increasing of bus dwell time. Figure 3 shows the corresponding sensitivity analysis by varying bus dwell time from 18 to 66 s under different bus demand levels. Some observations could be summarized as follows:

(1) Under the low bus demand condition (i.e. Demand ratio = 0.7 and 0.875), the MULTIBAND model can outperform INTEBAND in most cases since its signal offsets are set to benefit passenger-car users. However, the difference of

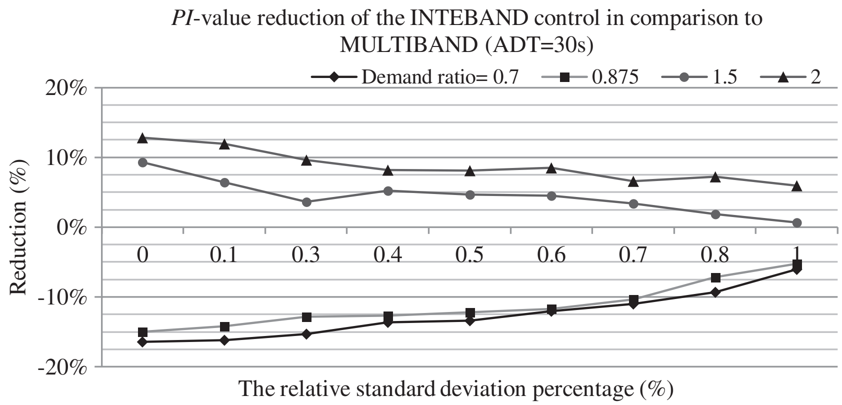

Figure 4. *PI*-value reduction of the INTEBAND control in comparison to MULTIBAND under various RSDP.

comprehensive person delay from MULTIBAND and INTEBAND is not significant when the bus dwell time closes to one minute.

(2) With the increasing of bus dwell time, the efficiency of INTEBAND is decreasing. This is due to the difficulty of satisfying the progression need of both buses and cars under such condition. Particularly, when the dwell time exceeds 60 s, the reduction in network person delay drops to negative.

To understand these interesting findings, this study further analyzed the simulation process and found out two reasons: (1) with low bus flows, no bus platoon can be formed on the arterial and the number of buses within the green band is relatively small, which can limit the efficiency of INTEBAND model; and (2) for those cases with longer dwell time, the progression of bus flows will become more difficult and consequently INTEBAND would generate similar offsets as MULTIBAND.

Standard deviation of bus dwell time

In both BUSBAND and INTEBAND models, the bus dwell time is assumed as a deterministic value, which cannot truly reflect the cases in practice. Therefore, the standard deviation of dwell time may also play as a key role in affecting progression models' efficiency. In this study, the relative standard deviation of dwell time is varying from 0 to 100% with various bus demand levels. Figure 4 shows the reduction of comprehensive person delay and it is obviously that INTEBAND can significantly decrease the network person delay if the passenger demand is high with the regardless of relative deviation of bus dwell time. On the other hand, the benefit of INTEBAND would be decreased with the increasing of dwelling time variance.

Bus stop coverage rate

Bus stop coverage rate defined in this paper is one of most important factors which requires further investigations. By testing the scenarios with average dwelling time of 30 s and standard deviation percentage of 10%, some key findings can be identified in Figure 5. Under the low bus stop coverage rate and bus demand, it is clear to observe that the person delay of INTEBAND is greatly larger than one of MULTIBAND. In addition, the benefit of INTEBAND is decreasing with the increasing of station coverage rate under high bus flow condition. The main reason is that bus bandwidth would be narrowed with higher station coverage rate. In particular, when the coverage rate is larger than 0.65, there is no obvious difference on network person delay for two kinds of models.

Control strategy selection

Data preparation

In the previous section, this study has presented a new passive TSP control to reduce the average person delay along the arterial. However, based on the sensitivity analysis, one can find that the INTEBAND control provides promising benefits for all road users under some specific scenarios (e.g. high bus demand, low mean, and standard deviation of bus dwelling time). Since it is difficult to quantitate the person delay of a signal-coordinated arterial before implementation of TSP plans, this study develops a simulated-based evaluation model as a convenient tool to help decision-makers make the selection between MULTIBAND and INTEBAND under given operational conditions. According to the sensitivity analysis, four decision variables, bus stop coverage rate, average dwelling time, relative standard deviation percentage, and ratio of bus passengers and passenger-car users, are selected as the inputs of the evaluation model. In particular, this study classifies all scenarios based on the following procedure:

Step 1: Generate 477 simulation scenarios on of the segment of Jingshi Road (between Shanda Road and Shungeng Road in the city of Jinan) with respect to previous four decision variables as follows:

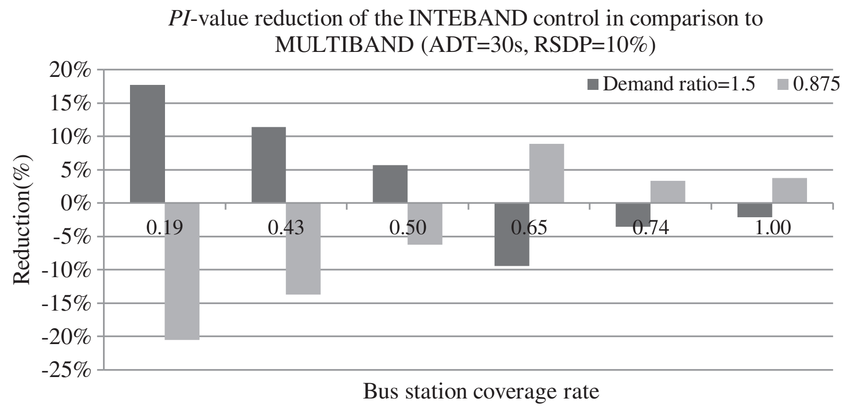

Figure 5. *PI*-value reduction of the INTEBAND control in comparison to MULTIBAND under various BSCR.

- Bus station coverage rate is set to be 0.19, 0.24, 0.26, 0.43, 0.5, 0.65, 0.74, 0.85, 0.985, and 1.0, respectively;
- Average bus dwell time ranges from 12 to 120 s by 6s step;
- Relative standard deviation percentage of dwell time ranges from 0 to 1 by 0.1 step, 1.1, 1.2, and 1.5; and
- Bus-to-car passenger demand ratio equals 0.7, 0.875, 1.15, 1.5, and 2, respectively.

Notably, there is a bus station between any two intersections along the simulated arterial. Therefore, the scenarios with different bus station coverage rate are built by selecting one or more bus stations based on the arterial.

Step 2: Based on designed signal timing plan using Webster's signal cycle formula, find the optimal offsets for each scenario using MULTIBAND and proposed INTEBAND models.

Step 3: Employ VISSIM to simulate each scenario with signal plans produced by MULTIBAND and INTEBAND. Then the simulation results can be obtained with virtual detectors configured in the VISSIM network and can be used to calculate the comprehensive person delay reduction using Equation (10). Also to overcome the stochastic nature of simulations, each scenario will be simulated for three replications with different random seeds.

Step 4: Categorize the simulated data-set into three groups according to delay reduction by Equation (10): INTEBAND preference, MULTIBAND preference, and either one. Using the simulated data-set, this study further developed a classifier based on the Support Vector Machine (SVM).

It is noticeable that the proposed selection model does not try to quantify the comprehensive person delay of INTEBAND control, but aims to classify all scenarios into three independent categories according to variable R in Equation (10). Each category defined below would indicates the prospective progression method in order to obtain the minimal person delay:

Class 1: MULTIBAND (MB) preference while $R < -\delta$, which means it is more suitable to employ the MULTIBAND model for designing signal progression;

Class 2: INTEBAND (IB) preference while $R \geq \delta$; and

Class 3: Either one while $R \in [-\delta, +\delta)$.

where δ is a user-defined threshold with the range from 0 to 1. Note that the last category means there is no significant difference between two models and either one can be selected.

Selection model development

Based on the aforementioned classification problem, this study employed SVM as the classifier to separate the entire scenario space into three groups in terms of four explanatory variables: ADT, RSDP, BSCR, and DR. Firstly, one should normalize these variables into a range from 0 to 1 below:

- BSCR: $x_1 = x_1$;
- ADT: $x_2 = x_2/120$ when assuming the maximum of bus dwell time is 2 min;
- RSDP: $x_3 = x_3/1.5$ when assuming the maximum of bus dwell time variance is 150%; and
- DR: $x_4 = (x_4 - 0.5)/2.5$ when assuming bus-to-car passenger demand ratio ranges from 0.5 to 3 because it should use MULTIBAND control on DR <0.5 and INTEBAND on DR >3.

In reviews of traditional classification analysis, SVM, one of supervised learning models with associated learning algorithms which analyze data and recognize patterns, can be one of the most robust and accurate classifier algorithms (Wu et al. 2008). In a typical two-class learning task, SVM could find the good classification function by maximizing the margin between the two classes. To introduce the binary SVM to the multi-class problem, some researchers proposed a series of algorithms, such as 'one-against-all,' 'one-against-one,' and directed acyclic graph

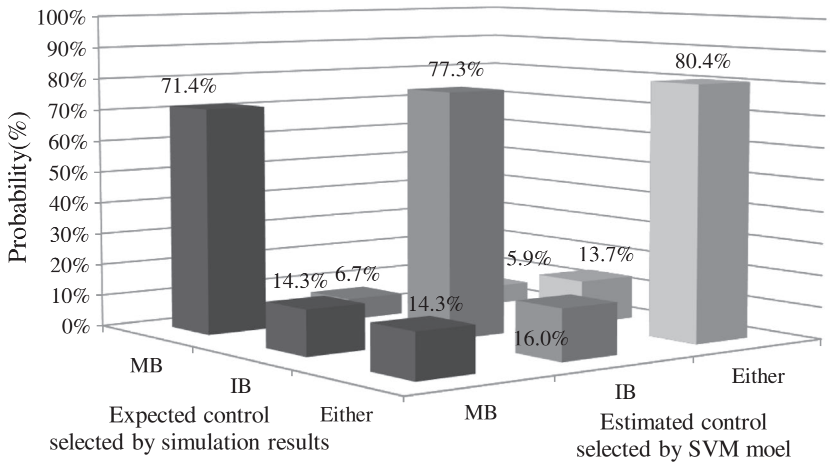

Figure 6. Classification accuracy of the SVM model with 2% threshold.

Table 2. Possible error type on SVM-based classifier.

Accuracy type	Possible groups (expected control to estimated one)	Probability with 2% threshold (%)
Rigorous accuracy	K1: INTEBAND to INTEBAND K2: MULTIBAND to MULTIBAND K3: Either to Either	77.6
Accuracy	K4: Either to INTEBAND K5: Either to MULTIBAND	6.8
Possible error	K6: INTEBAND to Either K7: MULTIBAND to Either	10.2
Rigorous error	K8: INTEBAND to MULTIBAND K9: MULTIBAND to INTEBAND	5.4

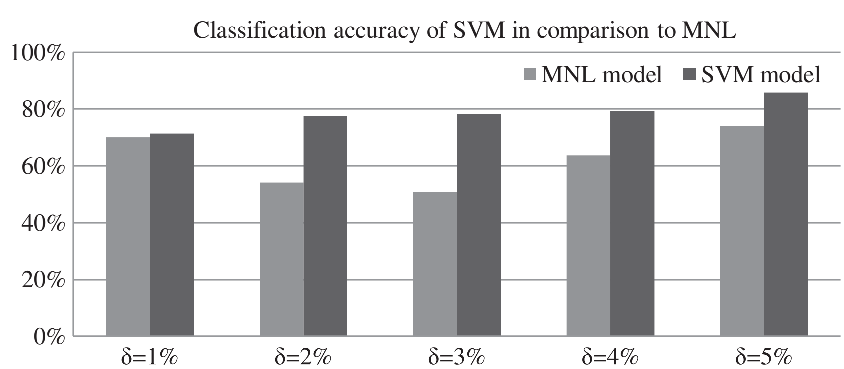

Figure 7. Classification accuary of SVM in comparison to MNL under various thresholds.

(DAG). Among, Hsu and Lin compared the performance with those three multi-class SVM methods (Hsu and Lin 2002). Their experiments revealed the 'one-against-one' and DAG methods are more suitable than others. Thus, this study employed SVM model with 'one-against-one' method to solve our three-class problem.

Model test

Based on the SVM with 'one-against-one' method, this paper employed 'e1071' package of R software to implement SVM-based classifier (Meyer 2006). For classification tasks, Meyer reported that it is good choice to use C-classification with the RBF kernel in R software because of its good general performance and the few number of parameters. Therefore, the C-classification with RBF kernel function is employed as basic parameters.

This study employed the data-set obtained by the simulated 477 scenarios on Jingshi Road to calibrate and test the proposed SVM model. About 75% of data-set is used for model parameter calibration. In addition, the scenario of $\delta = 2\%$ is selected for model evaluation. To quantitatively evaluate the performance of the proposed SVM classifier, this section defines the expected control method and the estimated one where the former is decided when it can yield more benefit than the other on comprehensive person delay reduction by δ or more. The latter is selected based on the output of the proposed SVM model under the given four decision variables. Therefore, the rigorous accuracy of the classifier means that the expected control method and the estimated one is the same.

Based on the aforementioned accuracy definition, the rigorous accuracy of individual classification for three groups in this section can reach to 71.4, 77.3, and 80.4% (see Figure 6), respectively. However, one should not arbitrarily regard some cases as classification error because there is no obvious difference in network person delay under expected and estimated signal control methods. Therefore, this study categorized the classifiable accuracy into four kinds in Table 2 to objectively evaluate the proposed classifier model. As shown in Table 2, the rigorous error is no more than 5.4% and one can conclude that the proposed SVM method can yield good fitness to classify the scenario data-sets into right categories.

To further validate the SVM-based model, this paper compared it with Multinomial Logit (MNL) model, a popular method in discrete choice model, under various threshold scenarios. This study employed R software to achieve baseline Category MNL classifier from Institute for Digital Research and Education, University of California. As shown in Figure 7, the SVM-based evaluation model can provide the promising classification accuracy than MNL. The maximum rigorous accuracy of SVM classifiers is up to 85.7% with 5% threshold, and the rigorous error is less than 2.6%.

Conclusions

Due to the fluctuation of bus dwell time at bus stations, conventional arterial coordination models often fail to offer efficiency controls to bus vehicles. To tackle this issue, this paper presented a new passive transit signal priority control by integrating the existing MULTIBAND and BUSBAND models for coordinating arterial traffic when bus flow is relatively high. The proposed INTEBAND model concurrently accounts for car users and bus passengers and aims to reduce the average person delay of the entire arterial. Using the field network from the city of Jinan, China, the sensitivity analysis based on VISSIM simulation tool has revealed that the proposed INTEBAND control can yield many benefits to bus passengers than car users when the ratio between bus passengers and car users is no less than 1.5, average dwell time is no greater than 42 s, and relative standard deviation of dwell time is less than 60% of the mean. Moreover, a SVM multi-classifier model based on simulation results of 477 scenarios is proposed to answer what condition is suitable for applying INTEBAND control. When INTEBAND is selected to deal with high bus volumes, it can help the control system to greatly reduce the frequency of calling active TSP which consequently decrease the negative impacts to other non-priority approaches.

Future research along this line will address the following four issues: (1) how to formulate the distribution of dwell time into the INTEBAND approach instead of using deterministic constraint; (2) how to conduct extensive experiments or field tests to validate the combination with INTEBAND and active TSP control under various geometry configurations and traffic demand patterns; (3) how to find a reasonable method to explain local optima of different scenarios to support field signal timing optimization; and (4) how to conduct comprehensive simulation tests and show the statistical difference of various models.

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No potential conflict of interest was reported by the authors.

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