Development and Evaluation of a Coordinated and Conditional Bus Priority Approach

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One problem in existing bus priority strategies is that while a decision is being made to grant priority at an intersection, the bus arrival time at the downstream intersections is not considered. Moreover, only strategies for late buses are discussed; the strategies for early buses are seldom studied. This research tests a different bus priority approach, coordinated and conditional bus priority (CCBP). Coordinated, signalized intersection groups are adopted as control objects. Buses are detected one or more cycles before their arrival at the first intersection of the control object. A CCBP, with two kinds of priority strategies (increasing and decreasing bus delay strategies), is proposed. A model was built to generate the optimal combination of priority strategies for intersection groups so that the real delay of buses would be close to the permitted delay defined by the bus operation system. In the field application, the CCBP approach is compared with other two options: no priority and unconditional priority. Significant reductions on bus delay deviation and bus headway deviation were achieved with the use of the CCBP approach. Application of the CCBP approach resulted in only minor increases in total average delay of motor vehicles. The results of the field application studies performed as part of this study suggested that the CCBP approach could be used to decrease bus delay deviation and enhance the reliability of bus service without significantly affecting the delay of other motor vehicles.

Since Wilbur Smith and Associates and the Bureau of Traffic Research, Los Angeles Department of Traffic, California, first conducted the earliest bus preemption experiments and indicated the significant effect of signal preemption on reduction of bus travel times (*1*), a handful of studies have proposed transit signal priority (TSP) strategies and documented the benefits of TSP implementation (*2–14*). These studies on signal priority strategies can be broadly divided into three categories: passive priority strategy; active priority strategy and real-time priority strategy; and various methodologies including experimental or field, simulation, or analysis methods.

Many traffic signal control systems have bus priority logic embedded in their software. Such systems provide signal priority at the local or the system level. The SCATS system (*15*) transit priority logic includes green extension, special phase sequences, and compensation to the nontransit phases. The SCOOT system (*16*) grants priority to buses (phase extension and recall) on the basis of user-specified intersection degree of saturation to avoid excessive delays to the rest of the traffic. Field evaluations in London showed bus delay savings ranging from 5 to 10 s per signal with no disadvantage to the rest of the traffic (*17*). The UTOPIA system in Turin, Italy (*18*), is an adaptive control system that provides absolute priority to transit by continually optimizing the signal settings over a short time interval (rolling horizon). Reported benefits include a 20% increase in the average bus speeds without disadvantages to the rest of the traffic.

Despite the promising progress reported in TSP studies, there still lacks a reliable optimal TSP model in the literature that is capable of capturing the critical operational issues of providing priority to priority requests. One problem with existing bus priority algorithms is that while making the decision to grant priority at an intersection, the bus arrival times at the downstream intersections are not considered (*19*). However, the coordination of priority strategies between sequential intersections is essential to ensure every priority decision is effective. For example, advancing the green time at the upstream signal may result in additional bus delay at downstream intersections, thus achieving no net delay benefit for the bus. Another problem with most current bus priority systems is that in most implementation and studies, only strategies for late buses are proposed, but strategies for early buses are neglected. However, early buses result in schedule deviations for themselves and other buses and may deteriorate the reliability of bus service. This kind of effect is more dramatically obvious in the situation of high bus-departure frequency. In most implementations, detection occurs no farther from the stopline than the closest upstream stop or signalized intersection. This short notice limits the degree to which the traffic signal can be adjusted to serve the coming transit vehicle, especially in view of the often long clearance times needed for pedestrian crossing, which is an important concern on transit arterials (*20, 21*). With such short notice, aggressive priority tactics can seriously disrupt other traffic (*22*).

Research by the authors tested the feasibility of a new control approach, coordinated and conditional bus priority (CCBP). A coordinated signalized intersection group is adopted as the control object of the bus priority control system. Buses are detected one or more cycles in advance of their arrival at the first intersection of the control object. A model was built to generate the optimal combination of priority strategies of the intersection group so that the real delay of buses would be very close to the delay defined by the bus operation system. The CCBP provides priority only to late or early buses and does not provide unconditional priority to any buses, as do most other research studies listed by Vasudevan and Chang (*23*).

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BASIC CONCEPT AND LOGIC

To avoid the limitations listed above, a new bus priority approach, CCBP, is proposed. The control object is a coordinated, signalized intersection group that includes several intersections and bus stops along an arterial. The control objective is minimizing the gap between estimated bus delay and permitted bus delay as defined by the user. It means that the real bus delay for passing the intersection group under the priority control plan should be close to the predefined bus delay.

In addition, the new bus priority approach

1. Provides priority without significantly affecting progression on the primary arterial street. The cycle length and offset are kept unchanging in the approach.
2. Provides priority without significantly altering the normal sequencing and duration of the noncoordinated phases. The approach can select the most appropriate priority strategy on the basis of predicted bus arrival time.
3. Provides priority only to the buses that are truly in need of priority on the basis of measurable bus operation system–defined criteria.
4. Provides priority at an intersection only when it is useful to minimize the total bus delay deviation at the coordinated signalized intersection groups.

Figure 1 illustrates the basic logic of the CCBP concept. The phase constraints, including phase duration, forced off time, and so on, are updated according to real-time traffic evaluation data such as queue length, delay, and saturation. They are used to keep the progression on the primary arterial, limit the use of aggressive priority strategies, and ensure the level of service of motor vehicles. The permitted bus delay at intersection groups is compared with the estimated bus delay to determine whether the bus needs to be given

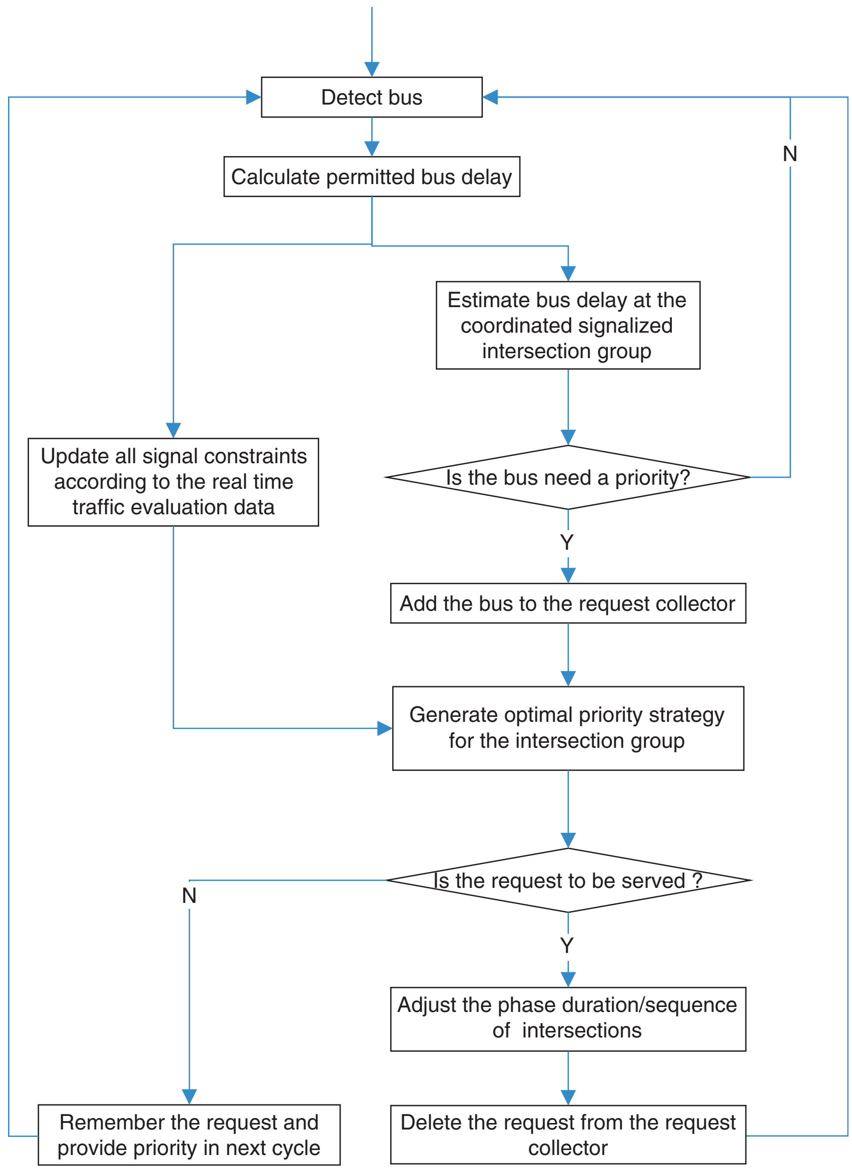

FIGURE 1 Basic logic of CCBP concept.

priority. If the estimated total bus delay exceeds the permitted bus delay by a user-defined amount, the bus is considered to be late or early and is granted priority treatment at the intersection. If, however, the estimated total bus delay does not exceed the permitted bus delay by a user-defined amount, the bus is not granted priority. If the request cannot be served in the bus arrival cycle, it would be remembered and considered in the next cycle.

APPROACH ARCHITECTURE

Module architecture was used to develop and implement the CCBP approach. The following four primary modules were developed on the basis of the functional requirements of the CCBP approach:

1. A bus delay prediction module that can predict bus delay under the control of a primary signal plan;
2. A priority request generation model that decides whether the bus needs to be given priority;
3. Bus signal priority strategies and a relative bus delay calculation model in which the above-mentioned two kinds of strategies are introduced, and bus delay under a different priority control is calculated; and
4. A priority strategies combination and optimization model in which the optimal priority strategy for the intersection groups is generated.

Notation

To facilitate the following illustration, all definitions and notation used are summarized below:

D_{stop} = total bus delays at bus stops,
D_{inter} = bus delay at intersection,
D_b = total bus delay,
D_{bi} = bus delay at intersection i,
I = index of each intersection and link,
v_i = bus speed at link i,
N = total number of intersections of the coordinated intersection groups,
C = common cycle length,
M_i = phase number of the ith intersection,
g_{ij} = jth phase length of the ith intersection,
I_{ij} = green interval of jth phase to next phase,
O_i = offset between $i-1$th intersection and ith intersection,
L_i = length of ith link, between $i-1$th intersection and ith intersection (L_1 represents the distance from the coordinating detector to the first intersection of the group),
K_i = signal time when bus arrival at intersection i,
t_{li} = time needed for bus traveling at link i,
t_i = time needed for bus travel from detector to downstream intersection stopline,
D_{bp} = total delay deviation of previous intersection groups,
D_{bs} = permitted bus delay at current intersection groups,
$D_{b\text{range}}$ = user-defined threshold for determining whether a bus needs priority,
g_{ge} = maximum green extension time,
g_{rt} = maximum red truncation time,
g_{in} = length of insertion phase,
t_{ba} = bus arrival time for a given intersection,
t_{in} = starting time of the insertion phase (s),
t_{rt} = red truncation starting time (s),
g_{ip} = time needed to provide priority for a bus priority request in a cycle at ith intersection,
g_i = length of bus green time of intersection i,
g_{ij}^p = jth phase length after bus priority of ith intersection,
x_{ij} = saturation of jth phase of ith intersection,
g_{gt} = maximum time of green truncation,
g_{re} = maximum time of red extension,
$g_{ij\,\min}$ = minimum green of jth phase of i intersection, and
$g_{ij\,\max}$ = maximum green of jth phase of i intersection.

Bus Delay Prediction Model

Bus delay includes two parts: delay at bus stop (D_{stop}) and delay at intersection (D_{inter}). D_{stop} is decided by multiple factors including dwell time, deceleration and acceleration times, and so on (*24*). In this study, to simplify the problem, five assumptions are made:

1. There is an exclusive bus lane;
2. The signal status of every intersection when the bus is detected is known;
3. Bus delay at each bus stop, d_{stop}, is a constant;
4. Bus speed at *ith* link, v_i, is a constant; and
5. No queue exists at the bus approach and the acceleration and deceleration delays are neglected.

The "constant bus delay at bus stop" and "no queue at bus approach" assumptions might be reasonable for exclusive bus lane operation. They should be modified if the CCBP strategy is applied to regular bus operation in mixed traffic.

According to the fifth assumption, bus delay at intersection is equal to the rest red signal when the bus arrives at the stopline. So the calculation of bus delay at intersections can be divided into two steps: the first step is bus arrival-time prediction, and the second step is calculation of the rest red signal at the time of bus arrival at the stopline. Then t_{li} can be calculated as

$$t_{li} = \frac{L_i}{v_i} \qquad i = 1, 2, \ldots, N \tag{1}$$

t_{si} is defined as a binary variable, that is,

$$t_{si} = \begin{cases} d_{\text{stop}} & \text{one bus stop at } i\text{th link} \\ 0 & \text{no bus stop at } i\text{th link} \end{cases}$$

If there are multiple bus stops, d_{stop} should be the sum of total stop delays.

The time needed for bus travel from detector to the downstream intersection stopline is

$$t_1 = t_{s1} + t_{l1} \tag{2}$$

The signal status when the bus arrives at the stopline of the first intersection, K_1, is the arithmetical complement of $(K_0 + t_1)$ divided by C. It can be calculated as follows:

$$K_1 = (K_0 + t_1)\,\text{mod}(C) \tag{3}$$

Then t_i and K_i can be calculated as follows:

$$t_i = t_{si} + t_{li}$$

and

$$K_i = \left(K_{i-1} - O_i + t_i + d_{bi-1}\right)\mathrm{mod}\left(C\right) \qquad I = 2, 3, 4, \ldots, N \tag{4}$$

According to the definition of K_i, if it is less than g_i, the bus delay is zero; otherwise, the bus delay is equal to the rest of the red time.

$$d_{bi}^{b} = \begin{cases} 0 & 0 < K_i \le g_{i,1} \\ C - K_i & g_{i,1} < K_i \le C \end{cases} \tag{5}$$

The total bus delay can be calculated as

$$D_b = \sum_{i=1}^{N} d_{bi}^{b} + \sum_{i=0}^{N} d_{si} \tag{6}$$

Priority Request Generation Model

Regardless of the criteria used to determine whether a bus needs priority, a priority algorithm needs to be smart enough to assess approaching buses and grant priority only to those buses that meet the established criteria. For the purposes of developing and testing the approach, delay adherence was defined as a state in which the bus delay is within a specified variance from its permitted delay at a coordinated signalized intersection group. The estimated total bus delay at the intersection group is compared to the permitted bus delay defined by the bus operation system to determine whether the scheduled bus is delayed and by how much time. If the estimated total bus delay exceeds the scheduled total bus delay by a user-defined amount, the bus is considered as late or early and is granted priority treatment at the intersection. If, however, the estimated total bus delay does not exceed the scheduled delay by a user-defined amount, then the bus is not granted priority. It is reasonable that all bus delay deviations of previous intersection groups be considered in the process of making a priority decision. Thus, P_{decision} is defined as binary variable 1 (give priority to the bus) or 0 (do not give priority to the bus), and it can be calculated by the following equation:

$$P_{\text{decision}} = \begin{cases} 0 & \left|D_b + D_{bp} - D_{bs}\right| \le D_{\text{brange}} \\ 1 & \left|D_b + D_{bp} - D_{bs}\right| > D_{\text{brange}} \end{cases} \tag{7}$$

Bus Signal Priority Strategies and Relative Bus Delay Calculation Model

Two kinds of priority strategies are proposed. One is used to decrease bus delay, and the other is used to increase bus delay at the intersection. If $D_b + D_{bp} - D_{bs} > D_{\text{brange}}$, the bus is late, and decreasing bus delay strategies should be adopted. If $D_b + D_{bp} - D_{bs} < -D_{\text{brange}}$, the bus is early, and increasing bus delay strategies should be adopted.

Decreasing Bus Delay Strategies

Three methods—green extension, phase insertion, and red truncation—are proposed as shown in Figure 2*a*. Different priority methods educe different bus delays.

Delay of Green Extension d_{ge} For a given intersection *i,* only if $g_i < t_{ba} \le g_{ge} + g_i$ can green extension be selected. After a successful green extension, the bus can pass the stopline at the green signal, which means $d_{ge} = 0$.

Delay of Phase Insertion d_{in} For a given intersection *i,* if $g_i < t_{ba} \le g_{ip} + \sum_{j=1}^{p-1} g_{ij} + I_{ij}$, then phase insertion can be selected. A special bus phase can be inserted after phase p or between the rest phases as shown in Figure 2. If the bus arrives at the stopline after the insertion phase has started, then the bus delay is 0 s; if the bus arrives at the stopline before the insertion phase begins, then the bus delay can be calculated as

$$d_{in} = t_{in} - t_{ba}$$

There are several time windows between different phases when a bus phase can be inserted, as shown in Figure 2. The most appropriate insertion time should be decided by the model built in the next part.

Delay of Red Truncation d_{rt} For a given intersection *i,* if $g_i < t_{ba} < C$, red truncation can be selected. As with the phase-insertion method, if the bus arrives after the red truncation time, the bus delay is 0 s; if the bus arrives at the stopline before the red truncation time, the bus delay can be calculated as

$$d_{re} = t_{rt} - t_{ba}$$

Increasing Bus Delay Strategies

The increasing bus delay strategies should be adopted when buses are early. Two methods—green truncation and red extension—are proposed as shown in Figure 2*b.*

Delay of Green Truncation d_{gt} For a given intersection *i,* only if $g_i - g_{gt} < t_{ba} \le g_i$ can green truncation be selected. After green truncation, the bus delay is increased from a negative to a positive number.

$$d_{gt} = C - t_{ba}$$

Delay of Red Extension d_{re} For a given intersection *i*, if $g_i < t_{ba} \le C$, then red extension can be selected, and the bus delay is updated as

$$d_{re} = C - t_{ba} + g_{re}$$

Allocation of Priority Time

The value g_{ip} is equal to one of g_{ge}, g_{rt}, g_{in}, g_{gt} and g_{re} of *i*th intersection in value. This value may be positive (increase bus delay strategies) or negative (decrease bus delay strategies). It is obvious that other phases should be compressed (negative) or extended (plus) to provide g_{ip}. The compress or extend time of each phase is weighted by saturation as follows:

$$g_{ij}^{p} = g_{ij} + \frac{x_{ij}}{\sum_{j=2}^{M_i} x_{ij}} g_{ip} \qquad g_{ip} > 0;\ i = 1, 2, \ldots, N;\ \text{and } j = 2, 3, \ldots, M_i \tag{8}$$

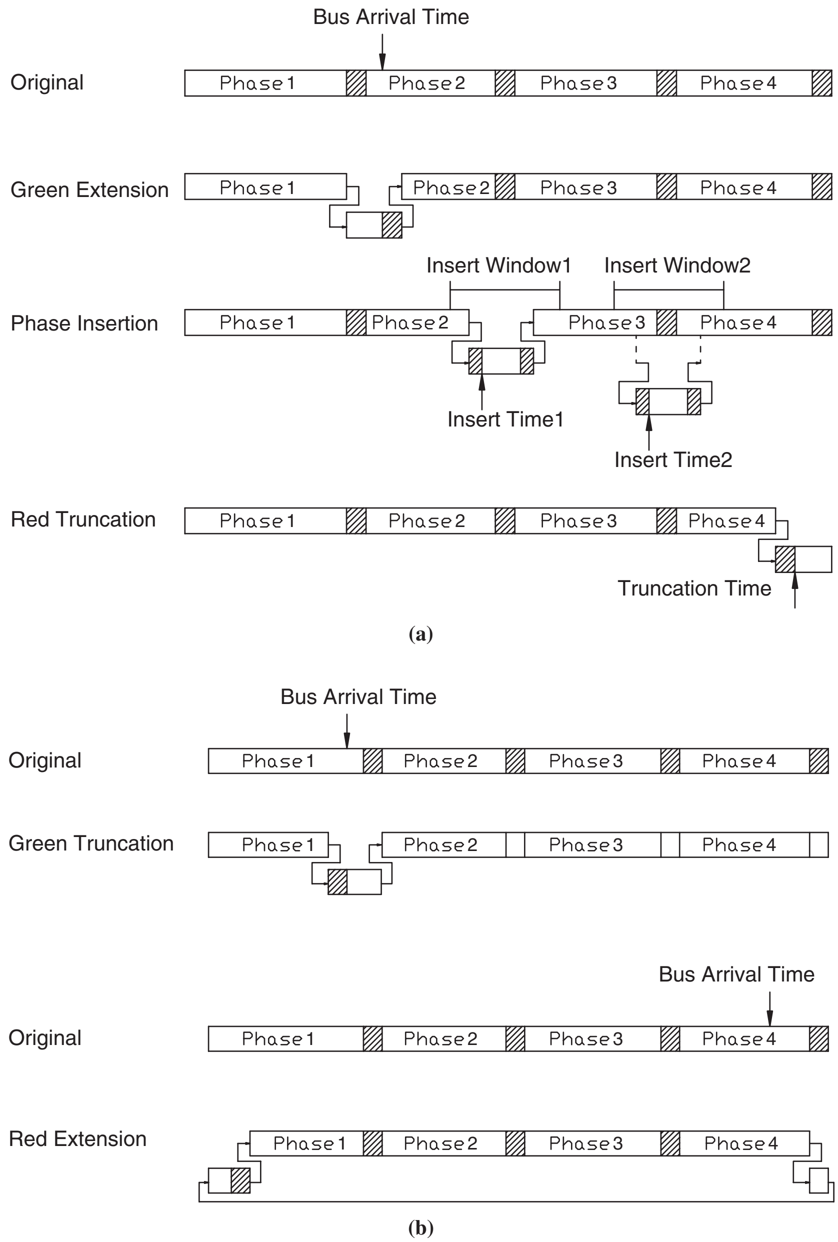

FIGURE 2 Bus signal priority strategies showing (*a*) decreasing and (*b*) increasing bus delay strategies.

$$g_{ij}^{p} = g_{ij} + \frac{\dfrac{1}{x_{ij}}}{\displaystyle\sum_{j=2}^{M_i} \frac{1}{x_{ij}}} g_{ip} \qquad g_{ip} < 0; i = 1, 2, \ldots, N; \text{and } j = 2, 3, \ldots, M_i \tag{9}$$

Priority Strategies Combination and Optimization Model

Priority Strategy Combination Analysis

The contribution of priority strategies of one intersection to the objective (minimizing delay deviation) is relevant with the priority strategies at other intersections as shown in Figure 3. Three trajectories of a bus are depicted, and the corresponding priority strategies at every intersection are listed as follows:

Trajectory 1: green extension + phase insertion + no priority,
Trajectory 2: phase insertion + red truncation + no priority, and
Trajectory 3: no priority + priority + no priority.

The three trajectories have the same total bus delay of 68 s. Compared with Trajectory 3, the bus priority strategies at the other trajectories are wasted. Because the bus has to stop at the intersections downstream, the bus delay is the same as in the case of no priority. Therefore, the signal settings at the adjacent intersections should be adjusted to take the priority effects into account.

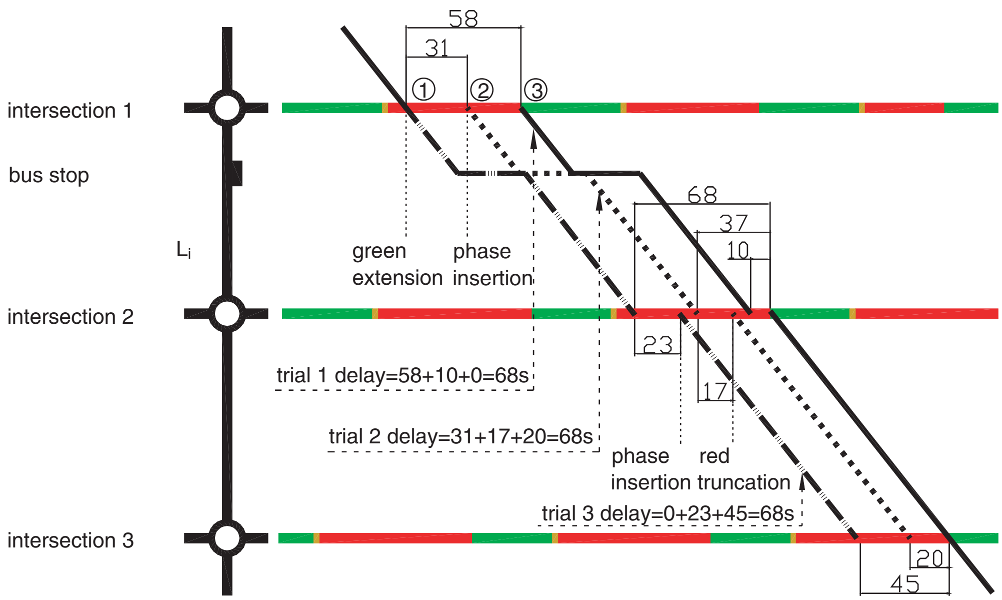

FIGURE 3 Bus trajectories.

Optimal Coordination Priority Model

On the basis of the analysis above, the optimal combination of priority strategies for a coordinated signalized intersection group can be presented as a mathematical programming formulation as

minimize $D_b^p + D_{bp} - D_{bs}$
(minimize total bus delay deviation)
subject to priority strategies selection constraints, cycle length constraint, and phase duration constraints

The priority strategies selection constraints have been introduced before. There is a new constraint to limit the strategies selection under the situation of a multipriority request: only one phase insertion strategy can be adopted in one cycle. At most two of all priority methods can be adopted simultaneously in one cycle.

The cycle length constraint is used to keep the signal progression of the intersection group. It is a simple equation constraint, and for a given intersection *i,* it can be shown as follows:

$$\sum_{j=1}^{M_i^p} g_{ij}^p + I_{ij}^p = C \qquad (10)$$

The phase duration constraint is used to ensure pedestrian safety and maintain the level of service for other motor vehicles. It would be reasonable to assume that the traffic engineer can set the initial minimum and maximum green times. For a given intersection *i,* the following equation constraint should be satisfied:

$$g_{ij\min} \le g_{ij}^p \le g_{ij\max} \qquad (11)$$

To avoid the occurrence of oversaturation of some phases, the minimum green phase can be updated according to real-time queue length. It is assumed that the primary coordinated signal plan is the optimal one for motor vehicle movements and that the queue length can be estimated. If the queue length of the *j*th phase is larger than the given maximum queue length, the minimum green time of the *j*th phase is set as the length of the phase. It means that this phase cannot be compressed.

Solution of the Model

Many algorithms can be used to solve the problem. The authors adopted an enumerate algorithm for the present research. The steps are as follows:

Step 1. Initial the range of permitted bus delays of all intersections according to the total permitted bus delay.
Step 2. Set a permitted delay value to every intersection; the sum of those permitted delays is the total permitted bus delay.
Step 3. Find the optimal strategy for the first intersection so that its bus delay is closest to the permitted delay of the intersection.
Step 4. Update the arrival time K_2 according to the delay of the first intersection and find the optimal strategy for the second intersection. Repeat this process to find the optimal strategy for all intersections.
Step 5. Calculate total bus delay and get the total bus delay deviation. Return to Step 2 and repeat the steps for all situations.
Step 6. Find the minimum bus delay deviation situations and record the corresponding priority strategies. The optimal solution set is formed.
Step 7. Select the optimal solution, that is, the one that has the fewest adverse effects on other traffic, as the final solution.

EVALUATION AND ANALYSIS

One of the most important coordinated signalized intersection groups, the Beiyuan Road, Wuyingshan, intersection group, is selected to test this CCBP concept. This group includes three intersections and six bus stops (both directions). Beiyuan Road is an arterial and a major bus corridor of Ji'nan City, Shandong province, China. A bus rapid transit exclusive lane is separated in the middle of the Beiyuan

Road. The bus rapid transit line is the backbone of the north area bus network of Ji'nan, providing service along the east–west length of Ji'nan City.

The trial is composed of three subtrials: no priority, unconditional priority, and CCBP. The length of the average trial is 2 h; each trial is held during the same 2-h period on 3 days. The traffic volume shown in Figure 4 is the average volume of the 6 h (they are nearly equal). All the bus stops are located 40 m upstream or downstream of the stop line on the Beiyuan Road on the middle approach to the intersection. In the trial, vehicle detectors were not laid out. This means that the update of minimum phase green is not implemented in the trial, and the signal is only changed in response to the priority requests of buses. However, field observations show that the length of queues of motor vehicles is acceptable. All buses are detected 2 km away from the stopline of the first intersection of the intersection groups. Signal timing data are shown in Table 1. At all subtrials, delay of buses and vehicles is on-street observed.

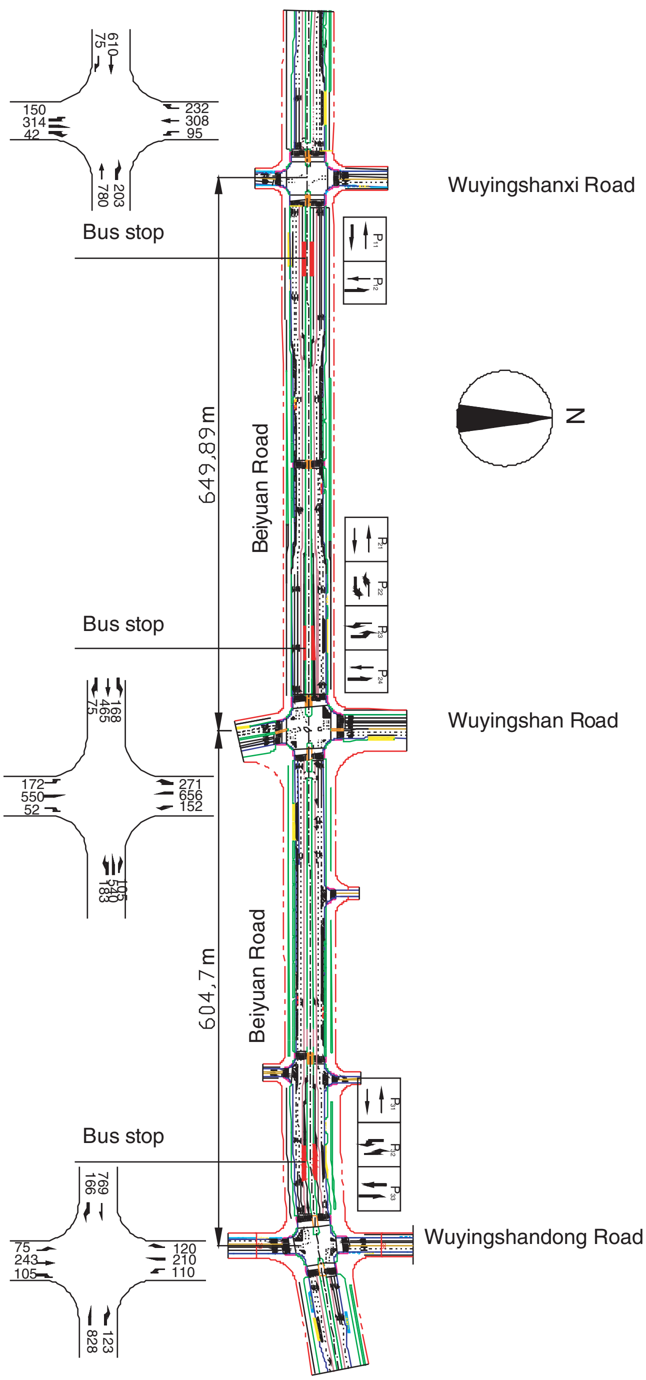

FIGURE 4 Layout of Wuyingshan Road intersection groups, Ji'nan City.

Three priority options were tested. In the first, no priority for transit, each intersection is fixed-time controlled and coordinated. The cycle length is 100 s. Because the no-priority option serves as a base case, a fair evaluation of the priority strategy demands a well formulated no-priority option. The base option performed well, with average total delay of coordinated phase per vehicle of only 19.3 s. In the second option, unconditional priority, the permitted bus delay is 0. This means that all buses generate priority requests; the increasing bus delay strategies of CCBP do not apply, and the priority strategies are coordinated. The third option is the CCBP approach proposed in this paper. For testing purposes, the permitted bus delay of this intersection is set at 20 s (except the average delay at every bus stop, 35 s), and D_{brange}, the threshold, is 5 s for determining whether a bus needs priority. The bus departure frequency is 120 s. Data for 117 buses (2 h, both directions) were collected and analyzed.

Figure 5*a* shows the effect of different priority approaches on average bus delay. Significant reduction in bus travel time is achieved by using the CCBP approach to provide priority treatment to buses. Compared with the no-priority situation, the average bus delay of the unconditional priority and CCBP situations is reduced by 38.9% and 34.7% per bus, respectively. The average bus delay of the unconditional priority situation is slightly lower than that of CCBP (by 6.4%). This is reasonable because the objective of CCBP is keeping bus delay around 20 s, while the objective of unconditional priority is minimizing bus delay.

Figure 5*b* shows the effects of the different priority approaches on motor vehicle delays. Compared with the no-priority situation, the CCBP approach produced a slight reduction in delay of the motor vehicles of priority phases of 7.3% (1.4 s), while the delay of motor vehicles in nonpriority phases increased by 12.4% (3.7 s). The CCBP also produced a slight increase in the total average delay of motor vehicles (delay of priority and nonpriority phases is weighted by respective traffic volume) of 8.8% (2.4 s). Compared with unconditional priority, CCBP increases delay of priority phases by 8.5% (1.4 s) and decreases delay of nonpriority phases by 4.8% (1.7 s). The increasing bus delay strategies of CCBP are the main reason for this phenomenon because they compress bus green and allocated it to nonpriority phases under the condition of bus delay lower than 20 s by 5 s. Increasing bus delay strategies provide priority to early buses and compensate nonpriority phases at the same time.

The effects of priority on delay deviation are shown in Figure 6. Without priority, bus delay fluctuates dramatically and ranges from 0 to 120.7 s. The variance is 1,129.15. With unconditional priority, bus delay ranges from 0 to 110 s. The variance is 833.1. With CCBP, bus delay ranges from 8 to 75 s. The variance is 274.7. It is obvious that the CCBP approach has significantly reduced the fluctuation of bus delay. Compared with no priority, CCBP decreases bus delay variance by 77.7%; unconditional priority slightly decreases the variance by 32.4%. For CCBP, 98 buses generate priority request (primary bus delay larger than 25 s or less than 15 s) and 81 buses (82.7%) are served. For unconditional priority, a total of 117 buses generate priority requests and 85 buses (72.6%) are served. The number of buses served is nearly equal, while the served–not served

TABLE 1 Signal Timing Data

Phase Sequence	Minimum Green (s)	Green Interval (s)	Intergreen (s)	g_{ge} (s)	g_{in} (s)	g_{rt} (s)	g_{gt} (s)	g_{re} (s)
11	15	4		5	5	5	5	5
12	15	4		5	5	5	5	5
—	—	—						
—	—	—						
21	20		4	5	5	5	5	5
22	15		4	5	5	5	5	5
23	20		4	5	5	5	5	5
24	15		4	5	5	5	5	5
31	15	4	—	5	5	5	5	5
32	15	4	—	5	5	5	5	5
33	15	4	—	5	5	5	5	5

ratio of CCBP is higher than that of unconditional priority. The main reason is that only two strategies can be used in (at most) one cycle. This constraint is useful to avoid dramatically worsening the level of service of motor vehicle movements. However, it limits the priority service times in one cycle to two times at most. With this constraint, unconditional priority does not give priority to the "real need" buses because the priority has been given to "no need" buses. The results of this constraint also indicate why the delay fluctuation range and delay variance are also very large under the unconditional priority control. Figures 5 and 6 jointly validate that the CCBP approach is able to produce substantial reductions in bus delay and bus delay deviation.

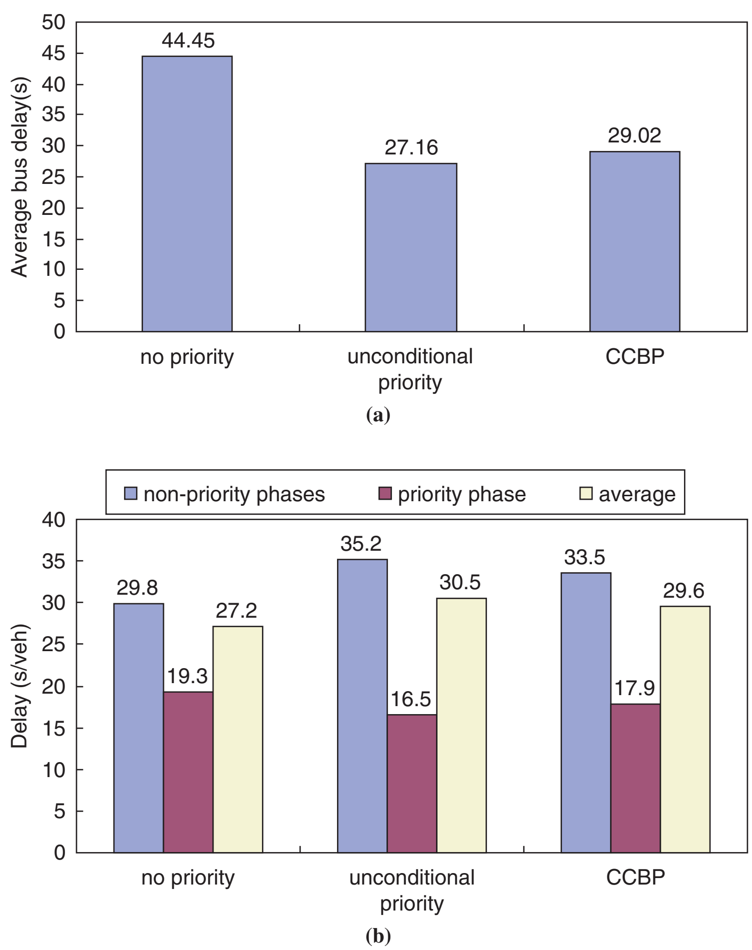

FIGURE 5 Effects of bus delay on (*a*) average bus delay and (*b*) motor vehicle movements.

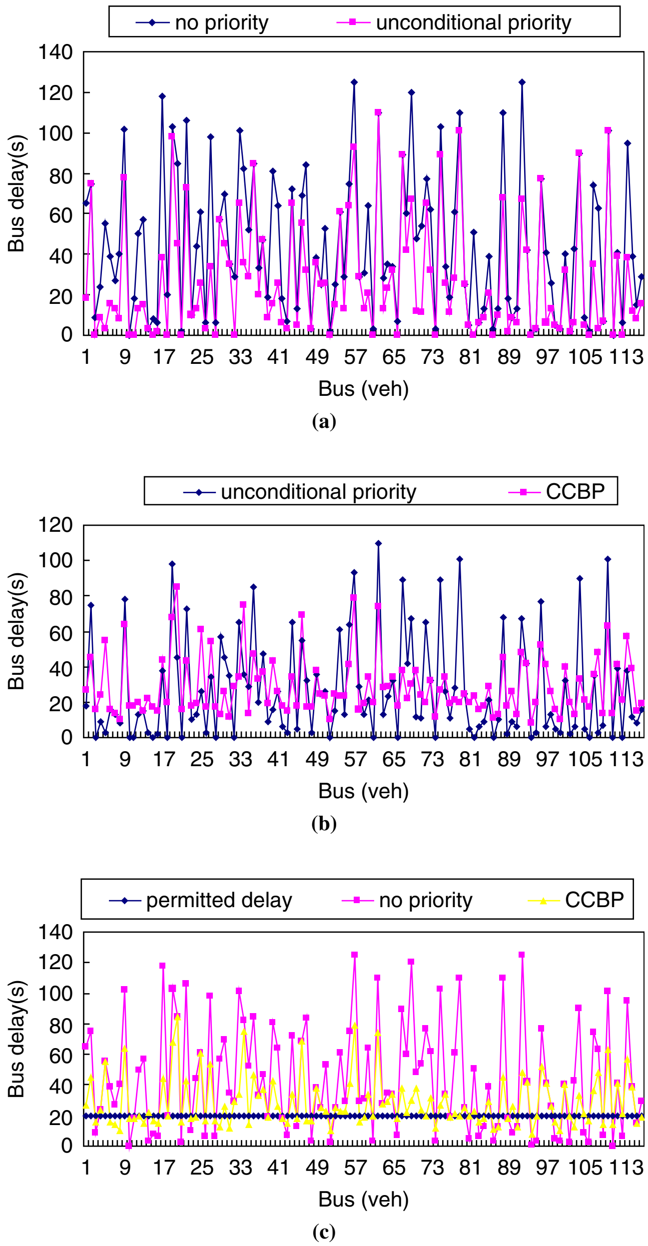

FIGURE 6 Effects on bus delay fluctuation.

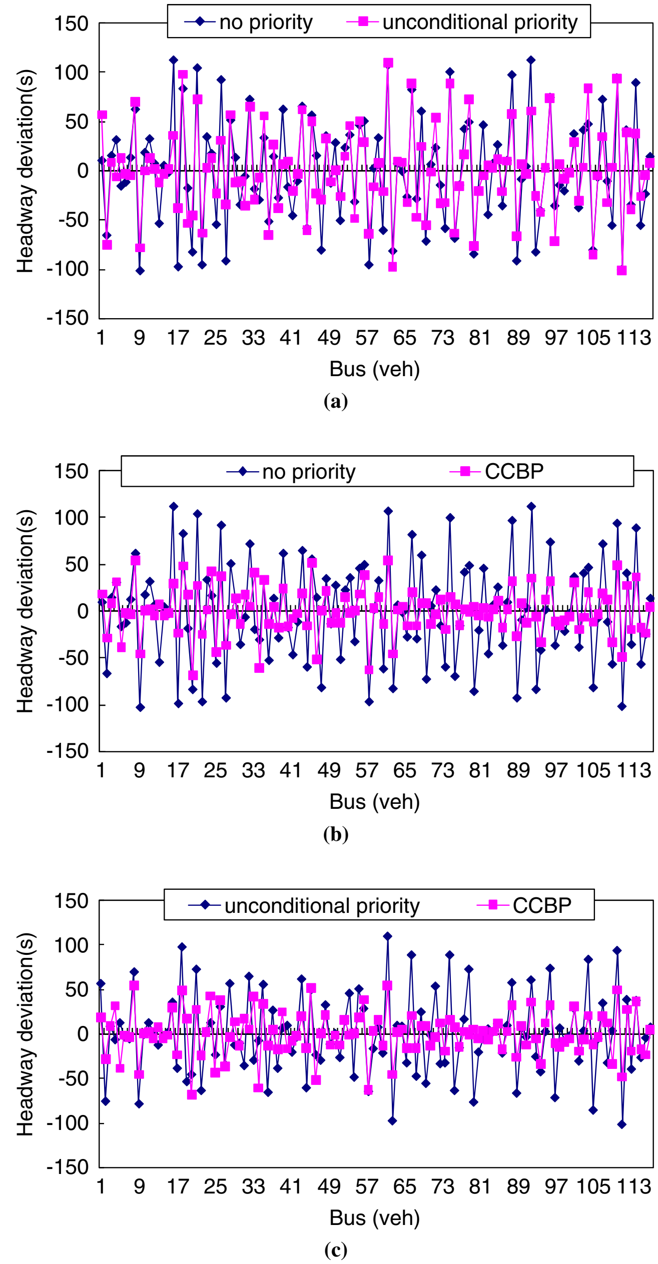

FIGURE 7 Effects on bus headway deviation.

Figure 6 also shows that CCBP can increase delay of the buses; this delay is less than 15 s with no priority. This is the effect of increasing bus delay strategies, a phenomenon seldom reported in other research. From the viewpoint of reliability of the total bus system, it is better to keep every bus delay around a predetermined value than to neglect shorter bus delays. Because less bus delay means that the bus arrival time at downstream stops is earlier than the time defined by the bus operation system, the bus becomes early and may be bunched with the next bus.

The effects of priority on bus headway regularity are shown in Figure 7. Without priority, average bus headway deviation is 44.4 s and ranges from –102 to 112 s. With unconditional priority, average bus headway deviation is 34.3 s and ranges from –101 to 98 s. With CCBP, average bus headway deviation is 16.7 s and ranges from –69 to 54 s. It is obvious that CCBP significantly reduces the fluctuation of bus headway. Compared with no priority, CCBP decreases average bus headway deviation by 27.7 s (62.4%), and unconditional priority slightly decreases bus headway deviation by 10.1 s (32.4%). Compared with unconditional priority, CCBP decreases average bus headway deviation by 17.6 s (51.2%).

CONCLUSION

The results of this study have shown that the CCBP approach could be developed. In this approach, a coordinated signalized intersection group is adopted as the control object of the bus priority control system, and buses are detected one or more cycles in advance of their arrival at the first intersection of the control object. Two kinds of priority strategies, increasing bus delay strategies and decreasing bus delay strategies, are proposed. A model was built to generate the optimal combination of priority strategies for intersection groups so that the real delay of buses would be closely approximated to the permitted delay defined by the bus operation system. A field application validated the CCBP approach.

1. Compared with no priority, significant reductions in bus delay were achieved by using the CCBP approach (by 34.7% per bus).
2. Compared with no priority and unconditional priority, the CCBP approach decreased bus delay deviation and bus headway deviation dramatically.
3. Compared with no priority, CCBP slightly increased the average delay of motor vehicles (by 8.9 %). However, CCBP produced much less average delay of motor vehicles than unconditional priority.
4. The increasing bus delay strategies can increase delay of early buses, and they will lessen the adverse effects of decreasing bus delay strategies to nonpriority phases.

The results suggested that the CCBP approach could be used to enhance the reliability of bus service without significantly affecting cross-street delays. However, more tests are needed before the approach can be popularized. In particular, the bus delay prediction model should be regulated when the approach is used in mixed traffic. The bus delay prediction model used in the paper also can be enhanced to address the effects of dwell time and queues.

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