TECHNICAL NOTE

Transit signal priority control at signalized intersections: a comprehensive review

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Transit signal priority (TSP) control widely used at signalized intersections has been recognized as a practical strategy to improve the efficiency and reliability of bus operations. A proper TSP control can effectively reduce bus travel time at local arterials without significantly bringing negative impacts to the network. This paper provides a comprehensive review of TSP controls by presenting two primary sections: priority control methods and system evaluations. Based on the different types of priority strategies, the existing control methods are sub-divided into two categories: passive control and active control. Particularly, the active control is further categorized as two groups: rule-based approach and model-based one. In the review section of system evaluations, this paper presents three effective ways found in the literature: analytical evaluation, simulation test, and field test. Also to further demonstrate the effectiveness of TSP in practice, this study analyzes its field benefits in 24 cities around the world.

Keywords: Transit signal priority, Passive priority control, Active priority control, System evaluation

Introduction

To improve the operational regularity and punctuality of transit systems, transportation researchers and transit agencies have devoted great efforts into the development of advanced transit systems during the past decades. Particularly, the transit signal priority (TSP) control, developed since the late 1960s (Wilbur, 1968), has been recognized as one of the most promising ways in reducing bus travel time at local arterials. Transit signal priority control is an operational strategy that facilitates the movement of transit vehicles, either buses or streetcars, through signalized intersections. A TSP system is usually operated by providing extra green time or reducing red time for buses, which allows them to pass the intersection without stopping by red signals (Seward and Taube, 1977). Nowadays, many state-of-practice priority controls have been developed and put into practice. Based on the findings of Ngan *et al.* (2004) and Zhou and Gan (2005, 2006), the major factors affecting TSP priority control are summarized as follows:

- Network configuration: number of lanes, pedestrian presence, number of signalized intersections, the existence of exclusive bus lanes, and bus stop location;
- Traffic demands: degree of saturation at the cross-street, traffic volume of left-turn movement, traffic volume of passenger cars, and bus demand at the cross-street; and
- Transit service characteristics: number of detected buses, bus arrival distribution, bus arrival sequence, bus dwelling time, bus delay, and the type of bus operation.

A well-designed TSP system can provide substantial benefits to transit vehicles. For example, TSP can help reduce bus delay (or passenger delay) at intersections as well as passenger waiting time at stops, prevent the occurrence of bus bunching, and minimize the required bus fleet size. Also, it can improve bus punctuality by increasing the percentage of on-scheduled buses. However, TSP may also bring some negative impacts to network. For instance, the extension of green time to the priority movement would inevitably reduce the green time of other movements, which consequently increases the delay of those non-priority vehicles. In addition, passenger cars at prioritized approaches would simultaneously receive the signal priority, which may potentially cause congestions at downstream intersections because of the surge of traffic volumes.

According to the different priority techniques, the control methods can be categorized into two general types: passive priority and active priority (Urbanik, 1977).

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Srinivasa *et al.* (1995) developed a model to evaluate the impacts of bus priority at signalized intersections and discussed the characteristics of both priority controls. To offer an in-depth review for the existing studies, this paper will focus on (1) presenting conventional passive priority control methods; (2) analyzing the characteristics of active priority control models and identifying the applicable condition of each approach; and (3) summarizing the existing evaluation methods.

Passive priority

Passive control technique is used to implement bus signal priority without explicitly recognizing actual bus presence, but rather by predetermining signal timings to provide some benefits to buses. Such methods usually assume bus arrival follow a given distribution (e.g. uniform distribution) and might be effective under high bus demand scenarios. Taking London for an example, when bus volume exceeds 60 buses per hour, the passive TSP with arterial coordination can provide much better performance than others (Hounsell and Wu, 1995). In literature, several passive methods are summarized (Urbanik, 1977):

Adjustment of cycle length and signal timings

Commonly, long cycle lengths tend to maximize vehicle throughput at intersections because of its reduced total lost time (Machemehl, 1996). Moreover, it is much easier to increase the arterial progression bandwidth in long cycle lengths than in shorter ones. However, the drawback of larger cycle length is the substantial stopped delay experienced by vehicles at intersections, because of the long duration of red phases.

In contrast, shorter cycle lengths may reduce the bus delay at the signalized intersections by reducing their waiting time within red signals. This approach, however, may decrease the vehicle capacity of the entire intersection under congested conditions. Using TRAF-Netsim simulation, Garrow and Machemehl (1998) tested the effectiveness of shortening cycle length at both isolated intersection and local coordinated arterial. The results showed that reducing signal cycle length might improve the network performance. In the city of Guangzhou, China, transit agencies improved BRT (Bus Rapid Transit, RFID is Radio Frequency Identification; and UTC is Urban Traffic Control) travel speed from 15 to 21 km h^{-1} during peak hours along Zhongshan Avenue, which benefits from constructing bus exclusive lane, reducing the number of phases, and shortening cycle length.

Also note that traffic environment in developing countries, such as China, is quite complex. To deal with the operational issues related to the mixed-flow traffic pattern, one should consider the impacts of bus passenger volume when designing the phases and signal timing plans (Zhang *et al.*, 2004; Ji *et al.*, 2005). To satisfy such a need, Zhang *et al.* (2004) proposed a new procedure, using the weighted summation of bus and passenger car volumes as input, to reassign available green time to signal phases. Similarly, Feng *et al.* (2007) proposed a passive signal priority strategy at an isolated intersection of having bus exclusive lanes such as to minimize the average person delay of the entire intersection. The developed model is summarized below

$$\min \; d_{\mathrm{p}} = \frac{\sum_{\mathrm{i}}\sum_{\mathrm{j}}\sum_{\mathrm{k}}(d_{\mathrm{ij}}^{\mathrm{b}} q_{\mathrm{ij}}^{\mathrm{b}} P_{\mathrm{b}} + d_{\mathrm{ij}}^{\mathrm{k}} q_{\mathrm{ij}}^{\mathrm{k}} P_{\mathrm{k}})}{\sum_{\mathrm{i}}\sum_{\mathrm{j}}\sum_{\mathrm{k}}(q_{\mathrm{ij}}^{\mathrm{b}} P_{\mathrm{b}} + q_{\mathrm{ij}}^{\mathrm{k}} P_{\mathrm{k}})} \tag{1}$$

s.t.

$$\begin{aligned} &\sum_{\mathrm{i}}(g_{\mathrm{i}} + L_{\mathrm{i}}) = C, \;\; \sum_{\mathrm{i}} F_{\mathrm{i}} < x_{\rho} \\ &40\,\mathrm{s} < C < 180\,\mathrm{s} \\ &g_{\mathrm{i}} \geq g_{\mathrm{i}}^{\min} \end{aligned} \tag{2}$$

where d_{p} denotes the average personal delay; P_{b} is the average number of bus loading passengers; $d_{\mathrm{ij}}^{\mathrm{b}}$ and $q_{\mathrm{ij}}^{\mathrm{b}}$ are bus delay and bus volume at phase i and approach j, respectively;$d_{\mathrm{ij}}^{\mathrm{k}}$ and $q_{\mathrm{ij}}^{\mathrm{k}}$ are other traffic delay and volume, respectively; k means the number of other traffic (car, truck, heavy truck, motorcycle, etc.); P_{k} is the number of passengers in other vehicles; F_{i} represents maximal v/c for phase i; g_{i} is the green duration of phase i, and L_{i} is the corresponding lost time; C is the cycle length; x_{ρ} is the maximum allowed degree of saturation; and $g_{\mathrm{i}}^{\min}$is the minimum of green time. The simulation results showed that this method of optimizing phases and signal timing can outperform the non-priority method in terms of 12·7% reduction in average person delay.

Splitting phases

Splitting phases occurs when the green times for bus vehicles are split into multiple shorter phases in one signal cycle. This method can reduce the delay for buses with different arrivals by repeating the priority phase at the same cycle without necessary shortening cycle length. However, it can increase the total lost time because of the frequent transition between signal phases. Also, the short duration of split phases may be unable to provide enough time for pedestrians at the non-priority approaches. Based on the simulation analysis, this approach can provide much more efficiency and lower impacts on the entire intersection than the adjustment of cycle length (Garrow and Machemehl, 1998).

Area-wide signal timing plan

This method can be categorized into two groups. The first one is to design the preferential bus progression based on the features of bus operations. However, this approach is extremely difficult to implement because buses need to load/unload passengers at bus stops, and the high fluctuation of dwelling time often makes buses miss the signal progression. Lin *et al.* (2013a) presented bus progression control along an arterial by considering bus dwelling time at bus stops. The objective functions are to maximize the weighted summation of bus vehicle and passenger-car's bandwidth based on Max-band control models, which is expressed as

$$\max \quad b^{\mathrm{B}} = \frac{1}{V^{\mathrm{B}}} \sum_{\mathrm{i}=1}^{\mathrm{N}-1} (v_{\mathrm{i}}^{\mathrm{B}} b_{\mathrm{i}}^{\mathrm{B}} + \bar{v}_{\mathrm{i}}^{\mathrm{B}} \bar{b}_{\mathrm{i}}^{\mathrm{B}}) \tag{3}$$

where

$$V^{\mathrm{B}} = \sum_{\mathrm{i}=1}^{\mathrm{N}-1} (v_{\mathrm{i}}^{\mathrm{B}} + \overline{v}_{\mathrm{i}}^{\mathrm{B}})$$

And $v_{\mathrm{i}}^{\mathrm{B}}$ and $\overline{v}_{\mathrm{i}}^{\mathrm{B}}$ are bus arrival rate at both inbound and outbound directions, respectively; $b_{\mathrm{i}}^{\mathrm{B}}$ and $\overline{b}_{\mathrm{i}}^{\mathrm{B}}$ are the corresponding green bandwidth for bus vehicles. Similar to the conventional two-way progression models, this model includes both interference constraints and loop integer constraints, and its control variables are the cycle length and offsets.

The second group of studies is to convert buses into equivalent passenger cars to justify the allocation of additional green time to bus approaches. A passive TSP control on area-wide timing plan is based on reassigning spatial and temporal resource and optimizing bus frequency (Ma and Yang, 2007). This method mathematically depicted the relationship of bus frequency, cycle length, and number of arrival bus vehicles during different signal phases. Furthermore, Skabardonis (2000) formulated the passive TSP control by modifying the objective functions of TRANSYT-7F to provide more green time to bus movements. In this control method, buses are regarded as moving along independent links, similar to exclusive bus lane. Evaluation results showed that buses could obtain more benefits as the number of buses increased, while reducing the impacts on passenger cars. A similar method is used in real-time, hierarchical, optimized, distributed, and effective system (RHODES) (Mirchandani *et al.*, 2001).

Metering vehicle

Metering vehicle is an approach that limits the number of passenger cars to enter the congested intersections or regions to ensure the reliability and efficiency of bus operations. This method is similar to priority entry based on-ramp metering on freeways to promote high occupancy vehicles or carpools to bypass the conflict area (Urbanik *et al.*, 1977). However, this strategy will improve the bus travel environments at the expense of significant impacts on passenger cars. In practice, this method is hardly used in urban road networks.

Active priority

Compared with passive priority methods, active priority systems take advantage of bus detection sensors located at the upstream of intersections. When a transit vehicle approaches the sensors, the signal controller would provide the designated TSP strategies (green extension, red truncation, phase insertion, etc.) for predetermined or variable durations. Based on the different computational complexities, one can further classify active methods into two categories: rule-based priority and model-based priority.

Rule-based priority control

This method is to grant priority for buses according to a series of decision rules, such as bus presence and the duration of bus lateness. The rule-based control might be categorized into unconditional and conditional strategies in terms of bus readiness.

Unconditional priority

Unconditional TSP controls grant the signal priority based on the actual presence of buses at the signalized junctions without the consideration of bus lateness. If one bus is detected at the end of the green phase, the signal control will take actions to extend green time by up to 10–20 s to discharge the detected bus (Ludwick, 1974). When the bus arrives at the middle of red phase, the signal control may insert a bus phase. If the bus is detected at the end of red phase, the controller might truncate the current red phase to recall the bus green time.

The unconditional priority control was first validated by simulation (Ludwick, 1974) under multiple scenarios by changing the location of bus stops, the type of bus route (express bus routes and local ones), and bus frequency. The TRAF-Netsim simulation results showed that the unconditional priority with 10 s green extension could provide 20% bus travel time saving with only 7% cross-street travel time increase, even at half-minute headways. Also, at both arterial and isolated intersections, it was proven that unconditional priority offered significant potential benefits on reliability and efficiency to express buses during off-peak periods.

However, with the increase of bus demand and the expansion of transit network, the signal control may receive multiple priority requests at the same time. In response to this issue, traffic engineers and researchers have started to focus on the accommodating of multiple priority requests. A popular method is depicted as follows (Dion and Hesham, 2005):

1. The detectors are located at the user-specified distance upstream of the signal stop line, which is typically set at 100 m.
2. The extra green time allocated to buses comes out from other phases to make sure the unchanging of cycle length and to preserve coordination with adjacent intersections.
3. If one bus is detected while another traffic movement is being served, the active green phase will be terminated and return to the prioritized approach only after having satisfied the minimum green, amber, and all-red intervals of all the intermediate phases in the phase sequence.
4. In order to minimize traffic disruption, there is only one priority request during the same cycle. If there are many priority requests from the same or conflicting approaches, they will be granted on the basis of the first-come-first-served (FCFS) policy.
5. Skipping of any phase is prohibited. Also, the duration of each phase is not less than minimum green times. Finally, green extension cannot result in green phases exceeding their defined maximum duration.

Dion and Hesham (2005) tested this method under different scenarios, such as the fix-time, adaptive splits, and adaptive splits with offsets, with fixed cycle length. Recently, it has become feasible to combine other methods to further improve the unconditional TSP control, such as the queue jumper lane (Zhou and Gan, 2009). Queue jumper lane is a special bus preferential treatment that combines a short stretch of a special lane with TSP control to only permit buses to bypass waiting queues of traffic at the stop line and then to cut out in front of the queue by getting an early green signal. Compared to the traditional actuated mixed-lane TSP control, this proposed combination could provide more benefits to buses. In particular, a nearside stop is superior to the far-side counterpart in terms of bus delay and overall intersection delay. Similar to other unconditional TSP, this combination control needs to limit the number of granted priority requests, which is usually not more than twice within one cycle.

In summary, unconditional priority is relatively simple and easy to implement. A key characteristic of this method is to grant signal priority to all buses without considering bus readiness.

Conditional priority

In contrast to unconditional TSP control, the conditional priority makes full considerations of the actual bus presence and readiness and grants priority buses at the expense of comparatively small time losses to travelers in other vehicles. The following basic rules should be considered within a conditional control system:

1. Ensure the level of service at the non-priority movements is not severely decreased after TSP.
2. On a coordinated arterial, the TSP control does not disrupt the designed signal progressions. Also, the excess discharging vehicles from extra priority green time do not cause overflow at the downstream intersections.
3. No matter whether the sequence of phases at the intersections is fixed or changeable, the conditional control cannot frequently destroy the sequence because this might confuse drivers.
4. The conditional TSP only grants priority to the late buses.
5. For multiple priority requests, it is necessary to estimate the delay of each bus to determine the priority.

Also to reduce the impacts on the passenger cars, some additional rules are proposed to restrict the function of TSP. In the early studies, the red truncation could be taken only if the previous green period was not extended so as to reduce the traffic disruption on the cross-street (Evans and Skiles, 1970). In other situations, the signal control would take priority action if and only if the arrival rate of buses or other vehicles exceeded some user-specified level (Tamoff, 1975; MacGowan and Fullerton, 1979). Other conservative strategies were to allow priority to be granted only if there were no priorities granted during the previous cycle or to calculate the timings in cycles where no priority is requested on the basis that priority will be granted with some expected frequency (Allsop, 1977; Cottinet *et al.*, 1980). In the real-world applications, a less restrictive rule recommended by the British Department of Transport (1977) allowed red truncation only if the previous one was not truncated because red truncation easily disrupted the traffic flow. In order to select an optimal decision making strategy, Gallivan *et al.* (1980) estimated the performance of each strategy. Interestingly, the green compensation to non-priority movements was also a feasible strategy. However, many studies and practical tests have shown that there is an extra delay during compensation cycles (El-Reedy and Ashworth, 1978; Cooper *et al.*, 1980; Department of Transport, London, 1980).

In the 1990s, the development of advanced signal control and traffic detection techniques led to more sophisticated conditional control to account for the overall benefits of passenger cars and buses. The ground-breaking work by Bowen *et al.* (1994) integrated TSP control into the split cycle offset optimization technique (SCOOT) kernel system for traffic responsive coordinated signal control. The SCOOT system did not attempt to measure or predict the dwelling time at bus stops, and only relied on detecting a bus on the link where it was to receive priority. However, the central control might estimate bus queuing to calculate the accurate extra green time for the detected buses. To such a need, Yagar and Han (1994) estimated the overall performance of an entire intersection with and without priority based on traffic data from detectors installed on the main roads and the cross-streets.

Also note that bus frequency may affect the performance of TSP control (Hounsell and Wu, 1995). Taking London for example, when buses were operated with 1 min headways, providing green extensions only was identified as the best strategy. When bus headway is shorter than 1 min, passive TSP control with adjusted signal timings to allow for bus progression was recommended. In a separate paper, Hounsell *et al.* (1996) tested different active priority strategies using a simulation model. The results showed that (1) bus delay savings of 20–30% were possible without significant impacts to general traffic; (2) TSP control could increase bus delay savings with decreasing intersection saturation levels; (3) TSP control with green extension alone has the best overall impact upon other traffic; (4) bus delay will be decreased by supplementing green extension with red truncation, but at a high expense to passenger cars. Similarly, Skabardonis (2000) analyzed the features of conditional TSP control on the arterial and proposed that it was necessary to completely consider the spare green time, bus progression, and schedule timetable when the TSP control was designed.

Recently, conditional TSP control has been widely applied in practice (Smith *et al.*, 2005; Gardner *et al.*, 2009; UTMS Society of Japan, 2012). A complete framework of TSP control system was designed by Balke *et al.* (2000). Their simulation results from three different volume-to-capacity levels have shown that the TSP control could be used at the moderate traffic level (v/c ratios of up to 0·9 or less). In practice, the collection of the bus location every second may be extremely difficult and expensive. Hence, another conditional TSP based on schedule timetable was proposed to grant the priority only to late buses (Janos and Furth, 2002; Satiennam *et al.*, 2005). In Japan, the TSP system can provide more flexible methods to grant priority by the use of the traffic facilities, such as exclusive bus lane and TSP control (Satiennam *et al.*, 2005; UTMS Society of Japan, 2012).

The flexible method is described as follows: (1) the basic strategies contain green extension, red truncation, and bus phase insertion; (2) switch green phase to cross-street when the bus is at the stop for loading/uploading passengers in order to minimize the impact on cross-street vehicles; and (3) signal control center may recommend the desired speed to transit in terms of traffic conditions.

With the increasing bus demand, the overlapped bus routes at local arterials can cause another issue for priority decision makings. Ma and Yu (2007) classified multiple priority requests into two kinds: multiple requests for single phase and multiple requests for multiple phases within the same cycle. The basic methods to deal with multiple requests are categorized into two types: (1) FCFS and (2) trade-off the overall performance of all buses and passenger cars on delays. Generally, the former method is more popular than the latter one because the former does not require the collection of other traffic data, such as traffic demand and queue length. For example, a decision tree was used to optimize the service sequence of these two kinds of multi-requests to minimize the average person delay of all priority requests (Ma and Yu, 2007). Liao and Davis (2007) took advantage of the already equipped global positioning system (GPS) and automated vehicle location system (AVLS) on the buses in Minneapolis, Minnesota and proposed an adaptive conditional control considering bus schedule adherence, number of passengers, bus stop location, dwelling time, and speed. This study first estimated the bus arrival time at the stop line. If the bus stop is close to the intersection, this arrival time is estimated by the summation of the current time, dwelling time, loss time (such as doors opening and closing), and historical observed travel time. Later, He *et al.* (2011) presented a heuristic algorithm for traffic signal control with simultaneous multiple priority requests at isolated intersections, which can achieve near-optimal signal timing and can be visualized in a phase-time diagram.

The aforementioned conditional TSP control is mainly suitable to timetable-based bus operations because the delay is calculated by the difference between actual arrival time and scheduled time. For headway-based bus systems, the delay is related to actual bus headways. The TSP control not only considers the travel time saving of in-vehicle passengers, but calculates bus passenger waiting time at bus stops. In contrast to be the timetable-based TSP research, only few headway-based methods have been reported in the literature. Assuming a small scheduled headway and randomly arriving passengers along a bus route, Kulash (1971) indicated that the average passenger waiting time at bus stops can be estimated with the following equation

$$E(w) = \frac{E(H)}{2} + \frac{\mathrm{Var}(H)}{2E(H)} \tag{4}$$

where $E(w)$ is the expected waiting time per passenger; $E(H)$ is the mean headway; and $\mathrm{Var}(H)$ denotes the variance of the headway distribution. Hence, under a fixed-headway operating system, one potentially effective way to reduce the average passenger waiting time is to reduce or minimize the headway variance of all buses on the same route.

According to equation (4), Hounsell *et al.* (2000) introduced a conditional TSP control to grant bus priority based on the headway between the current bus and the last proceeding bus. Similarly, Ling and Shalaby (2004) used reinforcement learning to determine the best duration of an extended signal phase based on the bus headway deviation from its schedule and employed the Paramics software for simulation and evaluation. Moreover, Hounsell *et al.* (2008) reported the operations of bus signal priority with the iBUS system in London, and then explored the effects of GPS locational errors on bus priority benefits. Following that, a combined method, including bus-holding at a stop and conditional signal priority to late buses, was presented to make buses operated under a more uniform headway (Altun and Furth, 2009). In March 2012, Hounsell and Shrestha presented a new approach to granting bus priority for a headway-based service. The key logic of their method is a headway adjustment rule for a route operation by concurrently considering three adjacent buses (the current bus, the bus in front, and the bus behind). In their model, the approaching bus will be given a priority if its forward headway is larger than the backward headway. Their control logic can improve the efficiency and reliability of headway-based bus operations by simultaneously considering the adjacent three buses. However, this method assumes that the bus headway follows the uniform distribution, which is not applicable in practice.

Different from other countries, most of the signalized intersections in China have installed countdown signals. At these intersections, it is prohibited to adjust signal timings during countdown periods. Therefore, Yan *et al.* (2009) studied the best bus detection location at these intersections. If the green extension will be employed to grant priority, the distance from bus detection location to the downstream stop line can be calculated as follows

$$L \geq v(t_{\mathrm{R}} + \Delta t_{\max}) \tag{5}$$

where v denotes bus average travel speed along the arterial; t_{R} is the duration of the countdown signal at prioritized approaches; and $\Delta t_{\max}$ is the maximal allowable duration for green extension in terms of traffic conditions. When the selected priority strategy is red truncation that distance should be changed by the following equation

$$L \geq v t'_{\mathrm{R}} \tag{6}$$

where t'_{R} denotes the duration of the countdown signal of the one ahead of priority phase. In most of the cities in China, the countdown duration for each phase is a constant. Thus, the bus detection location is decided by equation (5). In the city of Shanghai, the proper bus detection location is about 150 m. Simulation results showed that this detection distance by this method outperformed one of the SCATS and SCOOT systems.

Conditional priority is more complex than unconditional priority control, which needs extra detection information and bus readiness. However, this control is usually based on rules or judge conditions, not to quantitate the benefit with priority. The objective of this method is not to blindly minimize bus travel time, but to improve bus punctuality and regularity based on the bus readiness. As a result, it is not difficult to implement this logic in practice. For multiple priority requests, the principle of FCFS is usually employed to handle it without considering bus sequence (Lin *et al.*, 2013b).

Model-based priority control

Compared to the rule-based TSP control, model-based control grants the priority to specific buses in terms of bus readiness and traffic conditions in order to reduce bus passenger delay or total person delay. This method needs to detect bus locations, bus operations conditions, and traffic volume/queue length of passenger cars. The control objective is to quantify the performance of buses or total vehicles before and after TSP control to accurately justify the efficiency and effectiveness of system.

Based on the control targets, it could be categorized into two types: minimizing total bus passenger delay and total person delay. As known, the initial aim of transit priority is to reduce the total bus passenger delay without significantly increasing passenger-car's delay. However, in practice, it is extremely difficult and expensive to collect the demand and ridership of bus passengers and car passengers, especially in the developing countries (Lin *et al.*, 2013c).

Minimizing total bus delay

When passenger-car demand is not available, the objective of TSP control is used only to reduce the total bus delay with ignoring the impact on passenger cars. Under the timetable-based transit operation, total bus delay reduction after priority can be calculated as follows

$$D=\sum_{i} P_{i}^{B}\Delta t_{i}^{S}+\sum_{i} P_{i}^{S}\max(\max(t_{i,non}-\Delta t_{i}^{S}-t_{i,a},0)-\max(t_{non}-t_{i,a},0),0) \tag{7}$$

where P_i^B is the number of on-boarding bus passenger for bus i; P_i^S denotes the number of bus passengers waiting at the next stop; Δt_i^S is time saving after TSP control; $t_{i,non}$ is the arrival time to the next stop before TSP control for bus i; and $t_{i,a}$ denotes the on-scheduled arrival time. In this equation, the first term represents the reduction in on-boarding bus passenger delay before and after TSP control, and the second one is the variance in bus passenger waiting time. In reviews of the literature, most of the studies pay more attention to the first item.

For headway-based operations, the total bus delay reduction with TSP control can be expressed as follows

$$D=\sum_{i} P_{i}^{B}\Delta t_{i}^{S}+\sum_{i} P_{i}^{S}(\alpha_{i}-\alpha'_{i}) \tag{8}$$

The second part of this equation denotes the difference in bus passenger waiting time caused by headway variance before and after TSP control. α_i and α'_i are the bus passenger waiting time at the next stop with and without TSP, respectively. α_i can be estimated as shown

$$\alpha_i=\begin{cases} \frac{(h_i^{f'})^2+(h_i^{b'})^2}{2(h_i^{f'}+h_i^{b'})} & \text{if } h_i^{f'}>\theta_r \text{ and } h_i^{b'}>\theta_r \\ N+\frac{h_i^{b'}}{2} & \text{if } h_i^{f'}\le\theta_r \text{ and } h_i^{b'}>\theta_r \\ N+\frac{h_i^{f'}}{2} & \text{if } h_i^{f'}>\theta_r \text{ and } h_i^{b'}\le\theta_r \\ 2N & \text{if } h_i^{f'}\le\theta_r \text{ and } h_i^{b'}\le\theta_r \end{cases} \tag{9}$$

where $h_i^{f'}$ and $h_i^{b'}$ are the actual forward and backward headways of bus i, respectively, belonging to the same route at the next stop after receiving signal priority; θ_r is the threshold to determine if bus bunch for each route exits; and N is a positive constant for the resulting penalty. According to the aforementioned analysis, this general TSP control method can be formulated as follows

$$\begin{aligned} &\min\ D \\ &\text{s}\cdot\text{t}\cdot \\ &\begin{cases} \frac{x_i g_i}{(g_i-\Delta g_i)}\le\beta & i \text{ is non-priority approach} \\ g_i-\Delta g_i>g_i^{\min} & \forall i \end{cases}. \end{aligned} \tag{10}$$

where Δg_i is the duration of green time truncation at the non-prioritized approaches. The objective of this problem is to minimize the total bus passenger delay. The decision parameters include priority strategies (green extension, red truncation, bus phase insert, etc.) and the duration of priority time. Usually, the solution of this basic model is proven by exhaustion because the number of arrival buses is limited. In practice, most of the transit operation systems cannot collect the real-time bus occupancy and number of waiting passenger at stops (Lin *et al.*, 2013c). Thus, these two parameters should be assumed as a constant that is investigated.

A model-based TSP control based on operations research was reported by Head *et al.* (2006) in order to reduce the total bus delay of multiple priority requests. This method was formulated on the basis of the traditional North American dual-ring, eight-phase controller. The Excel Solver and the Lingo Excel extension were used to solve problems consisting of several cycles and multiple priority requests in reasonable solution times. The case study showed that a FCFS policy for serving multiple requests could result in more delay than a multiple-priority-request policy generated by the proposed model.

Another study presented a mathematical procedure to estimate the bus delay without collecting traffic demand (Ma *et al.*, 2010), which was equal to the sum of travel delay, signal delay and dwelling time at bus stops. The priority would be granted when the estimated bus delay was more than predefined threshold. Therefore, the bus delay estimation directly determined the performance of TSP control. The estimation method is usually based on the following assumptions: (1) the roadway has bus exclusive lane; (2) bus delay at bus stops is constant; (3) bus speed is deterministic; and (4) there is no queue at the bus exclusive lane, and the bus acceleration and deceleration process are ignored.

Minimizing total person delay

At some intersections or arterials, there are many detectors to collect the number of passenger cars, such as loop detector. In this situation, one can estimate the passenger-car's delay before and after TSP controls. Alternatively, the objective of TSP methods might be to minimize the total person delay for passenger-car drivers and bus passengers at the entire intersection or arterial.

According to the impacts of TSP controls on passenger cars, the affected general traffic can be categorized into two groups:

(1) Total person delay reduction for passenger-car users at the prioritized approaches

Assuming that the arriving rate of passenger cars to the TSP intersection is uniformly distributed when these buses are granted a priority, the person delay reduction of passenger-car user at the priority approach can be approximated as follows

$$t_{\mathrm{i,PC1}} = \begin{cases} r_{\mathrm{i}} - \Delta t/2 & \text{if the priority strategy is green extension} \\ \Delta t/2 & \text{if the priority strategy is red truncation} \end{cases} \tag{11}$$

where r_{i} is the duration of red phase i before TSP controls; Δt denotes the additional green durations for all detected buses, which needs to be optimized. Thus, the total person delay reduction for passenger cars when receiving priority with transit vehicles can be shown as follows

$$D_{\mathrm{R}}^{\mathrm{PC}} = P_{\mathrm{PC}} t_{\mathrm{i,PC1}} q^{\mathrm{PC}} \tag{12}$$

where P_{PC} is average number of persons per passenger car. Note that q^{PC} in equation (12) stands for the estimated queue of passenger cars proposed by Chang *et al.* (1996).

(2) Total person delay increase for passenger-car drivers at the non-prioritized approaches

Note that granting a priority to buses in the arterial will inevitably reduce the green time on the crossing street, which will consequently cause extra delay for those non-priority vehicles. The computation of the extra delay is based on two separate parts: one is the increased delay of those initial queuing vehicles because of the reduction of green time and the other is the extra delay of these vehicles approaching the intersection during the TSP execution period. The average delay per queuing vehicle can be expressed as

$$t_{\mathrm{i,PC2}} = \begin{cases} \Delta t & \text{if the priority strategy is green extension} \\ r_{\mathrm{i}} + \Delta t & \text{if the priority strategy is red truncation} \end{cases} \tag{13}$$

With the assumptions that vehicles arriving at the cross-street during the TSP execution period follow a uniform distribution and each cycle can clear the queue at the cross-street, the average delay per approaching vehicle can be calculated as follows

$$t_{\mathrm{i,PC3}} = \begin{cases} \Delta t/2 & \text{if the priority strategy is green extension} \\ r_{\mathrm{i}} + \Delta t & \text{if the priority strategy is red truncation} \end{cases} \tag{14}$$

Hence, one can approximate the increased person delay for passenger cars on the crossing street as follows

$$D_{\mathrm{I}}^{\mathrm{PC}} = P_{\mathrm{PC}}(q^{\mathrm{PC1}} t_{\mathrm{i,PC2}} + q^{\mathrm{PC1}} t_{\mathrm{i,PC3}}) \tag{15}$$

where $q^{\mathrm{PC1}}$and q^{PC2} denote the queue estimation of queuing/approaching vehicles proposed by Chang *et al.* (1996). In terms of the previous passenger-car delay variance, one can formulate this kind of TSP control in the following equation

$$\begin{aligned} &\min \; D + D_{\mathrm{R}}^{\mathrm{PC}} - D_{\mathrm{I}}^{\mathrm{PC}} \\ &\mathrm{s{\cdot}t{\cdot}} \begin{cases} \frac{x_{\mathrm{i}} g_{\mathrm{i}}}{(g_{\mathrm{i}} - \Delta g_{\mathrm{i}})} \le \beta & i \text{ is non-priority approach} \\ g_{\mathrm{i}} - \Delta g_{\mathrm{i}} > g_{\mathrm{i}}^{\min} & \forall i \end{cases} . \end{aligned} \tag{16}$$

The control objective is to minimize the total person delay for bus passengers and passenger-car users. In practice, the average number of persons per passenger car is usually assumed to be a constant.

On the basis of traffic demand collected by the inductive loop detectors, a real-time multi-objective TSP control was developed by Chang *et al.* (1996). The objective function is the weighted summation of bus passenger delay, passenger car delay, and bus schedule adherence delay. Based on the actuated signal control system, this TSP control could reduce the total person delay of the entire intersection. Later, Mirchandani *et al.* (2001) reported the core logic of bus priority signal based on RHODES. The control system took second-by-second data from inductive loop-detectors at the intersections as input, and the outputs the durations of the phases. The objectives of the control were to minimize bus delay, passenger-car delay, average queue length at the intersections, and the number of stops.

Later, Liu *et al.* (2003) formulated the dynamic signal optimization considering the real-time traffic conditions and bus operations. Vasudevan (2005) presented a neural network model to estimate the bus arrival time. The schedule delay is taken as zero if the bus is on time or ahead of schedule. Li *et al.* (2011) analyzed a single priority request for one particular intersection along a corridor coordinated by an actuated system, which was similar to that of Chang *et al.* (1996). This adaptive TSP model attempted to change green splits in at most three consecutive cycles. The first cycle accurately predicted bus arrival time, the second one provided bus priority, and the third one was used as a transition cycle to compensate the loss of other phases. The aims of the proposed method were to seek maximal bus speed and minimize vehicle delay with the weighted transit without considering bus readiness. A new model-based TSP strategy, mainly for headway-based bus operations, offers the responsible agency a reliable way to determine the optimal green extension or red truncation duration in response to multiple bus priority requests from different routes (Lin *et al.*, 2013b). The authors extended the objectives to minimize bus passenger waiting time at the downstream bus stop while ensuring that total person delay is not increased.

According to the above analysis, the model-based priority control needs more infrastructures and communication requirements to account for the total delay of the entire intersection or arterial, including passenger-car user's delay, on-boarding bus passenger's delay, and bus passenger waiting time at downstream stations. This priority control is to reduce bus passenger delay without significantly increasing passenger-car user's delay by the use of minor signal real-time adjustments. Also, this control not only can be implemented on the basis of the existing priority control scheme, but also able to re-optimize signal timings at intersections. The specific characteristic of the aforementioned TSP controls are listed in Table 1.

Control system evaluation and analysis

Evaluation methods of TSP controls can be categorized into three types: analytical evaluation, simulation test, and field test. The field test is extremely expensive and highly risky. Therefore, before implementing the systems in practice, the first step is to evaluate the performance of the TSP control by using the two other tests in the planning phase. In reviews of the literature, the common performance indexes are given as follows:

(1) reduction in bus travel time or travel delay (time savings), which is one of the most significant and useful indexes;
(2) improvement in bus travel speed;
(3) variance of headways under headway-based operations that is related to bus waiting passenger's delay;
(4) improvement of bus schedule adherence under schedule-based operations to reflect the deviation between actual arrival time and scheduled one;
(5) passenger-car driver's delay variance to evaluate the impacts of TSP controls on passenger cars, especially for non-prioritized approaches;
(6) total person delay reduction to assess the impacts of TSP methods on the entire intersection or arterial;
(7) number of bus vehicles blocked by red signals along the arterial which is used in the city of Beijing, China;
(8) reduction in stop time used in the city of Kawasaki, Japan, to capture the timeliness of TSP operations; and
(9) increase in queue length at the non-prioritized approaches to evaluate the impacts on non-prioritized approaches.

Analytical evaluation

Analytical evaluation is generally using the mathematical theories, such as queue theory and regression model, to assess the efficiency and reliability of TSP control, and identify influenced factors. Usually, this method is much more complex than the two others because it estimates the evolution process of traffic flow. Therefore, in the literature, analytical method is used to evaluate the simple priority control with green extension and red truncation on the basis of many assumptions.

Seward and Taube (1977) analyzed the process of the priority control and developed the evaluation models, which formulated bus operating saving, bus passenger saving, and passenger-car time losses, to estimate the revenue–cost ratio for the TSP control with the following hypotheses: (1) priority control with only green extension; (2) uniform bus arrival rate; (3) no bus in crossing streets; and (4) the constant number of bus passengers. The study extended this evaluation model to assess the performance of the priority control with green extension and red truncation at an isolated intersection (Jacobson and Sheffi, 1981). This extended model calculated the vehicle delay and person delay using the traditional delay formulation and the developed probability density function under bus priority. The formulated model assumed that (1) the bus

Table 1 Key characteristic of different transit signal priority (TSP) controls

Control methods		Comments
Passive TSP		Low cost and easy-to-implement
		Needs lesser infrastructure and communication requirement
		More suitable for headway-based service and high bus volume
		More suitable for low fluctuation of dwelling time at bus stations
		Possibility of network-based bus priority
		Less impact to crossing-street general traffic
		More applicable to both UTC controlled and isolated junctions
Active TSP	Unconditional TSP	Low cost and easy-to-implement
		Needs some infrastructure and communication requirement
		More suitable for bus vehicles ahead of schedule and low bus volume
		Applicable to signals under isolated junctions only
		Instant implementation gives higher potential delay savings
		Much impact to crossing-street general traffic
	Conditional TSP	Some cost and easy-to-implement
		Needs some infrastructure and communication requirement
		More suitable for timetable-based bus vehicles and low bus volume
		Applicable to both UTC controlled and isolated junctions
		Variable priority time gives higher potential delay savings
		Much impact to crossing-street general traffic
	Model-based TSP	Much cost and hard-to-implement
		Needs much infrastructure and communications
		More suitable for timetable-based service and low bus volume
		More applicable to both UTC controlled and isolated junctions
		Account of signal coordination and hence lesser impact to the general traffic
		Possibility of network based bus priority
		Compatible with multi-purpose use of the data

arrival rate followed the Poisson distribution; (2) the duration of green extension or red truncation is fixed; and (3) there is only one priority control in each cycle. Moreover, in this paper, the TSP control employed the FCFS policy to contend with multiple priority requests. However, it is difficult to satisfy the previous three assumptions in practice. Khasnabis *et al* (1991) has proved that the proper priority control could shorten the cycle length and reduce the bus delay and bus fleet size, thus generating more ridership and higher revenue.

With the development of priority control in terms of complication and diversification, many researchers have also analyzed the complex priority control in theory. Srinivasa *et al.* (1995) presented an analytical model, which was validated by actual data, to analyze the performance of different TSP controls. The study confirmed that it is beneficial to use the conditional priority rather than unconditional priority because unconditional priority is so disruptive to cross-street traffic. Moreover, it is a better choice to use the unconditional priority when there are far-side stops with medium to long headways. Notably, most studies conducted before the year 2000 only focused on the benefits of the main road without considering the impacts on the minor streets. However, Lin (2002) quantified the benefits of the priority system to buses in terms of delay reduction, which had a high variance/mean ratio and was bounded by signal delay but independent of queuing delay so that sufficient slack time should be built into a bus schedule to maintain reliable service. Furthermore, this study proposed that the benefits are more significant for buses traveling on cross-streets than for those on main streets because the red phase for the cross-street is much longer than the minimum red required for pedestrian crossing. The benefits of the TSP control to buses is restricted by traffic conditions, so Kimpel *et al.* (2005) rigorously analyzed the relationship of changes in bus running times, on-time performance, and excess passenger waiting time following TSP implementation, and gave a procedure to analyze the effectiveness of TSP by using an abundance of trip-level data from TriMet's Bus Dispatch System in Portland, Oregon. The results showed that expected benefits of TSP were neither consistent across routes and time periods, nor were they consistent across the various performance measures. Therefore, Kimpel *et al.* trusted that benefits would accrue only as the result of extensive evaluation and adjustment after initial deployment.

Nowadays, queue theory is regarded as one of the popular methods to estimate the delay impacts of green extension and red truncation (Liu *et al.*, 2008). This kind of model computed standard deviation of vehicle delay with and without priority, which depended on several critical assumptions: (1) the operation of TSP did not significantly change the randomness of traffic flow, and the random delay should remain unchanged with and without the TSP; (2) the traffic volume of all entry approaches was under saturated, and each cycle could clear the intersection; (3) the impact of priority at adjacent intersections, downstream and upstream, could be neglected; and (4) real-time bus operations could be ignored. However, an improved model was developed, with considering the impact of oversaturated approaches on vehicle delay at isolated intersections (Abdy and Hellinga, 2011). Compared with the simulated results, this method provided a much better estimation of vehicle delay under the TSP control. Zhang (2011) also presented a new idea to analyze the impacts of TSP control on traffic emissions.

Simulation test

The traffic simulation technique has been recognized as one of the promising tools for system evaluations. In particular, the micro-simulation technique has been widely used to evaluate and assess the efficiency and effectiveness of signal timing settings. Currently, there are several popular micro-simulation models, such as VISSIM, AIMSUM, TRANSMODELLER, and PARAMICS. Salter and Shahi (1979) designed and developed a group of programs to evaluate the performance of the TSP control in terms of average delay, queue length, and bus travel time. This software included a bus arrival time prediction module so that it was possible to accurately describe traffic environments. Ludwick (1976) reported that they simulated bus priority algorithms with green extension and red truncation, and analyzed the features of priority strategies based on simulation results under different frequent headways, bus stop location, the number of intersections, and the arterial coordination. The simulation results showed that the priority control must limit the maximum green extension and give minimum green time for cross-street traffic to clear the intersection.

In the early twenty-first century, some researchers analyzed the impacts of different priority controls on both buses and passenger cars (McLeod and Hounsell, 2003; Chang *et al.*, 2003; Rakha and Zhang, 2004). For example, Rakha and Zhang built a systematic simulation evaluation model to study the operations of a single signalized intersection within a coordinated arterial system. They presented some findings as follows: (1) TSP generally provided benefits to transit vehicles with the priority, and then the system-wide impact of TSP is directly proportional to the frequency of transit vehicles; (2) the bus arrival distribution affected the system-wide performance of TSP control, especially when conflicting approaches are heavily congested; (3) the system-wide benefits of TSP were highly dependent on the optimality of the basic signal timings; and (4) bus dwelling time at nearside bus stops could have significant system-wide impacts on the potential benefits of TSP controls.

Recently, other researchers analyzed the affected factors of the TSP control under the different scenarios by using VISSIM and PARAMICS simulations (Ngan *et al.*, 2004; Ling and Shalaby, 2004; Zhou and Gan, 2005; Satiennam *et al.*, 2005; Muthuswamy *et al.*, 2007; Zhou and Gan, 2006; Vlachou *et al.*, 2010; Vlachou *et al.*, 2010). These factors included bus frequency, cross-street volume to capacity ratio, bus stop location, bus check-in detector location, left-turn conditions, signal coordination, and the types of priority strategies. Some findings on the basis of these simulation analyses are as follows: First, TSP control would be most effective under moderate-to-heavy bus approach volume, little or no turning volume hindering bus movement, slight-to-moderate cross-street volume to capacity ratio, far-side bus stop, and good signal coordination (Ngan *et al.*, 2004). Second, queue jumper lanes with the TSP control were found to be more effective in reducing bus delay and improving passenger-car operations than those strategies without queue jumper lanes because through passenger cars on the bus approach would block the priority buses when the volume to capacity ratio exceeded 0·9 (Zhou and Gan, 2005). Third, nearside turning volumes had an insignificant impact on average bus delay. Finally, the bus detection system played a key role in determining when to trigger TSP control and which TSP strategy to use. An optimal check-in detector location might minimize bus delay under different bus arrival conditions.

Field test

Field test is not only the most accurate but the most expensive method to evaluate the performance of TSP control systems. Therefore, those systems tested in the field are usually evaluated by analytical evaluation or simulation tests in advance. Moreover, it is important to reevaluate TSP system when it has been operated for a long time to judge whether the system is providing continuing benefits.

In review of the literature, many successful field tests are reported around the world, such as those American cities (Sacramento County, California by Elias, 1976; NW seventh avenue in Miami by Wattleworth *et al.*, 1977), UK (Hounsell *et al.*, 1996; D'Souza *et al.*, 2010), Swansea (Cooper *et al.*, 1980), Sydney (Cornwell, 1986), Japan (Iwaoka *et al.*, 2000; Satiennam *et al.*, 2005), China (Qian *et al.*, 2007; Wu and Lin, 2007; Liang, 2011; Bi *et al.*, 2011), etc.

In general, the control logic in most actual TSP system is simple and easy-implemented, and the most common strategies are the unconditional and conditional priority control. Up to now, more than 109 cities around the world have implemented the TSP control system in the practice. According to the aforementioned MOEs, the results from field tests are shown in Table 2.

As shown in Table 2, more TSP control applications are found in USA and Europe. Also note that most of bus routes in USA and Europe are operated under timetable-based mode, and bus frequency is much lower than those in Asian. Their control objectives are mainly to maximize bus travel speed and promote bus vehicles into the next stop. In contrast, fewer TSP systems are implemented in most Asian countries. Up to now, it has been reported that only four cities in China has implemented unconditional TSP controls for bus routes operated at bus exclusive lanes, such as Beijing, Hangzhou (BRT routes), and Changzhou (BRT routes). For BRT system, Guangzhou Transit agencies reduced the number of phases and shorten cycle length to improve bus travel speed along arterial of having bus exclusive lane. Furthermore, from the TSP control applications of China and Japan, some key findings are summarized below:

(1) Bus detection technique is major GPS system, and the objective of TSP methods is to minimize the bus travel delay by priority to all detected buses;
(2) Under timetable-based operations, TSP control might provide much more benefits to bus vehicles if the bus routes have exclusive lane or bus queue jumper at intersections. If buses operate on the mixed lanes, the proper objective of TSP controls is to reduce travel time without considering bus-waiting time at stops.

Under headway-based modes for high bus volumes, it is quite difficult to decrease the variance of headways for many bus routes by active TSP controls because many buses are enforced to priority depending on the sequence of buses from different routes. Alternatively, the passive control may be a more proper method to improve the regularity of all buses along arterial, such as reducing the number of phases and shorten cycle length, optimizing signal timings of maximizing the throughput in bus passengers and passenger-car users.

Conclusion

This paper has provided an introduction of the existing TSP controls according to application and theoretical aspects. In fact, TSP has long been recognized as a promising method to improve public transit punctuality and reliability and attract more bus passengers to inhibit the growth rate of passenger cars. Currently, there are numerous priority control strategies and algorithms for different conditions. In reviews of literature, most studies focus on these three following aspects. First, early studies mainly explored different control strategies and analyzed the impact of priority control through analytical models, simulation tools, and field tests. Then, with the development of detection technology and signal control technologies, control strategies are extended to provide real-time priority service and further improve priority control effects by considering bus delay. Recently, most studies are reported to quantitative evaluate priority control feasibility and consider total passenger delay of the entire network.

Nowadays, transit-oriented development (TOD) has widely recognized as a promising mode of urban transport around the world. Transit signal priority control, as an efficient tool to enhance bus service, needs to be further improved and optimized from the systematic view. With increasing demand for public transport and passenger cars, TSP control will also become more complex with considering the impacts of bus sequence, bus dwelling time, bus arrival distribution, arterial coordination, etc. Therefore, the following researches need to be more extended:

- Most of TSP controls hardly considers bus passenger waiting time at downstream stations. However, for headway-based bus service, the saving of passenger waiting time could be a vital issue.
- With the growth of bus demand, bus bunching or overflow at bus stations could happen frequently if TSP control for multiple priority requests does not consider the impacts of bus sequence.
- Within coordinated arterials or networks, the traditional TSP control should analyze the impacts on overall coordination, especially for the active priority strategies. Otherwise, the extra discharging passenger-

Table 2 Effectiveness comparisons of TSP controls in different cities around the world

City	# nodes equipped	Priority for late buses only	Bus detection	Benefits	Impact on non-prioritized approaches
Oakland, USA	62	Yes	Encoded Infrared	About 9% time savings	Infinitesimal
Seattle, USA	28	No	Passive radio frequency	35–40% reduction in travel time, and 5·5–8% reduction in travel time variability during peak hours	Minimal
Los Angeles, USA	654	Yes	Loop detection	19–25% reduced travel times	Typically 1-s delay per vehicle per cycle
Chicago, USA	15	No	Loop detection	Average 15% (3 min) reduced running time	Impact studies show little impact
Tacoma, USA	110	No	Encoded Infrared	About 40% reductions in transit signal delay. 5–30% reduction in total signal delay on South. 19th Streat, and 18–21% on Pacific Ave.	Very little impact
Vancouver, USA	64	Yes	Encoded infrared and visual recognition technique	23% modal shift from auto to transit in the corridor, and significant reduction (40–50%) in travel time variability	No noticeable impact
London, UK	3200	Yes	GPS and odometer	9 s per bus at an isolated intersection, and 3–5 s per bus per node at SCOOT junctions in time savings	
Cardiff, UK	46	Yes	GPS	3–4% reduction in travel time, and improved schedule adherence	1–2% increase in travel time
Aalborg, Denmark	51	No	GPS and odometer	5·8 s per bus per node in delay saving, and 4% reduction in travel time	
Genoa, Italy	84	Yes	GPS	7–10% reduction in travel time	
Helsinki, Finland	Unknown	Yes	GPS, door opening sensor and odometer	11% reduction in travel time, an improvement of 20% in regularity and 58% in punctuality	
Malmo, Sweden	42	Unknown	GPS	Headway variability reduced from 10 to 7·5 min	
Prague, Czech republic	65	No	Beacon	2% reduction in travel time	
Stuttgart, Germany	34	Unknown	Infrared beacon and GPS	9–10 mile h^{-1} increase in travel speed	
Tallinn, Estonia	30	Unknown	Unknown	2 km h^{-1} increase in travel speed	
Toulouse, France	Unknown	Yes	GPS and odometer	5–24% decrease in travel time	
Auckland, New Zealand	174	No	GPS	11 s per bus per node delay saving	
Sydney, Australia	Unknown	Yes	GPS	Up to 21% reduction in travel time, and up to 49% reduction in travel time variability	
Kawasaki, Japan	Unknown	No	Infrared beacons	5·1% reduction in travel time, and 10·8% reduction in stop time	
Chiba, Japan	Unknown	No	Beacons	At Route No. 133 with four lanes arterial, 22% reduction in bus travel time, and 24% reduction in travel time for general traffic at main street. 3% reduction in travel time at Route No. 1 with two-lane arterial	At Route No.133 with multiple lanes arterial, 22% increase in travel time for general traffic at cross-street
Beijing, China	202	No	RFID	46·9% increase in travel speed during peak hours because of bus exclusive lane and signal priority control for route BRT1, and the number of BRT vehicles blocked by red signals is reduced by 4–6%. At the other street Zhongguancun Avenue for normal buses, 14·4% reduction in travel time during morning peak hours, and 7·1% reduction during evening peak hours	
Hangzhou, China	31	No	RFID	3·2 min per bus reduction in travel time	
Changzhou, China	Unknown	No	Loop detection	22% increase in travel speed	
Guangzhou, China	Unknown	No	No detection	40% increase in travel speed because of bus exclusive lane and signal priority control	Infinitesimal

GPS: global positioning system; SCOOT: split cycle offset optimization technique.

cars at the bus approaches will increase the initial queue length at the downstream intersections and destroy the coordination.

- Most of the priority controls slightly adjust signal timings based on the existing signal timing plans when bus vehicles arrive at the intersections. However, the bus benefit obtained by this method is very limited. Therefore, one should further consider bus operation nature when designing the base signal timing plans at local arterials.

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