

Design of Transit Signal Priority at Signalized Intersections with Queue Jumper Lanes

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Abstract

A queue jumper lane is a special bus preferential treatment that combines a short stretch of a special lane with a transit signal priority (TSP) to allow buses to bypass waiting queues of traffic and then to cut out in front of the queue by getting an early green signal. This paper first proposes a signal control design for queue jumper lanes with actuated TSP strategies and then compares its performance with that of the general actuated mixed-lane TSP. Different design alternatives were evaluated in the VISSIM microscopic simulation. The results show that the proposed TSP with queue jumper lanes can reduce more bus delays than can the commonly-used mixed-lane TSP, especially under high traffic volume conditions. It was also found that a near-side bus stop is superior to the far-side counterpart in terms of both bus delay and overall intersection delay for the proposed design.

Introduction

The provision of transit signal priority (TSP) on arterial streets is a transit preferential treatment that has received increasing attention in North America. In practice, however, studies have shown that TSP is ineffective during peak hours because buses are not able to bypass the long waiting queues during these hours

(Nowline 1997; Head 1998; Balke 2000). This paradox has had a limiting effect on the applications of TSP in practice.

A special type of bus preferential treatment that has the potential of avoiding this weakness is queue jumper lanes. A queue jumper lane combines a short stretch of a special lane, such as a right-turn lane, with signal priority to allow buses to bypass a waiting queue of traffic and then to cut out in front of the queue by getting an early green signal. Figure 1 shows an intersection with a standard queue jumper lane design. A queue jumper lane can essentially operate like a bus lane at the vicinity of an intersection. However, unlike bus lanes, a queue jumper lane does not take a lane away from the general traffic, making its implementation easier to justify. Instead, a queue jumper lane makes full use of an existing right- or left-turn bay that generally operates under low saturation conditions. In addition, the queue-bypassing capability of a queue jumper lane can avoid the queue uncertainties that limit the effectiveness of mixed-lane TSP, especially under congested conditions. When implemented with TSP, hereafter referred to as the jumper TSP, a queue jumper lane can potentially be more effective than a typical mixed-lane TSP and be more feasible than bus lanes (Zhou 2005, 2006).

While the queue bypassing capability of a queue jumper lane is similar to that of a bus lane, the operations of a queue jumper lane are quite different from a bus lane and deserve separate design considerations. Unlike a bus lane, a queue jumper lane requires that buses yield and wait for an acceptable gap to merge back into the main flow downstream. Consequently, the design of jumper TSP, including both the phasing and phase split, is also very different from that of bus lanes or mixed-lane TSP strategies.

The objectives of this paper are twofold. The first objective is to propose an actuated TSP strategy and its associated signal control designs for a queue jumper lane. In an actuated TSP strategy, a priority signal is provided only when a request from a bus is detected. The second objective is to evaluate the performance of the proposed queue jumper TSP strategy by comparing it with the general actuated mixed-lane TSP. The next section presents the design of various signal design elements for TSP and queue jumper lanes, including phasing, phase splits, multiple bus services, and coordination recovery and green reimbursement. This is followed by the implementation of the proposed designs in a simulation testbed for a performance evaluation with mixed-lane TSP. The results are then presented and conclusions drawn.

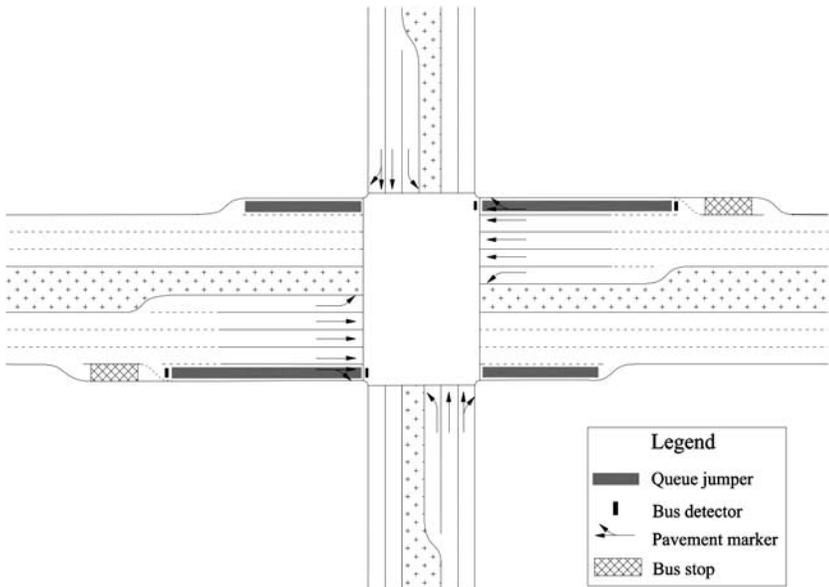


Figure 1. Configuration of a Queue Jumper Lane with Actuated TSP

Signal Design

As mentioned, this study considers a traffic actuated TSP strategy for jumper lanes that can actively respond to bus requests. Obviously, an actuated TSP system must have the ability to detect the presence of a bus at an intersection. Two kinds of detectors are generally used for bus detection: check-in detectors and check-out detectors (Liu 2004). A check-in detector is responsible for the detection of an arriving bus. Once a bus request is detected, a signal controller will activate the TSP control logic. Check-in detectors generally are located upstream of the jumper lane and are set at the downstream of a near-side bus stop to avoid uncertainties associated with bus dwell time. Check-out detectors are installed immediately downstream of the stopline on the jumper lane to detect bus departures from the stopline.

In this study, the following three actuated TSP strategies are considered: “green extension,” “early green,” and “phase insertion.” The “green extension” strategy extends the green time for a bus arriving at the end of a normal green phase and allows the bus to pass through the intersection without stopping. The “early green” strategy shortens the duration of the non-priority phases to the minimum green time when a bus priority call is requested during the red interval. Hence, it

returns the green time for the bus earlier than it would under the normal circumstances. In the “phase insertion” strategy, a special lead phase for the exclusive use of queue jumper lanes is inserted to allow buses to bypass the queue and then merge back into the main flow. Additional strategies implemented in this study include: (1) “coordination recovery” to maintain the signal coordination of the major-street through-traffic by returning to the coordination status in the immediate signal cycle after TSP is provided, and (2) “green reimbursement” to provide additional green time to the phases whose green times in the previous cycle(s) were shortened due to TSP service of bus arrivals. The last two TSP strategies are further detailed in the following sections.

Phasing

For a queue jumper lane to operate effectively, a lead phase for the exclusive uses of buses is needed to allow buses to bypass the queue and then merge back in front of the general through-traffic. During this lead phase, the through-traffic on the same approach is stopped. The lead phase is activated upon detection of a bus arrival during the red time. Figure 2 proposes a phasing design for a typical four-leg intersection with jumper lanes for both arterial approaches.

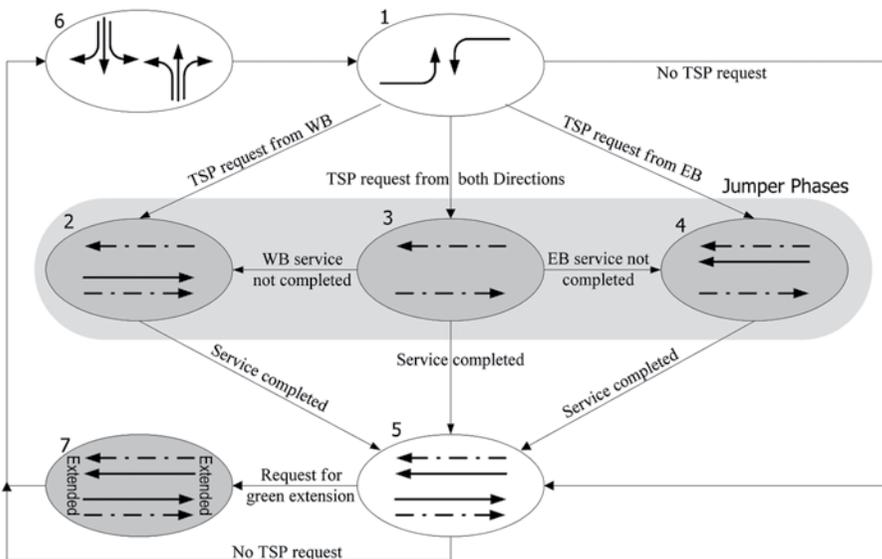


Figure 2. Jumper TSP Phase Design

In the phase diagram, the movements for queue jumper lanes are shown with dashed lines and the movements for the normal lanes are shown with solid lines. The three non-shaded phases (phases 1, 5, and 6) are used under normal conditions when the jumper TSP is not activated. The three shaded phases (phases 2, 3, and 4) are jumper phases designed for various bus requests during the red time from both directions of the arterial. Either phase 2 or phase 4 is activated when bus requests occur only on one arterial approach. When buses are detected on both arterial approaches simultaneously, phase 3 is activated. At the end of phase 3, if there are still bus requests that are not served in either jumper lane, the corresponding phase 2 or phase 4 will follow. During the jumper phases, the general traffic on the same approach(es) is/are stopped in order for the bus in the jumper lane to merge back into the main traffic flow at the downstream jumper lane. Phase 7 is activated when a bus requests a green extension.

Phase Splits

The signal cycle length and normal green time for each normal phase can be estimated using the Webster method for fixed-time signal timing. If the volume-to-capacity (v/c) ratios for the non-bus phases (phases 1 and 6) are at the low or medium saturation level (say, $v/c < 0.85$), the minimum green time for these phases, assuming that there are no pedestrians, can be calculated as follows:

$$g_{\min i} = g_{\text{normal } i} * (v/c)_i \quad (1)$$

where

$g_{\min i}$ is the minimum green time for normal phase i ,

$g_{\text{normal } i}$ is the normal green time for normal phase i without TSP provided, and

$(v/c)_i$ is the traffic volume-to-capacity for normal phase i .

The timing of the lead phase is determined based on the following considerations:

1. Whether a bus is serviced.
2. Whether new bus requests are detected on the jumper lanes.
3. Whether a right-turn queue exists and for how long.
4. Average bus start-up lost time, acceleration, and speed in the intersection area.
5. Lengths of upstream and downstream jumper lanes.

Like a typical actuated phase, the green time for the lead phase is constrained by its maximum green time. The lead phase is terminated by either a check-out detector or the maximum green time. If bus requests are received but have not been serviced, or if multiple bus requests occur in a jumper lane, the green time for the lead phase will last through the maximum green time. The determination of the maximum green time for a lead phase should consider some special cases when the green signal returns early to the jumper lane immediately after the detection of a bus request. In these cases, the green time needed for a bus to check out consists of two parts: (1) bus travel time from the check-in detector to the stopline, and (2) the discharge time of a right-turn vehicle queue before the arriving bus. Additional time should be included if continuous services to multiple bus requests on the same approach are permitted.

To simplify the calculation, it was assumed that during the red time the right-turn vehicles can make use of the unsaturated green time of other phases, and that the arrivals of the right-turn traffic are uniform throughout each signal cycle at isolated intersections. The maximum green time includes three components: the bus travel time from check-in detector to stop-line, the discharge time for right-turn vehicles queuing in the jumper lane, and the additional time for multiple bus requests in the same approach. Equations (2-4) show the calculation of the maximum green time:

$$t_{\max} = t_{\text{travel}} + t_{\text{RTdisch}} + \Delta t_{\text{multiple}} \tag{2}$$

$$t_{\text{travel}} = \frac{L_{\text{up}}}{V_{\text{bus}}} \tag{3}$$

$$t_{\text{RTdisch}} = \frac{Q_{\text{RT}} * \sum_{i=1}^k (x_i g_i)}{3600} * h_{\text{RT}} \tag{4}$$

where

t_{\max} is the maximum green time for lead phase

t_{RTdisch} is the discharge time for right-turn vehicles queuing in the jumper lane

t_{travel} is bus travel time from check-in detector to stopline

V_{bus} is the average free flow speed of buses in the jumper lane

$\Delta t_{\text{multiple}}$ is the additional time for multiple bus requests in the same approach

L_{up} is the distance from check-in detector to the stopline of a jumper lane

Q_{RT} is the flow rate of right-turn traffic in the jumper lane (pcph)

k is the number of normal phases other than the phase for major-street through-traffic

x_i is the design saturation level for phase i

g_i is the green time for phase i

h_{RT} is the average saturation headway for right-turn vehicles

To allow buses in a jumper lane to merge back easily to the main flow of traffic, a safety interval is inserted between the lead phase and the normal through phase. The safety interval can be calculated as follows:

$$t_{\text{safe}} = (t_{\text{bus}} - t_{\text{general}}) + \gamma, \text{ (if computed } t_{\text{safe}} < 0, \text{ then set } t_{\text{safe}} = 0) \quad (5)$$

$$t_{\text{bus}} = \frac{L_{\text{down}}}{V_{\text{bus}}} - \frac{V_{\text{bus}}}{2a_{\text{bus}}} \quad (6)$$

$$t_{\text{general}} = t_{L\text{general}} + \frac{L_{\text{down}}}{V_{\text{general}}} - \frac{V_{\text{general}}}{2a_{\text{general}}} \quad (7)$$

where:

t_{safe} is the safety interval between the lead phase and the general through phase

t_{bus} is the bus travel time from the check-out detector to the end of jumper lane

t_{general} is the general traffic travel time including start-up lost time from the stopline to the end of the jumper lane

γ is a constant term (1-2 seconds)

L_{down} is the distance from the stopline of a jumper lane to the end of a downstream jumper lane

a_{bus} is the average acceleration of buses in the jumper lane

a_{general} is the average acceleration of the general traffic

t_{Lgeneral} is the start-up lost time for the general traffic

V_{general} is the average free flow speed of the general traffic in an intersection area

To simplify the determination of the maximum green time for the extended phase (i.e., phase 7 in Figure 2), it is assumed that there is no vehicle queue before an arriving bus at the end of the normal green time. Thus, only two time components are included: the bus travel time from the check-in detector to the stopline and the additional time for multiple bus requests.

Multiple Bus Requests

Depending on bus arrival conditions, signal strategies for multiple bus requests can involve the following cases:

1. Multiple bus requests occur in the same approach and can be serviced during one TSP phase. In this case, the bus requests can be serviced by extending the green time of the TSP phase (lead phases 2, or 4, or extension phase 7, as shown in Figure 2). To reduce its adverse impact on the non-TSP phases, the extended TSP phase is limited by the maximum green time, as described previously.
2. Multiple bus requests occur in different approaches and can be serviced during one TSP phase. In this case, either lead phase 3 or extension phase 7, as shown in Figure 2, is called to service the requests. For lead phase 3, at least one request occurs in each major-street approach and is detected before phase 3 is activated. If a bus request in one approach is not serviced at the end of phase 3, phase 2 or phase 4 is called next. The possible serviced requests are also limited by the corresponding maximum green times.
3. Multiple bus requests occur and should be serviced in the lead TSP phases and the extension TSP phase (phase 7). In this case, TSP services can be called on no more than twice in one or two continuous signal cycles in order to reduce their adverse impact on the other phases. For example, if there are

three bus requests, one may be serviced in the lead phase, another may be serviced in the extension phase, but the third will not receive any priority.

Coordination Recovery and Green Reimbursement

When the TSP phases are called to service bus requests, the normal signal operation will be interrupted, and the green split and signal cycle may be changed. This may cause the major-street through-traffic to become uncoordinated. To recover arterial coordination following a TSP service, the signal cycle length and the normal green splits must be adjusted. As mentioned, the purpose of green reimbursement is to reimburse green time to the phases that were shortened to provide TSP services in the previous cycle(s). Together, these two strategies are integrated to mitigate the adverse impact of TSP services on the general traffic. Figure 3 describes the coordination recovery and the green reimbursement strategies according to different bus arrival types.

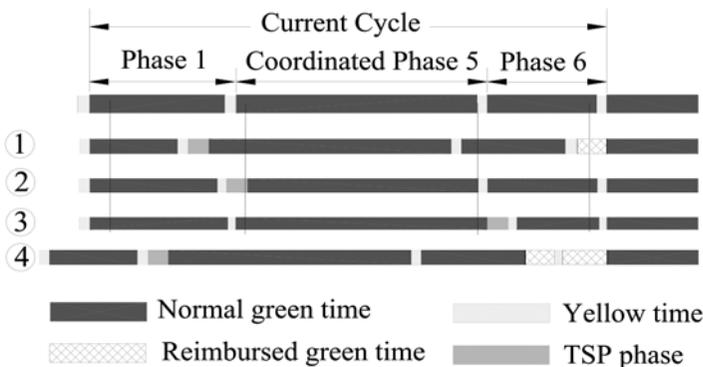


Figure 3. Coordination Recovery and Green Reimbursement

The first signal bar in Figure 3 represents a normal signal cycle and part of the green time of the first phase in the next signal cycle. The signal adjustment strategies for each case are described as follows:

1. If buses arrive during phase 1, as shown in signal bar 1 in Figure 3, the green time for phase 1 will be shortened to service the lead phase early (phase 2, 3, or 4). At this point, the green signal for phase 5 will start in advance. In this case, the green times for phase 5 and phase 6 will remain the same as their normal green times. The additional green time before the normal start

point of the next signal cycle will be reimbursed to phase 1 in the following cycle. Thus, the next signal cycle can be recovered to the normal status.

2. If buses arrive at the end of phase 1 and have to take part of the normal green time of phase 5, as shown in signal bar 2 in Figure 3, phase 5 will be terminated at the normal end point and the next phase will remain normal.
3. If buses arrive at the end of phase 5, the green time for phase 5 will be extended (phase 7), as shown in signal bar 3 in Figure 3. The green time for phase 6 will be shortened to allow the next cycle to start on time.
4. If buses arrive during phase 6 of the previous signal cycle, this phase plus phase 1 of the current cycle will be shortened to return the green signal to the lead phase early (phase 2, 3 or 4), as shown in signal bar 4 in Figure 3. The saved cycle time from phase 6 and phase 1 will be used to cover the lead phase(s), as well as the reimbursement time of phase 6 of the current cycle and phase 1 of the following cycle. This allows the next cycle to return to coordination. The reimbursed green time to phase 6 and phase 1 can be calculated individually by Equations (8) and (9) below:

$$g_{\text{reimb } 6} = (\Delta g_6 + \Delta g_1 - g_{\text{lead}}) \frac{\Delta g_6}{\Delta g_6 + \Delta g_1} \quad (\text{if } g_{\text{reimb } 6} < 0, \text{ then set } g_{\text{reimb } x} = 0) \quad (8)$$

$$g_{\text{reimb } 1} = (\Delta g_6 + \Delta g_1 - g_{\text{lead}}) \frac{\Delta g_1}{\Delta g_6 + \Delta g_1} \quad (\text{if } g_{\text{reimb } 1} < 0, \text{ then set } g_{\text{reimb } x} = 0) \quad (9)$$

where

$g_{\text{reimb } 6}$ is the reimbursed green time to phase 6

$g_{\text{reimb } 1}$ is the reimbursed green time to phase 1

Δg_j is the loss of green time for phase j

g_{lead} is the green time for the lead phase

5. For multiple TSP services, which may occur in one cycle or two continuous cycles, the saved cycle time will be cumulated and reimbursed in proportion to the green losses incurred by the corresponding phases using the following equation:

$$g_{\text{reimb } j} = (\sum \Delta g_j - \sum g_{\text{lead } k}) \frac{\Delta g_j}{\sum \Delta g_j} \text{ (if } g_{\text{reimb } j} < 0, \text{ then set } g_{\text{reimb } j} = 0) \quad (10)$$

where

$g_{\text{reimb } j}$ is the reimbursed green time to phase j

$g_{\text{lead } k}$ is the green time for lead phase k

Simulation Implementation

Because of the complex nature of traffic and human behaviors, TSP evaluation is increasingly relying on simulation tools (Dale 1999). VISSIM, a simulation tool known for its strengths in modeling transit operations, is selected for this study to simulate the different TSP design strategies with queue jumper lanes under different traffic scenarios. Modeling TSP control strategies in VISSIM requires three main input files: (1) network configuration file *.inp, (2) TSP control logic file *.vap, and (3) phase and inter-phase definition file *.pua. The intersection simulated is assumed to have the same configuration, as shown in Figure 1. As shown, two bus stops are installed along the upstream jumper lane immediately behind the entry of the jumper lane, and there are three through lanes, one left-turn pocket, and one right-turn bay (jumper lane) for major-street approaches.

In this study, the performance of jumper TSP is compared with typical TSP applications with mixed lanes. The same TSP strategies, including early green, green extension, coordination recovery, and green reimbursement, were applied to both jumper and mixed-lane TSP. The only difference was that the jumper phase (i.e., phase 2, 3, or 4) was applicable only to jumper TSP.

Because bus stop locations are known to have a major impact on bus operation, the performance comparison also considers both near-side and far-side bus stops. The near-side bus stops were located along the jumper lanes for jumper TSP, as shown in Figure 1. These stops were installed immediately upstream of the check-in detectors to avoid impact on the TSP operations from bus dwell time variations. For mixed-lane TSP, the near-side bus stops are designed with bus bays and are located at the same locations as those of jumper TSP. The far-side bus stops for both mixed-lane TSP and jumper TSP were set along the same downstream right-turn pocket. Thus, in the case of mixed-lane TSP, the right-turn pocket serves as an extended bus bay. For jumper TSP with a far-side bus stop, no

lead phases were included. This is obviously because buses are assumed to dwell at the bus stop and cannot make use of the lead phase effectively.

To analyze the sensitivity of the proposed jumper TSP under various traffic and control conditions, a series of simulation runs was created by varying one parameter at a time while keeping all of the other parameters constant. Two volume cases were tested: through volume and bus volume on the major street. Each of the volume cases includes eight volume levels ranging from low to high. The Webster method was used to determine the optimal cycle length and the normal green split (phases 1, 5, and 6) for both mixed-lane and jumper TSP.

Table 1 shows the input values used to create the simulation scenarios. Average travel delays, including those for bus vehicle delay, major-street through vehicle delay, minor-street through vehicle delay, and intersection vehicle delay, were used as measures of effectiveness (MOEs) to measure the performance of the two alternatives. To reduce the effect of simulation randomness, five simulation runs with different random seeds for each simulation input were performed. The MOEs for each simulation input were then averaged from the five runs. The length of simulation time was two hours for all runs.

Table 1. Traffic Volumes for Simulation Runs (veh/h)

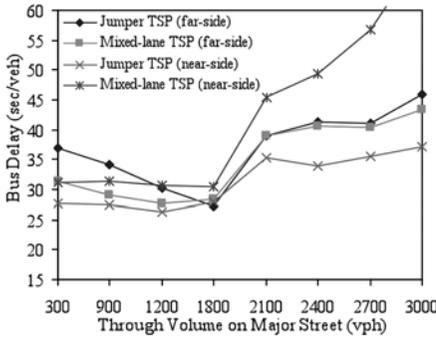
| Sources | Major street | Minor street |
|---------------------------------------|--|--------------|
| Default Values: Left-turn volumes | 240 | 20 |
| Through volumes | 2300 | 600 |
| Right-turn volumes | 240 | 80 |
| Bus volumes | 12 | 0 |
| Variants: Major-street through volume | 300, 580, 1100, 1500, 2300, 2750, 3000, 3450 | |
| Major-street bus volume | 3, 4, 6, 12, 20, 30, 40, 60 | |

Performance Evaluation

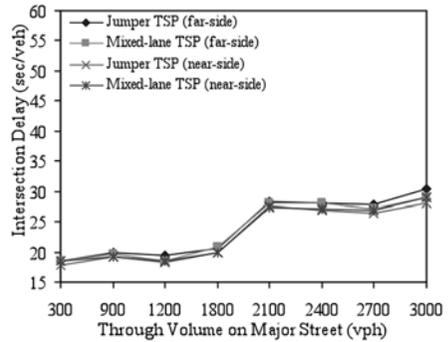
In this section, the performance of jumper TSP is analyzed by comparing it with that of mixed-lane TSP under various levels of major-street through-traffic and bus volumes. Both near-side and far-side bus stops were considered.

Under various major-street through-traffic volumes that range from 100 vphpl to 1,000 vphpl, it was found that jumper TSP with a near-side bus stop is the most beneficial design among the four alternatives. Figure 4(a) shows that jumper TSP with a near-side bus stop can reduce bus delay by up to 25 percent when

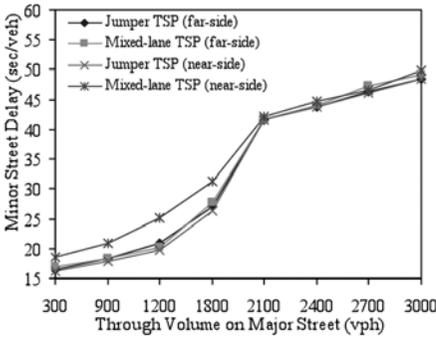
compared with jumper TSP with a far-side bus stop. This is because a TSP with a near-side bus stop can take advantage of the lead phase to jump in front of the through-traffic flow.



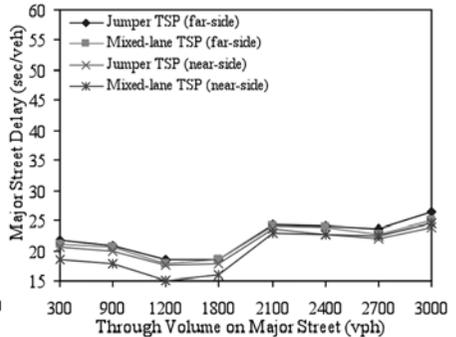
(a). Bus Delay



(b) Intersection Delay



(c) Minor Street Delay



(d) Major Street Delay

Figure 4. Performance Comparisons Under Various Through Volumes

It is also illustrated in Figure 4(a) that jumper TSP with a near-side bus stop is more beneficial than mixed-lane TSP with either a near-side or a far-side bus stop, resulting in a 3 to 17 percent reduction in bus delay for the far side and a 10 to 50 percent reduction in bus delay for the near side. The advantage becomes more prevalent under high traffic volume levels. Figures 4(b), (c), and (d) show that jumper TSP with a near-side bus stop slightly improves the operation of the entire intersection operation and has the lowest impact on the minor-street traffic operation. This is expected because the major-street through-traffic can gain more green time

from phases 2 and 4. For the minor-street traffic, the reduction in green time due to the early return of green to the bus approach is limited by the minimum green time, which was set to 90 percent of the normal green time. Furthermore, green reimbursement strategies also reduce the adverse impact of TSP callings to the lowest possible.

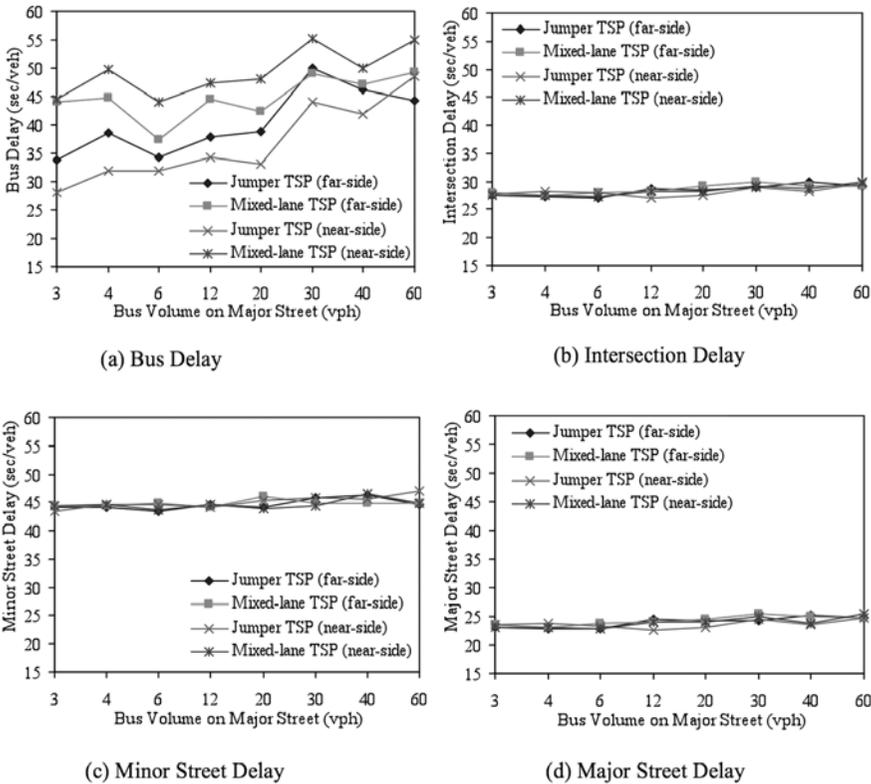


Figure 5. Performance Comparisons Under Various Bus Volumes

Figure 5(a) shows that, under various bus volumes that range from 3 to 60 vph, bus delays generally increase with bus volumes. The trends are similar among all four alternatives. This is because continuous calls for TSP phases were limited to no more than two (i.e., extra bus requests will be ignored and the corresponding bus arrivals will incur more delays). However, the bus delay for jumper TSP with a near-side bus stop is the lowest for most levels of bus volumes. Figures 5(b), (c), and (d) show that the impact of bus volumes on the general traffic are similar for

all four alternative TSP designs. This is expected as the general bus frequencies do not significantly affect the traffic load on the same approach.

Conclusions

In this study, an effective design of TSP with queue jumper lanes has been proposed, including special phase design, signal timing parameter determination, coordination recovery and green reimbursement strategies, and a strategy for multiple bus requests for priority service. The performance of the proposed jumper TSP was evaluated in a micro-simulation environment by comparing its performance with that of the general mixed-lane TSP under various traffic volumes and bus stop locations. The simulation results demonstrated that jumper TSP with a near-side bus stop and a consequent reduction of bus delay up to 25 percent is superior to its far-side counterpart. The simulation results also showed that jumper TSP with a near-side bus stop can reduce bus delay by 3 to 17 percent when compared with mixed-lane TSP with a far-side bus stop, which was the most commonly-used TSP design. The advantages become more prevalent in situations involving high traffic volumes. The simulation results also showed that major-street general traffic can also benefit from jumper TSP phases and the adverse impact on minor-street general traffic can be reduced to a negligible level through proper coordination recovery and reimbursement strategies. It was also shown that the impact of bus volumes on the general traffic on both major and minor streets is not significantly different from the mixed-lane TSP. This is achieved by limiting the continuous calls for TSP to no more than two.

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