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Analytical and simulation approaches to understand combined effects of transit signal priority and road-space priority measures ☆

Long Tien Truong [a,*], Graham Currie [a], Majid Sarvi [b]

[a] Public Transport Research Group, Institute of Transport Studies, Department of Civil Engineering, Monash University, 23 College Walk, Clayton, Victoria 3800, Australia

[b] Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia

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ABSTRACT

Transit signal priority (TSP) may be combined with road-space priority (RSP) measures to increase its effectiveness. Previous studies have investigated the combination of TSP and RSP measures, such as TSP with dedicated bus lanes (DBLs) and TSP with queue jump lanes (QJLs). However, in these studies, combined effects are usually not compared with separate effects of each measure. In addition, there is no comprehensive study dedicated to understanding combined effects of TSP and RSP measures. It remains unclear whether combining TSP and RSP measures creates an additive effect where the combined effect of TSP and RSP measures is equal to the sum of their separate effects. The existence of such an additive effect would suggest considerable benefits from combining TSP and RSP measures. This paper explores combined effects of TSP and RSP measures, including TSP with DBLs and TSP with QJLs. Analytical results based on time-space diagrams indicate that at an intersection level, the combined effect on bus delay savings is smaller than the additive effect if there is no nearside bus stop and the traffic condition in the base case is under-saturated or near-saturated. With a near-side bus stop, the combined effect on bus delay savings at an intersection level can be better than the additive effect (or over-additive effect), depending on dwell time, distance from the bus stop to the stop line, traffic demand, and cycle length. In addition, analytical results suggest that at an arterial level, the combined effect on bus delay savings can be the over-additive effect with suitable signal offsets. These results are confirmed by a micro-simulation case study. Combined effects on arterial and side-street traffic delays are also discussed.

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1. Introduction

Public transport (PT) systems provide an effective means of transporting a large number of passengers around cities and therefore can reduce urban traffic congestion. However, urban traffic congestion also significantly affects PT systems, leading to increases in PT travel times and service irregularity. Providing priority to PT vehicles hence is crucial to improve PT travel time and travel time reliability.

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* Corresponding author.
E-mail address: long.truong@monash.edu (L.T. Truong).

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Transit signal priority (TSP), which adjusts traffic signal timings at intersections to give priority to PT vehicles, is a cost-effective option. TSP can be categorised as passive, active, and adaptive priority (Baker et al., 2002). Passive priority usually involves optimising signal timing offline to give priority for PT vehicles, such as offset optimization (Estrada et al., 2009). Following the detection of PT vehicles, active priority dynamically adjusts signal timings to facilitate their movements. A number of active priority strategies have been investigated in previous studies, including green extension, early green, actuated transit phases, phase insertion, and phase rotation strategies (Lee et al., 2005; Skabardonis and Geroliminis, 2008; Ekeila et al., 2009). Adaptive priority gives priority to PT vehicles while optimising certain measures of performance such as total person delay (Christofa et al., 2013). Moreover, TSP can improve regularity by giving priority conditionally, e.g. to a bus behind schedule or based on the comparison of the headway of a bus with the scheduled headway (Hounsell and Shrestha, 2012). The effectiveness of TSP measures has been reported in previous studies, which employs empirical approaches (Furth and Muller, 2000; Kimpel et al., 2005), simulation approaches (Stevanovic et al., 2008; Shourijeh et al., 2013), and analytical approaches (Lin, 2002). A potential adverse impact of TSP however is the increase in side street delay. Moreover, the effectiveness of TSP can be compromised with heavy conflicting traffic since traffic signals need to accommodate both PT and general traffic at the same time.

To increase its effectiveness, TSP may be combined with road-space priority (RSP) measures such as dedicated bus lanes (DBLs) and queue jump lanes (QJLs). DBLs have long been used to improve PT travel time and travel time reliability and their performance has been investigated in a number of studies (Shalaby and Soberman, 1994; Waterson et al., 2003; Currie et al., 2007; Surprenant-Legault and El-Geneidy, 2011; Truong et al., 2015). A QJL is a short bus lane at traffic signals, which allows buses to travel in and then move forward from a left or right turning lane depending on left-hand or right-hand driving, bypassing traffic queues in adjacent lanes (TCRP, 2010; Farid et al., 2015). Previous studies have investigated the combination of TSP and RSP measures, such as TSP with DBLs (Sakamoto et al., 2007; TCRP, 2010; Ma et al., 2013) or TSP with QJLs (Zhou et al., 2006; Lahon, 2011). In these studies, combined effects are usually not compared with separate effects of TSP or RSP measures. Recently, a micro-simulation study has suggested a possible cumulative effect from combining TSP with QJLs (Zlatkovic et al., 2013). However, there is no comprehensive study dedicated to understanding combined effects of TSP and RSP measures. It remains unclear whether combining TSP and RSP measures creates an additive effect where the combined effect of TSP and RSP measures is equal to the sum of their separate effects. The existence of such an additive effect would suggest considerable benefits from combining TSP and RSP measures.

This paper explores the combined effects of TSP and RSP measures, including TSP with DBLs and TSP with QJLs. Time-space diagrams are used to analyse the combined effect on bus delay at an isolated intersection and at a signalized arterial. An analytical delay model is also proposed to further examine the effects of TSP and RSP measures at an intersection level, accounting for near-side stops. A case study using traffic micro-simulation is then adopted to evaluate analytical results and further investigate the combined effects on arterial and side-street traffic delays.

This paper is organized as follows: a time-space analysis of the combination of TSP and DBLs is presented first, followed by an analysis of the combination of TSP and QJLs, both at an isolated intersection level. A discussion on the combined effects at an arterial level is then given. An analytical delay model is presented next. A simulation case study is then presented, followed by a summary of key findings.

2. Time-space diagram analysis

2.1. Isolated intersection level

2.1.1. TSP with DBLs

Two typical TSP strategies are considered in this paper, including green extension and early green strategies with a predetermined maximum priority time (e seconds). A time-space analysis is undertaken for a common cycle length (c) with the effective red time of r seconds and the effective green time of g seconds in the base case. Let t denote the projected arrival time of a bus at the stop line in free-flow traffic condition, t_0 denote the departure time of a bus from the stop line in the base case, t_1 denote the departure time in the DBL case, t_2 is the departure time in the TSP case, t_3 is the departure time in the TSP with DBLs case. Δ_1 is bus delay saving in the DBL case ($\Delta_1 = t_0 - t_1$), Δ_2 is bus delay saving in the TSP case ($\Delta_2 = t_0 - t_2$), and Δ_3 is bus delay saving in the TSP with DBLs case ($\Delta_3 = t_0 - t_3$). Thus the combined effect is an additive effect if $\Delta_1 + \Delta_2 - \Delta_3 = 0$ and better than an additive effect (hereinafter over-additive effect) if $\Delta_1 + \Delta_2 - \Delta_3 < 0$. In this analysis, all possible bus arrivals within a cycle is considered ($t \in [0, c)$).

Fig. 1 depicts bus trajectories in time-space diagrams by different priority and bus arrival cases. It is noted that the queue forming shockwave (v_1) and the queue discharging shockwave (v_2) presented are for the base case. In addition, the slope of the queue forming shockwave can vary with different traffic arrival rates. In this analysis, it is assumed that there is no near-side bus stop and traffic conditions in the base case are under-saturated or near-saturated. These assumptions will be relaxed later in the following sections.

Case 1 ($t < e$): In this case, the bus can be served by the green extension strategy. Therefore, in the TSP case or TSP with DBLs case, the bus will cross the intersection without delay ($t = t_2 = t_3$). In other words, bus delay savings in the TSP case and TSP with DBL case are equal ($\Delta_2 = \Delta_3$). In the DBL case, the bus will depart from the stop line at the beginning of the

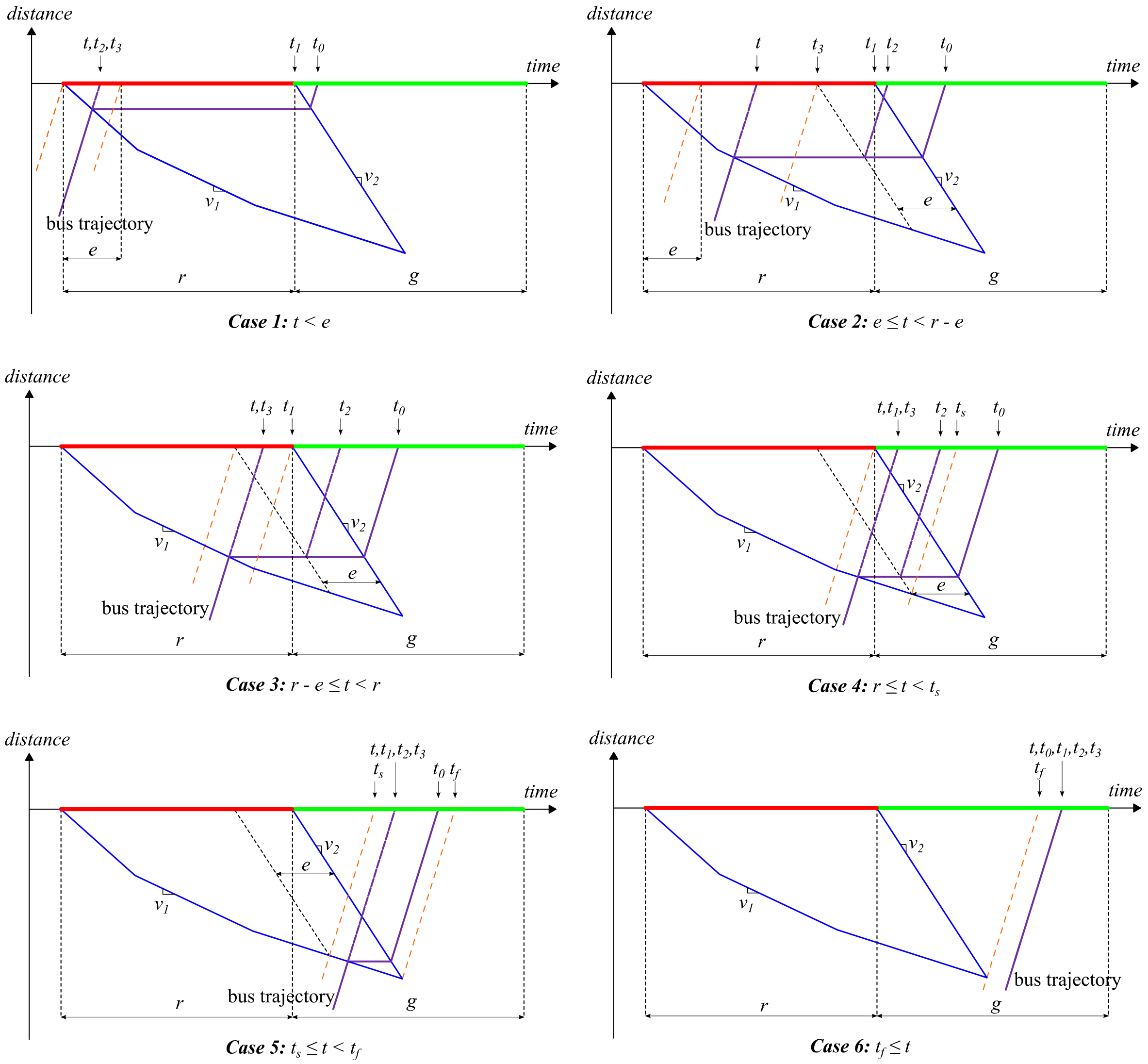

Fig. 1. Time-space diagrams with different priority and bus arrival cases. Note: red = effective red time, green = effective green time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

green time. It can be seen that $\Delta_1 \leqslant e$ as the slope of v_2 is greater than that of v_1. As a result, $e \geqslant \Delta_1 + \Delta_2 - \Delta_3 > 0$, indicating an overlapping effect, which is smaller than the additive effect.

Case 2 ($e \leqslant t < r - e$): In the TSP with DBLs case, the bus will stop at the stop line and depart at time $t_3 = r - e$ as the early green strategy is activated with the maximum priority time. In the DBL case, the bus will cross the intersection at the beginning of green time. In the TSP case, the bus will cross the intersection at time $t_2 = t_0 - e$ as the early green strategy is activated with the maximum priority time. Therefore, $\Delta_1 + \Delta_2 - \Delta_3 = 0$, suggesting an additive effect.

Case 3 ($r - e \leqslant t < r$): In the TSP with DBLs case, the bus will cross the intersection without delay ($t = t_3$). In DBL case, the bus will cross the intersection at the beginning of green time. In the TSP case, the bus will cross the intersection at time $t_2 = t_0 - e$ as the early green strategy is activated with the maximum priority time. It can be observed that $t_1 - t_3 \leqslant e$. Hence, $e \geqslant \Delta_1 + \Delta_2 - \Delta_3 > 0$, indicating an overlapping effect.

Case 4 ($r \leqslant t < t_s$) where t_s is the projected arrival time of the bus that experiences no delay as the maximum early green time is activated: In the DBL case or TSP with DBLs case, the bus will cross the intersection without delay ($t = t_1 = t_3$), indicating that bus delay savings in the DBL case and TSP with DBLs case are equal ($\Delta_1 = \Delta_3$). It can be observed that in the TSP case, the bus delay saving is equal to the maximum priority time ($\Delta_2 = e$). Therefore, $\Delta_1 + \Delta_2 - \Delta_3 = e$, suggesting an overlapping effect.

Case 5 ($t_s \leqslant t < t_f$) where t_f is the projected arrival time of the earliest bus that experiences no delay as the queue forming shockwave dissipates: In the DBL case, TSP case, and TSP with DBLs case, the bus will cross the intersection without being delayed. It can be seen that bus delay savings are smaller than or equal to the maximum priority time ($\Delta_1 = \Delta_2 = \Delta_3 \leqslant e$). Thus, $e \geqslant \Delta_1 + \Delta_2 - \Delta_3 > 0$, indicating an overlapping effect.

Case 6 ($t_f \leqslant t$): In all priority case and the base case, the bus will cross the intersection without being delayed. Therefore, bus delay savings in all priority cases are equal to zero.

Overall, there is an overlapping effect between DBLs and TSP. The additive effect only exists in one of the six bus arrival cases. It is clear that for an isolated intersection without a near-side stop, the combined effect of TSP and DBLs is smaller than the additive effect. However, if the maximum priority time is relatively small compared to the cycle time, the combined effect is close to the additive effect.

2.1.2. Over-saturated condition

When the traffic condition in the base case is over-saturated, there are situations where the combined effect of TSP and DBLs is the over-additive effect. For example, Fig. 2 illustrates that in the base case, if a bus arrives at the intersection when traffic queue is long and the projected arrival time t is red time of the following cycle, it first joins the traffic queue and then the residual queue of the following cycle (two stops). In the TSP case, the bus also encounters the residual queue and is served by the early green strategy in the following cycle. In the DBL case, the bus arrives at the stop line at the beginning of the red time of the following cycle and departs at the beginning of the green time. However, in the TSP with DBLs case, the bus experiences no delay as it is served by the green extension strategy. It can be seen that in this arrival situation, the combined effect is better than the additive effect.

Therefore, depending on bus arrival patterns, the combined effect can be the over-additive effect in over-saturated conditions. This suggests significant impacts of the combination of TSP with DBLs on bus delay savings in over-saturated conditions.

2.1.3. Impact of near-side bus stops

It is worth noting that the time-space analysis in previous sections assumes that there is no near-side bus stop. However, the presence of a near-side stop could affect the combined effect as suggested in Fig. 3. In the base case, a bus first joins a traffic queue before reaching a near-side stop, then encounters another traffic queue, and then crosses the intersection during the green time of the following cycle. Similarly, in the TSP case, the bus can only be provided with the early green strategy in the following cycle. In the DBL case, the bus crosses the intersection in the beginning of the green time of the following cycle. In the TSP with DBLs case, the bus is served by the green extension strategy and therefore crosses the intersection without being delayed. It can be seen that the combined effect of TSP with DBLs in this example is better than the additive effect. Therefore, the combined effects could be the over-additive effect with the presence of a near-side stop depending on bus arrival and dwell time patterns. The combined effect with near-side bus stops will be further examined in a numerical analysis using an analytical bus delay model and a case study using traffic micro-simulation.

2.1.4. TSP with QJLs

Note that similar time-space analyses can be undertaken for understanding the combined effect of TSP with QJLs. If a bus arrives when the traffic queue is shorter than the QJL, the QJL works as a DBL. If a bus arrives when the traffic queue is longer than the QJL, the QJL case performs as the base case while the TSP with QJLs case performs as the TSP case. Therefore, the combined effect of TSP and QJLs at an isolated intersection is also smaller than the additive effect when there is no nearside bus stop and the traffic condition in the base case is under-saturated or near-saturated. However, if there is a near-side bus stop or the traffic condition is over-saturated, the combined effect can be the over-additive effect depending on bus arrival and dwell time patterns.

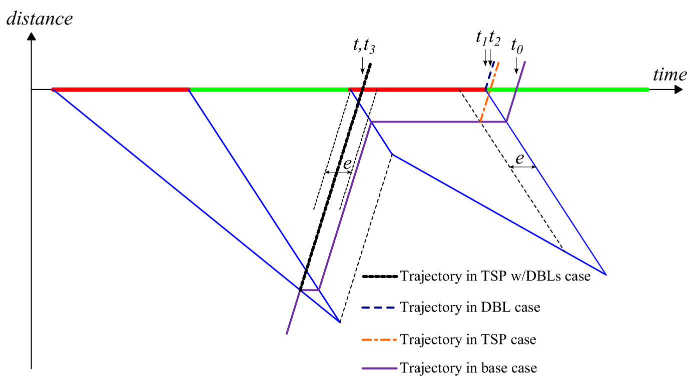

Fig. 2. Example of combined effects with over-saturated conditions in the base case. Note: red = effective red time, green = effective green time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

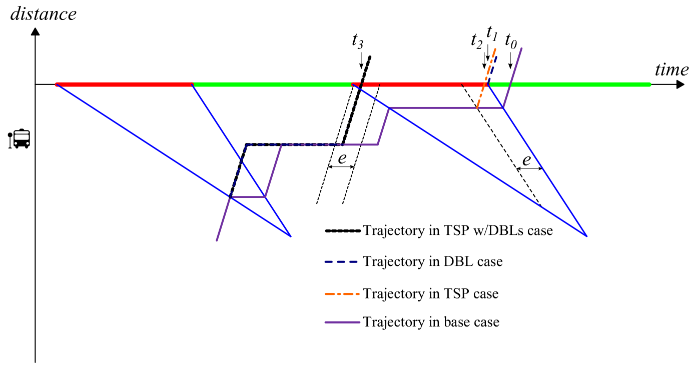

Fig. 3. Impact of a near-side stop on combined effects. Note: red = effective red time, green = effective green time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Arterial level

It is well-known that the performance of PT priority measures is affected by signal coordination (Skabardonis, 2000). For example, benefits obtained from upstream intersections may be reduced or even removed if the bus has to stop at the following intersection as a result of uncoordinated signals. In contrast, benefits obtained from upstream intersections may be enlarged if signal coordination and priority measures at the following intersection allow the bus to cross the intersection without being delayed.

Fig. 4 depicts that in certain arrival cases and offset settings, benefits from combining TSP and DBLs are considerably higher than the sum of benefits from individual measures. The queue forming shockwave and queue discharging shockwave are for the base case. In the base case, a bus encounters traffic queue at the upstream intersection, leaves the intersection during the green time, stops at the bus stop, and then encounters traffic queue at the downstream intersection. In the TSP case, the bus also encounters traffic queues and is provided with the early green strategy at both intersections. In the DBL case, the bus also has to wait at the stop lines of both intersections. The bus however crosses the two intersections without being delayed in the TSP with DBLs case. Based on bus trajectories in each priority cases, it can be derived that $\Delta_3 - (\Delta_1 + \Delta_2) > r' - 2e$. This indicates that the combined effect is the over-additive effect in this situation.

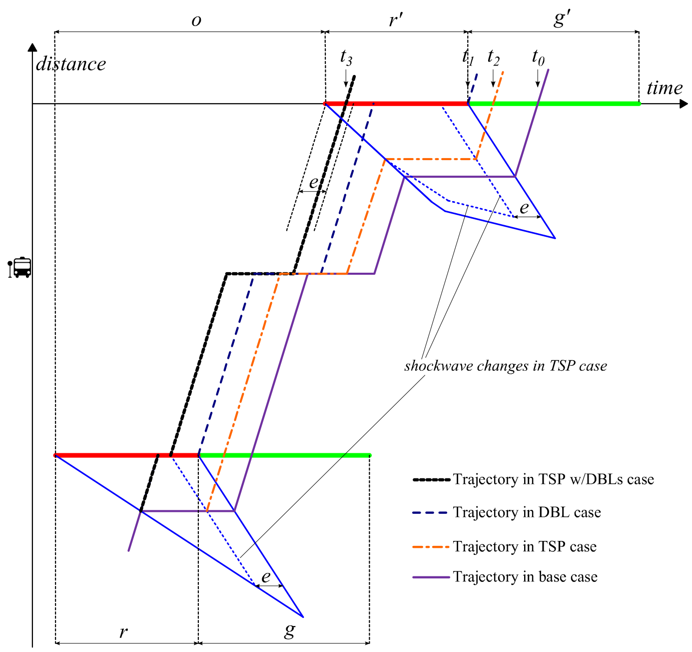

Fig. 4. Significant effect of combining TSP with DBLs with coordinated signals for bus progression. Note: red = effective red time, green = effective green time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Let T_{ff} denote the link free-flow travel time and $\bar{\theta}$ denote mean dwell time. Hence, if the offset (o) is calculated using Eq. (1), buses, which arrive at the upstream intersection with $e \leqslant t < r$, tend to be given early green priority at the upstream intersection and then green extension priority at the downstream intersection in the TSP with DBLs case and therefore cross the downstream intersection without further delay. These buses tend to be delayed at the downstream intersection in the DBL or TSP cases. Therefore, if the variation in bus dwell times is not too high, it is likely that the combined effect will be the over-additive effect.

$$o = r + T_{ff} + \bar{\theta} \tag{1}$$

It can be argued that with a similar offset setting, the combined effect of TSP and QJLs also can be the over-additive effect providing that dwell time variations are not high and the lengths of QJLs are sufficient. This hypothesis will be investigated in the case study.

3. Analytical bus delay model for isolated intersections and numerical analysis

3.1. Bus delay model

Kinematic wave theory (Lighthill and Whitham, 1955; Richards, 1956) has been employed to examine impacts of a near-side bus stop on bus delay in mixed traffic in few studies (Furth and SanClemente, 2006; Gu et al., 2014). In this paper, an analytical model based on kinematic wave theory and a triangular fundamental diagram is developed to investigate impacts of a near-side bus stop on the combined effect of TSP and DBLs. For simplicity in formulating the analytical model, it is assumed that traffic arrival rate is constant and traffic condition is under-saturated. Note that the time-space diagram analysis in Section 2.1 can deal with variable traffic arrival rates, but not a near-side stop.

Fig. 5 illustrates a triangular fundamental diagram with parameters: v_f as the free-flow speed, s as the saturation flow rate, k_j as the jam density, and w as congested shockwave speed. Arrival traffic state A has flow rate q and density q/v_f, J is jam state with zero flow rate and density k_j, and S is capacity state where vehicles are discharged with saturation flow rate s and density s/v_f. By kinematic wave theory, queue dynamic at a signalised intersection can be described by queue forming shockwave v_1 between traffic states A and J, queue discharging shockwave v_2 between traffic states J and S, and departure shockwave v_3 between traffic states S and A (see Fig. 6a). The speeds of the shockwaves can be expressed as follows:

$$v_1 = \left|\frac{-q}{k_j - q/v_f}\right|; \quad v_2 = \left|\frac{s}{s/v_f - k_j}\right| = w; \quad v_3 = v_f \tag{2}$$

3.1.1. Base case

Let us denote d as the distance between a bus stop and the stop line, Lq_m as the maximum distance between the rear of the queue and the stop line, d_b as bus delay after serving at the stop, d_b^* as bus delay before reaching the stop, t^* as the time instance within a cycle when traffic queue starts blocking the bus from reaching the stop. The overall bus delay D_b is the sum of d_b^* and d_b. In addition, T_a is defined as $t + d_b^* + \theta$ where θ is dwell time. Note that t is the projected arrival time of a bus at the stop line in free-flow traffic condition as if there is no bus stop ($t \in [0, c)$).

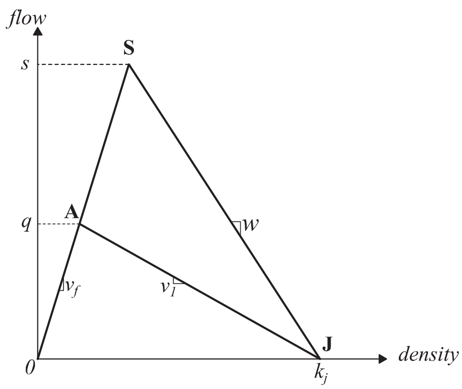

Fig. 5. Fundamental diagram.

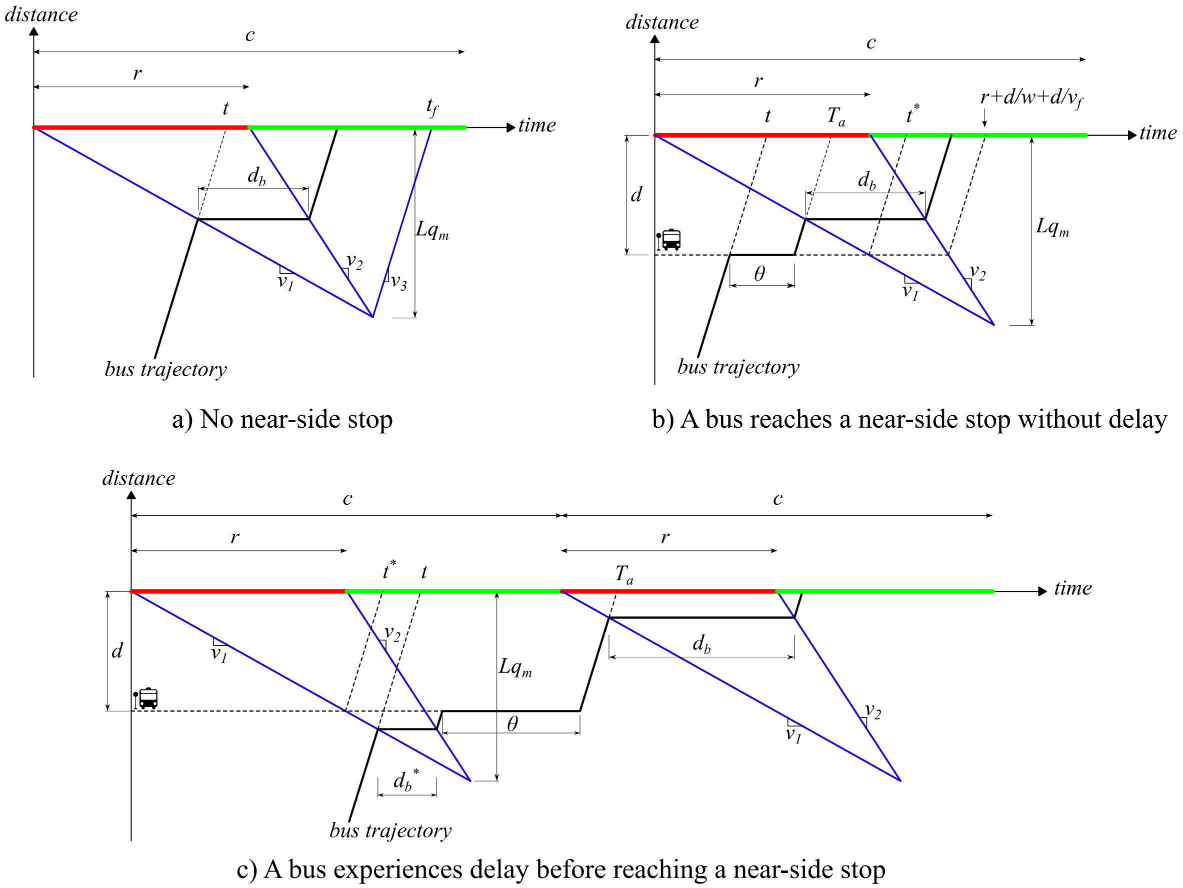

Fig. 6. Time-space diagram for a bus with/without a near-side stop.

Let us start with a simple case when there is no near-side stop as depicted in Fig. 6a. In this case, $d_b^* = 0$ and $\theta = 0$. By conservation of flows, the number of vehicles arriving at the intersection from the start of the cycle to t_f is equal to the number of vehicles discharging at the saturation flow rate from the start of the green time to t_f, ($qt_f = s(t_f - r)$). Hence, t_f can be expressed as follows:

$$t_f = \frac{rs}{s-q} \tag{3}$$

It can also be seen that queue is formed by vehicles arriving from the start of the cycle to t_f. Thus, given jam density k_j, Lq_m can be formulated as:

$$Lq_m = \frac{qt_f}{k_j} = \frac{qrs}{k_j(s-q)} \tag{4}$$

Based on geometry in Fig. 6a, d_b can be expressed as:

$$r\frac{t_f - t}{t_f} = r - t\frac{s-q}{s} \tag{5}$$

Therefore, when there is no near-side stop, bus delay can be summarised as follows:

$$d_b = \max\left\{0, r - t\frac{s-q}{s}\right\} \tag{6}$$

According to Eq. (6), bus delay is positive if $t < t_f$ and equal to zero if $t \geqslant t_f$, which is intuitive.

When there is a near-side stop and $d < Lq_m$, it is important to examine whether a bus experiences delay before reaching the stop. Fig. 6b shows that a bus can reach the stop without delay when $t < t^*$ ($d_b^* = 0$). In addition, Fig. 6c indicates a bus encounters traffic queue before arriving at the stop when $t^* \leqslant t < t_f$ ($d_b^* > 0$). It also suggests d_b^* can be calculated as bus delay in the case of no near-side stop using Eq. (6). Hence, d_b^* is formulated as follows:

$$d_b^* = \begin{cases} r - t\frac{s-q}{s} & \text{if } (d < Lq_m) \ \& \ (t^* \leqslant t < t_f) \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

Similar to the formulation of Lq_m, d can be calculated as qt^*/k_j. Thus, t^* can be expressed as:

$$t^* = \frac{dk_j}{q} \tag{8}$$

The overall bus delay can be summarised as follows:

$$D_b = \begin{cases} \max\{0, r - T_a(s-q)/s\} & \text{if } (d \geqslant Lq_m) \ \& \ (T_a < c) & \text{(a)} \\ \max\{0, r - (T_a - c)(s-q)/s\} & \text{if } (d \geqslant Lq_m) \ \& \ (T_a \geqslant c) & \text{(b)} \\ \max\{0, r - T_a(s-q)/s\} & \text{if } (d < Lq_m) \ \& \ (t < t^*) \ \& \ (T_a < t^*) & \text{(c)} \\ \max\{0, r + d/w + d/v_f - T_a\} & \text{if } (d < Lq_m) \ \& \ (t < t^*) \ \& \ (t^* \leqslant T_a < c) & \text{(d)} \\ \max\{0, r - (T_a - c)(s-q)/s\} & \text{if } (d < Lq_m) \ \& \ (t < t^*) \ \& \ (c \leqslant T_a < c + t^*) & \text{(e)} \\ \max\{0, r + d/w + d/v_f - (T_a - c)\} & \text{if } (d < Lq_m) \ \& \ (t < t^*) \ \& \ (c + t^* \leqslant T_a) & \text{(f)} \\ d_b^* & \text{if } (d < Lq_m) \ \& \ (t \geqslant t^*) \ \& \ (T_a < c) & \text{(g)} \\ d_b^* + \max\{0, r - (T_a - c)(s-q)/s\} & \text{if } (d < Lq_m) \ \& \ (t \geqslant t^*) \ \& \ (c \leqslant T_a < c + t^*) & \text{(h)} \\ d_b^* + \max\{0, r + d/w + d/v_f - (T_a - c)\} & \text{if } (d < Lq_m) \ \& \ (t \geqslant t^*) \ \& \ (c + t^* \leqslant T_a) & \text{(i)} \end{cases} \tag{9}$$

Eqs. (9a and 9b) describe the cases where the bus stop is unaffected by traffic queue ($d_b^* = 0$). Hence, delay of a bus with the projected arrival time t and dwell time θ can be calculated as delay of a bus with the projected arrival time $T_a = t + 0 + \theta$ by using Eq. (6). Since dwell times vary, after serving at the stop, a bus may arrive at the stop line during the current cycle or the next cycle. Eq. (9a) corresponds to the case where a bus arrives during current cycle whereas Eq. (9b) corresponds to the case where a bus arrives during the next cycle. If θ is very high, e.g. $\theta > c$, a bus may arrive during another cycle; however, bus delay can be estimated similarly.

Eqs. (9c–9f) describe the cases where a bus reaches the stop before its entrance is blocked by traffic queue ($d_b^* = 0$). For Eq. (9c), a bus leaves the stop and joins traffic queue before crossing the intersection (see Fig. 6b). Eq. (9d) accounts for delay when a bus completes serving at the stop, but traffic queue prevents it from leaving the stop. Eqs. (9e) and (9f) are similar to Eqs. (9c) and (9d) respectively, accounting for buses arriving during the next cycle, e.g. due to large dwell times. Note that in Eqs. (9a–9f), d_b^* is omitted since it is equal to zero.

Eqs. (9g–9i) correspond to the cases where a bus may experience delay before reaching the stop. In Eq. (9g), a bus leaves the stop and cross the intersection during green time of the current cycle. In Eq. (9h), a bus leaves the stop, but joins traffic queue in the next cycle (see Fig. 6c). Similar to Eq. (9f), Eq. (9i) accounts for delay of a bus that finishes serving passengers at the stop, but has to wait until the traffic queue discharges.

3.1.2. TSP case

When there is a near-side stop, a common practice is to place a detector of the TSP system immediately after the bus stop. This eliminates the need for the TSP system to consider the randomness of dwell times in the prediction of bus arrival times. In other words, a bus can only make a priority request when it finishes serving at a stop. Fig. 6b and c suggests T_a is the projected arrival time of a bus at the stop line if there is no delay after serving at the near-side stop. The time of bus request or detection T_d can be calculated as T_a minus free-flow travel time from the bus stop to the stop line. Therefore, $T_d = T_a - d/v_f$.

If a bus is projected to arrive at the start of the red time of a cycle and it is not detected during that red time ($T_a < e \ \& \ T_d < 0$ or $c \leqslant T_a < c + e \ \& \ T_d < c$), the green extension strategy can be activated so that $d_b = 0$. For the early green strategy, the time window between detection time and the end of the red time is important. Let I_g denote the inter-green period. If the bus is detected at the end of the red time when the inter-green period of the conflicting phase is already in place ($r - T_d < I_g$), it is too late to activate the early green strategy. The priority time available for the early green strategy (t_P) can be expressed as follows:

$$t_P = \begin{cases} \min\{e, \max\{0, r - T_d - I_g\}\} & \text{if } T_a < c & \text{(a)} \\ \min\{e, \max\{0, c + r - T_d - I_g\}\} & \text{if } T_a \geqslant c & \text{(b)} \end{cases} \tag{10}$$

Eqs. (10a) and (10b) corresponds to the case, in which a bus is projected to arrive during the current cycle and next cycle respectively. Note that for the early green strategy, bus delay after serving at the stop can be saved by up to t_P. By incorporating these effects of priority strategies into Eq. (9), bus delay in the TSP case can be expressed as follows:

$$D_b = \begin{cases} 0 & \text{if } (d \geqslant Lq_m)\ \&\ (T_a < e)\ \&\ (T_d < 0) & \text{(a1)} \\ \max\{0, r - T_a(s-q)/s - t_P\} & \text{if } (d \geqslant Lq_m)\ \&\ [(T_a \geqslant e) or (T_d \geqslant 0)]\ \&\ (T_a < c) & \text{(a2)} \\ 0 & \text{if } (d \geqslant Lq_m)\ \&\ (c \leqslant T_a < c+e)\ \&\ (T_d < c) & \text{(b1)} \\ \max\{0, r - (T_a - c)(s-q)/s - t_P\} & \text{if } (d \geqslant Lq_m)\ \&\ [(T_a \geqslant c+e) or (T_d \geqslant c)] & \text{(b2)} \\ 0 & \text{if } (d < Lq_m)\ \&\ (t < t^*)\ \&\ (T_a < e)\ \&\ (T_d < 0) & \text{(c1)} \\ \max\{0, r - T_a(s-q)/s - t_P\} & \text{if } (d < Lq_m)\ \&\ (t < t^*)\ \&\ [(T_a \geqslant e) or (T_d \geqslant 0)]\ \&\ (T_a < t^*) & \text{(c2)} \\ \max\{0, r + d/w + d/v_f - T_a - t_P\} & \text{if } (d < Lq_m)\ \&\ (t < t^*)\ \&\ [(T_a \geqslant e) or (T_d \geqslant 0)]\ \&\ (t^* \leqslant T_a < c) & \text{(d)} \\ 0 & \text{if } (d < Lq_m)\ \&\ (t < t^*)\ \&\ (c \leqslant T_a < c+e)\ \&\ (T_d < c) & \text{(e1)} \\ \max\{0, r - (T_a - c)(s-q)/s - t_P\} & \text{if } (d < Lq_m)\ \&\ (t < t^*)\ \&\ [(T_a \geqslant c+e) or (T_d \geqslant c)]\ \&\ (T_a < c + t^*) & \text{(e2)} \\ \max\{0, r + d/w + d/v_f - (T_a - c) - t_P\} & \text{if } (d < Lq_m)\ \&\ (t < t^*)\ \&\ [(T_a \geqslant c+e) or (T_d \geqslant c)]\ \&\ (T_a \geqslant c + t^*) & \text{(f)} \\ d_b^* & \text{if } (d < Lq_m)\ \&\ (t \geqslant t^*)\ \&\ (T_a < c) & \text{(g)} \\ d_b^* & \text{if } (d < Lq_m)\ \&\ (t \geqslant t^*)\ \&\ (c \leqslant T_a < c+e)\ \&\ (T_d < c) & \text{(h1)} \\ d_b^* + \max\{0, r - (T_a - c)(s-q)/s - t_P\} & \text{if } (d < Lq_m)\ \&\ (t \geqslant t^*)\ \&\ [(T_a \geqslant c+e) or (T_d \geqslant c)]\ \&\ (T_a < c + t^*) & \text{(h2)} \\ d_b^* + \max\{0, r + d/w + d/v_f - (T_a - c) - t_P\} & \text{if } (d < Lq_m)\ \&\ (t \geqslant t^*)\ \&\ [(T_a \geqslant c+e) or (T_d \geqslant c)]\ \&\ (T_a \geqslant c + t^*) & \text{(i)} \end{cases} \tag{11}$$

Eqs. (11a1), (11b1), (11c1), and (11e1) describe the cases when a bus crosses the intersection without delay as a result of the green extension strategy. For Eq. (11h1), a bus experiences delay before reaching the stop, but crosses the intersection after that without further delay. In Eq. (11g), the bus is delayed before arriving at the stop, but crosses the intersection during green time of the first cycle; hence, no priority is needed. In other situations, a bus would be benefited by the early green strategy with possible delay savings of t_P when compared to the base case.

3.1.3. DBL case

Bus delay in the DBL case can be considered as in a special case of the base case with $q = 0$ since buses are not affected by traffic queue. Hence, using Eqs. (9a and 9b), bus delay the DBL case is simply expressed as follows:

$$D_b = \begin{cases} \max\{0, r - T_a\} & \text{if } T_a < c \quad \text{(a)} \\ \max\{0, r - (T_a - c)\} & \text{if } T_a \geqslant c \quad \text{(b)} \end{cases} \tag{12}$$

3.1.4. TSP with DBLs case

Similarly, bus delay in the TSP with DBLs case is considered as in a special case of the TSP case with $q = 0$. Using Eqs. (11a1 and 11b2), bus delay in the TSP with DBLs case can be formulated as follows:

$$D_b = \begin{cases} 0 & \text{if } (T_a < e)\ \&\ (T_d < 0) & \text{(a1)} \\ \max\{0, r - T_a - t_P\} & \text{if } [(T_a \geqslant e) \text{ or } (T_d \geqslant 0)]\ \&\ (T_a < c) & \text{(a2)} \\ 0 & \text{if } (c \leqslant T_a < c+e)\ \&\ (T_d < c) & \text{(b1)} \\ \max\{0, r - (T_a - c) - t_P\} & \text{if } (T_a \geqslant c+e) \text{ or } (T_d \geqslant c) & \text{(b2)} \end{cases} \tag{13}$$

3.2. Tests

The analytical model is applied to examine the combined effect on bus delay by calculating $\Delta_1 + \Delta_2 - \Delta_3$, which is delay saving in the DBL case plus delay saving in the TSP case minus delay saving in the TSP with DBLs case. A three-lane intersection approach is selected for analysis with parameters: s = 1900 veh/h/lane, k_j = 140 veh/km/lane, v_f = 60 km/h. Two cycle lengths are tested: c = 90 s and c = 120 s, in which $r = 0.5c$, I_g = 5 s, and e = 10 s. In addition, two traffic demand levels are considered, with the volume-to-capacity ratio (VCR) of the intersection approach calculated for the base case ranging from 0.7 and 0.9. Note that the VCR is calculated as $q/(s(c - r)/c)$.

It is assumed that bus arrival times, measured before the section affected by traffic queue, are uniformly distributed over a signal cycle. In other words, t is uniformly distributed over the interval of $[0, c)$. In addition, dwell times, which are independent to t, are uniformly distributed over the interval of [50 s, 70 s]. Therefore, the expected combined effect is estimated by averaging over 10,000 random samples of t and θ from their respective distributions.

Simulation using VISSIM (PTV, 2014) is also performed to estimate the combined effect. TSP control is modelled using Vehicle Actuated Programming (VAP). Simulation time is 2 h, excluding the warm-up time of 10 min. Since the analytical model only considers one bus arrival per cycle, bus headway is set as high as 6 min in simulation for consistency. A program is developed to run each scenario sequentially until the combined effect is estimated with a 2% error at a confidence level of 95% and the number of runs is at least 20 (Truong et al., 2016b).

Fig. 7 shows that a similar trend is evident between analytical and simulation results. Analytical results of $\Delta_1 + \Delta_2 - \Delta_3$ tend to be slightly higher than simulation results and the difference between them seems to be higher with increasing distances from the bus stop to the stop line (d), particularly in Fig. 7a and b. This difference is mainly associated with delay sav-

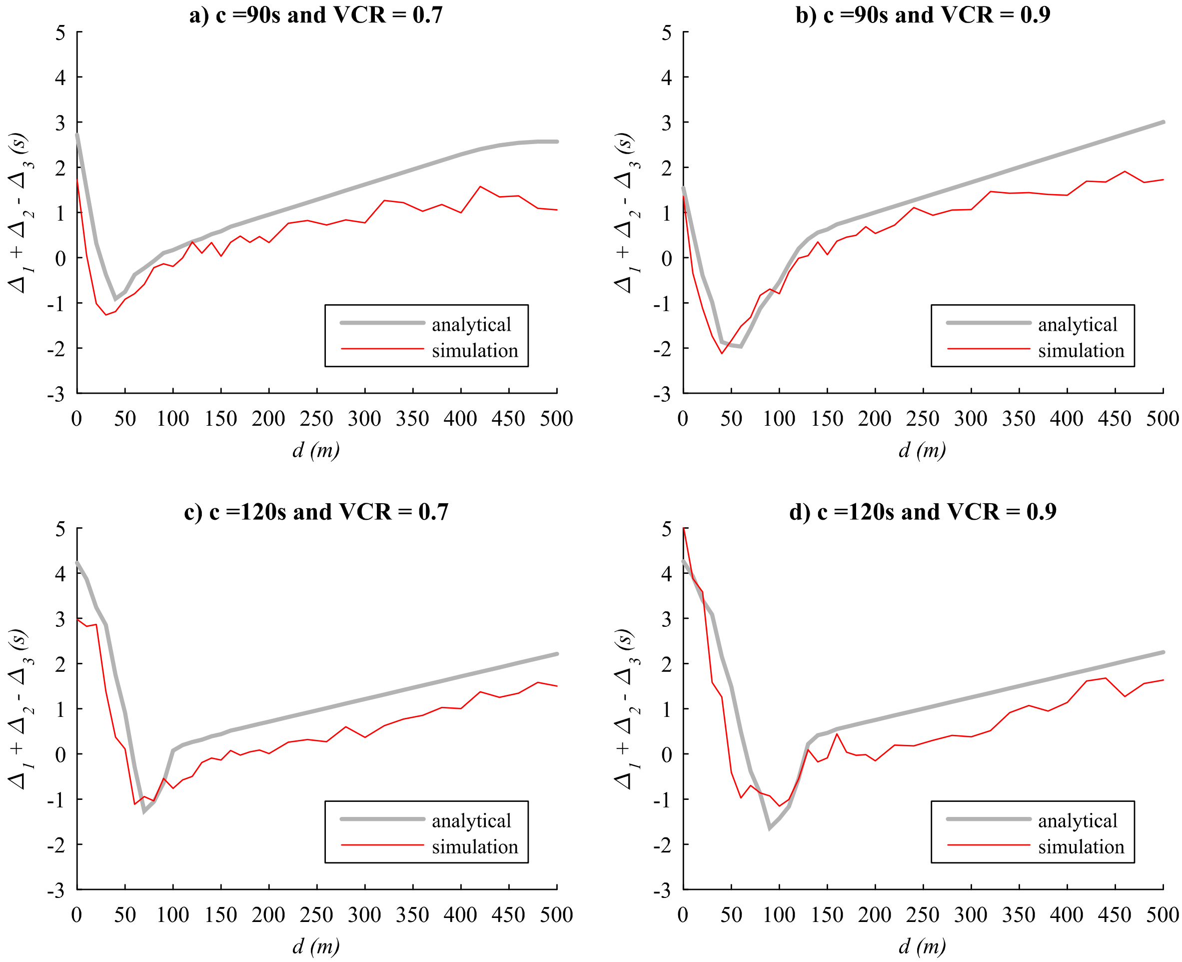

Fig. 7. Analytical and simulation comparison of combined effects.

ings in the TSP case (Δ_2) that are in general smaller in simulation than in the analytical model. It is noted that the performance of TSP strategies is influenced by bus arrival time prediction following detection immediately after the bus stop. Unlike in the analytical model, the randomness in simulation results in variations in bus arrival times, particularly with larger *d* and mixed traffic conditions. This leads to smaller estimated delay savings of TSP strategies in simulation, when compared to the analytical model. Both simulation and analytical results indicate that the combined effect is significantly affected by *d*. For example, when $c = 90$ s and VCR = 0.9, the combined effect is significantly greater than the additive effect ($\Delta_1 + \Delta_2 - \Delta_3 < 0$) with $d = 50$ m and significantly smaller than the additive effect ($\Delta_1 + \Delta_2 - \Delta_3 > 0$) with $d = 300$ m (*t*-test p-values < 0.01 for both simulation and analytical results). When $c = 120$ s and VCR = 0.9, the combined effect is significantly greater than the additive effect with $d = 80$ m and significantly smaller than the additive effect with $d = 10$ m or 400 m (*t*-test p-values < 0.05 for both simulation and analytical results).

It can also be seen that when *d* is large, the effect is smaller than the additive effect, which is consistent with the time-space analysis in Section 2.1. Moreover, Fig. 7a suggests simulation and analytical curves level off as *d* reaches a threshold, e.g. 450 m for $c = 90$ s and VCR = 0.7, when the performance of TSP strategies is no longer affected by *d*. Nevertheless, Fig. 7 demonstrates an acceptable consistency between the analytical and simulation results.

3.3. Numerical analysis

The analytical model is now employed to further investigate the combined effect under various dwell time scenarios, e.g. various mean dwell times. Similar to the previous tests, dwell times are uniformly distributed with the different between the minimum and maximum dwell times is 20 s. Fig. 8 presents contour maps of $\Delta_1 + \Delta_2 - \Delta_3$ under various scenarios. Negative values show the combined effect is the over-additive effect. Results confirm the combined effect may be the over-additive effect when a near-side bus stop is close to the stop line ($d < Lq_m$), depending on mean dwell times, cycle length, and VCR.

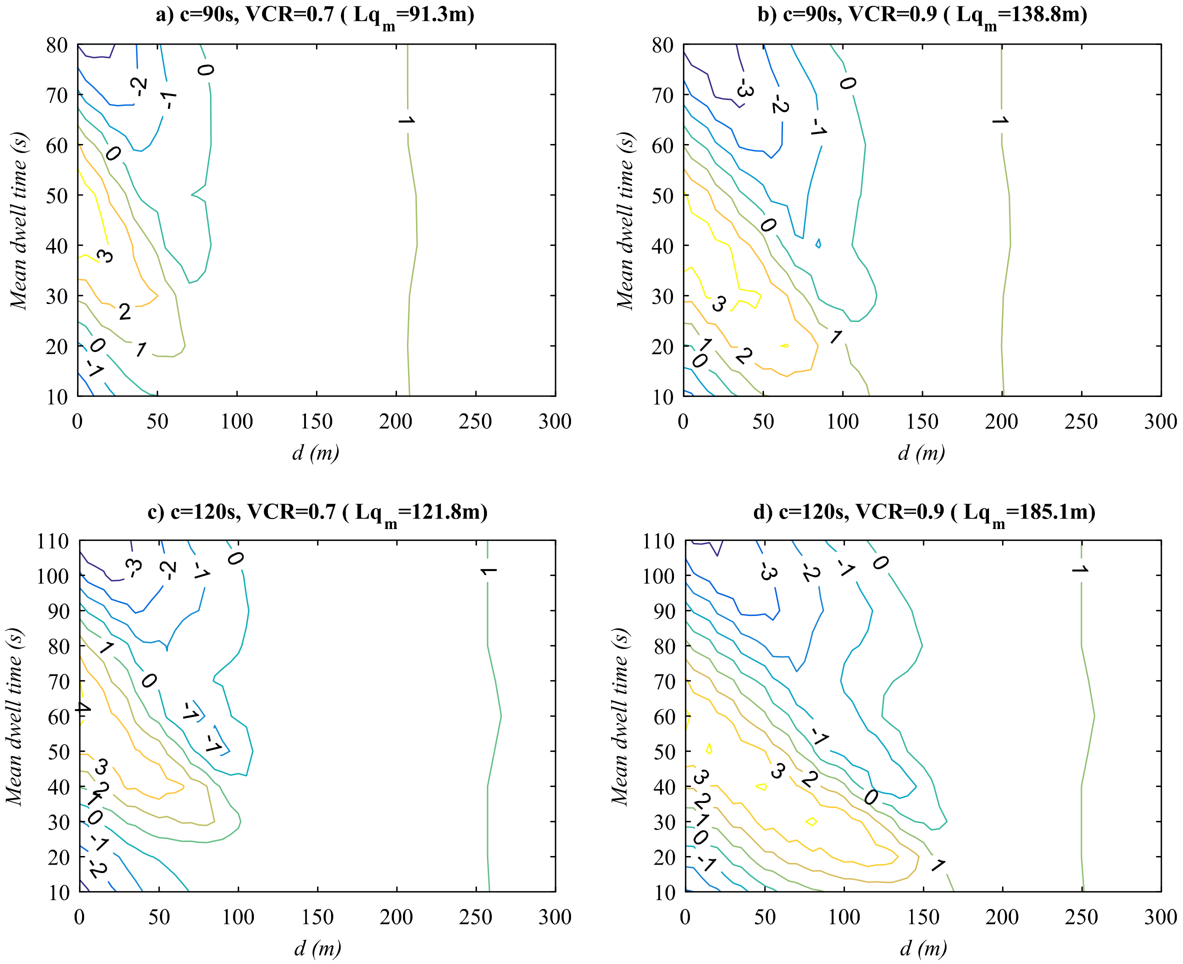

Fig. 8. Analytical results of $\Delta_1 + \Delta_2 - \Delta_3$ (s).

For example, when the bus stop is next to the stop line, the combined effect is greater than the additive effect if dwell times are close to either zero or c whereas it is smaller than the additive effect if dwell times are close to $c/2$. Note that $r = c/2$ in this analysis. An explanation is that for the base case, there is a high possibility that a bus has to join traffic queue before reaching the stop during green time. This probability is even greater with increasing VCRs (increasing Lq_m). Hence, if dwell time is either very small or as large as c, the bus crosses the intersection during green time. In this case, TSP alone offers no benefits whereas TSP with DBLs can offer more benefits than DBLs, particularly for arrivals during red time ($t < r$). In contrast, if dwell time is close to r, in the DBL case, a bus arriving during red time tends to complete serving at the stop during green time. Thus, providing TSP in addition to DBLs is unlikely to offer more benefits.

4. Arterial case study using traffic micro-simulation

4.1. Setup

A six-link arterial is proposed as a case study, where the length of each link is 500 m. Fig. 9a shows a layout of two consecutive intersections. The arterial has three lanes on each direction whereas side streets have two lanes on each direction. Signal control is fixed time with a common cycle of 120 s, of which 70% and 30% are allocated for the arterial and side street respectively. It is assumed that traffic volumes on side streets are 20% of that on the arterial. Turning proportions from the arterial and from the side streets are 5% and 25% respectively. Desired speed distribution ranges from 55 to 65 km/h. A bus line is eastbound with a headway of 5 min. There is a nearside bus stop for each intersection (d = 30 m). Dwell times for each nearside stop are assumed be normally distributed with a mean of 15 s and a standard deviation of 10 s. A bus will skip a stop if random dwell time is non-positive. In addition, a bus stop with very high dwell time variations is placed near the start of the arterial to create realistic bus arrivals.

A maximum priority time of 10 s is provided for early green and green extension strategies. To maintain signal coordination, the green phases for side streets will be reduced by the amount of the activated priority time. A check-out detector is

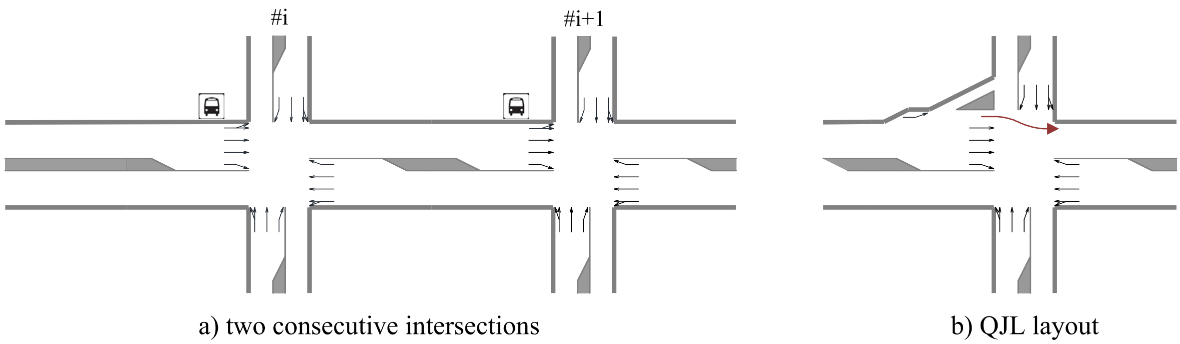

Fig. 9. Layouts of two consecutive intersections and QJL.

placed after each stop line and a check-in detector is placed after each nearside bus stop. When a bus is detected at the check-in detector, a predetermined travel time with a slack time is used to predict its arrival interval at the stop line and activate either early green or green extension strategies.

The layout of a QJL is depicted in Fig. 9b. Once a waiting bus is detected, a short leading bus phase of 8 s is provided so that the bus can cross the intersection and move into regular traffic lanes ahead of through traffic. Since the leading bus phase is taken from the green time of the through movement, it only affects the through movement on the arterial. Although the optimum length of the QJL should be longer than the maximum queue length, a typical QJL length of 100 m is selected in this case study.

Scenarios for understanding combined effects include: (i) base case, (ii) TSP case where TSP is provided at all intersections, (iii) DBL case where a curb-side lane on each link of the arterial is converted to a DBL, (iv) QJL case where QJLs are implemented at all intersections, (v) TSP w/DBL case where TSP and DBLs are implemented at all links and intersections, and (vi) TSP w/QJL case where TSP and QJLs are implemented at all intersections. Each scenario will be tested with three traffic demand levels, with the VCR of the arterial approach to the first intersection in the base case ranging from 0.5 to 0.9. It is noted that when the VCR in the base case (three lanes) is 0.9, traffic demand far exceeds the capacity of the remaining two lanes in the DBL case. Hence, considerable increases in general traffic delay are expected for DBL or TSP w/DBL cases with the VCR of 0.9.

Three measures of performance are considered, including average bus delay, average general traffic delay (eastbound on the arterial), and average side-street delay. To investigate combined effects at an isolated intersection, the first intersection is selected. At the arterial level, two offset settings are tested. In the first offset setting (OS1), offsets are optimised to minimise general traffic delay on both directions of the arterial in the base case with the VCR of 0.9, obtained using offset optimisation models developed by Truong et al., (2016a). In the second offset setting (OS2), offsets are calculated using Eq. (1) to evaluate the hypothesis described in the analytical section about the possible over-additive effect at the arterial level.

Sensitivity tests on bus headways, side-street demand levels, and cycle lengths are also conducted. All scenarios are modelled in VISSIM. In addition, TSP and QJL control is modelled using VAP. Simulation time is 2 h, excluding the warm-up time of 10 min. To obtain reliable outputs, each scenario is sequentially run until all measures of performance are estimated with a 2% error at an overall confidence level of 95% and the number of runs is at least 20 (Truong et al., 2016b).

4.2. Intersection results

Table 1 presents results of average delays at an intersection level. In addition, percentage changes in bus delay, general traffic delay, and side-street delay compared to the base cases are summarised in Fig. 10. The dash curves represent the sums of separate effects of TSP and DBL or QJL measures.

Fig. 10a shows that the combined effect of TSP with DBLs on bus delay is almost equal to the additive effect with VCRs of 0.5 and 0.7, but smaller with the VCR of 0.9. In the DBL and TSP w/DBL cases, bus delay savings increase with higher VCRs. Results also show that compared to TSP, DBL generates slightly smaller savings with low traffic volumes, but considerably higher savings with increasing traffic volumes.

Fig. 10b suggests that the combined effect of TSP with DBLs on general traffic delay is slightly better than the additive effect as the TSP w/DBL curve is below the dash curve. Results also suggest that providing TSP can improve traffic on the main approach as green time is extended by the early green and green extension strategies. As expected, when the VCR is 0.9, general traffic delay is considerable in both the DBL case and TSP w/DBL case. Fig. 10c shows that side-street delay increases with increasing VCRs in the TSP case and TSP w/DBL case. Note that there is no change in side-street delay for the DBL and QJL cases. Compared to the TSP case, the increase in side-street delay of the TSP w/DBL case is almost the same for VCRs of 0.5 and 0.7, and slightly smaller with the VCR of 0.9. This suggests the combined effect on sides-street delay is close to the additive effect.

The combined effect of TSP with QJLs on bus delay appears to be close to the additive effect (Fig. 10d). In addition, with low traffic volumes, TSP can be more effective in reducing bus delay than QJL. Fig. 10e indicates that the combined effect of

Table 1
Average delay results at an intersection level by scenarios and VCRs.

VCR	Measure of performance	Scenarios					
		Base	TSP	QJL	DBL	TSP w/QJL	TSP w/DBL
0.5	Average bus delay (s)	35.7	30.1	30.7	30.7	25.1	25.0
	Average general traffic delay (s)	16.8	15.9	17.3	19.4	16.1	18.4
	Average side-street delay (s)	40.1	41.4	40.1	40.1	41.5	41.5
0.7	Average bus delay (s)	41.3	35.4	32.7	30.7	26.8	25.0
	Average general traffic delay (s)	19.6	18.6	19.7	39.5	18.4	32.6
	Average side-street delay (s)	40.8	42.5	40.8	40.8	42.5	42.5
0.9	Average bus delay (s)	50.6	42.9	37.2	30.8	30.4	25.0
	Average general traffic delay (s)	25.1	23.4	23.8	99.5	21.7	95.3
	Average side-street delay (s)	42.3	44.7	42.3	42.3	44.6	44.3

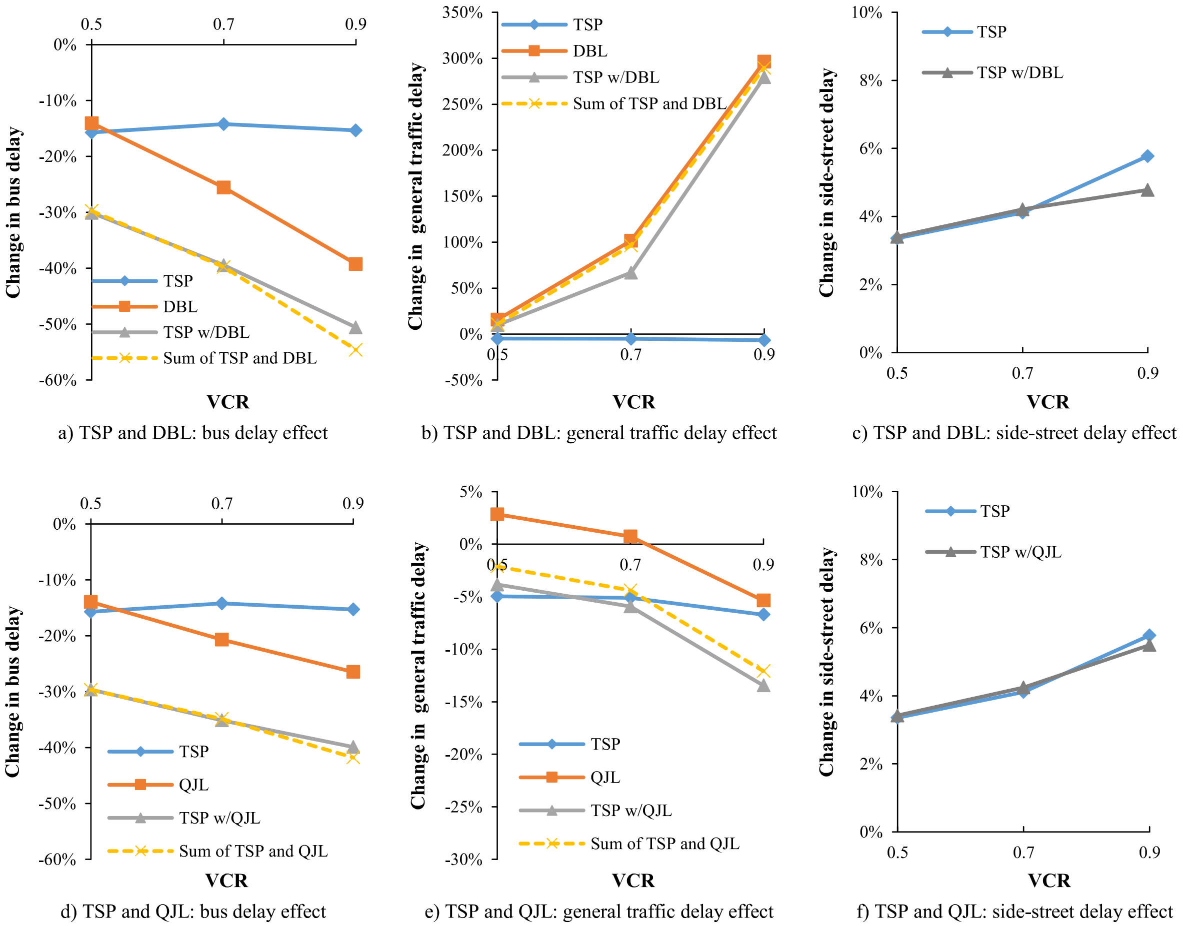

Fig. 10. Change in delays compared to the base case at an intersection level.

TSP with QJLs on general traffic delay on the main approach is better than the additive effect as the TSP w/QJL curve is well below the dash curve. Interestingly, in the QJL case, general traffic delay effects are improved with a high VCR of 0.9. The activation of the leading bus phase, which is taken from green times of the main approach, in the QJL case may increase general traffic delay on the main approach. However, providing a QJL also means that the nearside bus stop, which has negative impacts on general traffic particularly with high traffic volumes, is moved to the QJL and no longer affects general traffic. This could be the reason for the improvement in general traffic delay in the QJL case, particularly with increasing traffic volumes. In addition, Fig. 10f shows that side-street delay effects are almost the same for the TSP case and the TSP w/QJL case, suggesting the additive effect.

Compared to the combination of TSP with DBLs, the combination of TSP with QJLs provides smaller bus delay savings, significantly higher general traffic delay savings particularly with high traffic volumes, and similar negative impacts on side-street delay. This is expected since the QJL requires adding lanes. Note that when the length of the QJL is longer than the maximum traffic queue length, bus delay savings from the QJL and the DBL can be similar.

4.3. Arterial results

4.3.1. OS1 offset setting

Results of average delays at an arterial level with OS1 are presented in Table 2. In addition, percentage changes in bus delay, general traffic delay, and side-street delay compared to the base cases are depicted in Fig. 11.

Table 2
Average delay results at an arterial level (OS1).

VCR	Measure of performance	Scenarios					
		Base	TSP	QJL	DBL	TSP w/QJL	TSP w/DBL
0.5	Average bus delay (s)	208.0	177.3	193.4	193.9	153.7	152.6
	Average general traffic delay (s)	101.2	96.0	100.3	122.2	93.6	117.1
	Average side-street delay (s)	39.8	41.4	39.8	39.8	41.5	41.5
0.7	Average bus delay (s)	232.2	202.6	196.0	193.8	158.0	152.8
	Average general traffic delay (s)	128.7	121.3	126.6	192.2	115.8	179.6
	Average side-street delay (s)	40.8	42.5	40.8	40.8	42.8	42.8
0.9	Average bus delay (s)	263.8	233.8	208.1	195.3	173.5	157.1
	Average general traffic delay (s)	171.0	158.2	163.1	337.2	147.3	321.2
	Average side-street delay (s)	42.3	44.7	42.3	42.3	44.9	44.9

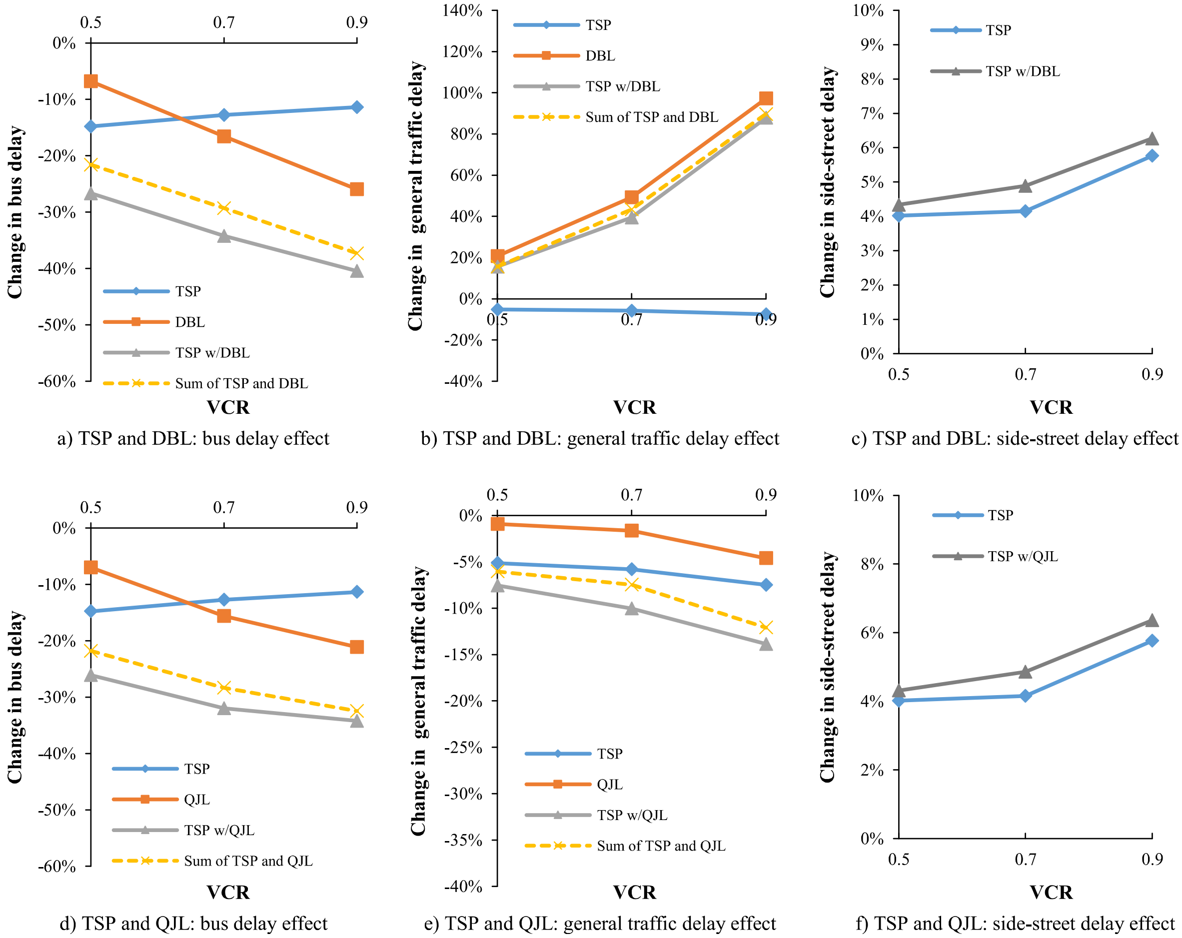

Fig. 11. Change in delays compared to the base case at an arterial level (OS1).

Fig. 11a and d indicates the combined effects of TSP with DBLs or TSP with QJLs on bus delay savings are the over-additive effect as the curves of combined effects are below the dash curves. For example, bus delay savings from combining TSP with DBLs are 27–40% whereas the sums of separate bus delay savings from TSP or DBLs are 22–37%. In other words, the over-additive effect of TSP with DBLs results in an 8–24% increase in bus delay savings, when compared to the additive effect. In addition, the over-additive effect of TSP with QJLs results in a 5–20% increase in bus delay savings. Compared to the additive effect, combined effects on general traffic delay are slightly better in the TSP w/DBLs case (see Fig. 11b). It is evident that combining TSP with QJLs improves general traffic delay, which also is the over-additive effect (see Fig. 11e). The over-additive effect of combining TSP with QJLs results in a 15–34% increase in general traffic delay savings, when compared to the additive effect. In addition, Fig. 11c and f illustrates that the combined effects on side-street traffic delay are slightly smaller than the additive effect.

Table 3
Average delay results at an arterial level (OS2).

VCR	Measure of performance	Scenarios					
		Base	TSP	QJL	DBL	TSP w/QJL	TSP w/DBL
0.5	Average bus delay (s)	277.1	190.8	260.0	260.1	157.7	156.0
	Average general traffic delay (s)	118.7	109.0	116.0	122.1	108.7	118.7
	Average side-street delay (s)	39.7	41.4	39.7	39.7	41.4	41.4
0.7	Average bus delay (s)	287.2	207.9	262.4	260.0	162.3	156.8
	Average general traffic delay (s)	142.7	122.6	144.2	204.1	118.7	187.8
	Average side-street delay (s)	40.8	42.5	40.8	40.8	42.6	42.7
0.9	Average bus delay (s)	308.8	239.2	273.2	262.2	178.6	159.7
	Average general traffic delay (s)	191.8	161.0	195.2	340.0	146.7	329.1
	Average side-street delay (s)	42.2	44.6	42.2	42.2	44.7	44.7

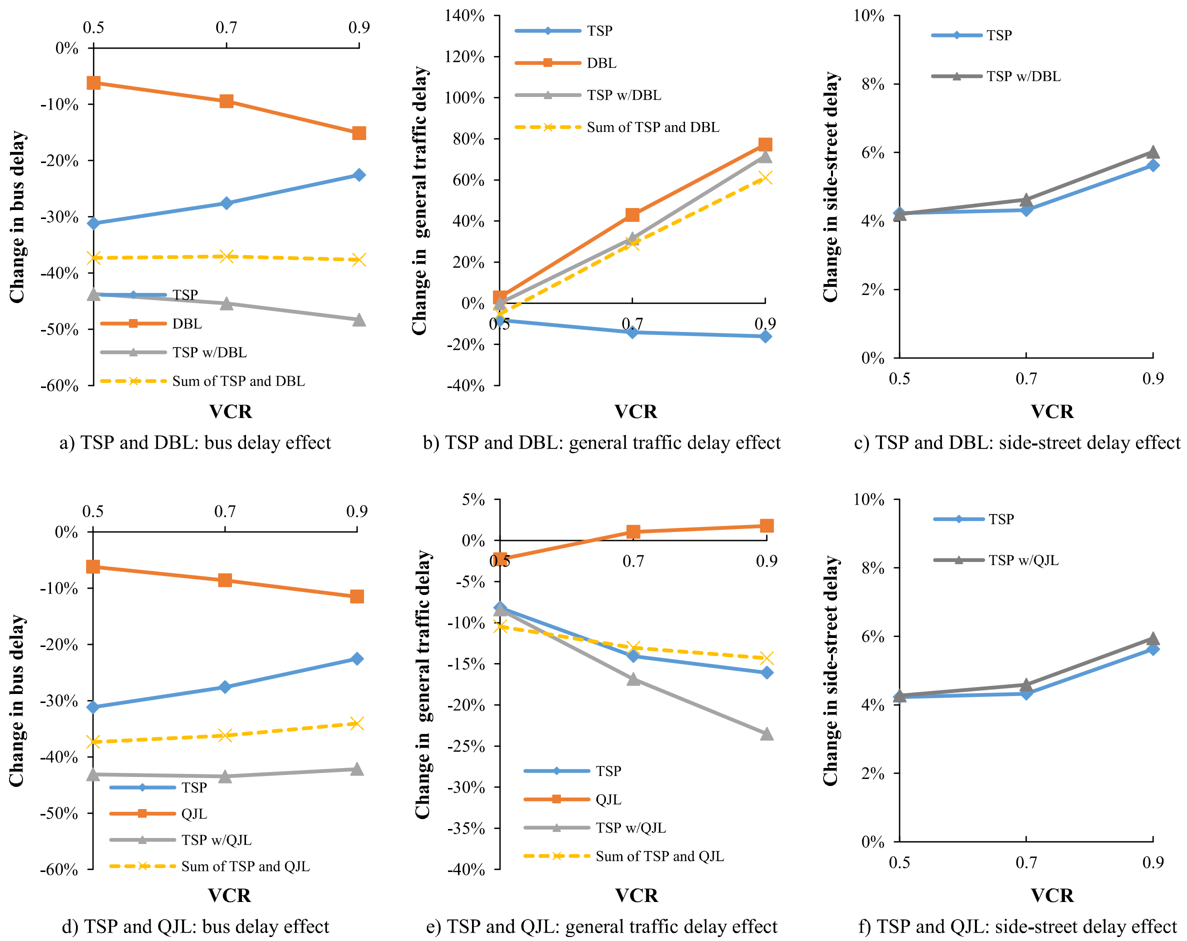

Fig. 12. Change in delays compared to the base case at an arterial level (OS2).

4.3.2. OS2 offset setting

Table 3 summarises results of average delays at an arterial level with OS2. In addition, percentage changes in bus delay, general traffic delay, and side-street delay compared to the base cases are described in Fig. 12. Results show that bus and general traffic delays are smaller in OS1 than in OS2, suggesting that OS1 provides coordination for both bus and traffic.

Fig. 12a and d demonstrates the existence of the over-additive effect on bus delay savings as the TSP w/DBL curve and TSP w/QJL curve are well below the respective dash curves. For example, the over-additive effect of TSP with DBLs results in a 17–28% increase in bus delay savings, when compared to the additive effect. In addition, the over-additive effect of TSP with QJLs results in a 15–24% increase in bus delay savings. These results support the hypothesis described in the analytical section about the possible over-additive effect at the arterial level with suitable offsets. Unlike to the OS1 offset setting, bus delay savings from TSP are higher than those from DBL or QJL in the OS2 offset setting. The reason may be that in the OS2 setting, buses are more likely to be provided with the green extension priority. Fig. 12b indicates that combining TSP with DBLs creates a negative effect on general traffic delay, which is slightly smaller than the additive effect. In contrast, combining TSP with QJLs generates a positive effect on general traffic delay, which is better than the additive effect with VCRs of 0.7 and 0.9 (Fig. 12e). For side-street delay, the combined effects of TSP with DBLs or TSP with QJLs are almost the additive effect with the VCR of 0.5 and slightly smaller than the additive effect with VCRs of 0.7 and 0.9.

Over-additive effects on bus delay savings are demonstrated for both offset settings, but with different scales. The combined effect of TSP and DBLs on general traffic is mixed between the two offset settings. Overall, results suggest the influence of signal offsets on the combined effects on bus delay and general traffic delay at the arterial level.

4.4. Sensitivity tests

4.4.1. Cycle lengths

Analytical results at an intersection level demonstrate that the interaction between the cycle length and mean dwell time can affect the combined effect on bus delay. Hence, investigating the combined effect at an arterial level with different cycle

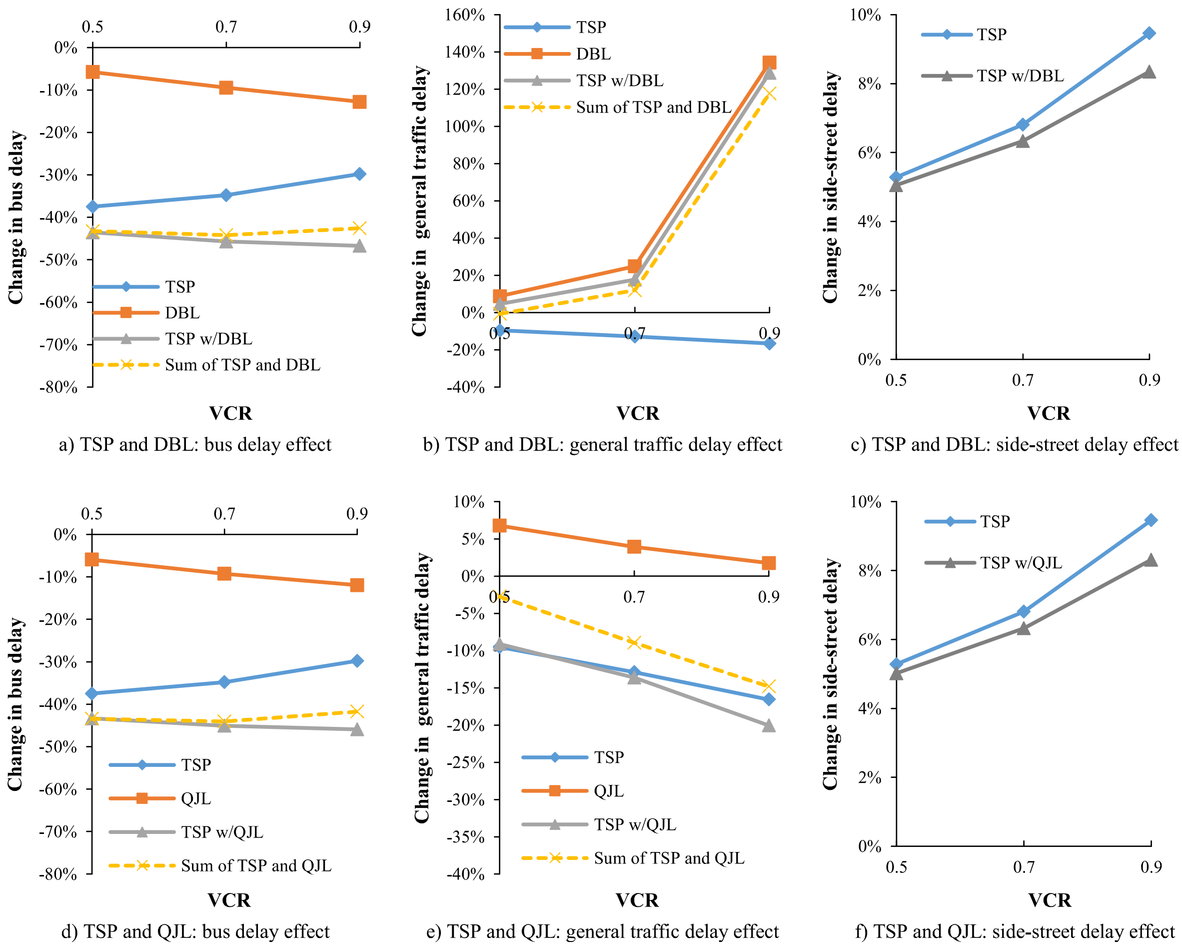

Fig. 13. Change in delays compared to the base case at an arterial level ($c = 90$ s and OS2).

lengths is necessary. Fig. 13 depicts percentage changes in delays when $c = 90$ s and the offset setting is OS2. In general, effects on bus and general traffic delays with $c = 90$ s are similar to those with $c = 120$ s. For example, the TSP w/DBL curve and the TSP w/QJL curve for bus delay are below the dash curves although the differences are small with VCRs of 0.5 and 0.7. This suggests the combined effect on bus delay saving is the over-additive effect. In addition, the effect of combining TSP with DBLs on general traffic delay is smaller than the additive effect. However, the effect of combining TSP with QJLs on general traffic delay saving is the over-additive effect. The combined effect on side-street delay is slightly better than the additive effect by up to 1%. It can also be observed that the effect of TSP on side-street delay is higher with $c = 90$ s than with $c = 120$ s. This is expected since the maximum priority time $e = 10$ s has a larger impact with a smaller cycle length.

Fig. 14 presents percentage changes in delays when $c = 60$ s and offsets are optimised for general traffic delay in both directions (OS1). Due to the small cycle length, the leading bus phase is set as 4 s and the maximum priority time for TSP strategies is set as 5 s. Given the average speed of 60 km/h, link length of 500 m, and cycle length of 60 s, it is expected that the offset setting OS1 provides coordination for general traffic in both directions. Bus delay savings in the DBL and QJL cases are small (under 4%), which is attributed to short traffic queues in the base case due to signal coordination. Results indicate that the combined effect on bus delay savings is over-additive. The over-additive effects of TSP with DBLs or TSP with QJLs result in a 9–15% increase in bus delay savings, when compared to the additive effect. Interestingly, TSP results in a 4–15% decrease in general traffic delay. It is noted that while TSP strategies, such as early green and green extension, may affect signal coordination, they provide extra green times for general traffic on the arterial. Results also show that combining TSP with QJLs reduces general traffic delay, resulting in an over-additive effect.

4.4.2. Bus headways

Sensitivity test on bus headways is undertaken with headways ranging from 1 min to 60 min. These tests are performed with $c = 120$ s and the OS1 offset setting. Fig. 15 presents differences in the sum of bus delay savings from individual priority measures versus bus delay saving from combining priority measures under various VCRs and bus headways. Negative values

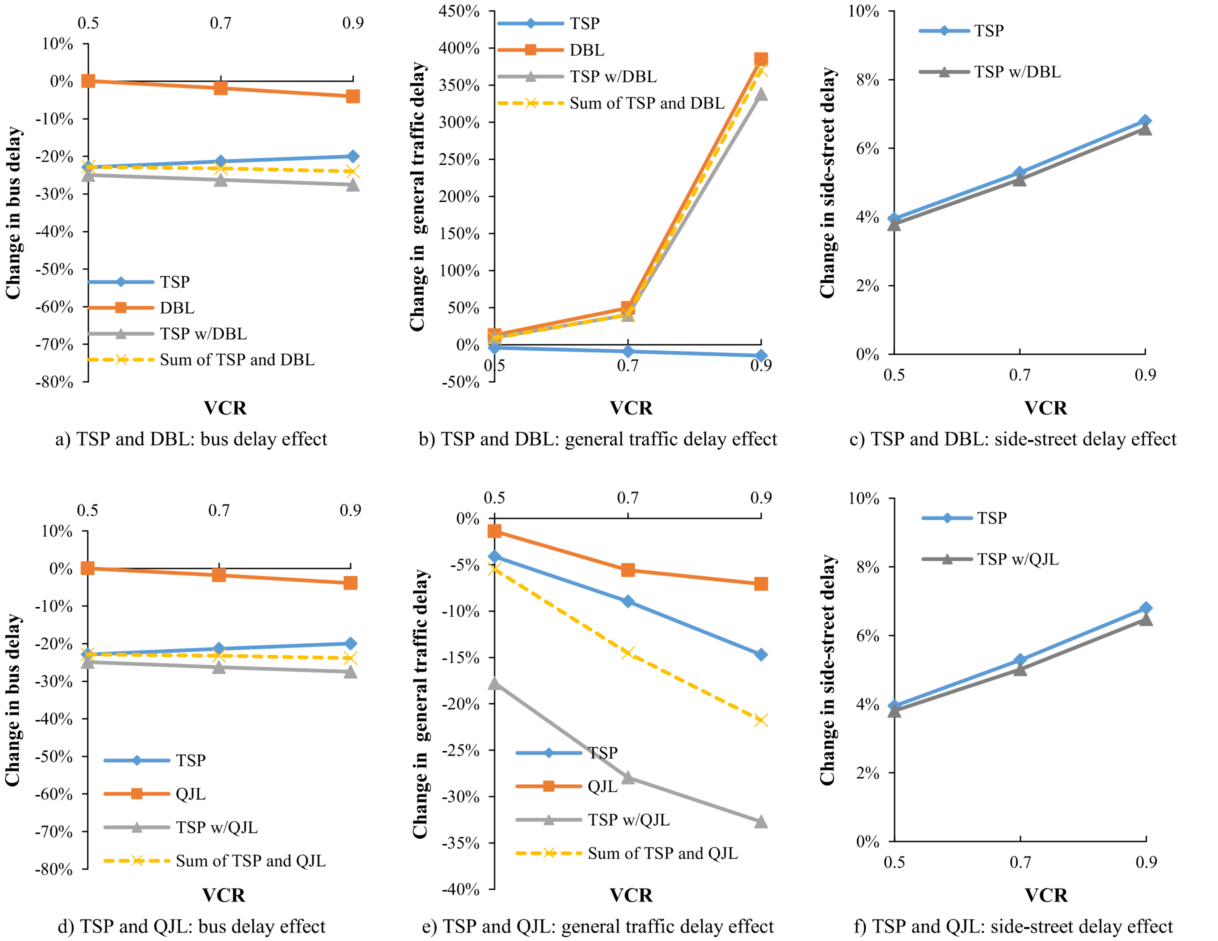

Fig. 14. Change in delays compared to the base case at an arterial level ($c = 60$ s and OS1).

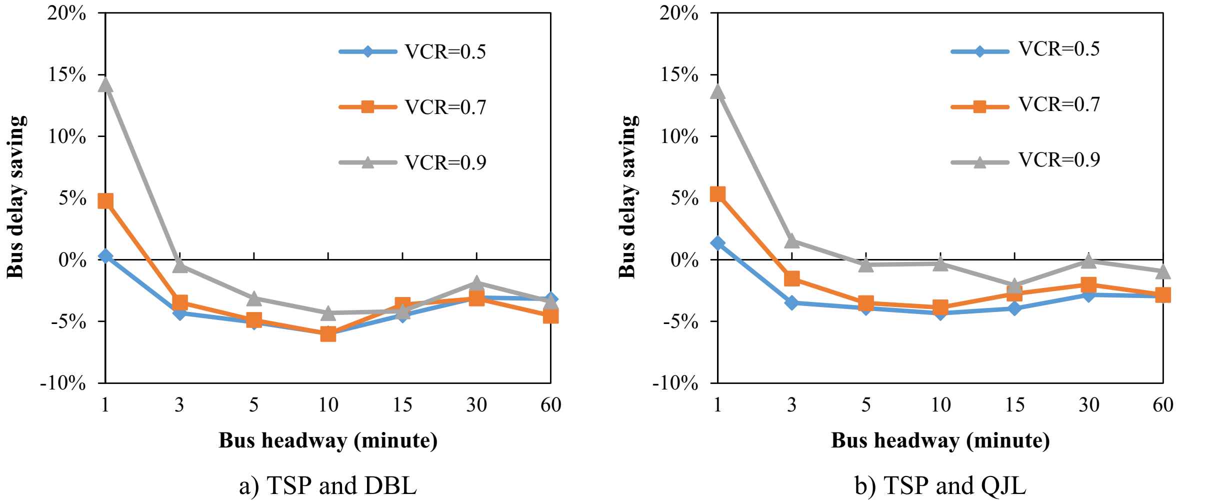

Fig. 15. Difference in the sum of delay savings from individual priority measures versus delay saving from combining priority measures (c = 120 s and OS1).

indicate the over-additive effect. In general, results suggest that the combined effect is the over-additive effect when headways are at least 3 min, except for the case of TSP with QJLs and VCR of 0.9. It is clear that the combined effect on bus delay saving is smaller than the additive effect with a headway of 1 min. Given a cycle length of 2 min, this very small headway leads to multiple bus arrivals per cycle. Hence, in the TSP case, the early green strategy provided for the first arrival is likely to clear the traffic queue for the second arrival, which is not possible in the TSP with DBLs case and unlikely in the TSP with QJLs case. This additional benefit in the TSP case is higher with increasing VCRs. Therefore, the combined effect with 1-min headway is smaller than the additive effect, particularly for high VCRs. Simulation results also indicate that the combined effect on side-street delay is almost unchanged whereas the combined effect on general traffic delay slightly varies with different headways.

4.4.3. Side-street traffic demand

In previous tests, side-street volumes are set as 20% of the arterial traffic volume. When the VCR on the arterial is 0.9, the VCRs on side-streets are 0.7. To examine the efficiency of TSP with different side-street traffic demand levels, side-street volume are now set as 25% of the arterial traffic volume, e.g. side-street VCRs are about 0.9 with the arterial VCR of 0.9. Results are presented in Fig. 16. Compared to results in Fig. 11c and f, the increases in side-street delay are larger, especially with the

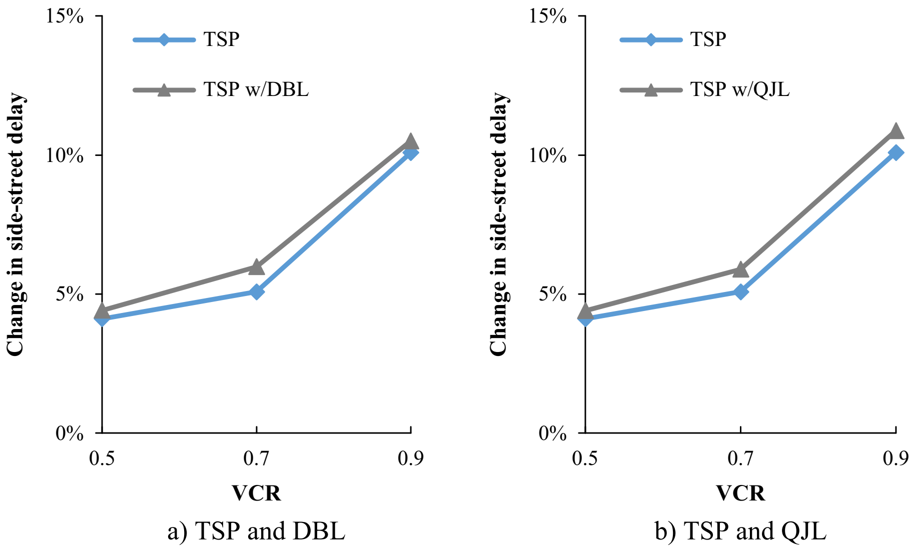

Fig. 16. Change in side-street delay (c = 120 s, OS1, side-street volumes = 25% arterial volume, headway = 5 min).

VCR of 0.9, which is expected. However, these negative impacts on side-street delay can be compensated by bus benefits (Fig. 11a and d).

5. Conclusions

This paper has explored the combined effects of TSP and RSP measures, including TSP with DBLs and TSP with QJLs. Time-space diagrams were used to analyse the combined effect on bus delay at an intersection level and to discuss the combined effect on bus delay at an arterial level. An analytical delay model was also proposed to further examine the effects of TSP and RSP measures at an intersection level, accounting for near-side stops. A micro-simulation study was then undertaken to investigate the combined effects on bus delay, general traffic delay and side-street traffic delay at intersection and arterial levels.

Analytical results indicated that at an intersection level, the combined effects of TSP with DBLs or TSP with QJLs on bus delay savings are smaller than the additive effect if there is no nearside bus stop and the traffic condition in the base case is under-saturated or near-saturated. When there is a near-side bus stop, the combined effect on bus delay savings at an intersection level can be the over-additive effect, depending on dwell times, distance from the bus stop to the stop line, VCRs, and cycle lengths. In addition, analytical results suggested that at an arterial level, the combined effect on bus delay savings can be the over-additive effect with suitable signal offset settings.

Simulation results confirmed that at the arterial level, the combined effects on bus delay savings can be the over-additive effect, depending on factors such as signal offsets. For example, the over-additive effect of TSP with DBLs results in an 8–28% increase in bus delay savings, when compared to the additive effect. The over-additive effect of TSP with QJLs results in an 8–24% increase in bus delay savings. In general, the combined effect on side-street delay is close to the additive effect. The combined effect of TSP and QJLs on general traffic delay tends to be the over-additive effect whereas the combined effect of TSP and DBLs on general traffic delay is mixed compared to the additive effect. From a policy perspective, the existence of the over-additive effects on bus delay savings suggests considerable benefits from combining TSP and RSP measures, in particular from combining TSP with QJLs.

A limitation of this paper is that the time-space analysis and analytical delay model only consider bus delay effects. The analytical approaches should be extended to investigate general traffic delay effects. Combined effects on person delay are also important to be considered. In addition, future research should further explore these combined effects using empirical analyses.

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References

Baker, R.J., Collura, J., Dale, J., Greenough, J., Head, L., Hemily, B., Ivanovic, M., Jarzab, J., McCormick, D., Obenberger, J., 2002. An Overview of Transit Signal Priority. Intelligent Transportation Society of America, Washington, D.C.
Christofa, E., Papamichail, I., Skabardonis, A., 2013. Person-based traffic responsive signal control optimization. IEEE Trans. Intell. Transp. Syst. 14 (3), 1278–1289.
Currie, G., Sarvi, M., Young, B., 2007. A new approach to evaluating on-road public transport priority projects: balancing the demand for limited road-space. Transportation 34 (4), 413–428.
Ekeila, W., Sayed, T., El Esawey, M., 2009. Development of dynamic transit signal priority strategy. Transp. Res. Rec.: J. Transp. Res. Board 2111, 1–9.
Estrada, M., Trapote, C., Roca-Riu, M., Robusté, F., 2009. Improving bus travel times with passive traffic signal coordination. Transp. Res. Rec.: J. Transp. Res. Board 2111, 68–75.
Farid, Y.Z., Christofa, E., Collura, J., 2015. Person-based evaluation of dedicated bus lanes and queue jumper lanes at signalized intersections with near-side bus stops. In: Transportation Research Board 94th Annual Meeting, Washington, D.C..
Furth, P., Muller, T.H., 2000. Conditional bus priority at signalized intersections: better service with less traffic disruption. Transp. Res. Rec.: J. Transp. Res. Board 1731, 23–30.
Furth, P., SanClemente, J., 2006. Near side, far side, uphill, downhill: impact of bus stop location on bus delay. Transp. Res. Rec.: J. Transp. Res. Board 1971, 66–73.
Gu, W., Gayah, V.V., Cassidy, M.J., Saade, N., 2014. On the impacts of bus stops near signalized intersections: models of car and bus delays. Transp. Res. Part B: Methodol. 68, 123–140.
Hounsell, N., Shrestha, B., 2012. A new approach for co-operative bus priority at traffic signals. IEEE Trans. Intell. Transp. Syst. 13 (1), 6–14.
Kimpel, T., Strathman, J., Bertini, R., Callas, S., 2005. Analysis of transit signal priority using archived TriMet bus dispatch system data. Transp. Res. Rec.: J. Transp. Res. Board 1925, 156–166.
Lahon, D., 2011. Modeling transit signal priority and queue jumpers for BRT. ITE J. 81 (12), 20–24.
Lee, J., Shalaby, A., Greenough, J., Bowie, M., Hung, S., 2005. Advanced transit signal priority control with online microsimulation-based transit prediction model. Transp. Res. Rec.: J. Transp. Res. Board 1925, 185–194.
Lighthill, M.J., Whitham, G.B., 1955. On kinematic waves. II. A theory of traffic flow on long crowded roads. Proc. R. Soc. Lond. A 229 (1178), 317–345.
Lin, W.-H., 2002. Quantifying delay reduction to buses with signal priority treatment in mixed-mode operation. Transp. Res. Rec.: J. Transp. Res. Board 1811, 100–106.
Ma, W., Ni, W., Head, L., Zhao, J., 2013. Effective coordinated optimization model for transit priority control under arterial progression. Transp. Res. Rec.: J. Transp. Res. Board 2356, 71–83.
PTV, 2014. VISSIM 7 - User Manual. PTV AG, Karlsruhe.
Richards, P.I., 1956. Shock waves on the highway. Oper. Res. 4 (1), 42–51.

Sakamoto, K., Abhayantha, C., Kubota, H., 2007. Effectiveness of bus priority lane as countermeasure for congestion. Transp. Res. Rec.: J. Transp. Res. Board 2034, 103–111.
Shalaby, A.S., Soberman, R.M., 1994. Effect of with-flow bus lanes on bus travel times. Transp. Res. Rec.: J. Transp. Res. Board 1433, 25–30.
Shourijeh, M.T., Faghri, A., Stevanovic, A., 2013. Simulation-based planning framework for choosing where to implement bus signal priority in mixed-mode operations. Transp. Res. Rec.: J. Transp. Res. Board 2352, 31–40.
Skabardonis, A., 2000. Control strategies for transit priority. Transp. Res. Rec.: J. Transp. Res. Board 1727, 20–26.
Skabardonis, A., Geroliminis, N., 2008. Real-time monitoring and control on signalized arterials. J. Intell. Transp. Syst. 12 (2), 64–74.
Stevanovic, J., Stevanovic, A., Martin, P.T., Bauer, T., 2008. Stochastic optimization of traffic control and transit priority settings in VISSIM. Transp. Res. Part C: Emerg. Technol. 16 (3), 332–349.
Surprenant-Legault, J., El-Geneidy, A., 2011. Introduction of reserved bus lane. Transp. Res. Rec.: J. Transp. Res. Board 2218, 10–18.
TCRP, 2010. Bus and rail transit preferential treatments in mixed traffic: a synthesis of transit practice. In: TCRP Synthesis 83. Transportation Research Board. Transit Cooperative Research Program, Washington, DC.
Truong, L.T., Sarvi, M., Currie, G., 2015. Exploring multiplier effects generated by bus lane combinations. Transp. Res. Rec.: J. Transp. Res. Board 2533, 68–77.
Truong, L.T., Sarvi, M., Currie, G., 2016a. An investigation of multiplier effects generated by implementing queue jump lanes at multiple intersections. J. Adv. Transp. http://dx.doi.org/10.1002/atr.1424.
Truong, L.T., Sarvi, M., Currie, G., Garoni, T.M., 2016b. Required traffic micro-simulation runs for reliable multivariate performance estimates. J. Adv. Transp. 50 (3), 296–314.
Waterson, B., Rajbhandari, B., Hounsell, N., 2003. Simulating the impacts of strong bus priority measures. J. Transp. Eng. 129 (6), 642–647.
Zhou, G., Gan, A., Zhu, X., 2006. Determination of optimal detector location for transit signal priority with queue jumper lanes. Transp. Res. Rec.: J. Transp. Res. Board 1978, 123–129.
Zlatkovic, M., Stevanovic, A., Reza, R., 2013. Effects of queue jumpers and transit signal priority on bus rapid transit. In: Transportation Research Board 92nd Annual Meeting, Washington, D.C..