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Exploring multiplier effects generated by combining transit signal priority with dedicated bus lanes or queue jump lanes on arterials

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Abstract

Prioritising Public Transport (PT) vehicles is essential to enhancing the performance of PT systems. There has been an extensive body of literature dealing with the design and operation of PT priority measures. However, it remains unclear whether providing Transit Signal Priority with Dedicated Bus Lanes (TSPwDBL) or Transit Signal Priority with Queue Jump Lanes (TSPwQJL) at multiple intersections creates a multiplier effect on PT benefits, i.e. the benefit from providing priority together at multiple intersections is greater than the sum of benefits from providing priority separately at each of those individual intersections. From a policy perspective, the existence of a multiplier effect would indicate considerable benefits through providing both time and space priority in combination on a corridor-wide scale. This paper therefore explores the effects of providing TSPwDBL or TSPwQJL at multiple intersections on bus delay savings and person delay savings. Simulation results reveal that providing TSPwDBL or TSPwQJL at multiple intersections can create a multiplier effect on bus delay savings. In general, the multiplier effect results in a 5-8% improvement in one-directional bus delay savings for each additional intersection with TSPwDBL or TSPwQJL, when signal offsets provide bus progression for that direction. An explanation for the multiplier effect is that TSPwDBL and TSPwQJL reduce variations in bus travel times and thus enable signal offsets, which account for bus progression, to perform even better. Furthermore, simulation results show limited evidence of a multiplier effect on person delay savings, particularly for TSPwQJL, with offsets optimised for person delay savings.

Keywords: bus priority, bus lane, queue jump lane, transit signal priority, multiplier effect

1. Introduction

Urban traffic congestion is a major challenge in almost every major city worldwide. Given their greater capacity, public transport (PT) vehicles can increase throughput of urban transport systems and therefore reduce urban traffic congestion. The performance of on-road PT systems is however restricted by urban traffic congestion. Hence, giving priority to PT vehicles is crucial to improving the efficiency of urban transport systems. A common approach is to restrict road space from general traffic use and allocate it to PT vehicles. For example, dedicating a lane to bus use, which is also known as a Dedicated Bus Lane (DBL), improves bus travel time, but might increase general traffic travel time, particularly with congested traffic conditions (Tanaboriboon and Toonim, 1983; Shalaby and Soberman, 1994; Jepson and Ferreira, 2000; Currie et al., 2007). To mitigate the negative impact on general traffic, dynamic bus lanes where general traffic is allowed to travel on the bus lane intermittently when it is not used by a bus, has been proposed, particularly with low bus frequencies (Viegas and Lu, 2004; Eichler and Daganzo, 2006). Another widely-used priority measure is the Queue Jump Lane (QJL). A QJL is a short bus lane at traffic signals, allowing buses to travel in and then move forward from a left or right turning lane, depending on left-hand or right-hand driving, while bypassing queues in adjacent traffic lanes (VicRoads, 2003; TCRP, 2010).

Transit Signal Priority (TSP), designed to facilitate PT vehicle movement at signalised intersections, can be categorised as either passive, active, or adaptive priority (Baker et al., 2002). Passive priority operates continuously based on an understanding of PT route and ridership patterns without the need for detection or priority request systems. An example of passive priority is providing signal progression for PT vehicles by offline optimisation of signal offsets. Adaptive priority gives priority to PT vehicles while optimising certain performance criteria such as minimising traffic impacts or person delay. Active priority dynamically adjusts signal timings to facilitate PT vehicle movement following their detection. Several active priority strategies have been used, such as green extension, early green, actuated transit phases, phase insertion, and phase rotation strategies (Furth and Muller, 2000; Lee et al., 2005; Smith et al., 2005; Ekeila et al., 2009; Truong et al., 2016b). To provide improved priority to PT vehicles, TSP may be combined with DBLs (Sakamoto et al., 2007; TCRP, 2007; Ma et al., 2013; Truong, 2016) or QJLs (Zhou and Gan, 2009; Zlatkovic et al., 2013; Truong et al., 2016a).

The performance of public transport priority (PTP) measures on signalised arterials has been a focus of much research. However, the effects of providing PTP measures in combination at multiple locations, such as road sections or intersections, on the performance of buses and general traffic have only been examined in few studies (Chiabaut et al., 2012; Truong et al., 2015, forthcoming). For example, Chiabaut et al. (2012) investigated the relationship between the number of bus lanes with intermittent priority, a variant of dynamic bus lanes, and corridor bus travel time savings, and found that six sections are in general enough to generate positive bus travel time savings. In addition, Truong et al. (2015) showed a linear link between the number of combined set-back bus lane sections and bus travel time savings when signal coordination is not provided. Nevertheless, little is understood about the effects of providing PTP measures, such as TSP with DBLs (TSPwDBL) and TSP with QJLs (TSPwQJL), in combination at multiple locations. Given the impact of signal coordination on the effectiveness of TSP (Skabardonis, 2000), these effects should be examined particularly when signal coordination allows bus progression. In addition, there is a need to examine the effects on person delay savings considering both bus and general traffic impacts.

From a policy perspective, it is important to establish if providing PTP measures combined at multiple locations creates a multiplier effect where the benefit from providing them at multiple locations is greater than the sum of benefits from providing them individually at each of those locations. In other words, a multiplier effect is an increasing return to scale effect. If a multiplier effect exists, it would suggest scale economies in wider implementation of PTP measures on a corridor-wide scale. This paper therefore explores the effects of providing TSPwDBL or TSPwQJL in combination at multiple intersections on bus delay savings and person delay savings, using an extensive traffic micro-simulation modelling test-bed.

The remainder of this paper is structured as follows: The next section presents the methodology with descriptions of the test-bed, priority strategies, and combination scenarios. Results for TSPwDBL and TSPwQJL are then presented, including results from different offset settings and sensitivity tests. The paper concludes with a summary of key findings and directions for future research.

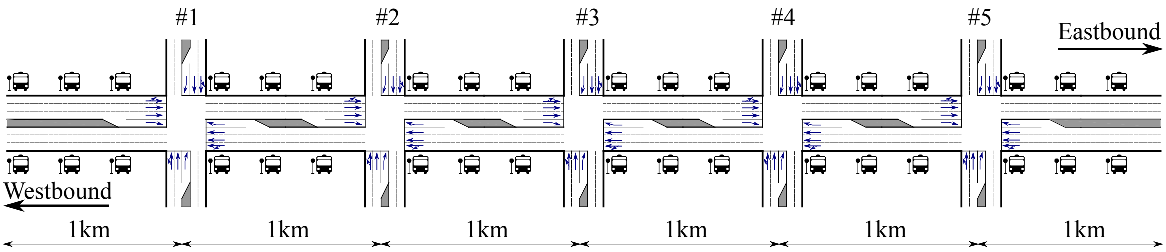
2. Methodology

2.1. Test-bed

A hypothetical arterial with five signalised intersections is proposed as a test-bed to explore the effects of providing TSPwDBL or TSPwQJL at multiple intersections. The arterial is designed with typical suburban arterial settings in Melbourne, Australia. Figure 1 depicts the layout of the test-bed arterial where distances between intersections are uniformly 1km. The arterial has three lanes in each direction while side streets have two lanes in each direction. Arterial traffic volumes are assumed to be five times greater than side-street traffic volumes. In addition, turning proportions from the arterial and side streets are set as 5% and 25%

respectively, to maintain similar traffic volumes on each link of the arterial. Signal control is fixed-time with a common signal cycle of 120s, of which 70% and 30% are allocated for the arterial and side streets respectively. Desired speed distribution ranges from 55 to 65 km/h. There is a bus line for each direction on the arterial with an average stop spacing of three stops per km. The eastbound (EB) bus line is designed to include far-side and mid-block stops while the westbound (WB) bus line is designed to include near-side and mid-block stops. This aims to capture possible impacts of near-side and far-side stops. Bus dwell times are assumed to be normally distributed with a mean of 15s and a standard deviation of 10s, in which stop skipping is activated when a random bus dwell time is non-positive. To capture random variations in bus entrance times to the arterial, it is assumed that deviations between actual and scheduled entrance times follow a normal distribution with a mean of 0s and standard deviation of 20s. The settings of stop spacing, bus dwell time, and bus entrance time are made in agreement with previous studies (TCRP, 1996, 2003; Lee et al., 2005). Traffic micro-simulation models for the test-bed are developed using the VISSIM traffic simulator (PTV, 2014).

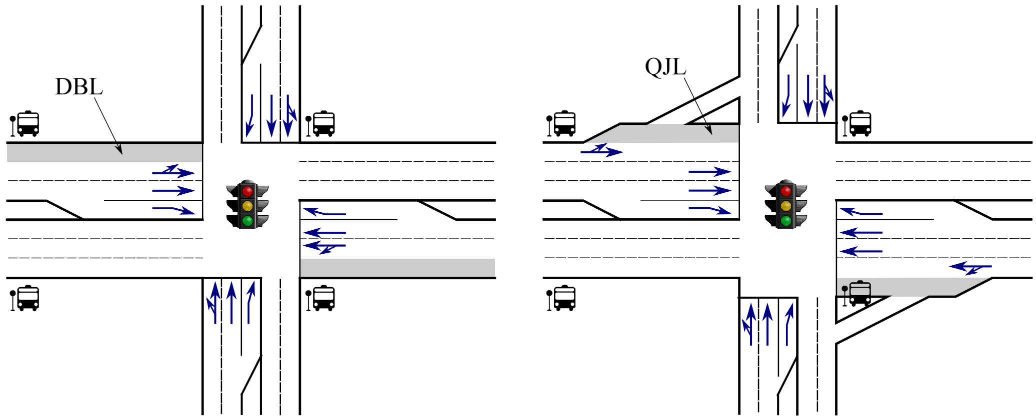
Figure 1 Layout of the test-bed arterial



2.2. Priority design

Figure 2 illustrates the design of TSPwDBL and TSPwQJL for an intersection. In the TSPwDBL case, left-turning vehicles turn from the traffic lane next to the DBL. In contrast, they turn from a left-turning lane in the TSPwQJL case. A short leading bus phase is provided to allow a waiting bus to cross the intersection and move into through lanes ahead of general traffic in the TSPwQJL case. To accommodate the leading bus phase, green time of the parallel general traffic movement is shortened. In this study, a leading bus phase of 8s is implemented. Figure 2 also shows that unlike the TSPwDBL case, the TSPwQJL case requires roadway expansion to provide the QJL and the left-turning lane when compared to the base (without priority) case. Although the optimum length of the QJL should be longer than the maximum queue length, this study examines the QJL with a typical length of 100m (Espada et al., 2012).

Figure 2 Layout of TSPwDBL and TSPwQJL measures



a) TSPwDBL b) TSPwQJL

The TSP system employs two commonly-used strategies, including green extension and early green, with a maximum priority time of 10s. To maintain signal coordination, green time for side streets is reduced by the amount of the activated priority time. For each direction, a check-out detector is placed at the stop line. In addition, a check-in detector is placed 100m before the stop line if there is no near-side stop or immediately after the bus stop where there is a near-side 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 to consider the activation of either an early green or green extension strategy. If the green extension strategy is provided, the green time is extended until either the bus is detected at the check-out detector or the maximum green extension time is reached. For an intersection, TSP strategies can only be activated once per cycle based on a first-come first-served basis. For the TSPwQJL case, the leading bus phase and TSP strategies are implemented simultaneously. The controls of TSPwDBL and TSPwQJL are modelled in the traffic simulator using Vehicle Actuated Programming (VAP).

2.3. Combination scenarios

To investigate the effects of providing TSPwDBL or TSPwQJL combined at multiple intersections, it is essential to consider all possible combinations of priority measures at the five intersections. There are a total of 32 (=2^5) combination scenarios, including the base scenario (without priority). Performance criteria include average EB bus delay, average WB bus delay, average EB traffic delay, average WB traffic delay, and average side-street delay. To provide a combined performance criterion, average network person delay is calculated with the occupancies of 1.2 persons per car and 40 persons per bus.

To provide demand sensitivity analysis, each scenario associated with TSPwQJL is evaluated under three arterial traffic demand levels, equivalent to volume-to-capacity ratios (VCRs) of 0.5, 0.7, and 0.9 in the base scenario. Each scenario associated with TSPwDBL is tested under two arterial traffic demand levels, equivalent to VCRs of 0.5 and 0.7 in the base scenario. TSPwDBL is not tested with the VCR of 0.9 as traffic demand far exceeds the capacity of the remaining traffic lanes, creating excessive traffic delays (Truong et al., 2015). Bus headway is set as 5 minutes. Furthermore, two signal offset settings are considered: balanced (BAL) and eastbound bus coordination (EBC) offsets. The BAL offsets minimise average person delay in both directions of the arterial in the base scenario with a VCR of 0.9. The EBC offsets minimise eastbound bus delay in the base scenario with a VCR of 0.9. The BAL and EBC offsets are obtained using offset optimisation models developed by Truong et al. (forthcoming). Although the calculated BAL and EBC offsets might be slightly different to the optimal settings for other combination scenarios and VCRs, it is likely that they still perform relatively well in those cases. Overall, two priority measures, various demand levels, and two offset settings lead to a total of 316 simulation experiments. Further sensitivity tests are also provided, such as tests on bus dwell time variance and bus headway.

Estimating the minimum number of independent runs for each simulation experiment is crucial for obtaining reliable simulation outputs. Hence, a program is developed to run simulation sequentially until all performance criteria are estimated with a 5% error at an overall confidence level of 95% and the number of runs is at least 20 (Truong et al., 2016c). The simulation time for each run is set as 2 hours, excluding a warm-up time.

3. Results and Discussion

3.1. Transit Signal Priority with Dedicated Bus Lanes (TSPwDBL)

3.1.1. Balanced (BAL) offsets

Results for TSPwDBL combinations, aggregated from 32 combination scenarios, with the BAL offsets are summarised in Table 1. Overall, bus delays are considerably higher than general traffic delays, which is expected given that there are three bus stops per km. The relatively low general traffic delays in both directions indicate traffic coordination provided by the BAL offsets. Figure 3 further illustrates average delay savings by the number of intersections with TSPwDBL. Note that the discontinuous lines represent a constant return to scale (CRS) effect where the effect from providing priority measures at multiple locations is equal to the sum of effects from providing them at each of those individual locations. The CRS effect is calculated by multiplying the number of intersections with the average delay saving when each of the five intersections is provided with TSPwDBL.

Table 1 Summary of average delays for TSPwDBL combinations with BAL offsets and 5-minute headway

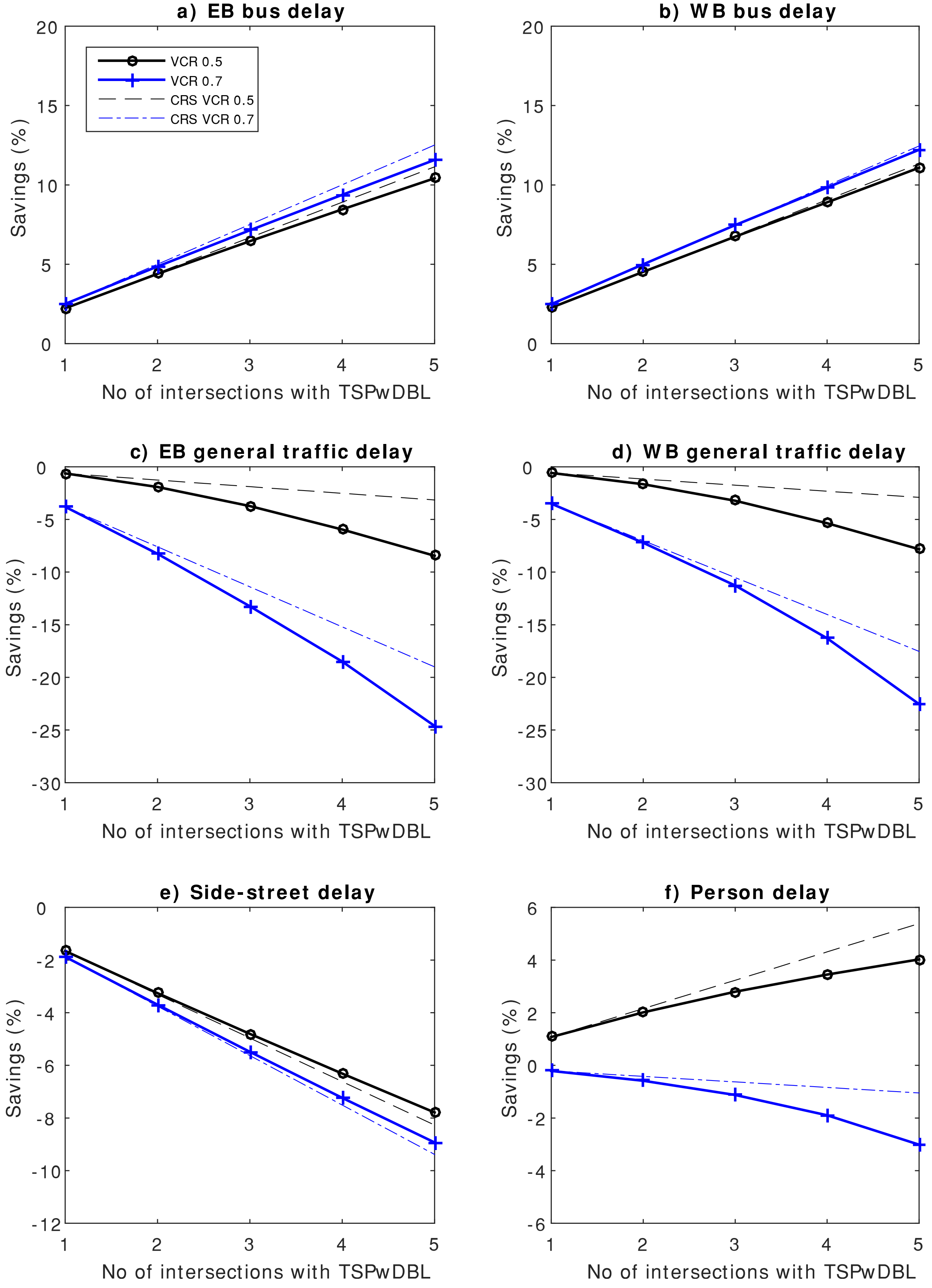
VCR	No of intersections with TSPwDBL	Avg. vehicle delay (s)					Avg. network person delay (s)
		Bus EB	Bus WB	General traffic EB	General traffic WB	Side-street	
0.5	0 (Base)	356.0	351.6	32.0	32.3	41.2	83.2
	1	348.0	343.6	32.2	32.5	41.9	82.3
	2	340.3	335.7	32.6	32.8	42.5	81.6
	3	333.0	327.9	33.2	33.3	43.2	80.9
	4	325.9	320.3	33.9	34.0	43.8	80.4
	5	318.9	312.6	34.7	34.8	44.4	79.9
0.7	0 (Base)	360.5	356.5	42.7	44.1	42.5	78.6
	1	351.5	347.6	44.3	45.6	43.3	78.8
	2	343.0	338.7	46.3	47.2	44.1	79.1
	3	334.8	329.8	48.4	49.0	44.9	79.5
	4	326.7	321.4	50.6	51.2	45.6	80.1
	5	318.8	312.9	53.2	54.0	46.3	81.0

Figure 3a-b show that bus delay savings increase almost linearly with increasing numbers of intersections with TSPwDBL. In fact, bus delay saving curves are slightly below the corresponding CRS lines. In addition, bus delay savings are slightly greater with greater VCRs, which is anticipated.

Figure 3c-d however indicate that TSPwDBL results in negative general traffic delay savings. In other words, general traffic delays increase with increasing numbers of intersections with TSPwDBL. Furthermore, the increases in general traffic delays are much larger with higher VCRs and seem to be greater than a CRS effect. A possible explanation is that converting a lane into a DBL reduces capacity for general traffic, whose impacts are expected to be greater with more congested traffic conditions. In addition, the activation of TSP strategies may reduce the effectiveness of traffic coordination created by the BAL offsets. Figure 3e clearly shows that negative side-street delay savings are associated with the number of intersections with TSPwDBL, which nearly follows a CRS effect. This is expected since more intersections with TSPwDBL lead to more side streets affected by the TSP strategies.

Interestingly, Figure 3f depicts differing trends in network person delay effects by demand levels. For example, with low traffic demand (VCR=0.5), person delay savings are positive and increase with more intersections with TSPwDBL. The effect on person delay savings is however smaller than a CRS effect. With higher traffic demand (VCR=0.7), negative person delay savings are more evident with more TSPwDBL-provided intersections. The reason may be that the benefits from bus delay savings outweigh the impacts on general traffic with low traffic demand whereas with higher traffic demand the latter negate the former.

Figure 3 Percentage delay savings for TSPwDBL combinations with BAL offsets and 5-minute headway



3.1.2. Eastbound Bus Coordination (EBC) offsets

Table 2 summarises results for TSPwDBL combinations with the EBC offsets. As the EBC offsets provide EB bus coordination, EB bus delays with the EBC offsets are smaller than those with the BAL offsets. However, general traffic delays are significantly higher with the EBC offsets than with the BAL offsets, leading to greater network person delays with the EBC offsets. This is expected since the BAL offsets minimise person delays. Percentage delay savings by the number of intersections with TSPwDBL are depicted in Figure 4.

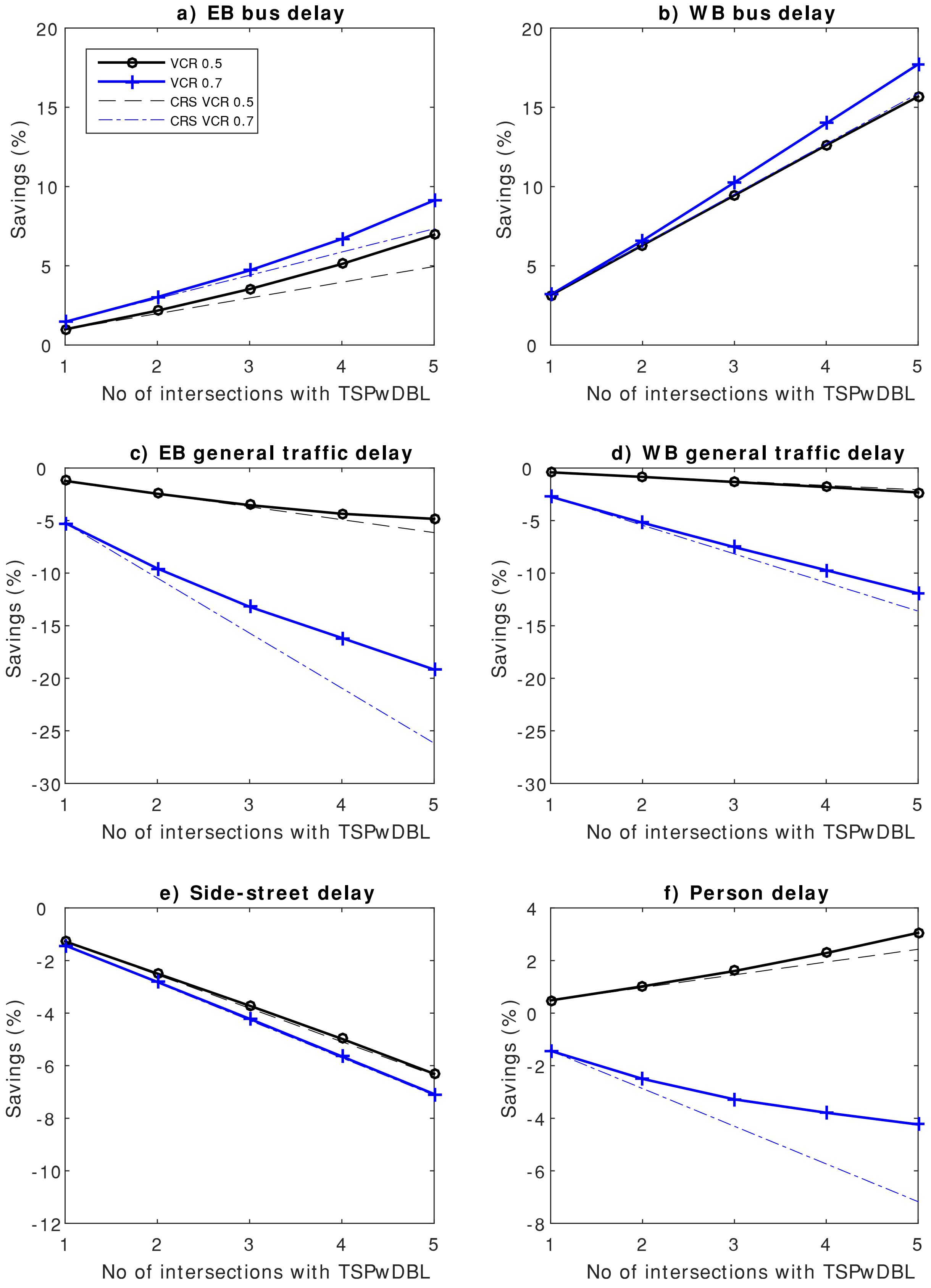
Table 2 Summary of average delays for TSPwDBL combinations with EBC offsets and 5-minute headway

VCR	No of intersections with TSPwDBL	Avg. vehicle delay (s)					Avg. network person delay (s)
		Bus EB	Bus WB	General traffic EB	General traffic WB	Side-street	
0.5	0 (Base)	317.0	368.1	82.9	97.9	41.3	114.6
	1	313.9	356.5	84.0	98.3	41.8	114.0
	2	310.1	344.9	85.0	98.8	42.3	113.4
	3	305.8	333.3	85.9	99.2	42.8	112.8
	4	300.8	321.7	86.6	99.7	43.4	112.0
	5	295.0	310.4	87.0	100.2	43.9	111.1
0.7	0 (Base)	324.6	377.4	99.0	104.7	42.3	112.3
	1	319.8	365.4	104.2	107.6	42.9	113.9
	2	314.8	352.5	108.4	110.2	43.5	115.1
	3	309.3	338.7	112.0	112.6	44.1	116.0
	4	302.8	324.6	115.0	114.9	44.7	116.6
	5	295.0	310.6	118.0	117.2	45.3	117.1

A multiplier effect on EB bus delay savings is evident in Figure 4a. The EB bus delay saving curves are above the corresponding CRS lines and the differences between them tend to be larger with more intersections with TSPwDBL. For example, EB bus delay benefits from providing TSPwDBL at all five intersections (7% and 9.1% for VCRs of 0.5 and 0.7 respectively) is higher than the sum of benefits from providing TSPwDBL at each intersection (5% and 7.3% for VCRs of 0.5 and 0.7 respectively). This suggests additional benefits of 40% and 25% for VCRs of 0.5 and 0.7 respectively when compared to a CRS effect. In other words, the multiplier effect results in a 5-8% increase in bus delay savings for each additional intersection with TSPwDBL. It is worth noting that TSPwDBL can reduce the variations in bus travel times as buses bypass traffic queues. Hence, providing TSPwDBL at multiple intersections is likely to make bus coordination offsets perform better, providing that variations in bus travel times in the base scenario are not too high. This may contribute to the multiplier effect on EB bus delay savings in the EBC offsets.

Figure 4b shows that WE bus delay savings are higher than EB bus delay savings, suggesting that priority measures may be more effective in reducing bus delay in more congested conditions. With a VCR of 0.5, WB bus delay savings appear to follow a CRS effect. However, with a VCR of 0.7, the relationship between WB bus delay savings and the number of intersections with TSPwDBL seems to follow a multiplier effect. For example, compared to a CRS effect, the effect of five intersections with TSPwDBL on WB bus delay savings with a VCR of 0.7 is about 1.1 times higher (17.7% versus 15.9%).

Figure 4 Percentage delay savings for TSPwDBL combinations with EBC offsets and 5-minute headway

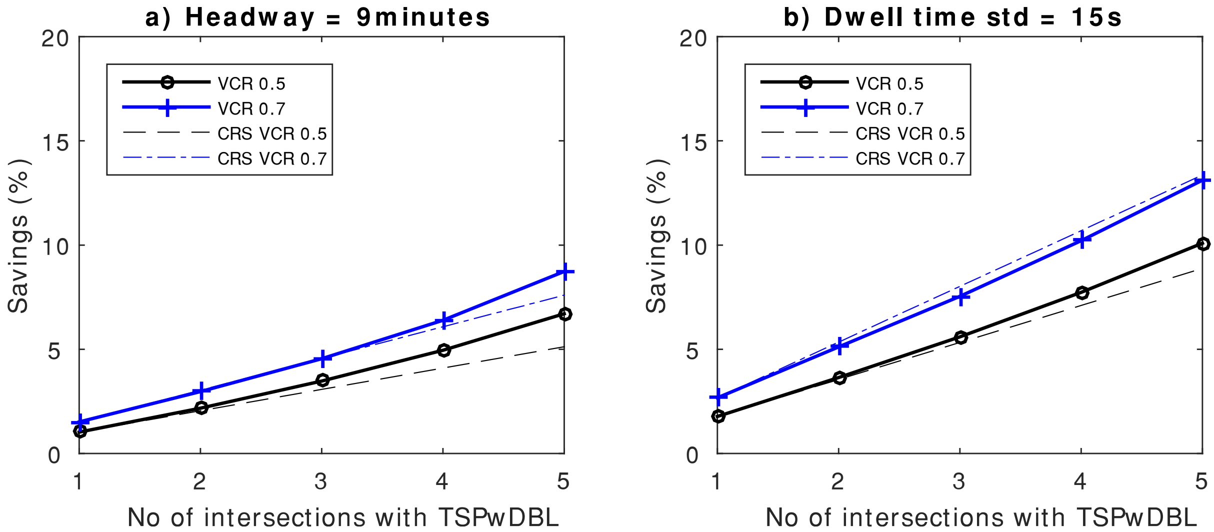


Similar to results with the BAL offsets, Figure 4c-d indicate that general traffic delays increase with more TSPwDBL-provided intersections. However, the increases in general traffic delays tend to be smaller than a CRS effect. In addition, Figure 4e illustrates a CRS effect on the increases in side-street delays. Figure 4f shows that with a VCR of 0.7, network person delays increase when more intersections are provided with TSPwDBL. With a VCR of 0.5, network person delay savings increase when more intersections are provided with TSPwDBL. Interestingly, person delay savings appear to follow a multiplier effect, which is slightly better than a CRS effect. This may be attributed by the multiplier effect on EB bus delay savings and the CRS effect on WB bus delay savings, which are larger than the negative impacts on general traffic with low traffic demand.

3.1.3. Sensitivity tests

The possible multiplier effect of TSPwDBL on EB bus delay savings in the EBC offsets is further examined with different bus headways and levels of bus dwell time variations. Figure 5a clearly shows that there is a multiplier effect on EB bus delay savings with a bus headway of 9 minutes. Figure 5b presents results EB bus delay savings when the standard deviation of dwell time is set as 15s, a large increase from 10s in the previous experiments. The effect on EB bus delay savings is a multiplier effect with a VCR of 0.5, but smaller than a CRS effect with a VCR of 0.7. This suggests that the effectiveness of bus progression may be reduced with larger variations in bus travel time, resulting from larger dwell time variations.

Figure 5 Results of sensitivity tests for EB bus delay savings from TSPwDBL combinations



3.2. Transit Signal Priority with Queue Jump Lanes (TSPwQJL)

3.2.1. Balanced (BAL) offsets

Table 3 presents results for TSPwQJL combinations with the BAL offsets. General traffic delays in both directions are relatively low, suggesting that the BAL offsets provide traffic coordination. Bus delays are much larger than general traffic delays, which is attributed to the dense stop spacing. Percentage delay savings by the number of intersections with TSPwQJL are presented in Figure 6.

Figure 6a-b indicate bus delay savings are greater when more intersections are provided with TSPwQJL. In addition, bus delay savings are greater with higher traffic demand. It is clear that the bus delay saving curves are below the corresponding CRS lines, particularly for the EB direction.

Table 3 Summary of average delays for TSPwQJL combinations with BAL offsets and 5-minute headway

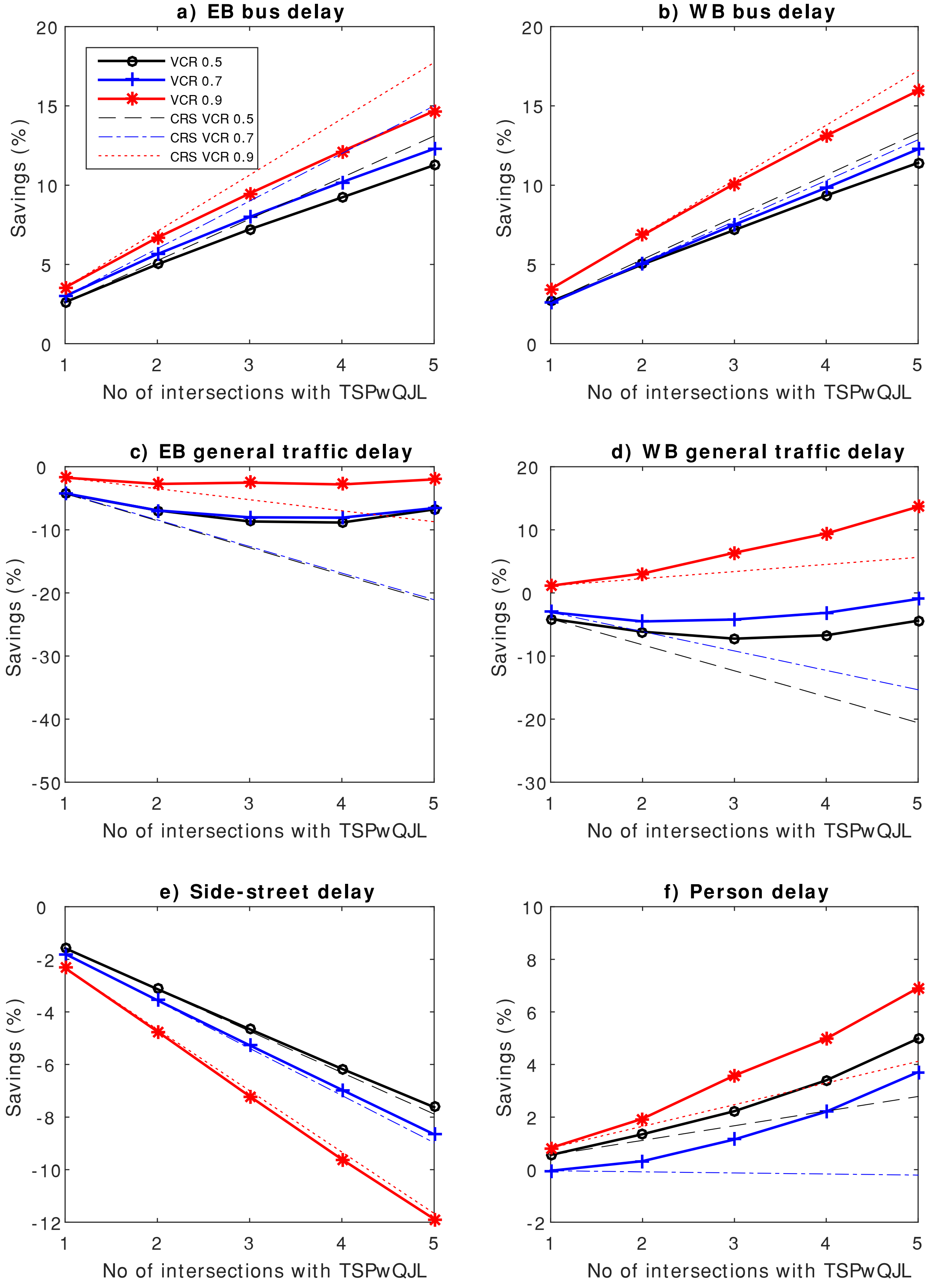
VCR	No of intersections with TSPwQJL	Avg. vehicle delay (s)					Avg. network person delay (s)
		Bus EB	Bus WB	General traffic EB	General traffic WB	Side-street	
0.5	0 (Base)	356.0	352.0	32.0	32.2	41.2	83.3
	1	346.6	342.6	33.4	33.5	41.8	82.8
	2	338.2	334.4	34.2	34.2	42.5	82.1
	3	330.3	326.8	34.8	34.5	43.1	81.4
	4	323.1	319.1	34.8	34.4	43.7	80.4
	5	315.9	311.9	34.2	33.6	44.3	79.1
0.7	0 (Base)	360.5	356.4	42.7	44.0	42.5	78.6
	1	349.7	347.2	44.5	45.4	43.3	78.7
	2	340.1	338.3	45.7	46.0	44.0	78.4
	3	331.7	329.6	46.2	45.9	44.8	77.7
	4	323.8	321.4	46.2	45.4	45.5	76.9
	5	316.2	312.7	45.5	44.4	46.2	75.7
0.9	0 (Base)	372.4	375.4	70.7	77.1	43.7	91.7
	1	359.2	362.5	71.9	76.2	44.7	90.9
	2	347.5	349.7	72.6	74.7	45.7	89.9
	3	337.1	337.5	72.4	72.2	46.8	88.4
	4	327.2	326.2	72.7	69.8	47.9	87.1
	5	317.8	315.5	72.1	66.6	48.9	85.3

Figure 6c shows that TSPwQJL results in negative EB general traffic delay savings. EB general traffic delays slightly increase as the number of intersections with TSPwQJL increases from one to a certain value and then starts to slightly decrease. It can be argued that the activation of TSPwQJL control in general may affect traffic coordination in the BAL offsets. However, traffic coordination seems to be slightly regained when more intersections are provided with TSPwQJL.

Figure 6d presents similar patterns on WB general traffic delay savings with VCRs of 0.5 and 0.7. However, with a VCR of 0.9, TSPwQJL results in positive WB general traffic delay savings, which increase with more prioritised intersections. Moreover, the WB general traffic delay curve is above the corresponding CRS line, suggesting a multiplier effect. Since there are near-side bus stops in the WB direction, they are expected to have a significant impact on WB traffic, particularly in near congested conditions with a VCR of 0.9. However, the impact of a near-side bus stop on traffic is removed when TSPwQJL is provided as the near-side bus stop is relocated to the QJL. Hence, providing TSPwQJL at multiple intersections tends to create smoother traffic with a VCR of 0.9, which leads to a multiplier effect.

As expected, Figure 6e illustrates a nearly CRS effect on side-street traffic delays where they increase linearly with the number of intersections with TSPwQJL. Interestingly, Figure 6f depicts a multiplier effect on network person delay savings where the person delay savings curves are clearly above the corresponding CRS lines. For example, five intersections with TSPwQJL create a 6.9% person delay saving with a VCR of 0.9, which is 1.7 times higher when compared to a CRS effect (4.1%). This suggests that the multiplier effect results in a 14% increase in person delay saving for each additional intersection with TSPwQJL. The reason for the multiplier effect may be attributed to the general traffic delay patterns discussed above and the BAL offsets that provide coordination in terms of person delay. In addition, greater savings are associated with higher VCRs. Overall, results show that TSPwQJL can create benefits both in terms of bus delay and person delay.

Figure 6 Percentage delay savings for TSPwQJL combinations with BAL offsets and 5-minute headway



3.2.2. Eastbound Bus Coordination (EBC) offsets

Table 4 shows results for TSPwQJL combinations with the EBC offsets. EB bus delays with the EBC offsets are smaller than those with the BAL offsets, which is expected since the EBC offsets provide bus coordination in the eastbound direction only. However, general traffic delays and network person delays are higher when compared to the BAL offsets. Percentage delay savings by the number of intersections with TSPwQJL are summarised in Figure 7.

Table 4 Summary of average delays for TSPwQJL combinations with EBC offsets and 5-minute headway

VCR	No of intersections with TSPwQJL	Avg. vehicle delay (s)					Avg. network person delay (s)
		Bus EB	Bus WB	General traffic EB	General traffic WB	Side-street	
0.5	0 (Base)	317.0	368.5	82.9	97.9	41.3	114.6
	1	313.3	356.1	82.3	97.6	41.8	113.3
	2	309.2	344.2	81.7	97.3	42.3	112.0
	3	304.6	332.7	81.4	97.0	42.9	110.7
	4	299.4	321.4	81.2	97.0	43.4	109.6
	5	292.8	310.4	81.3	97.8	44.0	108.7
0.7	0 (Base)	324.6	377.0	99.0	104.6	42.3	112.3
	1	319.8	365.0	98.2	104.4	42.9	111.2
	2	314.7	353.0	97.6	104.1	43.5	110.1
	3	308.8	341.6	97.0	103.7	44.1	109.1
	4	302.0	330.5	96.3	103.2	44.8	107.9
	5	294.7	318.5	96.1	103.5	45.4	107.0
0.9	0 (Base)	330.1	387.3	120.7	114.8	43.7	116.9
	1	325.9	376.4	120.0	114.2	44.6	116.1
	2	320.7	364.6	119.4	113.4	45.4	115.2
	3	314.8	352.5	118.9	112.6	46.2	114.2
	4	308.5	339.6	119.0	112.1	47.1	113.6
	5	300.0	328.4	119.4	111.4	48.1	112.9

Figure 7a clearly shows a multiplier effect on EB bus delay savings as the curves are above the corresponding CRS lines. For example, the EB bus delay benefit from providing TSPwQJL at five intersections with a VCR of 0.9 is 1.4 times higher when compared to a CRS effect (9.1% versus 6.5%). This suggests that the multiplier effect results in an 8% increase in bus delay savings for each additional intersection with TSPwQJL. Similar to the multiplier effect of TSPwDBL, a possible explanation for the multiplier effect of TSPwQJL is that multiple intersections with TSPwQJL tend to make bus coordination offsets perform better. Figure 7b shows that WE bus delay savings are higher than EB bus delay savings. However, the WB bus delay saving curves are under or close to the corresponding CRS lines with VCRs of 0.5 and 0.7. On the contrary, with a VCR of 0.9, the relationship between WB bus delay savings and the number of intersections with TSPwQJL appears to follow a multiplier effect.

Figure 7c shows that in contrast to the BAL offsets, TSPwQJL generates positive EB general traffic delay savings with EBC offsets. However, more intersections with TSPwQJL do not necessarily create more savings. Note that general traffic delays in the EBC offsets scenario are much higher than in the BAL offsets scenario. Overall, results suggest different general traffic impacts for the two offset settings. Similarly, Figure 7d also indicates positive WB general traffic delay savings. Furthermore, with a VCR of 0.9, the WB general traffic delay saving curve is above the corresponding CRS line, suggesting a multiplier effect. This is similar to results in the BAL offsets scenario.

Figure 7 Percentage delay savings for TSPwQJL combinations with EBC offsets and 5-minute headway

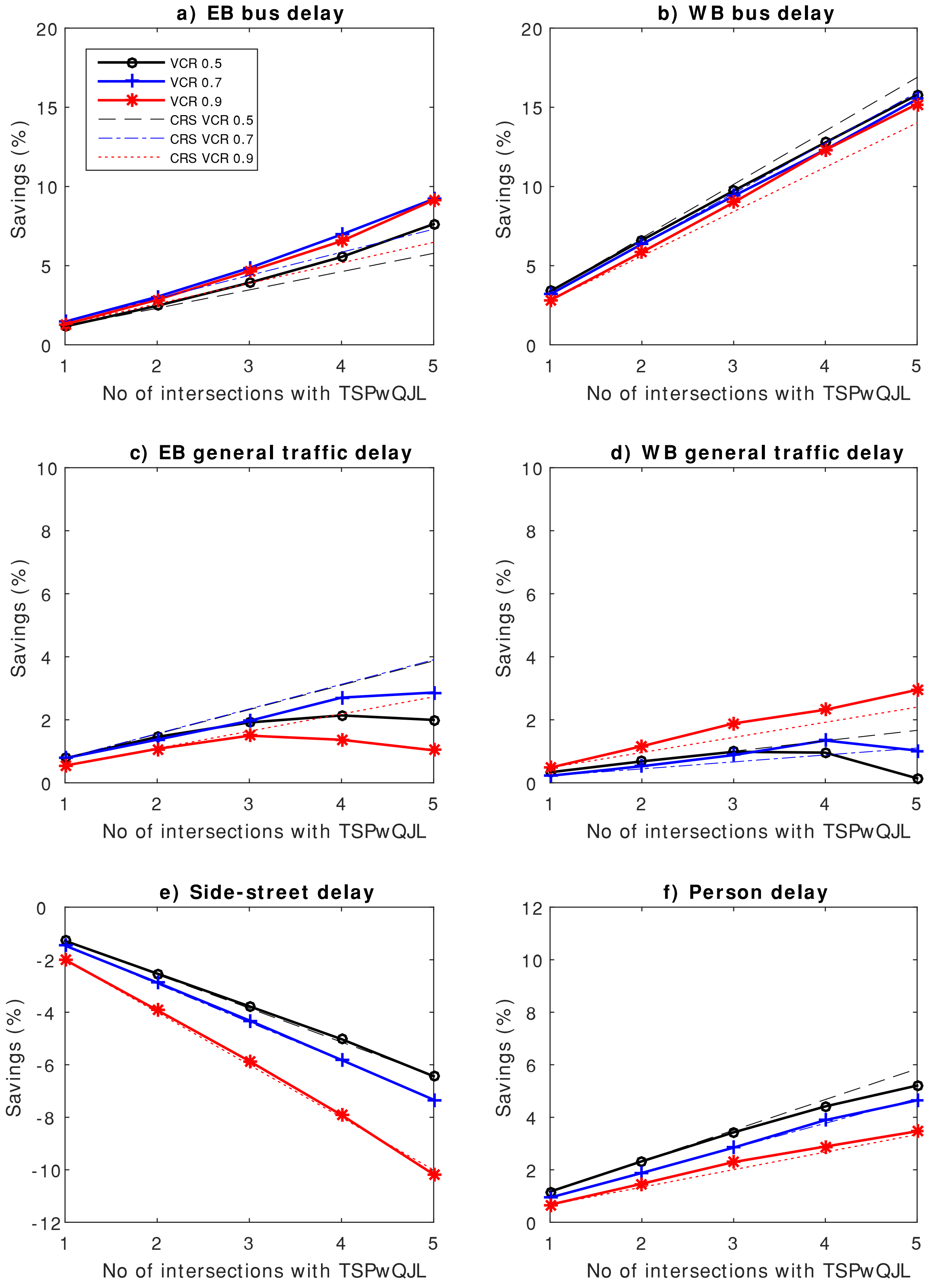
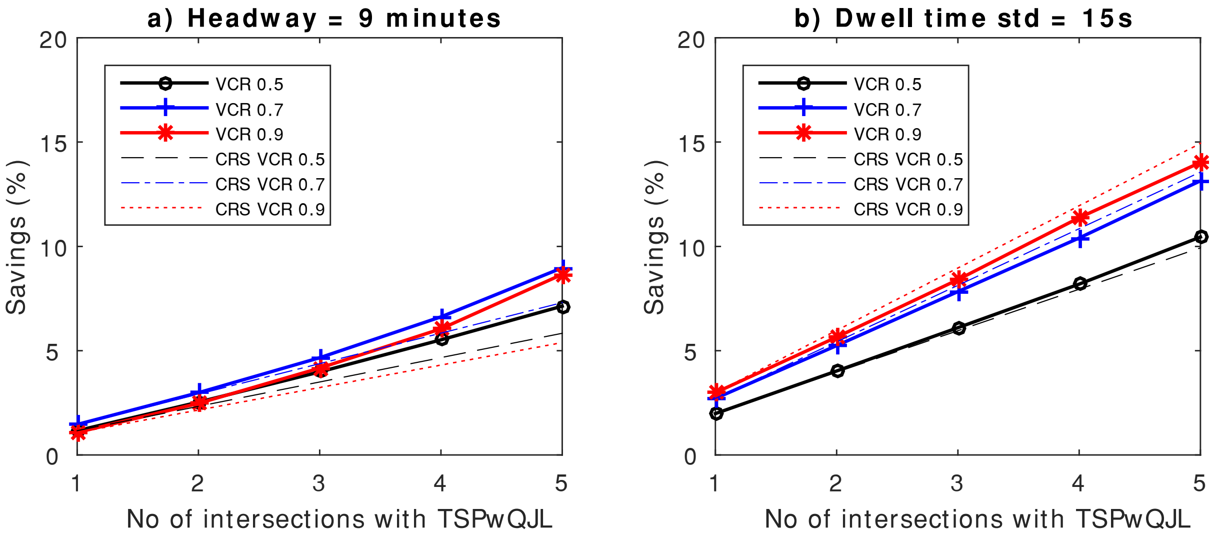


Figure 7e illustrates a CRS effect on side-street traffic delay where side-street traffic delays increase linearly with increasing numbers of prioritised intersections. Figure 7f indicates that person delay savings increase with more prioritised intersections, which slightly deviates from a CRS effect. In addition, person delay savings tend to decrease with higher VCRs, which is in contrast to the pattern in the BAL offsets. Overall, results suggest that person delay savings from TSPwQJL and TSPwDBL are affected by offset settings. It is noted that in this analysis, the length of QJLs is set as 100 m. If QJLs are implemented with the optimum length, i.e. longer than the maximum traffic queue length, it is expected that benefits of TSPwQJL are at least as high as the benefits shown in this analysis.

3.2.3. Sensitivity tests

The possible multiplier effect of TSPwQJL on EB bus delay savings in the EBC offsets is also examined with a bus headway of 9 minutes and a dwell time standard deviation of 15s. Figure 8a clearly shows that there is also a multiplier effect on EB bus delay savings with a bus headway of 9 minutes. Figure 8b suggests that when the dwell time standard deviation increases to 15s, the effect on EB bus delay savings is slightly better than the CRS effect with a VCR of 0.5, but smaller than the CRS effect with VCRs of 0.7 and 0.9. These patterns are similar to the case of TSPwDBL. Overall, results suggest a multiplier effect on one-directional bus delay savings may be achieved by providing bus progression for that direction, providing that the variations in bus dwell times are not too high.

Figure 8 Results of sensitivity tests for EB bus delay savings from TSPwQJL combinations



4. Conclusions

This paper has explored the effects of providing Transit Signal Priority with Dedicated Bus Lanes (TSPwDBL) or Transit Signal Priority with Queue Jump Lanes (TSPwQJL) at multiple intersections on bus delay savings and person delay savings. An extensive traffic micro-simulation modelling test-bed based on a hypothetical arterial was developed to evaluate the performance of possible combinations of priority measures at all intersections along the arterial.

Simulation results revealed that providing TSPwDBL or TSPwQJL at multiple intersections may create a multiplier effect on one-directional bus delay savings, particularly when signal offsets provide bus progression for that direction. For example, the multiplier effect resulted in a 5-8% increase in bus delay savings for each additional intersection with TSPwDBL or TSPwQJL. The multiplier effect is more visible if the variations in bus dwell times are not very high. A possible explanation for the multiplier effect on bus delay savings is that TSPwDBL and TSPwQJL can reduce the variations in bus travel times and thus enable signal offsets, which account for bus progression, to perform even better. While it is not always possible to provide coordination for both directions, providing coordination for a more congested direction may generate significant benefits, particularly with a possible multiplier effect on bus delay savings. Furthermore, simulation results also showed limited evidence of the existence of a multiplier effect on network person delay savings, particularly for TSPwQJL with offsets that favour person delay savings. A policy implication of these findings is that considerable PT benefits and system-wide benefits, such as person delay benefits, can be achieved through providing both time and space priority on a corridor-wide scale. The implementation of TSPwDBL or TSPwQJL at multiple intersections will help to improve travel times and reliability for PT passengers, ultimately enhance the PT user experience.

It is worth noting that these findings are purely based on the setup of the traffic micro-simulation modelling test-bed. Future research should further examine these effects with a wider range of variable characteristics, such as car and bus occupancies, queue jump lane length, link length, and signal cycle length. It is also worth exploring these effects when signal offsets for each combination scenario are optimised individually. This will provide better comparisons where possible benefits from each combination scenario are maximised. Nevertheless, empirical studies and field experiments will be needed to validate these findings.

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