Does Combining Transit Signal Priority with Dedicated Bus Lanes or Queue Jump Lanes at Multiple Intersections Create Multiplier Effects?

Long T. Truong, Graham Currie, Mark Wallace, and Chris De Gruyter

An extensive body of literature deals with the design and operation of public transport (PT) priority measures. However, there is a need to understand 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. If 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, a multiplier effect exists. This paper 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 may create a multiplier effect on one-directional bus delay savings, particularly when signal offsets provide bus progression for that direction. The multiplier effect may result in a 5% to 8% increase in bus delay savings for each additional intersection with TSPwDBL or TSPwQJL. A possible explanation is that TSPwDBL and TSPwQJL can reduce the variations in bus travel times and thus allow signal offsets—which account for bus progression—to perform even better. Furthermore, results show little evidence of the existence of a multiplier effect on person delay savings, particularly for TSPwQJL with offsets that favor person delay savings. A policy implication of these findings is that considerable PT benefits can be achieved by providing both time and space priority in combination on a corridorwide scale.

Urban traffic congestion is a major challenge in almost every major city worldwide. Because of 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, however, is restricted by urban traffic congestion. Hence, priority for 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, dedicated bus lanes (DBLs) improve bus travel time but could increase general traffic travel time, particularly in congested traffic conditions (*1, 2*). To mitigate the negative impact on general traffic, dynamic bus lanes, in which general traffic is allowed to travel on the bus lane intermittently when it is not used by a bus, have been proposed, particularly where bus frequencies are low (*3*). Another widely used priority measure is the queue jump lane (QJL). A QJL is a short bus lane at traffic signals that allows buses to travel in and then move forward from a left or right turn lane, depending on left-hand or right-hand driving, while bypassing queues in adjacent traffic lanes (*4, 5*). Transit signal priority (TSP), designed to facilitate PT vehicle movement at signalized intersections, is categorized as passive, active, or adaptive priority (*6*). Active priority dynamically adjusts signal timings to give priority to PT vehicles when they are detected. Several active priority strategies have been used, such as green extension, early green, and phase insertion (*7–9*). To provide improved priority to PT vehicles, TSP may be combined with DBLs (*10–12*) or QJLs (*13–15*).

The performance of PT priority measures on signalized arterials has been a focus of much research. However, the effects of providing PT priority measures in combination at multiple locations, such as road sections or intersections, on the performance of buses and general traffic have been examined in only a few studies (*16–18*). For example, Chiabaut et al. 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 generally are enough to generate positive bus travel time savings (*16*). In addition, Truong et al. showed a linear link between the number of combined setback bus lane sections and bus travel time savings when signal coordination is not provided (*17*). Nevertheless, little is understood about the effects of providing PT priority measures, such as TSP with DBLs (TSPwDBL) and TSP with QJLs (TSPwQJL), in combination at multiple locations. Because of the impact of signal coordination on the effectiveness of TSP (*19*), these effects should be examined particularly for 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 must be established whether PT priority measures combined at multiple locations create a multiplier effect by which the benefit from measures at multiple locations is greater than the sum of benefits from individual measures at each of the 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 PT priority measures on a corridorwide scale. This paper explores the effects of

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TSPwDBL or TSPwQJL in combination at multiple intersections on bus delay savings and person delay savings by using an extensive traffic microsimulation modeling test bed.

The rest 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 for various offset settings and sensitivity tests. The paper concludes with a summary of key findings and directions for future research.

METHOD

Test Bed

A hypothetical arterial with five signalized intersections is proposed as a test bed for exploring the effects of TSPwDBL or TSPwQJL at multiple intersections. The arterial was designed with typical suburban arterial settings in Melbourne, Australia. Figure 1*a* depicts the layout of the test bed arterial. The arterial has three lanes in each direction, and 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 120 s, 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 kilometer. The eastbound bus line includes farside and midblock stops, and the bus line includes nearside and midblock stops. Bus dwell times are assumed to be normally distributed with a mean of 15 s and a standard deviation of 10 s; stop skipping is activated when a random bus dwell time is nonpositive. To capture random variations in times of bus entrance to the arterial, it is assumed that deviations between actual and scheduled entrance times follow a normal distribution with a mean of 0 s and standard deviation of 20 s. Traffic microsimulation models for the test bed were developed with the Vissim traffic simulator (*20*).

Priority Design

Figure 1, *b* and *c,* 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. However, 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, the green time of the parallel general traffic movement is shortened. In this study, a leading bus phase of 8 s was implemented. Figure 1*c* also shows that unlike the TSPwDBL case, the TSPwQJL case requires roadway expansion to provide the QJL and the left-turning lane compared with the base (without priority) case. Although the optimum length of the QJL should be greater than the maximum queue length, this study examined the QJL with a typical length of 100 m.

The TSP system uses two common strategies—green extension and early green—with a maximum priority time of 10 s. To maintain signal coordination, green time for side streets is reduced by the

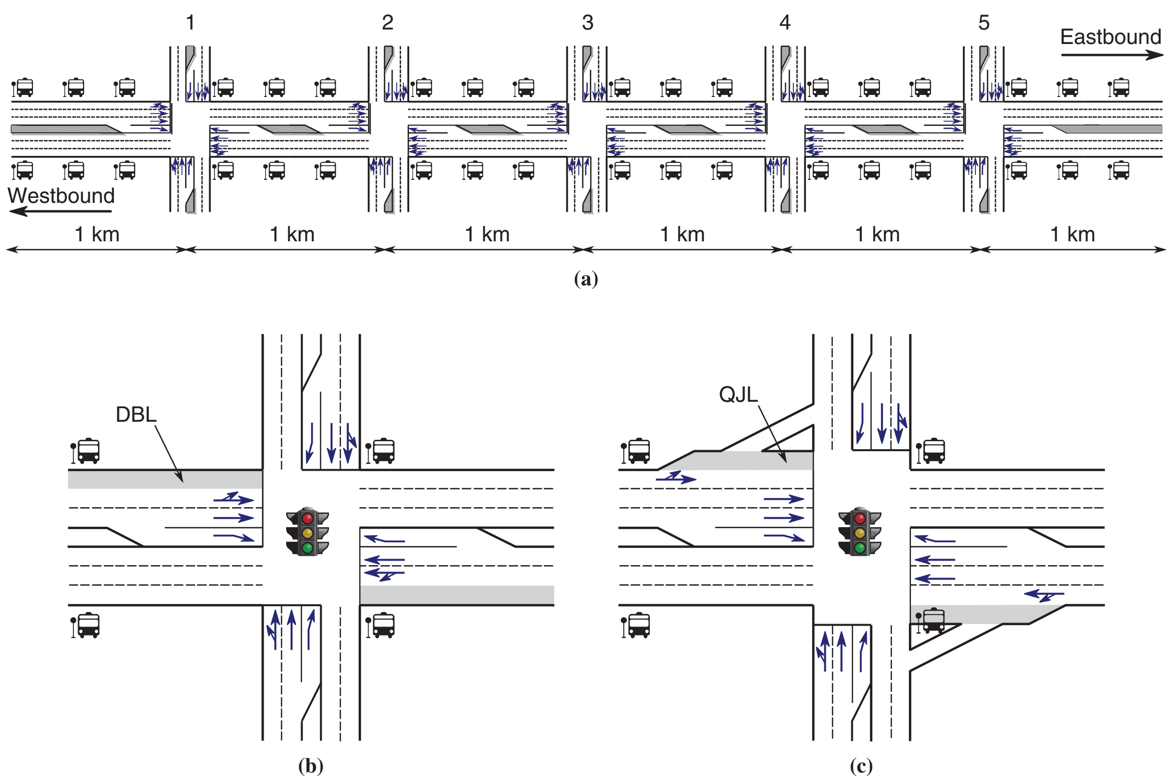

FIGURE 1 Layouts: (*a*) test-bed arterial, (*b*) TSPwDBL, and (*c*) TSPwQJL.

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 100 m before the stop line if there is no nearside stop or immediately after the bus stop if there is a nearside 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 a 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 be activated only once per cycle and 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 modeled in the traffic simulator with vehicle actuated programming.

Combination Scenarios

To investigate the effects of TSPwDBL or TSPwQJL combined at multiple intersections, all possible combinations of priority measures at the five intersections must be considered. There is a total of 32 (2^5) combination scenarios, including the base scenario (without priority). Performance criteria include average eastbound bus delay, average westbound bus delay, average eastbound traffic delay, average westbound traffic delay, and average side-street delay. For a combined performance criterion, average network person delay is calculated with occupancies of 1.2 persons per car and 40 persons per bus.

For the demand sensitivity analysis, each scenario associated with TSPwQJL is evaluated for three arterial traffic demand levels, equivalent to volume-to-capacity (V/C) ratios 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 V/C ratios of 0.5 and 0.7 in the base scenario. TSPwDBL is not tested with the V/C ratio of 0.9 as traffic demand far exceeds the capacity of the remaining traffic lanes, creating excessive traffic delays (*17*). Bus headway is set at 5 min. Furthermore, two signal offset settings are considered: balanced (BAL) and eastbound bus coordination (EBC) offsets. The balanced offsets minimize average person delay in both directions of the arterial in the base scenario with a V/C ratio of 0.9, and the EBC offsets minimize eastbound bus delay in the base scenario with a V/C ratio of 0.9. The balanced and EBC offsets are obtained with offset optimization models developed by Truong et al. (*18*). Although the calculated balanced and EBC offsets might be slightly different from the optimal settings for other combination scenarios and V/C ratios, it is likely that they still perform relatively well in those cases. Overall, two priority measures, various demand levels, and two offset settings led to a total of 316 simulation experiments. Further sensitivity tests are also provided, such as tests of variance in bus dwell time, bus headway, bus occupancy, link length, signal cycle length, and westbound bus coordination (WBC) offsets that minimize westbound bus delay in the base scenario with a V/C ratio of 0.9.

Estimates of the minimum number of independent runs for each simulation experiment are necessary to obtain reliable simulation outputs. Thus, a program was developed to run simulation sequentially until all performance criteria have been estimated with 5% errors at an overall confidence level of 95% and the number of runs is at least 20 (*21*). The simulation time for each run is 2 h, excluding warm-up time.

RESULTS AND DISCUSSION

TSPwDBL

TSPwDBL BAL Offsets

Results for TSPwDBL combinations, aggregated from 32 combination scenarios, with the BAL offsets are summarized in Table 1. Overall, bus delays are considerably higher than general traffic delays, which is as expected because there are three bus stops per kilometer. The relatively low general traffic delays in both directions indicate traffic coordination provided by the BAL offsets.

Figure 2 further illustrates average delay savings by the number of intersections with TSPwDBL. The discontinuous lines represent a constant return to scale (CRS) effect: the effect of 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 by the average delay savings from providing priority separately at each of the five individual intersections.

Figure 2, *a* and *b,* shows that bus delay savings increase almost linearly with increasing numbers of intersections with TSPwDBL. In fact, bus delay–savings curves are slightly below the corresponding CRS lines. In addition, bus delay savings are slightly greater with greater V/C ratios, which was anticipated. Figure 2, *c* and *d,* however, indicates 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 V/C ratios and appear 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 2*e* shows that negative side-street delay savings are associated with the number of intersections with TSPwDBL, which nearly follows a CRS effect. This was expected because more intersections with TSPwDBL lead to more side streets affected by the TSP strategies. Figure 2*f* depicts differing trends in network person delay effects by demand levels. For example, with low traffic demand (V/C ratio = 0.5), person delay savings are positive and increase with more intersections with TSPwDBL. The effect on person delay savings, however, is smaller than a CRS effect. With higher traffic demand (V/C ratio = 0.7), negative person delay savings are more evident with more TSPwDBL-provided intersections. A possible reason is 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.

TSPwDBL EBC Offsets

Table 1 also presents results for TSPwDBL combinations with the EBC offsets. As the EBC offsets provide eastbound bus coordination, eastbound 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 was expected because the BAL offsets minimize person delays.

TABLE 1 Summary of Average Delays for TSPwDBL Combinations with 5-Min Headway and BAL/EBC Offsets

V/C Ratio	Number of Intersections with TSPwDBL	Average Vehicle Delay (s)					Average Network Person Delay (s)
		Bus EB	Bus WB	General Traffic EB	General Traffic WB	Side Street	
BAL Offsets							
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
EBC Offsets							
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

NOTE: EB = eastbound; WB = westbound.

Percentage delay savings by the number of intersections with TSPwDBL are given in Figure 3.

A multiplier effect on eastbound bus delay savings is evident in Figure 3*a*. The eastbound bus delay–savings curves are above the corresponding CRS lines, and the differences between them tend to be larger with more intersections with TSPwDBL. For example, eastbound bus delay benefits from having TSPwDBL at all five intersections (7% and 9.1% for V/C ratios of 0.5 and 0.7, respectively) are significantly greater than the sum of benefits from having TSPwDBL at each intersection (5% and 7.3% for V/C ratios of 0.5 and 0.7, respectively) at $p < .001$, suggesting additional benefits of 40% and 25% for VCRs of 0.5 and 0.7, respectively, compared with a CRS effect. In other words, the multiplier effect results in an increase of 5% to 8% in bus delay savings for each additional intersection with TSPwDBL. 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, if variations in bus dwell times are not too high. This effect may contribute to the multiplier effect on eastbound bus delay savings in the EBC offsets.

Figure 3*b* shows that westbound bus delay savings are higher than eastbound bus delay savings, suggesting that priority measures may more effectively reduce bus delay in more congested conditions. With a V/C ratio of 0.5, westbound bus delay savings appear to follow a CRS effect. However, with a V/C ratio of 0.7, the relationship between westbound bus delay savings and the number of intersections with TSPwDBL appears to follow a multiplier effect. For example, compared with a CRS effect, the effect of five intersections with TSPwDBL on westbound bus delay savings with a V/C ratio of 0.7 is about 1.1 times higher (17.7% versus 15.9%).

Similar to results with the BAL offsets, Figure 3, *c* and *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 3*e* illustrates a CRS effect on the increases in side-street delays. Figure 3*f* shows that with a V/C ratio of 0.7, network person delays increase when more intersections are provided with TSPwDBL. With a V/C ratio of 0.5, network person delay savings increase when more intersections are provided with TSPwDBL. Person delay savings appear to follow a multiplier effect, which is slightly better than a CRS effect, possibly attributable to the multiplier effect on eastbound bus delay savings and the CRS effect on westbound bus delay savings, which are larger than the negative impacts on general traffic with low traffic demand.

TSPwDBL Sensitivity Tests

The possible multiplier effect of TSPwDBL on eastbound bus delay savings in the EBC offsets was further examined with different bus headways and levels of bus dwell time variations. Figure 4*a* shows that there is a multiplier effect on eastbound bus delay savings with a bus headway of 9 min. Figure 4*b* presents results for eastbound bus delay savings when the standard deviation of dwell time is set as 15 s, a large increase from 10 s in the previous experiments. The effect on eastbound bus delay savings is a multiplier effect with a

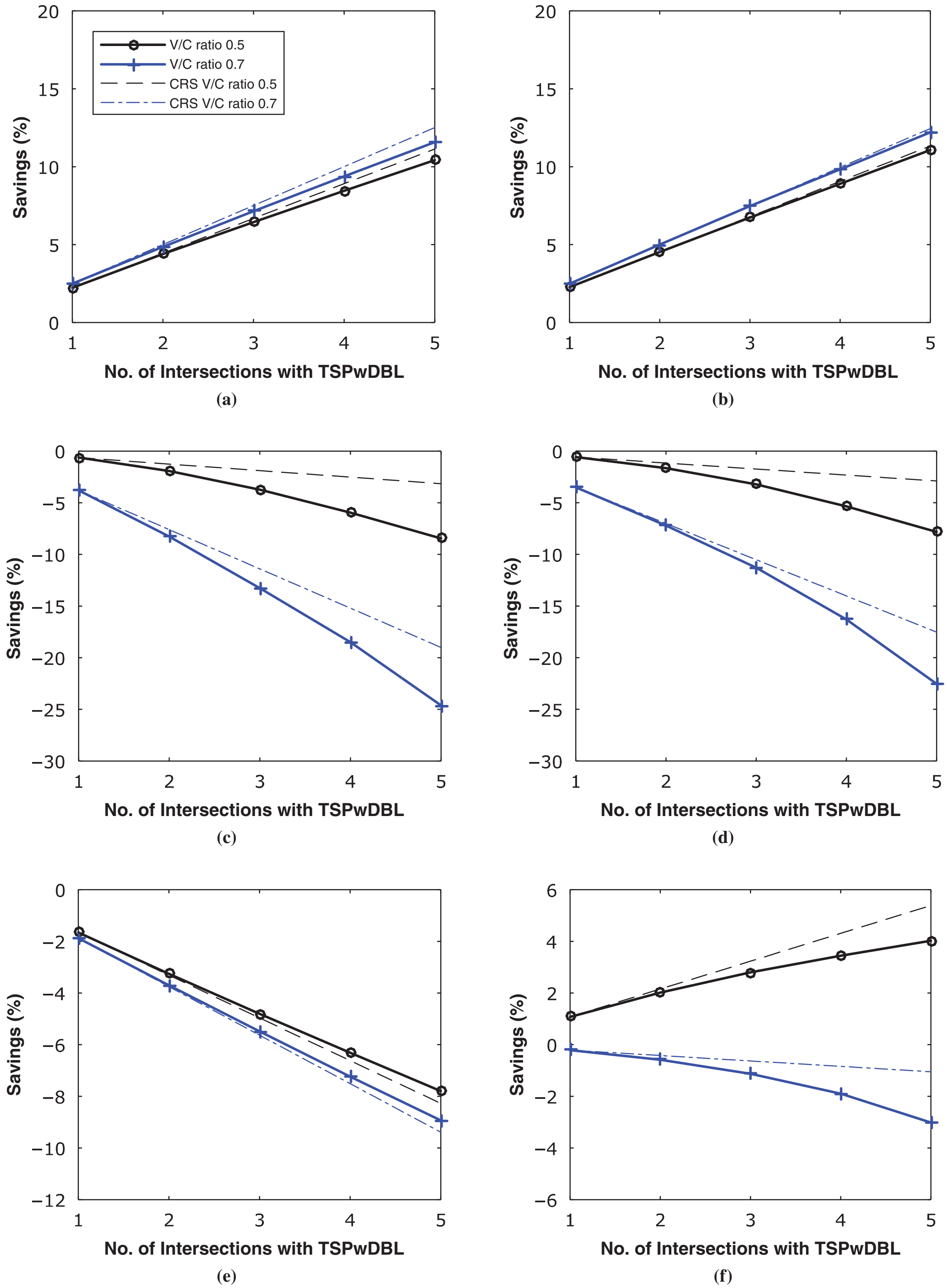

FIGURE 2 Percentage delay savings for TSPwDBL combinations with BAL offsets and 5-min headway: (*a*) eastbound bus delay, (*b*) westbound bus delay, (*c*) eastbound general traffic delay, (*d*) westbound general traffic delay, (*e*) side-street delay, and (*f*) person delay.

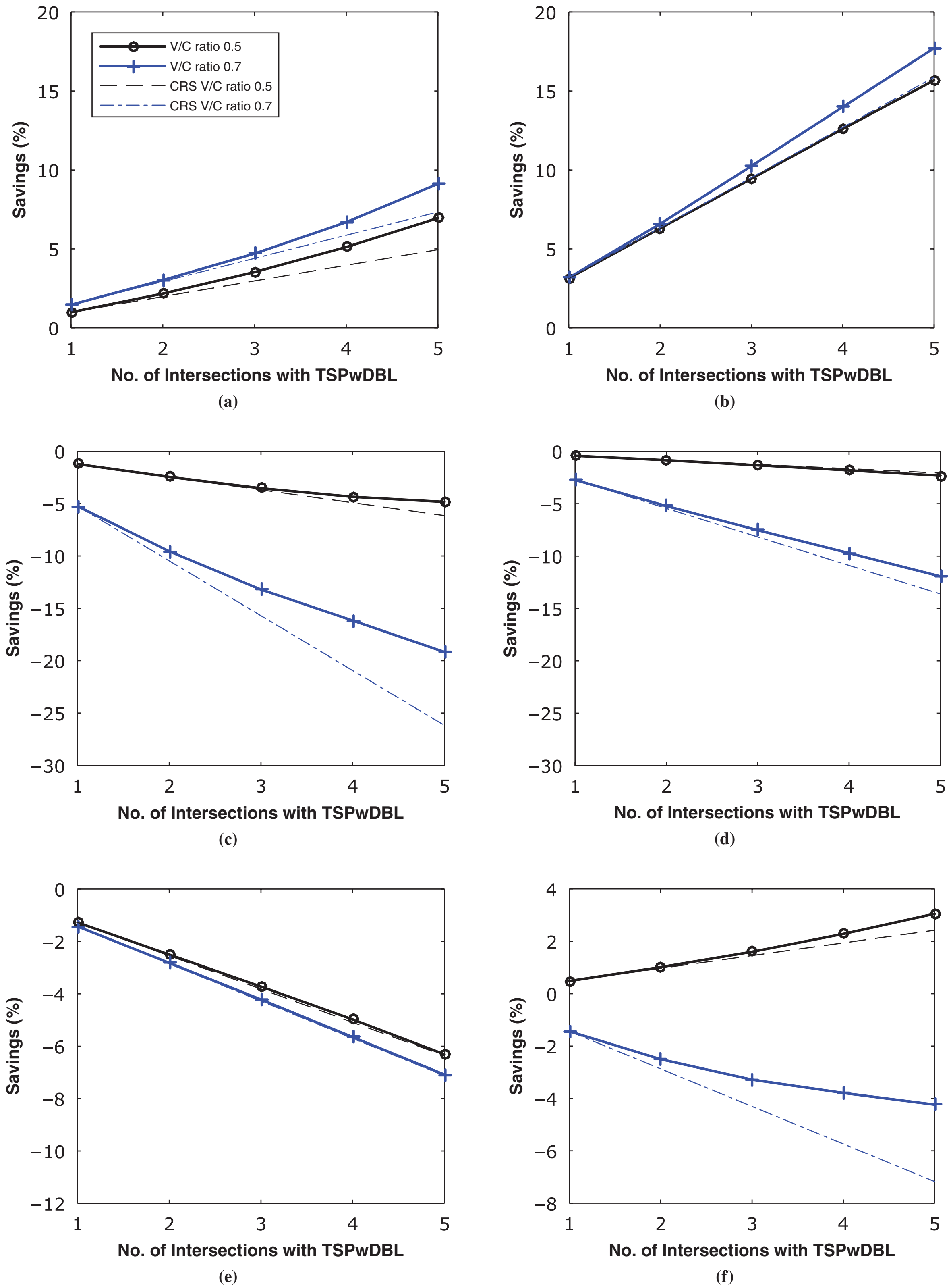

FIGURE 3 Percentage delay savings for TSPwDBL combinations with EBC offsets and 5-min headway: (*a*) eastbound bus delay, (*b*) westbound bus delay, (*c*) eastbound general traffic delay, (*d*) westbound general traffic delay, (*e*) side-street delay, and (*f*) person delay.

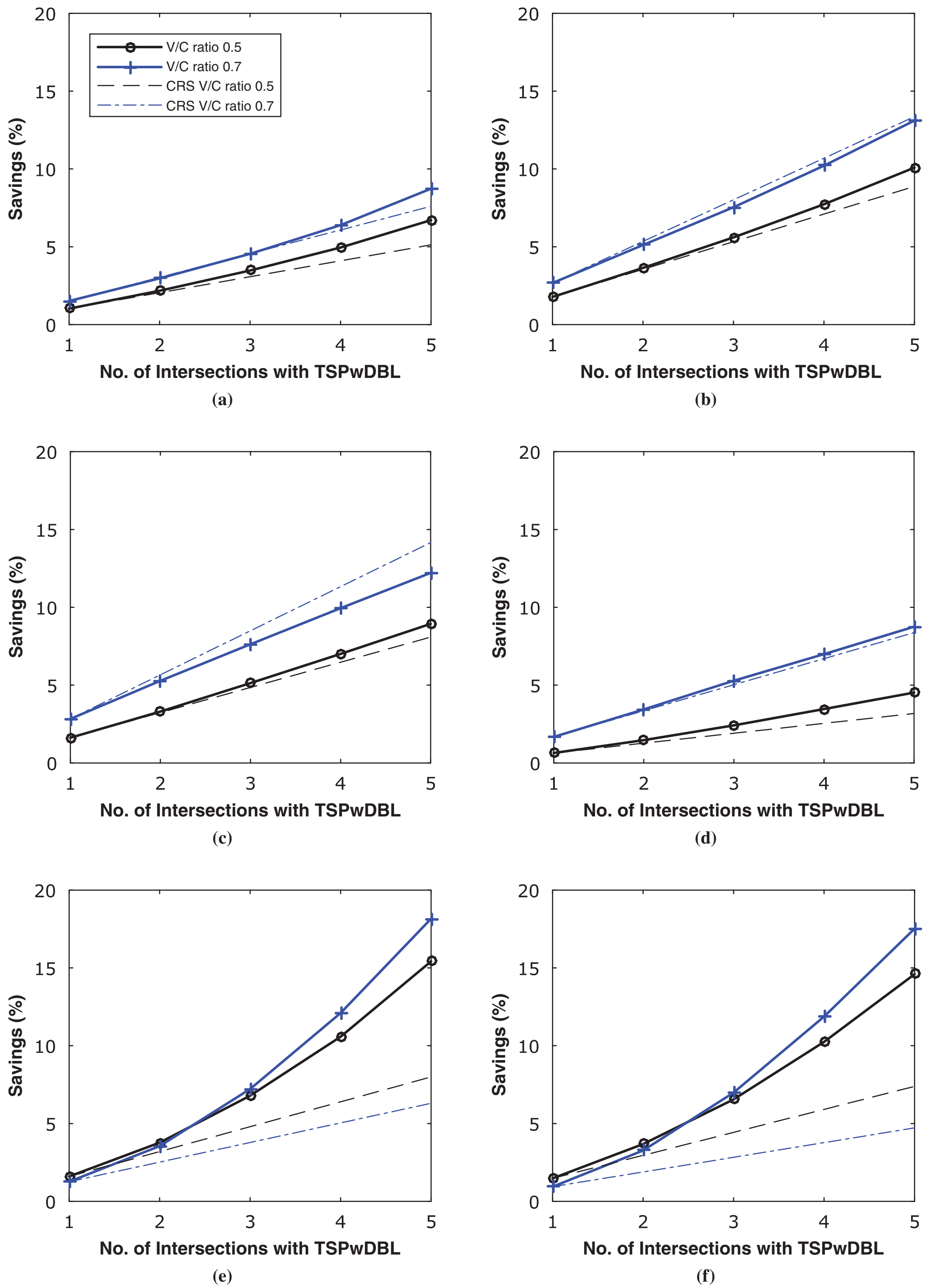

FIGURE 4 Results of sensitivity tests for TSPwDBL combinations: (*a*) eastbound bus delay, EBC offset, 9-min headway; (*b*) eastbound bus delay, EBC offset, 15-s dwell time SD; (*c*) westbound bus delay, WBC offset, 10-s dwell time SD; (*d*) westbound bus delay, WBC offset, 5-s dwell time SD; (*e*) eastbound bus delay, 500-m link length, 90-s cycle length, EBC offset, 5-min headway; and (*f*) eastbound bus delay, 500-m link length, 90-s cycle length, EBC offset, 9-min headway.

V/C ratio of 0.5 but smaller than a CRS effect with a V/C ratio of 0.7, suggesting that the effectiveness of bus progression may be reduced with larger variations in bus travel time, resulting from larger dwell time variations. The combined effect of TSPwDBL on westbound bus delay savings was also tested with WBC offsets that minimize westbound bus delay in the base scenario. Figure 4, *c* and *d,* demonstrates that a multiplier effect on westbound bus delay savings may also exist in the WBC offsets, particularly with smaller dwell time variations.

The possible multiplier effect in the EBC offsets was also tested with a shorter link length of 500 m and a signal cycle length of 90 s. In these tests, each link had a bus stop, and the maximum priority time and leading bus phase are 8 and 6 s, respectively. Figure 4, *e* and *f,* shows a clear multiplier effect on eastbound bus delay savings with bus headways of 5 and 9 min. The magnitude of the multiplier effect is higher compared with the previous settings, which could be attributed to lower variations in bus dwell times associated with fewer bus stops in this setting.

TSPwQJL

TSPwQJL BAL Offsets

Table 2 presents results for TSPwQJL combinations with 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 5.

Figure 5, *a* and *b,* indicates that 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–savings curves are below the corresponding CRS lines, particularly for the eastbound direction. Figure 5*c* shows that TSPwQJL results in negative eastbound general traffic delay savings. Eastbound general traffic delays slightly increase as the number of intersections with TSPwQJL increases from one to a certain

TABLE 2 Summary of Average Delays for TSPwQJL Combinations with 5-Min Headway and BAL/EBC Offsets

		Average Vehicle Delay (s)					
V/C Ratio	Number of Intersections with TSPwQJL	Bus EB	Bus WB	General Traffic EB	General Traffic WB	Side Street	Average Network Person Delay (s)
BAL Offsets							
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
EBC Offsets							
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

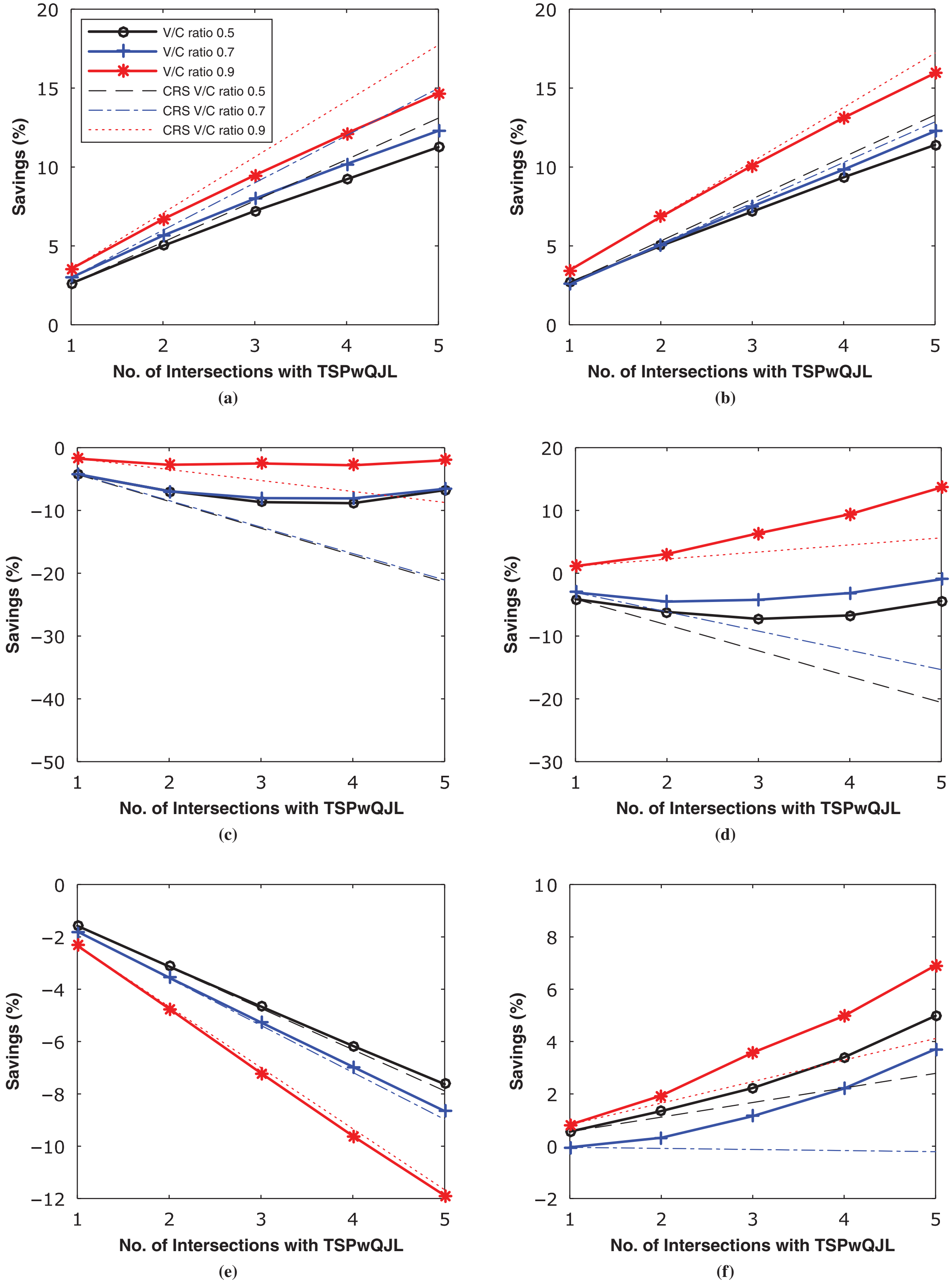

FIGURE 5 Percentage delay savings for TSPwQJL combinations with BAL offsets and 5-min headway: (*a*) eastbound bus delay, (*b*) westbound bus delay, (*c*) eastbound general traffic delay, (*d*) westbound general traffic delay, (*e*) side-street delay, and (*f*) person delay.

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 appears to be slightly regained when more intersections are provided with TSPwQJL.

Figure 5*d* presents similar patterns on westbound general traffic delay savings with V/C ratios of 0.5 and 0.7. However, with a V/C ratio of 0.9, TSPwQJL results in positive westbound general traffic delay savings, which increase with more prioritized intersections. Moreover, the westbound general traffic delay curve is above the corresponding CRS line, suggesting a multiplier effect. Since there are nearside bus stops in the westbound direction, they are expected to have a significant impact on westbound traffic, particularly in near-congested conditions with a V/C ratio of 0.9. However, the impact of a nearside bus stop on traffic is removed when TSPwQJL is provided as the nearside bus stop is relocated to the QJL. Hence, providing TSPwQJL at multiple intersections tends to create smoother traffic with a V/C ratio of 0.9, which leads to a multiplier effect.

Figure 5*e* illustrates a nearly CRS effect on side-street traffic delays where they increase linearly with the number of intersections with TSPwQJL. Figure 5*f* 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 V/C ratio of 0.9, which is 1.7 times higher compared with a CRS effect (4.1%). This is statistically significant at $p < .01$. This finding suggests that the multiplier effect results in a 14% increase in person delay savings for each additional intersection with TSPwQJL. A possible reason for the multiplier effect is 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 V/C ratios. Overall, results show that TSPwQJL can create benefits with respect to both bus delay and person delay.

TSPwQJL EBC Offsets

Table 2 also shows results for TSPwQJL combinations with the EBC offsets. Eastbound bus delays with the EBC offsets are smaller than those with the BAL offsets, which is as expected because the EBC offsets provide bus coordination in the eastbound direction only. However, general traffic delays and network person delays are higher compared with the BAL offsets. Percentage delay savings by the number of intersections with TSPwQJL are summarized in Figure 6.

Figure 6*a* shows a multiplier effect on eastbound bus delay savings as the curves are above the corresponding CRS lines. For example, the eastbound bus delay benefit from having TSPwQJL at five intersections with a V/C ratio of 0.9 is 1.4 times higher compared with a CRS effect (9.1% versus 6.5%), which is significant at $p < .001$, suggesting 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 6*b* shows that westbound bus delay–savings are higher than eastbound bus delay savings. However, the westbound bus delay savings curves are under or close to the corresponding CRS lines with V/C ratios of 0.5 and 0.7. On the contrary, with a V/C ratio of 0.9, the relationship between westbound bus delay savings and the number of intersections with TSPwQJL appears to follow a multiplier effect.

Figure 6*c* shows that in contrast to the BAL offsets, TSPwQJL generates positive eastbound general traffic delay savings with EBC offsets. However, more intersections with TSPwQJL do not necessarily create more savings. 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 6*d* indicates positive westbound general traffic delay savings. Furthermore, with a V/C ratio of 0.9, the westbound general traffic delay–savings curve is above the corresponding CRS line, suggesting a multiplier effect. This is similar to results in the BAL offsets scenario.

Figure 6*e* illustrates a CRS effect on side-street traffic delay where side-street traffic delays increase linearly with increasing numbers of prioritized intersections. Figure 6*f* indicates that person delay savings increase with more prioritized intersections, which slightly deviates from a CRS effect. In addition, person delay savings tend to decrease with higher V/C ratios, 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.

TSPwQJL Sensitivity Tests

The possible multiplier effect of TSPwQJL on eastbound bus delay savings in the EBC offsets was examined with a bus headway of 9 min and a dwell time standard deviation of 15 s. Figure 7*a* shows that there is a multiplier effect on eastbound bus delay savings with a bus headway of 9 min. Figure 7*b* suggests that when the dwell time standard deviation increases to 15 s, the effect on eastbound bus delay savings is slightly better than the CRS effect with a V/C ratio of 0.5 but is smaller than the CRS effect with V/C ratios 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, if the variations in bus dwell times are not too high. Figure 7*c* also shows multiplier effects on westbound bus delay savings in the WBC offsets, particularly with higher V/C ratios. The possible multiplier effect of TSPwQJL on person delay savings in the BAL offsets was also tested with a lower bus occupancy rate of 20 persons per bus. Figure 7*d* demonstrates that a multiplier effect on person delay savings may also exist with a lower bus occupancy rate in the BAL offsets.

Simulation tests were conducted for a shorter link length of 500 m and a signal cycle length of 90 s. Similar to the results of TSPwDBL, a multiplier effect of TSPwQJL on eastbound bus delay savings in the EBC offsets is evident in Figure 7, *e* and *f*.

CONCLUSIONS

This paper explores the effects of providing TSPwDBL or TSPwQJL at multiple intersections on bus delay savings and person delay savings. An extensive traffic microsimulation modeling 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 may result in a 5% to 8% increase in bus delay savings

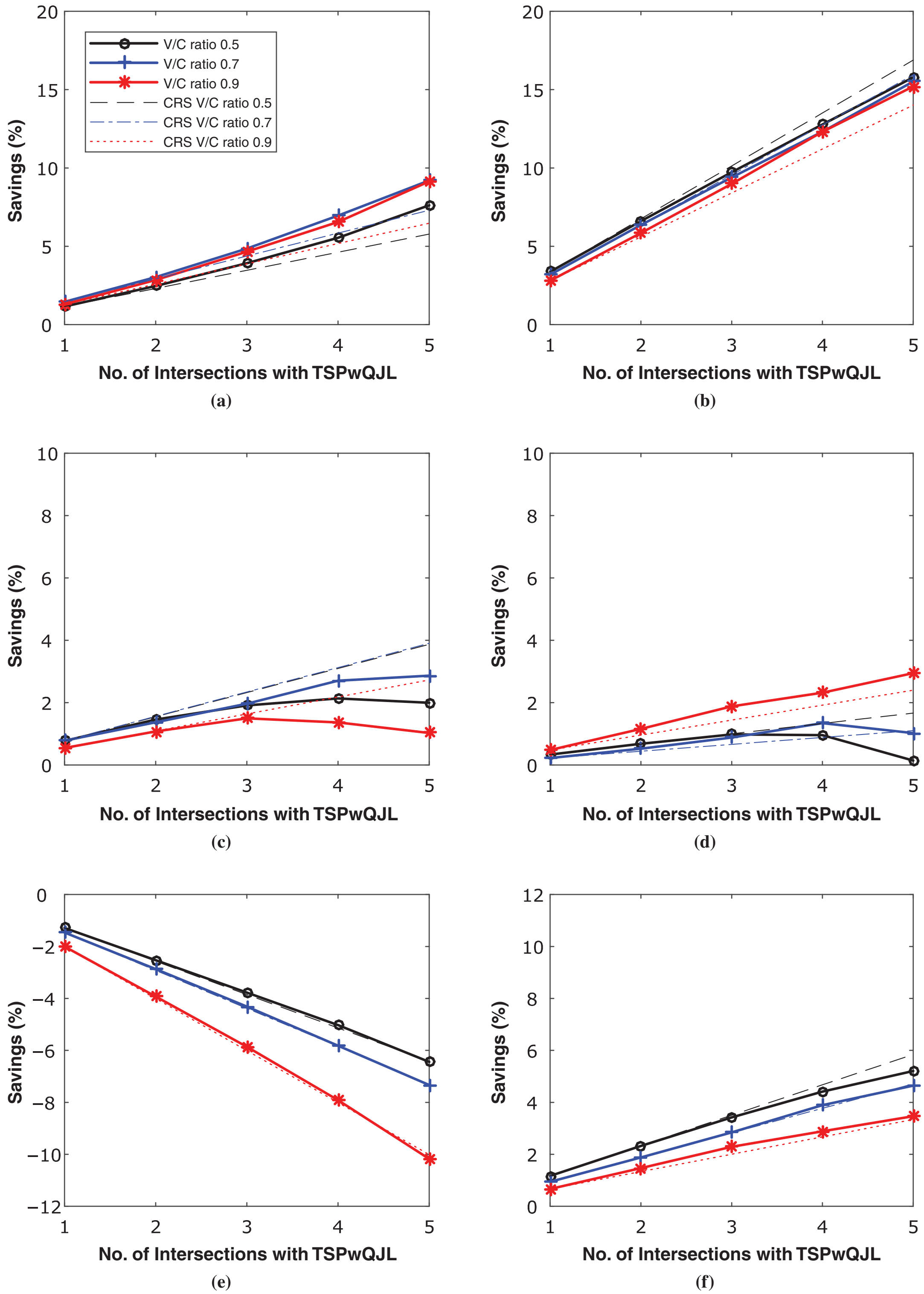

FIGURE 6 Percentage delay savings for TSPwQJL combinations with EBC offsets and 5-min headway: (*a*) eastbound bus delay, (*b*) westbound bus delay, (*c*) eastbound general traffic delay, (*d*) westbound general traffic delay, (*e*) side-street delay, and (*f*) person delay.

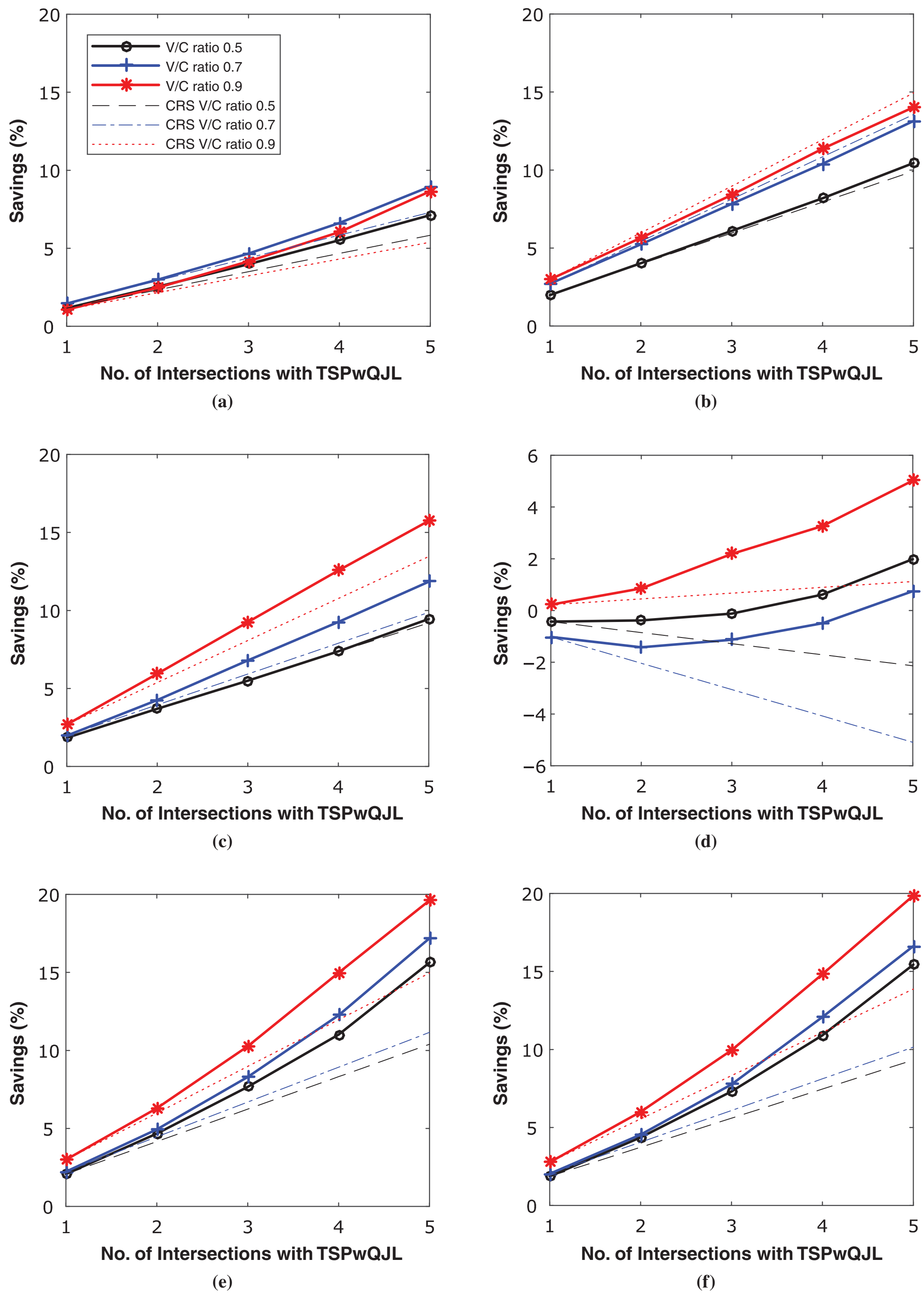

FIGURE 7 Results of sensitivity tests for TSPwQJL combinations: (*a*) eastbound bus delay, EBC offset, 9-min headway; (*b*) eastbound bus delay, EBC offset, 15-s dwell time SD; (*c*) westbound bus delay, WBC offset, 10-s dwell time SD; (*d*) person delay, BAL offset, 20 persons per bus; (*e*) eastbound bus delay, 500-m link length, 90-s cycle length, EBC offset, 5-min headway; and (*f*) eastbound bus delay, 500-m link length, 90-s cycle length, EBC offset, 9-min headway.

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 showed limited evidence of the existence of a multiplier effect on network person delay savings, particularly for TSPwQJL with offsets that favor person delay savings. A policy implication of these findings is that considerable public transit benefits can be achieved through both time and space priority on a corridorwide scale. The implementation of TSPwDBL or TSPwQJL at multiple intersections will improve travel times and reliability for public transit passengers, ultimately enhancing user experience.

These findings were based on the setup of the traffic microsimulation modeling test bed. Future research should examine these effects with a wider range of variable characteristics. Impacts of pedestrians and bicycles may also need to be considered in future research. It would be worth exploring these effects when signal offsets for each combination scenario are optimized individually. This approach would provide better comparisons in which possible benefits from each combination scenario are maximized. Nevertheless, empirical studies and field experiments will be needed to validate these findings.

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Any omissions or errors in the paper are the responsibilities of the authors.

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