Presignal Used to Increase Bus- and Car-Carrying Capacity at Intersections

Theory and Experiment

Yiguang (Ethan) Xuan, Vikash V. Gayah, Michael J. Cassidy, and Carlos F. Daganzo

In theory midblock presignals can be used to increase the capacity of signalized intersections [The authors define "presignal" as "a set of signal heads that are installed in the middle of a block upstream of an intersection."—Ed.]. The capacity is increased because presignals can reorganize how traffic is stored between a presignal and an intersection downstream. However, different vehicle classes have different acceleration characteristics, and the effectiveness of presignals hinges on the assumption of linear superposition; that is, the total time to discharge a mixture of distinct vehicle classes equals the sum of the times to discharge each vehicle class separately. This assumption has not been tested in the field. In this study, results from a natural experiment are used to validate the assumption for the case of cars and buses. The effectiveness of presignals to increase intersection capacity is also demonstrated.

A presignal is a special class of traffic signal. [The authors define "presignal" as "a set of signal heads that are installed in the middle of a block upstream of an intersection."—Ed.] It is placed midblock and is used to resolve the conflicts that arise between vehicles as they approach the signalized intersection downstream. To date, presignals have been used to enable buses to bypass car queues at intersections (*1–3*). In a few instances, this kind of preferential treatment has been extended to bicycles (*4–6*), though bicycle demand is often too low to justify this treatment (*6*). Presignals have also been used in conjunction with radically altered intersection geometries (continuous-flow intersections) to resolve conflicts between left-turning vehicles and their through-moving counterparts in the opposing direction (*7, 8*).

More recently, researchers have proposed the use of presignals to reorganize how distinct vehicle classes are stored at the intersections downstream. Ideas of this kind have been developed for intersection approaches that serve distinct turning movements of a single travel mode (*9*) or multiple modes (*10, 11*).

Theories predict that this reorganization of traffic can increase the intersection's capacity to serve all of its vehicles. These predictions have yet to be tested against real data, however. Of note, the predicted capacity gains rest on the assumption of linear superposition, that is, the total time it takes to discharge a mixture of vehicle classes equals the sum of the times that it would take to discharge the vehicle classes separately. Though this assumption seems reasonable, it may not hold when the vehicle classes have different performance characteristics, as in the case of buses and cars, for example.

The current study presents the findings from a natural experiment at a signalized intersection in a large Chinese city. The findings confirm that the assumption of linear superposition is reasonable for the case of buses and cars and indicate that a presignal can be very effective in increasing the intersection's capacity to serve both of these modes.

THEORETICAL ANALYSIS

It is assumed that buses travel on a dedicated bus lane, and the focus is only on the through-moving buses and right-turning cars. To draw insights, simplified models are used to study possible ways to increase the capacity for these two vehicle classes. More realistic situations will be considered later in the case study.

Left to their own devices, right-turning cars and through-moving buses will conflict, such that both vehicle classes cannot simultaneously discharge into the intersection during a green time. In Figure 1 this case is labeled "side-by-side operation with conflicts." These conflicts can be resolved by using a midblock presignal to reorganize the two vehicle classes. The presignal allocates green times to each class in an alternating fashion. Vehicles pass through the presignal and move to their assigned lanes on the downstream approach to the intersection, which is termed the "sorting area."

Two possible sorting strategies are shown in Figure 1. Both resolve the conflicts between the two vehicle classes. In the first strategy, side-by-side operation with no conflicts, the vehicle classes laterally swap positions within the sorting area. In the second strategy, the two classes are sorted in a tandem fashion, such that each class discharges into the intersection in sequence.

To determine the capacity of the three cases in Figure 1, a special unit system is adopted, consistent with work by Xuan et al. (*9*), such that the cycle length of the intersection signal is the unit of time and the saturation flow per lane for car traffic is the unit of flow. To convert car flow (in cars per hour) into its dimensionless counterpart, car flow is normalized by the saturation flow per lane for cars in cars per hour per lane. Bus flow, however, is normalized by the saturation flow per lane for buses in buses per hour per lane. It can be shown that in this dimensionless unit system, dimensionless capacity can be represented by the product of dimensionless green time (or green ratio) and the number of lanes available for discharge.

It is assumed that (*a*) the road has two lanes as in Figure 1 and the green ratio at the intersection signal, G, is given; (*b*) the lost time

University of California, Berkeley, 416D McLaughlin Hall, Room 1720, Berkeley, CA, 94720-1720. Corresponding author: Y. Xuan, xuanyg@berkeley.edu.

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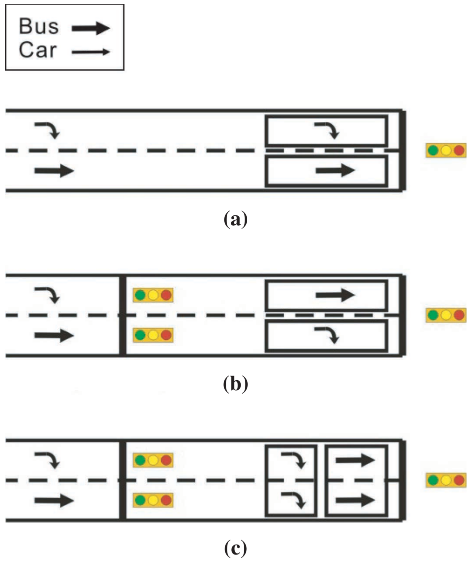

FIGURE 1 Sorting strategies (including do-nothing).

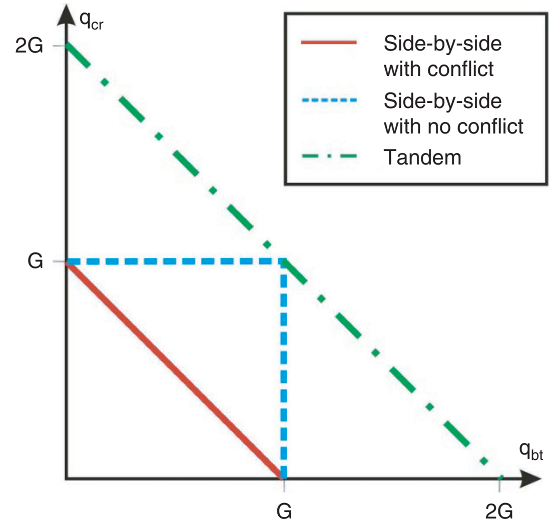

FIGURE 2 Capacity constraints for different sorting strategies when $G \leq ½$.

between the presignal phases is negligible; and (*c*) the two vehicle classes in question are each characterized by their dimensionless demand q_{cr} (right-turning cars) and q_{bt} (through-moving buses). The capacity constraint for side-by-side operation with conflicts can then be expressed as

$$q_{bt} + q_{cr} \leq G \quad (1)$$

because only one vehicle class can discharge at a time. The capacity constraints for side-by-side operation with no conflicts are

$$q_{bt} \leq G$$

$$q_{cr} \leq G \quad (2a)$$

$$q_{bt} + q_{cr} \leq 1 \quad (2b)$$

The first constraint pertains to the intersection signal, and the second pertains to the presignal. The capacity constraint for the tandem case can be formulated as follows:

$$q_{bt} + q_{cr} \leq 2G \quad (3a)$$

$$q_{bt} + q_{cr} \leq 1 \quad (3b)$$

It is assumed that the vehicle classes are evenly distributed in all lanes and that capacity is the product of the green ratio and the number of lanes available for discharging. The linear superposition is assumed in Constraint 3*a*.

Figure 2 shows the capacity constraints just derived when $G \leq ½$. In this situation, the capacity constraint at the presignal as shown in Constraints 2*b* and 3*b* is never binding because the total green time at the intersection signal is equal to or less than half of the cycle length, whereas the presignal can use the whole cycle to sort traffic. Side-by-side sorting with no conflicts increases capacity, especially when the flows of buses and right-turning cars are of similar magnitudes. Tandem sorting increases capacity even more, especially in instances when the flows of buses and right-turning cars are unbalanced. This increased capacity happens because the tandem scheme makes full use of all lanes, as long as there is sufficient demand. Though the two-lane model is simplistic, it nonetheless illustrates that the tandem strategy has huge potential to increase intersection capacity. Generalizations are easy to study by using similar logic, for example, as in the next section.

In real-world settings, complications can arise to diminish the effectiveness of the tandem strategy. For example, conflicts may arise between right-turning cars in the left lane and through-moving buses in the right lane (top diagram, Figure 1). To remedy this type of problem, the tandem strategy can be modified so that only one lane is operated in tandem. Two examples are shown in Figure 3*a*. The capacity constraints for these modified strategies are easily derived and are shown in Figure 3*b*. The bounds in Figure 3*b* fall between those of the standard tandem strategy and side-by-side operation with no conflicts (see Figure 2). The type of modification should be based on the relative demand for the two vehicle classes.

EMPIRICAL EVIDENCE

Observations come from the southbound approach at the intersection of the First Ring Road and Gaoshengqiao Road in the city of Chengdu, China. The geometry of the approach is shown in the top half of Figure 4. It has three lanes: two for cars (Lanes 1 and 2, plus a left-turn pocket) and one that is dedicated to buses (Lane 3). The current regulation is that cars are only allowed to use the bus lane to turn right. However, bus demand is very low (about two buses per minute) and the bus lane is underutilized even with the inclusion of right-turning cars. Demand for car traffic is so heavy that Lanes 1 and 2 discharge at saturation during the whole peak period. Queues even spill back to the upstream intersection.

To increase capacity on the approach and keep providing preferential treatment to buses, a presignal that allows for through-moving cars on Lane 3 has been proposed for this site (*12*). In the proposed design, which is shown in the bottom half of Figure 4, the presignal

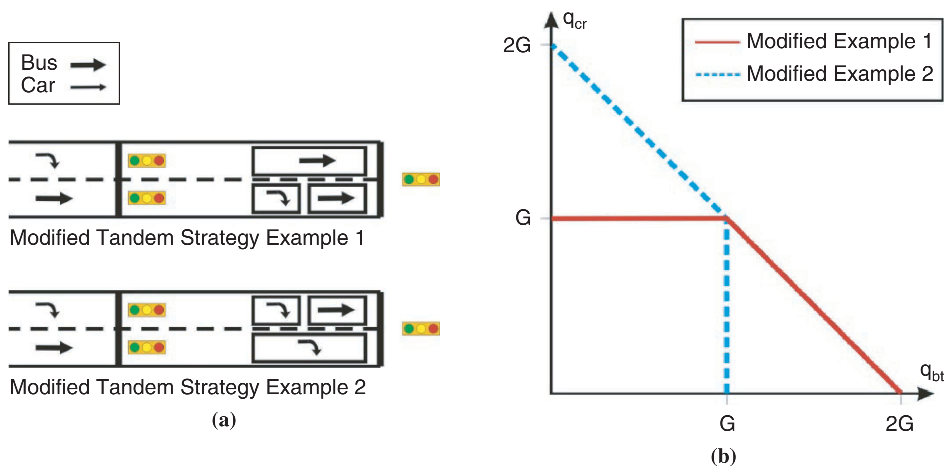

FIGURE 3 Modified tandem strategies: (*a*) diagrams and (*b*) capacity constraints.

has the same cycle length as the intersection signal and displays two green phases: one for buses only, the other for cars.

Design variables include (*a*) the lanes designated for buses and for cars in the sorting area, (*b*) the duration of the presignal phases, (*c*) the offset between the presignal and the intersection signal, and (*d*) the physical length of the sorting area. These variables are described next.

1. The lane designations in the sorting area allow through-moving cars in the bus lane to avoid underutilizing that lane.
2. The presignal phases should be long enough in duration to serve the bus demand (e.g., allowing 10 s per bus). The presignal switches to the bus phase whenever a bus arrives (which assumes that bus arrivals can be detected), to make sure that buses are never delayed by the presignal. The duration of the car phase should be capped such that all the cars and buses passing through the presignal during each cycle are able to discharge into the intersection without forming residual queues. The remaining time in the cycle, if any, is added to the bus phase duration.
3. The offset between the presignal and the intersection signal is set to minimize the delay in the sorting area, that is, so that the last car that discharges from the presignal during its car phase can discharge into the intersection without delay.
4. The length of the sorting area needs to be long enough to hold all the vehicles that are to be discharged in one cycle, plus some buffer space for vehicle maneuvering. For the approach of interest, the length of the sorting area was calculated to be about 150 m (*12*). A sorting area of this size easily fits within the block, which is about 450 m long.

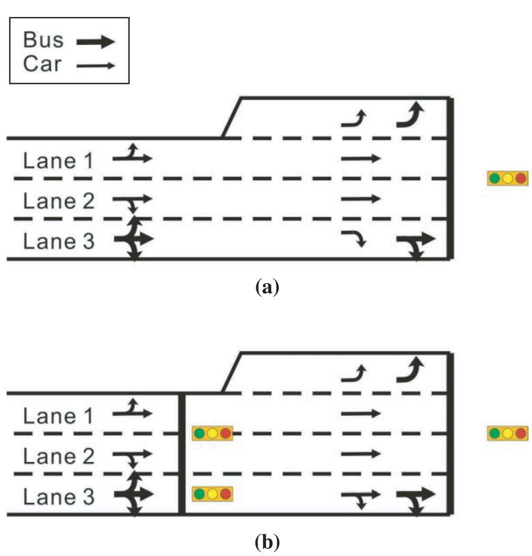

FIGURE 4 Geometry of approach in case study: (*a*) status quo and (*b*) proposal.

Since the capacity of Lane 1 is unaffected by the presignal, the capacity analysis can be confined to Lanes 2 and 3 (see Figure 4). The derivations of the capacity constraints are similar to those in the previous section, where distinct vehicle classes are characterized by their demand y_{ct}, y_{bt}, y_{cr}, y_{br}, where the first subscript denotes mode (car or bus) and the second denotes movement (through or right). Clearly, the capacity constraints for the status quo are

Lane 2:

$$y_{ct} \le G \qquad (4a)$$

Lane 3:

$$y_{bt} + y_{br} + y_{cr} \le G \qquad (4b)$$

Only Equation 4*a* is binding in this case study because the bus lane is underutilized.

Consideration also shows that the capacity constraints with a presignal are as follows:

Lane 3 underutilized:

$$y_{bt} + y_{br} + y_{cr} \le G \qquad (5a)$$

Lanes 2 and 3 at intersection:

$$y_{ct} + \left(y_{bt} + y_{br} + y_{cr}\right) \le 2G \qquad (5b)$$

Lanes 2 and 3 at presignal:

$$\left(y_{bt} + y_{br}\right) + \left(y_{ct} + y_{cr}\right) \le 1 \qquad (5c)$$

Equation 5*b* assumes linear superposition. In this case only Equation 5*b* is binding because the bus lane is underutilized (Equation 5*a* not binding) and because $G \approx 0.3 < ½$ (Equation 5*c* not binding).

The maximum possible flow of cars and buses combined (i.e., the capacity) is increased here because the bus lane could not be saturated with the original configuration given the low flow of buses, but the lane can be saturated with the presignal.

Natural Experiment

Contrary to regulation, drivers of through-moving cars frequently avail themselves of the bus lane in obvious attempts to reduce their own delay. This behavior is even encouraged by the traffic police stationed at the intersection, since it increases the use of the bus lane. The outcome of this behavior mimics what would occur in a more organized way if lanes were designated in the sorting area as per the proposed tandem strategy (see Figure 3*a*) but the presignal was replaced by a yield sign for cars. This configuration would produce capacity constraints identical to those in Equation 5 if the assumption of linear superposition holds. Thus there is a natural experiment to test this assumption and to verify the benefits of using a presignal.

The approach was videotaped during the evening peak on June 11, 2009, and again 1 year later on June 17, 2010. Vehicle counts are furnished by mode and by movement for 10 signal cycles on the first day in Table 1. Through-moving cars in Lane 3, the bus lane, are in violation of the regulation but would be legal under the proposed system.

The saturation flows estimated from the data for cars [1,550 (cars/h)/lane] and for buses [20 (buses/h)/lane] were used to convert bus flows to car-equivalent flows: 1,550/920 = 1.7 (cars/bus). Of further interest, the intersection signal's effective green times for the approach were different in each cycle because traffic (including cross traffic) commonly entered the intersection even after its green times had ended. To make comparisons, vehicle counts in each estimated effective green time were proportionally adjusted by using the signal's nominal effective green time of 50 s.

Outcomes from this natural experiment were favorable, as revealed in Figure 5. The data points marked by an o symbol are the adjusted counts per cycle for the combination of buses and right-turning cars in Lane 3 and through-moving cars in both Lanes 2 and 3, that is, the counts constrained by binding Equation 5*b*. The data points marked × are the same counts after subtracting the through-moving cars in Lane 3 (which are only legal with the presignal). These counts should be constrained by binding Equation 4*a*. The o's and ×'s that correspond to the same cycle are connected by lightly drawn vertical lines.

The ×'s cluster closely around the horizontal dashed line segment in Figure 5 (corresponding to Equation 4*a*), indicating that the theoretical capacity constraints in the absence of a presignal are reasonable descriptions of real-world conditions. The o's fall either near or below the slanted solid line (corresponding to Equation 5*b*). This finding demonstrates that the theoretical capacity constraint Equation 5*b* is nearly reached by a real traffic stream despite the lack of suitable traffic regulations and organization. The two outliers well below the slanted line (Cycles 3 and 5) are explained by some drivers' reluctance to use the bus lane illegally. Videos clearly show that Lane 3 (the bus lane) was vacant toward the end of the green phase in those cycles despite an abundance of through-moving cars on Lane 2. This finding suggests that the use of a presignal would reduce the Lane 3 vacancies, producing a more perfect fit and supporting the linear superposition assumption.

The data from the second observation day (the evening peak of June 17, 2010) support the preceding argument. Ten more cycles were manually processed as previously described. The vehicle counts are shown in Table 2, and the comparison between the natural experiment and the theoretical derivation is shown in Figure 6. There are some changes to the traffic conditions: first, the flow of buses and right-turning cars in Lane 3 increases slightly; second,

TABLE 1 Field Observations, June 11, 2009

Signal Cycle No.	Lane No.	Bus Counts Through	Bus Counts Right	Car Counts Through	Car Counts Right	Effective Green Time (s)
1	2	0	0	18	0	43
	3	3	1	4	7	38
2	2	0	0	19	0	41
	3	4	1	8	4	44
3	2	0	0	19	0	49
	3	4	2	2	4	43[a]
4	2	0	0	23	0	49
	3	5	1	4	7	53
5	2	0	0	21	0	47
	3	5	0	6	1	33[a]
6	2	0	0	25	0	54
	3	3	1	8	6	52
7	2	0	0	24	0	51
	3	4	1	5	7	50
8	2	0	0	20	0	57
	3	8	0	3	11	57
9	2	0	0	18	0	42
	3	2	1	5	5	42
10	2	0	0	20	0	49
	3	4	1	9	5	49

NOTE: No. = number.
[a]Lane became vacant before the end of green time.

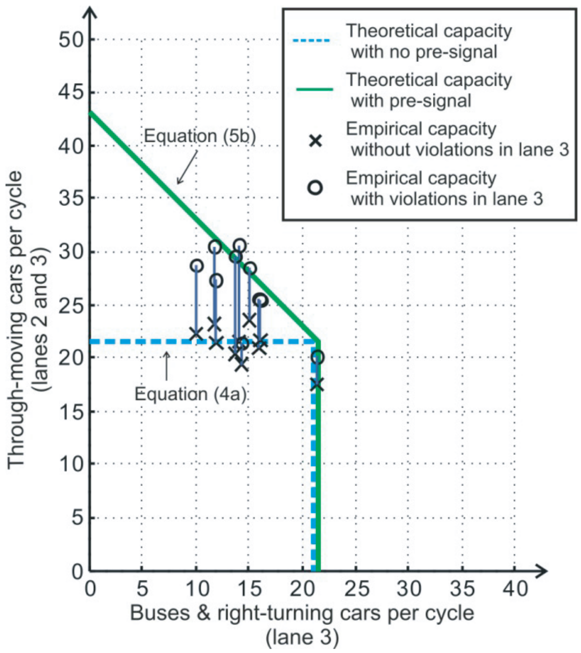

FIGURE 5 Comparison of natural experiment results versus theoretical capacity constraints, June 11, 2009.

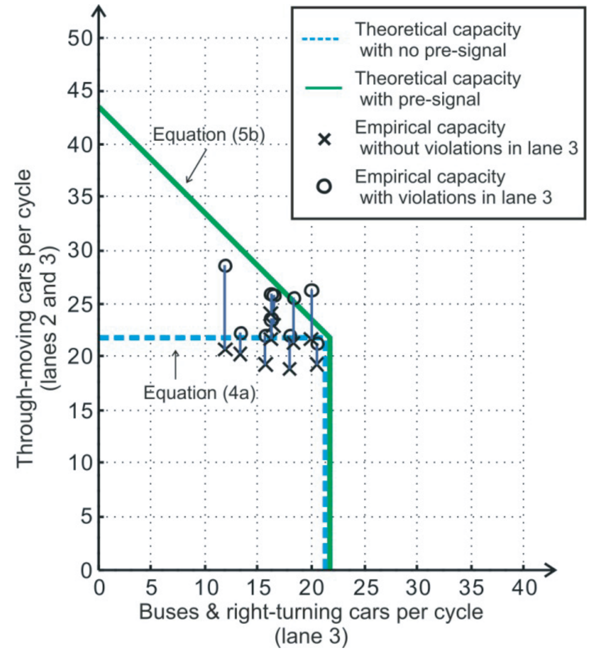

FIGURE 6 Comparison of natural experiment results versus theoretical capacity constraints, June 17, 2010.

there were four (instead of two) outliers with the same features as in the first day's data, probably still caused by drivers' reluctance to use the bus lane under police surveillance. However, the results are otherwise similar: four of the o's cluster around the slanted line corresponding to capacity constraint 5b, whereas all the ×'s cluster closely around the horizontal dashed lane segment. This finding shows that in this second case too, the capacity constraint 5b can be reached by real traffic.

These empirical results are admittedly limited. More independent empirical evidence to further validate the linear superposition assumption would be useful. Furthermore, field tests using presignals would be preferred over a natural experiment.

TABLE 2 Field Observations, June 17, 2010

Signal Cycle No.	Lane No.	Bus Counts		Car Counts		Effective Green Time (s)
		Through	Right	Through	Right	
1	2	0	0	21	0	69
	3	5	2	3	3	71
2	2	0	0	24	0	61
	3	5	0	3	7	68
3	2	0	0	18	0	62
	3	4	2	3	5	60
4	2	0	0	21	0	66
	3	3	1	8	4	59[a]
5	2	0	0	19	0	59
	3	4	3	2	6	64
6	2	0	0	20	0	61
	3	7	0	4	3	52[a]
7	2	0	0	23	0	69
	3	4	3	2	3	64
8	2	0	0	20	0	64
	3	5	0	2	3	43[a]
9	2	0	0	23	0	68
	3	5	1	5	9	69
10	2	0	0	24	0	65
	3	4	1	2	6	57[a]

NOTE: No. = number.
[a]Lane became vacant before the end of green time.

Discussion of Empirical Results

Empirical evidence shows that with proper lane designations in the sorting area, the capacity of a studied intersection could be significantly increased with the use of either a midblock yield sign or a presignal. The presignal would provide additional benefits over the yield sign in at least two ways. First, signal control could bring safety benefits compared with the yield sign because the chance for drivers to run a red light might be smaller than the chance for drivers to fail to yield. Second, when congestion is heavy, left-turning buses have difficulty weaving through car traffic toward the approach's left-turn pocket. The presignal expedites left turns for buses by generating big gaps in car traffic. This function is the original motivation for using the presignal (*1*).

Of further note, the traffic demand of distinct vehicle classes in this case study is relatively stable and thus justifies a fixed lane designation. If traffic demand were to be more volatile, dynamic lane designations could be considered.

CONCLUSION

It has been shown in theory that presignals can be used to increase the capacity of signalized intersections with both car and bus traffic. But the predicted improvement hinges on the assumption that the time it takes to discharge a mixture of vehicle classes equals the sum of the times that it would take to discharge the vehicle classes separately. A natural experiment was presented confirming that the assumption is reasonable for cars and buses. It also demonstrates the effectiveness of presignals to increase an intersection's capacity to serve these two vehicle classes.

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