Using a Pre-signal to Increase Bus- and Car-Carrying Capacity at Intersections: Theory and Experiment

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ABSTRACT

It has been shown in theory that mid-block pre-signals can be used to increase the capacity of signalized intersections. This is because pre-signals can reorganize how traffic is stored between the pre-signal and the intersection downstream. However, different vehicle classes have different acceleration characteristics, and the effectiveness of pre-signals hinges on the assumption of linear superposition, i.e., 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 paper, results from a natural experiment are used to validate this assumption for the case of cars and buses. The effectiveness of pre-signals to increase intersection capacity is also demonstrated.

1 INTRODUCTION

A pre-signal is a special class of traffic signal. It is placed mid-block, and is used to resolve the conflicts that arise between vehicles as they approach the signalized intersection downstream. To date, pre-signals have been used to enable buses to bypass car queues at intersections [*1, 2, 3*]. In a few instances, this kind of preferential treatment has been extended to bicycles [*4, 5, 6*], though bicycle demands are often too low to justify this [*6*]. Pre-signals 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 pre-signals 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, i.e., 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 very different performance characteristics, as in the case of buses and cars, for example.

The present paper 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 pre-signal can be very effective in increasing the intersection's capacity to serve both of these modes.

The paper is organized as follows. The following section presents strategies for reorganizing cars and buses using a pre-signal, and analyzes the capacity under these strategies assuming linear superposition. The assumption is verified by means of a natural experiment in Section 3. Conclusions are drawn in Section 4.

2 THEORETICAL ANALYSIS

Let us assume that buses travel on a dedicated bus lane, and focus 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 in the case study in Section 3.

Left to their own devices, conflicts will arise between the right-turning cars and the through-moving buses, such that both vehicle classes cannot simultaneously discharge into the intersection during a green time. This case is labeled in FIGURE 1 as "side-by-side operation with conflicts".

These conflicts can be resolved by using a mid-block pre-signal to reorganize the two vehicle classes. The pre-signal allocates green times to each class in an alternating fashion. Vehicles pass through the pre-signal and move to their assigned lanes on the downstream approach to the intersection, which we term 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, labeled "side-by-side operation with no conflicts", the vehicle classes are laterally swapped in position 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.

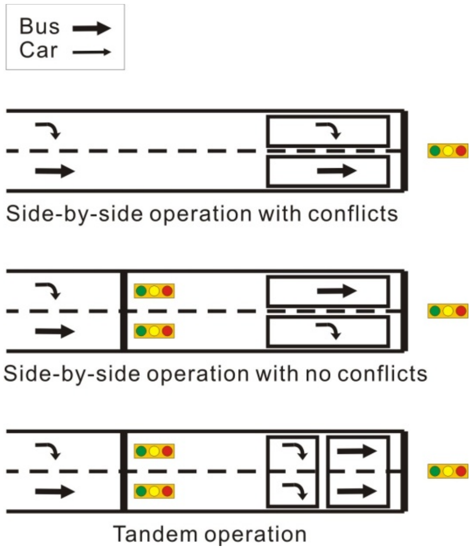


FIGURE 1 Different sorting strategies (including do-nothing).

Now we determine the capacity of the three cases in FIGURE 1. Consistent with [*9*], we adopt a special unit system, 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/hour) into its dimensionless counterpart, car flow is normalized by the saturation flow per lane for cars (in cars/hour/lane). Bus flow, on the other hand, is normalized by the saturation flow per lane for buses (in buses/hour/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.

We assume that: (a) the road has 2 lanes as in FIGURE 1, and the green ratio at the intersection signal, G, is given; (b) the lost time between the pre-signal phases is negligible; (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

$$q_{bt} + q_{cr} \le G, \tag{1}$$

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

$$q_{bt} \le G, q_{cr} \le G, \tag{2a}$$

$$q_{bt} + q_{cr} \le 1. \tag{2b}$$

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

$$q_{bt} + q_{cr} \le 2G, \tag{3a}$$

$$q_{bt} + q_{cr} \le 1, \tag{3b}$$

if we assume that vehicle classes are evenly distributed in all lanes and recall that capacity is the product of the green ratio and the number of lanes available for discharging. Note that linear superposition is assumed in (3a).

FIGURE 2 shows the capacity constraints derived above when $G \le 1/2$. In this situation, the capacity constraint at the pre-signal as shown in (2b) and (3b) is never binding. This is because the total green time at the intersection signal is equal to or less than half of the cycle length, while the pre-signal 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 happens because the tandem scheme makes full use of all lanes, as long as there is sufficient demand.

Though the 2-lane model is simplistic, it nonetheless illustrates that the tandem strategy has huge potential to increase intersection capacity. Generalizations are easy to study using similar logic; e.g. as in Section 3.

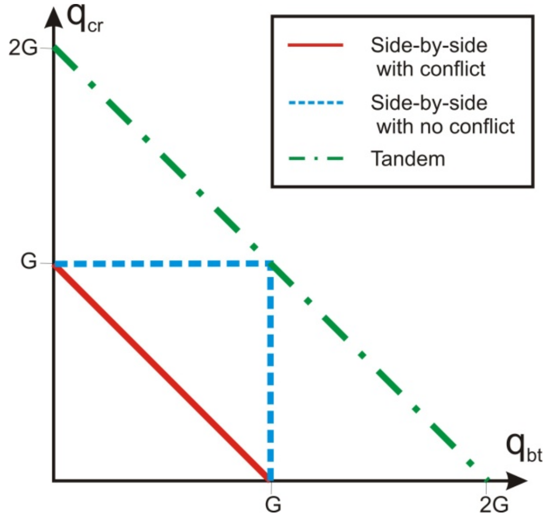
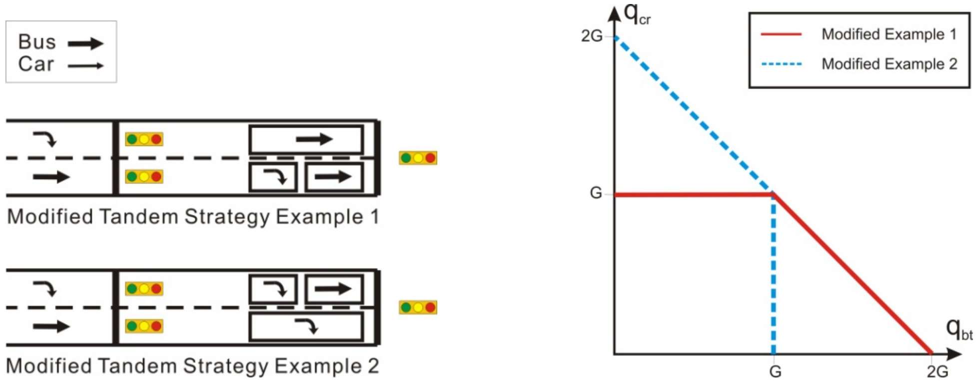


FIGURE 2 Capacity constraints for different sorting strategies when $G \leq 1/2$.

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 (see again the top diagram of 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 3a. The capacity constraints for these modified strategies are easily derived and are displayed in FIGURE 3b. Note that the bounds in this figure fall between those of the standard tandem strategy and side-by-side operation with no conflicts (see again FIGURE 2). The type of modification should be based on the relative demand for the two vehicle classes.



(a) (b)

FIGURE 3 Modified tandem strategies. (a) Graphic illustrations; (b) capacity constraints.

3 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 2 buses/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 rush period. Queues even spill back to the upstream intersection.

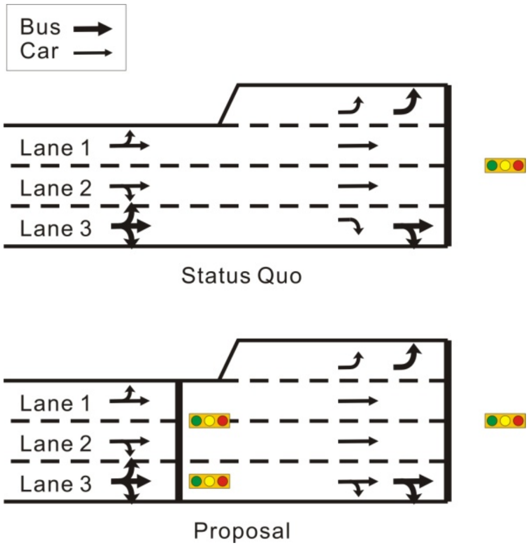


FIGURE 4 Geometry of the approach of our case study, status quo and proposal.

To increase capacity on the approach while still providing preferential treatment to buses, a pre-signal that allows for through-moving cars on lane 3 has been proposed for this site; see [*12*]. In the proposed design, which is depicted on the bottom half of FIGURE 4, the pre-signal 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 pre-signal phases, (c) the offset between the pre-signal and the intersection signal, and (d) the physical length of the sorting area. These are described next.

(a) The lane designations in the sorting area allow through-moving cars in the bus lane, to avoid underutilizing that lane.

(b) The pre-signal phases should be long enough in duration to serve the bus demand (e.g., allowing 10 seconds per bus). The pre-signal switches to the bus phase whenever a bus arrives (which assumes that bus arrivals can be detected), to make sure buses are never delayed by the pre-signal. The duration of the car phase should be capped such that all the cars and buses passing through the pre-signal 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.

(c) The offset between the pre-signal and the intersection signal is set to minimize the delay in the sorting area; i.e., so that the last car that discharges from the pre-signal during its car phase can discharge into the intersection without delay.

(d) 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 meters; see [*12*]. A sorting area of this size easily fits within the block, which is about 450 meters long.

Since the capacity of lane 1 is unaffected by the pre-signal, our capacity analysis can be confined to lanes 2 and 3 (see again FIGURE 4). The derivations of the capacity constraints are similar to those in Section 2, where distinct vehicle classes are characterized by their demand y_{ct}, y_{bt}, y_{cr}, y_{br} with the first subscript denoting mode (**c**ar or **b**us) and the second denoting movement (**t**hrough or **r**ight). Clearly, the capacity constraints for the status quo are

$$y_{ct} \leq G\,, \quad \text{(lane 2)} \tag{4a}$$

$$y_{bt} + y_{br} + y_{cr} \leq G\,. \quad \text{(lane 3)} \tag{4b}$$

Note that only equation (4a) is binding in our case study because the bus lane is underutilized.

Consideration also shows that the capacity constraints with a pre-signal are

$$y_{bt} + y_{br} + y_{cr} \le G\,, \quad \text{(lane 3 is underutilized)} \tag{5a}$$

$$y_{ct} + (y_{bt} + y_{br} + y_{cr}) \le 2G\,, \quad \text{(lanes 2 and 3 at the intersection)} \tag{5b}$$

$$(y_{bt} + y_{br}) + (y_{ct} + y_{cr}) \le 1\,. \quad \text{(lanes 2 and 3 at the pre-signal)} \tag{5c}$$

Note that (5b) assumes linear superposition. Also note that in this case only (5b) is binding because the bus lane is underutilized ((5a) not binding) and because $G \approx 0.3 < 1/2$ ((5c) not binding).

Also note that 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 pre-signal.

3.1 Natural Experiment

Contrary to regulation, drivers of through-moving cars frequently avail themselves of the bus lane, in obvious attempts to reduce their own delays. This behavior is even encouraged by the traffic police that are 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 again FIGURE 3a), but the pre-signal 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. We thus have a natural experiment to test this assumption and to verify the benefits of using a pre-signal.

The approach was videotaped during the evening peak on June 11, 2009 and again one 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. Note that 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 (1550 cars/hour/lane) and for buses (920 buses/hour/lane) were used to convert bus flows to car equivalent flows: 1550/920 = 1.7 (cars/bus). Of further interest, the intersection signal's effective green times (thereafter EGTs) for the approach were different in each cycle. This is because traffic (including cross-traffic) commonly entered the intersection even after its green times had ended. To make comparisons, vehicle counts in each estimated EGT were proportionally adjusted using the signal's nominal EGT of 50 seconds.

Outcomes from this natural experiment were favorable, as revealed in FIGURE 5. Its o-shaped data points 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; i.e., the counts constrained by binding equation (5b). The x-shaped data points are the same counts after subtracting the through-moving cars in lane 3 (which are only legal with the pre-signal). These counts should be constrained by binding equation (4a). The o's and x's that correspond to the same cycle are connected by the lightly-drawn vertical lines.

Note that the x's cluster closely around the horizontal dashed line segment in FIGURE 5 (corresponding to equation (4a)), indicating that the theoretical capacity constraints in the absence of a pre-signal are reasonable descriptions of real-world conditions.

Further note how the o's fall either near or below the slanted solid line in the figure (corresponding to equation (5b)). This demonstrates that the theoretical capacity constraint (5b) 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 suggests that the use of a pre-signal 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 our argument. Ten more cycles were manually processed as previously described. The vehicle counts 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, 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), while all the x's cluster closely around the horizontal dashed lane segment. This 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 pre-signals would be preferred over a natural experiment.

3.2 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 mid-block yield sign or a pre-signal. The pre-signal would provide additional benefits over the yield sign in at least two ways. First, signal control could bring safety benefits compared with yield signs, because the chance for drivers to run red lights might be smaller than the chance that drivers 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 pre-signal expedites left turns for buses by generating big gaps in car traffic. This function is the original motivation for using pre-signals [*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.

4 CONCLUSION

It has been shown in theory that pre-signals 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. This paper presents a natural experiment, confirming that the assumption is reasonable for cars and buses. It also demonstrates the effectiveness of pre-signals to increase an intersection's capacity to serve these two vehicle classes.

TABLE 1 Field observations, June 11, 2009

Signal Cycle #	Lane #	Through Bus Counts	Right Bus Counts	Through Car Counts	Right Car Counts	Effective Green Time (seconds)
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 †
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 †
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

† Lane became vacant before the end of green time.

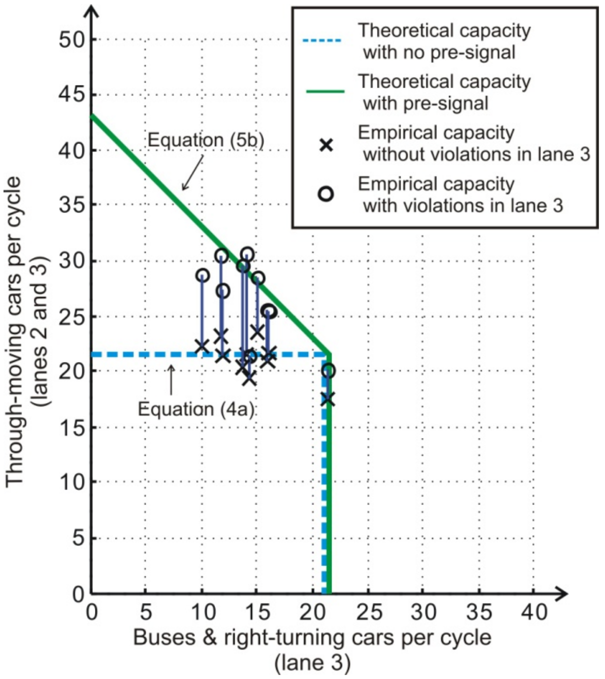


FIGURE 5 Comparison of the natural experiment result versus theoretical capacity constraints, June 11, 2009.

TABLE 2 Field observations, June 17, 2010

Signal Cycle #	Lane #	Through Bus Counts	Right Bus Counts	Through Car Counts	Right Car Counts	Effective Green Time (seconds)
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 †
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 †
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 †
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 †

† Lane became vacant before the end of green time.

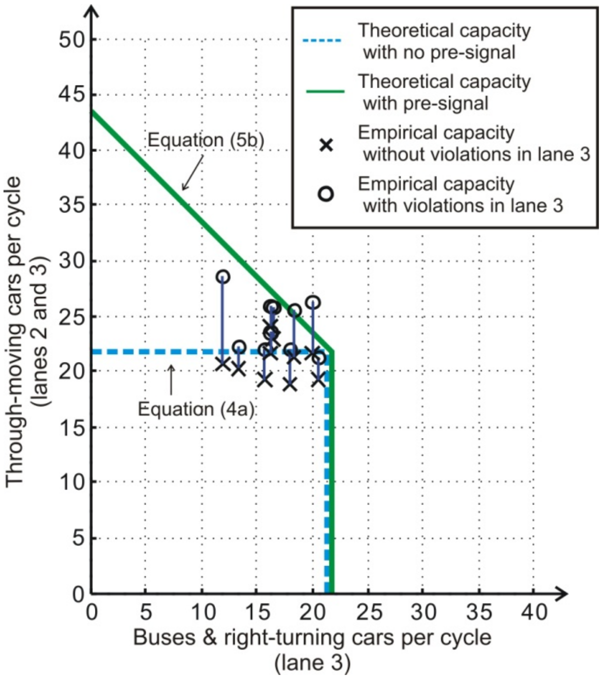


FIGURE 6 Comparison of the natural experiment result versus theoretical capacity constraints, June 17, 2010.

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