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Multimodal Traffic at Isolated Signalized Intersections: New Management Strategies to Increase Capacity

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UC Berkeley Center for Future Urban Transport

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Multimodal Traffic at Isolated Signalized Intersections: New Management Strategies to Increase Capacity

Abstract

New ideas are explored for managing multimodal traffic on isolated approaches to signalized intersections. Strategies are proposed that both: segregate distinct modes along the approach, and more effectively resolve the disruptive capacity-reducing conflicts that arise between through-moving and turning traffic traveling in adjacent lanes. The proposed schemes produce capacities that consistently and significantly exceed those of conventional intersection treatments, and reduce travel delays for all modes. Observations at a real intersection support these claims.

1 Introduction

Urban infrastructure in much of the world has been designed to favor automobiles and to treat other modes as secondary. By discouraging the use of alternative travel modes, e.g. buses, bicycles, and pedestrians, present designs increase dependence on automobiles and help spur the rapid and unsustainable motorization that now characterizes cities throughout the developing world. Ironically, alternative modes are often more environmentally friendly, and are more prominent in much of the world, since they are more affordable than automobiles. Thus there is need to rethink how urban infrastructure should be deployed and operated to benefit all travel modes. As an initial step in this direction, we examine how to manage two travel modes at one of the most basic elements of the urban infrastructure: the signalized intersection.

Most previous studies of multimodal traffic have focused on the treatment of different vehicle types on the links between intersections. These studies have found that this kind of segregation, as in the cases of sidewalks, bicycle lanes, and dedicated bus lanes, can improve safety and increase flows. However, segregation on approach links does not eliminate certain key intermodal conflicts: the segregated modes still must re-coalesce at intersections to perform turning maneuvers. The few studies of multimodal intersections have provided site-specific treatments to accommodate two travel modes. These treatments fall into two categories. The first is priority treatment, which enables one mode to proceed through the intersection ahead of the other mode. Cases of this category include the bicycle box (Kuijper, 1982; Heys and Vrefeveld, 1983; Salomons, 1985; Wheeler, 1992; Wheeler, 1993; Wheeler, 1995) and the bus pre-signal (Wu and Hounsell, 1998; Transport for London, 2005), shown in Figure 1a and Figure 1b, respectively. Priority treatments are typically deployed to improve the safety (visibility) of one mode (as for the bicycle box) or to promote its use (as for the bus pre-signal). Where properly

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implemented, priority treatments may also be Pareto efficient, such that all modes enjoy higher capacity. The second category is sorting, which lets vehicles swap positions laterally at some location at or upstream of the intersection to resolve intermodal conflict. Treatments of this type include the weaving area (FHWA, 2003), like the one for bicycles and right-turning cars shown in Figure 1c, and the refugee island shown in Figure 1d. As we will show in later sections of this paper, upstream sorting can significantly increase the discharge flows of all modes.

(a)

(b)

(c)

(d)
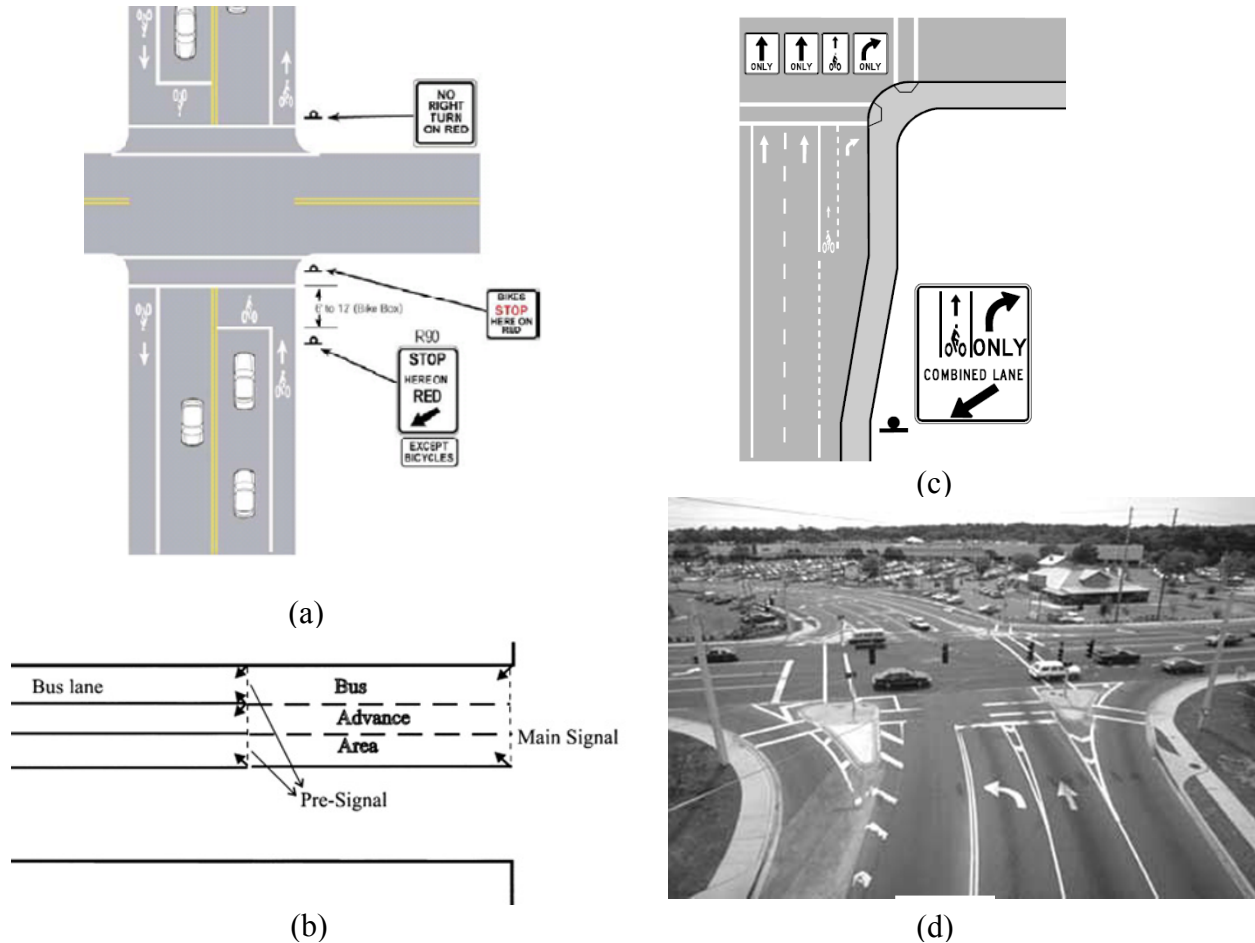
Figure 1. Examples of Multimodal Treatments.
Priority Treatments: (a) Bicycle Box; (b) Bus Pre-signal.
Upstream Sorting: (c) Weaving Area; (d) Refugee Island.

The present paper is, to our knowledge, the first to estimate how the above treatments affect the capacity of a generic intersection. The present paper examines the intermodal conflicts that occur at a signalized intersection, develops an analysis framework for determining the maximum flows that these intersections can serve, proposes strategies to increase these maximum flows for all modes, and applies and tests the above ideas to a real intersection approach.

In the following section, we examine the simple case of managing an intersection approach used by only two traffic streams; where a traffic stream is defined here as the collection of vehicles of a specific mode that make a specific movement (e.g. through-moving bicycles or right-turning

cars). The insights gained from this analysis are then applied in Section 3 to a more complicated intersection with four traffic streams. We explore the space of possible segregation strategies under the restriction that each mode and each movement is segregated using the same treatment, and explain how these candidate strategies work. We also determine the capacities induced by each strategy, compare them to see which is superior, and discuss more general strategies. In Section 4, we examine a real intersection approach. We show that our models accurately predict approach capacities, and that our ideas can be adapted to increase discharge flows in real-world settings. Conclusions and future work are discussed in Section 5.

2 Basic Scenario: Two Traffic Movements on Two Lanes

We start with the simple case of two traffic streams with different destinations on two lanes approaching a signalized intersection, and analyze the capacity flows generated by each possible treatment.

2.1 Segregation Treatments

There are three possible ways to segregate two traffic streams at an intersection; these are depicted in Figure 2. One can segregate the two streams side-by-side such that their discharge paths intersect, creating a conflict between the two streams; or segregate the streams side-by-side such that their discharge paths do not intersect, resulting in no conflict; or, finally, segregate the two streams in tandem in the direction of movement. In the last case, conflicts are avoided independent of order.
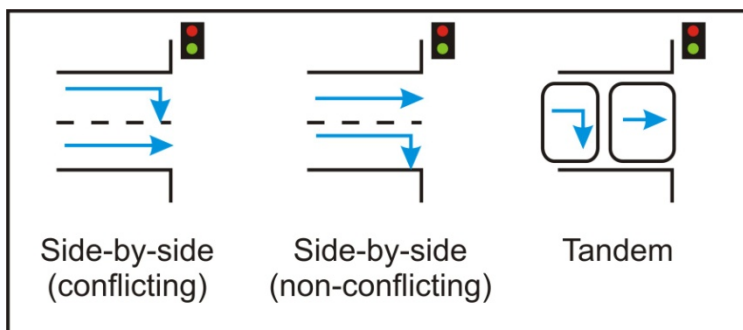

Figure 2. Possible Ways to Segregate Two Traffic Streams at an Intersection.

2.2 Capacity Analysis

We next analyze the range of capacities allowed by all possible methods of segregation; where capacity is defined as a combination of steady-state inflows that can be sustained indefinitely, but if increased create an infinite queue for at least one stream.

2.2.1 Definitions and Notation

To simplify calculations, we define the cycle length of the intersection's signal as the unit of time; and we define the number of vehicles from each traffic stream (e.g. right-turning bicycles) that can discharge from one lane in one unit of time as the unit of vehicle quantity. With these

definitions of time and flow all saturation flows equal 1. The two traffic streams are characterized by their inflows, y_1 and y_2. In our system of units, each stream's demand is also the green time needed to serve it. We also define the signal's effective green time for the intersection approach of interest as G.

2.2.2 Side-by-side Segregation of Conflicting Streams

Let the right-turning vehicles on the left lane and the through-moving vehicles on the right lane have inflows of y_1 and y_2, respectively. Since the conflict between the streams is not resolved directly by the signal, we stipulate how it is self-resolved to determine capacity. The following assumptions are based on observation of many intersections in the city of Chengdu, China, in which the right-turning vehicles are cars and the through-moving vehicles are bicycles.

1. The intersection functions like a polling system during its green phase, i.e. streams fully discharge their queues in alternating fashion. There is a fixed lost time, L, between the switching of streams during which time no vehicles discharge.
2. Vehicle arrival rates and saturation flows are constant.
3. At the beginning of the green, through-moving bicycles discharge through the intersection prior to the right-turning cars. This assumption is consistent with the literature on bicycle traffic (Allen et al, 1998).

Figure 3a shows how these rules play out with a cumulative input-output diagram. The main discrepancy with the videos is that the stopped modes sometimes interrupts the discharging stream prior to the dissipation of the latter's queue. This increases the total lost time during a green phase and reduces capacity. Therefore, our idealized analysis overestimates the capacity of two conflicting streams segregated side-by-side. As such, the estimates provide a tough benchmark for improvement.

We also assume that the intersection: (a) has no pedestrians; (b) does not allow right turns on red; (c) has all the technologies needed to implement any of our proposed designs; (d) has full driver compliance[1]; and (e) does not experience spillovers from downstream intersections.

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[1] Driver compliance is an empirical question that needs to be tested in the field.
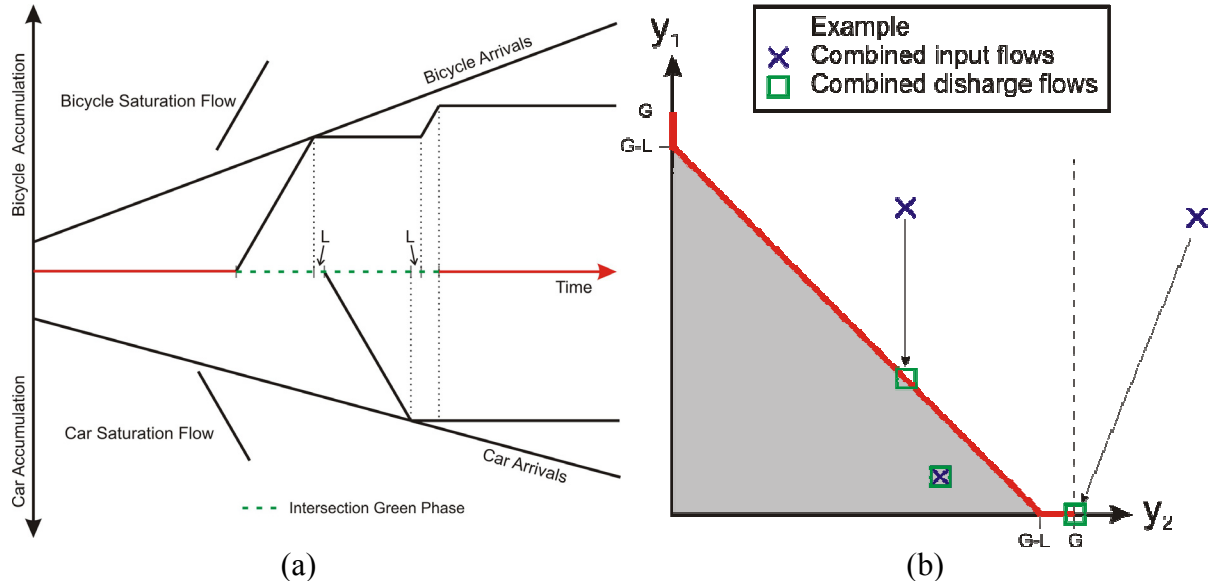
Figure 3. Analysis of Two Conflicting Streams Segregated Side-by-side.
(a) Cumulative arrival & departure curves for cars and bicycles;
(b) Capacity diagram for right-turning cars (y_1) and through-moving bicycles (y_2).

With these assumptions and assuming that G and L are fixed, we use simulation to determine the relationship between the maximum flows of right-turning cars (y_1) and through-moving bicycles (y_2) that can be sustained. This relationship is shown graphically in Figure 3b. The shaded area is the set of feasible, persistent flows that can discharge without creating an infinite queue. The upper boundary of this region is the "capacity curve" which delineates the capacity flows. For flow pairs lying on or below the curve, the system eventually converges to an equilibrium state in which the discharge flow is equal to the inflow, regardless of the initial queues present. For inflows above the curve, discharge flows converge to the capacity curve as shown with arrows, and the queue for at least one stream grows unbounded. From this diagram we also see that when only one travel mode is present, the maximum flow is equal to the signal's effective green time, G. When both modes are present, the maximum (combined) flow is reduced by L units to G-L. This occurs because the system settles into a steady state where exactly one "switch" occurs during the green phase. Thus, the mathematical expression for the feasible combined flow is:

$$y_1 + y_2 \leq G - L \qquad \text{when } y_1 > 0, y_2 > 0 \qquad \text{(1)}$$

Equation (1) can also be derived analytically. To this end, one can verify that if the inflows are on the capacity line, then the discharge flow during each cycle is exactly equal to the inflow and no infinite queues will exist. Also verify that, if the inflows are above the capacity line, there is insufficient green time to discharge all the vehicles that arrive during a single cycle, such that one or both queues will grow without bound.

2.2.3 Side-by-side Segregation of Non-Conflicting Streams

When two traffic streams are segregated side-by-side and are not in conflict, their discharge rates are only bounded by G. Thus the capacity constraint becomes:

$$y_1 \leq G, y_2 \leq G \tag{2}$$

2.2.4 Tandem Segregation

When two traffic streams are segregated in tandem, each stream can make use of both lanes to discharge. Because each lane only serves half of the demand, the required green time to serve each stream is halved to $y_1 / 2$ and $y_2 / 2$. And, since the traffic streams discharge in series, the total green time needed is $y_1 / 2 + y_2 / 2$, such that the capacity constraint becomes:

$$y_1 / 2 + y_2 / 2 \leq G \tag{3}$$

2.3 Comparison and Discussion

The capacity curves for the three segregation methods are shown in Figure 4. Segregating side-by-side with conflicting streams provides the lowest capacity because the conflict must be self-resolved at the intersection during the intersection's green period. Segregating side-by-side with non-conflicting streams does not have this restriction and, therefore, provides greater capacity. With side-by-side segregation methods, unbalanced flows (i.e. $y_1 \neq y_2$) will cause a portion of the green period to be when one lane discharges vehicles while the other lane is empty. Since this does not happen with the tandem approach, the latter is equivalent or superior to the side-by-side segregation strategies.
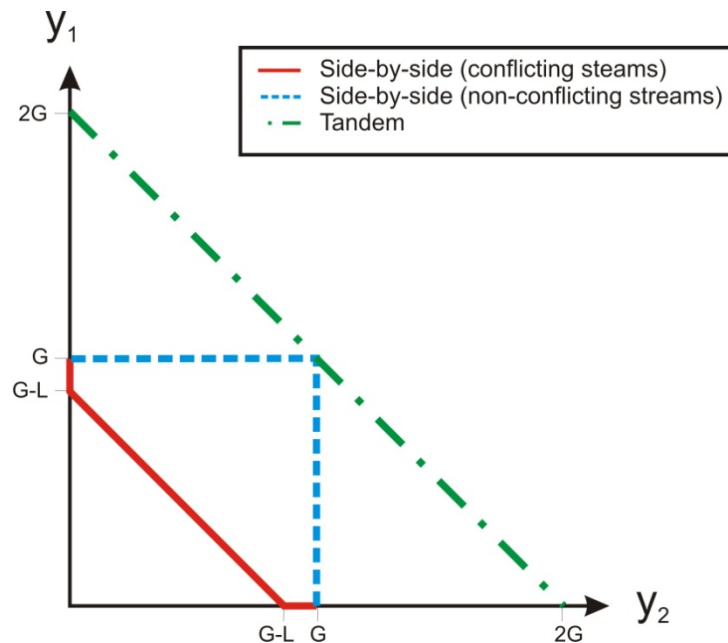

Figure 4. Comparison of Capacities for the Three Segregation Methods.

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The capacity curves in Figure 4 ignore the effect of the upstream sorting mechanism used to segregate the streams. This sorting can be accomplished with the installation of an additional signal (known as a pre-signal) well upstream of the intersection. The pre-signal will impose an additional capacity constraint but can still be helpful as we shall see. If the pre-signal is located far enough upstream to never be affected by the transient queues at the intersection, a set of flows that can pass through both the pre-signal and the intersection signal (considering these to be a system of two separate intersections) is determined by (1), (2), or (3), depending on our choice of segregation treatment, and the details of the pre-signal control. Since the pre-signal only needs two phases – one for each traffic stream – the extra constraint is $y_1 + y_2 \leq 1 - 2L$.

The latter constraint will not be binding when $2G \leq 1 - 2L$, as can be readily verified with the aid of Figure 4. When $2G > 1 - 2L$, however, the pre-signal constraint is binding for tandem segregation, and also for side-by-side segregation of non-conflicting streams if y_1/y_2 is sufficiently close to 1. Note that the capacity of the pre-signal is always greater than that of the intersection signal handling two conflicting streams segregated side-by-side. Thus, if a pre-signal is used to resolve this type of conflict by rearranging the two streams, either in tandem or side-by-side, the capacity of the system will increase. This happens because the pre-signal resolves the intermodel conflict upstream of the intersection during the entire cycle whereas the signal can only resolve the the conflict during its green phase.

Tandem segregation of the two traffic streams leads to the greatest capacity flows because it makes use of the entire roadway width to discharge each stream, effectively increasing the saturation flow of both. This, however, can only be achieved with perfect driver compliance. If drivers do not behave in the manner expected, the capacity gains from this treatment may be reduced. For example, when through-moving bicycles and right-turning cars are segregated in tandem at a wide intersection, with the through-moving bicycles placed in front of the right-turning cars, the through-moving bicycles may not occupy the full width of the road.

The simple example presented here assumed that there are only two lanes available for the two traffic streams and, in the side-by-side segregation methods, each stream occupies exactly one lane. However, if there are many lanes available or each stream can occupy a non-integer number of lanes, side-by-side segregation of non-conflicting streams can achieve the same capacity as tandem segregation by allocating space laterally according to the demand. However, streams segregated side-by-side require that the lanes be marked upstream of the signal. If these markings are permenant and the demand is not, inefficiencies will result. Tandem segregation eliminates the need for markings, and may therefore better accommodate time-varying demands.

3   Four-Stream Scenario: Two Movements and Two Modes
We now expand our analysis to a more complicated situation to gain more general insights about managing multimodal traffic at intersections. Consider a four-stream scenario involving two

modes and two destinations. Assume that the intersection serves only cars and bicycles, and that these vehicles make only through or right-turning movements as shown in Figure 5; that each traffic stream has its own lane; and that each lane has the width of a car lane[2]. The conventional lane striping creates a conflict between the right-turning cars and through-moving bicycles during the signal's green phase, as is also shown in Figure 5.
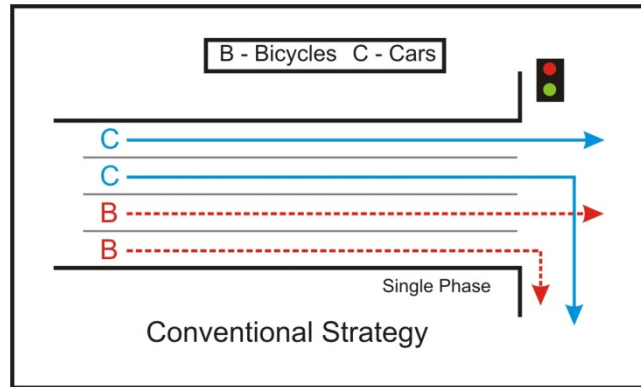

Figure 5. Simplified Conventional Intersection Layout.

3.1 Candidate Segregation Strategies

The possible ways to manage four traffic streams are numerous, and simple enumeration is not insightful. Instead we restrict ourselves to segregation strategies that apply a common treatment (side-by-side or tandem) to both modes and also a common treatment to both movements.

In addition, this double segregation can be done in one of two ways: either using a primary segregation by movement and a secondary segregation within each movement by mode, or vice versa. This double sort can be realized with a pre-signal. Table 1 summarizes the eight possibilities.

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[2] Bicycle lanes are usually not divided into through-moving lanes and right-turning lanes. However, bicyclists tend to sort themselves as they arrive to an intersection; this provides a natural division as if the bicycle lane really was divided. Wide lanes exist in cities where bicycle traffic is heavy.

Table 1. Possible Segregation Strategies

Primarily by mode Secondarily by movement		Segregation of Mode	
		Side-by-side	Tandem
Segregation of Movement	Side-by-side	Conventional	Modified Bicycle Box
	Tandem	Turn Box	N/A

Primarily by movement Secondarily by mode		Segregation of Mode	
		Side-by-side	Tandem
Segregation of Movement	Side-by-side	Fine Sort	Modified Bicycle Box
	Tandem	Turn Box	N/A

Strategies in which modes and movements are segregated in tandem are ignored in the table because they seem impractical. After all, a right-turning bicyclist probably would not want to stay on the opposite side of the road when approaching an intersection. Of the remaining options, some are duplications of others. In the end, we find only four practical strategies that identically treat both modes and both movements, shown in Figure 6.
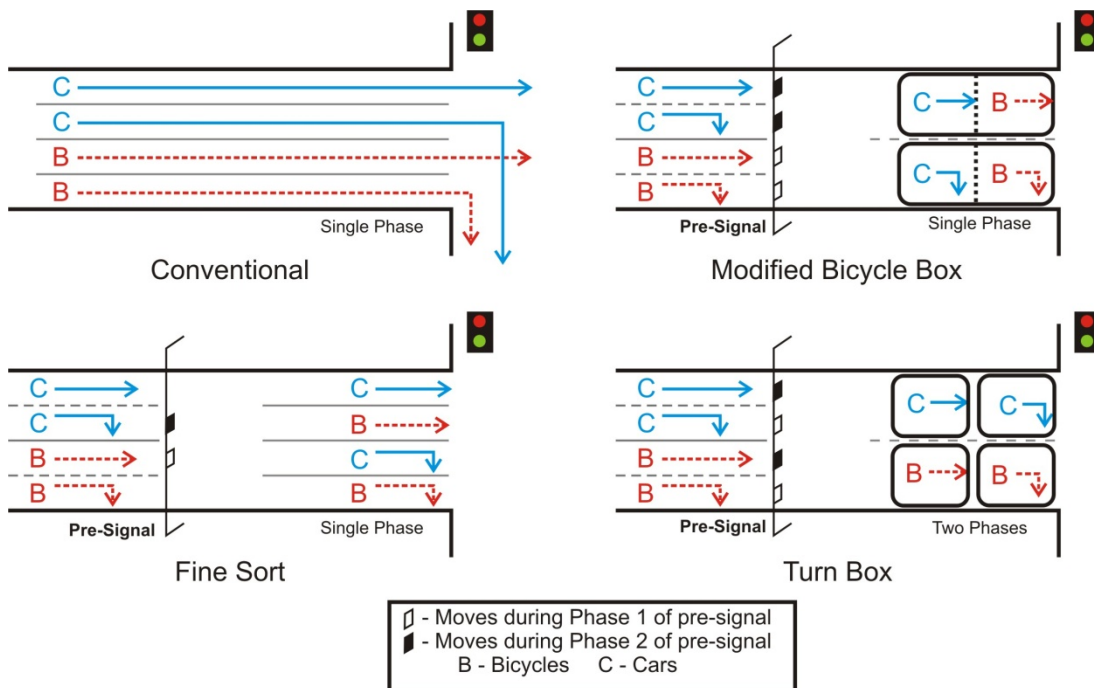

Figure 6. Feasible Segregation Strategies.

3.2 Description of the Strategies

Every strategy, save for the conventional one, requires a pre-signal. A pre-signal, operating with the same cycle length as the intersection signal, would ensure that vehicles advance without

conflicts. Its phases perform the needed sorting operations: either tandem sort– by mode for the modified bicycle box[3] or by movement for the turn box – or side-by-side sort for the case of the fine sort. For the latter strategy, the pre-signal controls movements in the middle two lanes only. Pavement markings can be used to guide vehicles from the pre-signal to the intersection.

In all cases except for the turn box strategy, the intersection signal can be operated in the conventional way, with a single green phase for the approach. In the case of the turn box, through-moving bicycles are held until the right-turning cars discharge. To improve safety, a separate sub-phase can be used to hold through-moving vehicles until all right-turning vehicles have discharged.

The conventional and the fine sort strategies both use side-by-side segregation, but in the former the through-moving bicycles and the right-turning cars conflict at the intersection, while the latter resolves this conflict at the pre-signal. Therefore, we can expect higher capacity for the fine sort than for the conventional strategy. The modified bicycle box and turn box strategies use tandem segregation, so their capacities should be even greater. We also expect the capacities of these latter two strategies to be similar to each other, since both use one side-by-side sort and one tandem sort.

3.3 Capacity Analysis

The capacity constraints of Section 2 are sufficient to determine the capacity for the more complicated strategies now addressed. The four traffic streams are characterized by their inflows: y_{ct}, y_{bt}, y_{cr} and y_{br} with the first index denoting mode (**c**ar or **b**icycle) and the second denoting movement (**t**hrough or **r**ight). As before, we use a system of units such that these flows are the green times needed to serve them.

3.3.1 Conventional Strategy

Since through-moving cars and right-turning bicycles are not affected by the middle lanes (see again Figure 6), they are bounded only by the green time available at the intersection signal as per (4a) and (4b). And since the capacity of the two middle lanes follows from (1), the complete set of capacity constraints of the conventional strategy for the non-trivial case where y_{bt}, $y_{cr} > 0$ is:

$$y_{ct} \leq G, \qquad \text{median lane} \qquad (4a)$$

$$y_{br} \leq G, \qquad \text{shoulder lane} \qquad (4b)$$

$$y_{bt} + y_{cr} \leq G - L, \qquad \text{middle lanes} \qquad (4c)$$

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[3] Note that the modified bicycle box differs from the conventional bicycle box (shown in Figure 1a) because the latter does not use a pre-signal and does not allow cars to use the full width of the intersection. Pre-signal control was included in the original implementation of the conventional bicycle box (Wheeler, 1993) but later removed because its inclusion was found to provide no real operational benefits (Wheeler, 1995), most likely due to the low bicycle flows observed. We will return to this issue in Section 3.5.1.

Note from (4c) that the combined capacity of the two middle lanes is $G - L$ which is less than the individual capacity, G, of a single lane. This underscores the inefficiencies of treating intermodal conflicts in the conventional way.

3.3.2 Fine Sort

For the fine sort strategy (see again Figure 6), each stream flow at the intersection is bounded by the available green time, G, yielding the constraints in (5a) and (5b) and the last two inequalities of (5c). At the pre-signal, the through-moving bicycles and right-turning cars need minimum phase lengths of y_{bt} and y_{cr}, respectively, and there is a lost time of $2L$ (one L for each phase) per cycle. Thus the fine sort's capacity constraint due to the pre-signal is the first inequality of (5c), and the complete set of constraints is:

$$y_{ct} \leq G, \qquad\qquad \text{median lane} \qquad\qquad \text{(5a)}$$

$$y_{br} \leq G, \qquad\qquad \text{shoulder lane} \qquad\qquad \text{(5b)}$$

$$\begin{cases} y_{bt} + y_{cr} + 2L \leq 1, \\ y_{bt} \leq G, y_{cr} \leq G, \end{cases} \qquad \text{middle lanes} \qquad\qquad \text{(5c)}$$

3.3.3 Modified Bicycle Box

All traffic streams in the modified bicycle box strategy discharge via two lanes upstream of the intersection as in Figure 6 (and there would be two lanes downstream for receiving these streams). Therefore, the green time needed for any stream is halved. Since bicycles and cars are arranged in tandem, the green time needed for all the through-moving vehicles (both bicycles and cars) is $y_{bt} / 2 + y_{ct} / 2$. Similarly, the green time needed for all right turning vehicles is $y_{br} / 2 + y_{cr} / 2$. There is a lost time of $2L$. Thus, the capacity constraint due to the intersection signal is given in (6a).

At the pre-signal, there are separate phases for bicycles and cars. The bicycle phase needs a length of at least $\max\{y_{bt}, y_{br}\}$ and the car phase needs at least $\max\{y_{ct}, y_{cr}\}$. The two phase lengths plus the lost time of $2L$ are bounded by the cycle length (scaled to one time unit), yielding the constraint in (6b), such that the complete set of capacity constraints for the modified bicycle box is:

$$\max\{y_{bt} / 2 + y_{ct} / 2, y_{br} / 2 + y_{cr} / 2\} + 2L \leq G \qquad\qquad \text{(6a)}$$

$$\max\{y_{bt}, y_{br}\} + \max\{y_{ct}, y_{cr}\} + 2L \leq 1 \qquad\qquad \text{(6b)}$$

3.3.4 Turn Box

Here again, all traffic streams discharge from two lanes and the required green time can be halved. At the intersection, two separate phases will be needed – the first phase for the right-turning vehicles and the second for the through-movers. The first phase needs a minimum length of $\max\{y_{br} / 2, y_{cr} / 2\}$ and the second a minimum of $\max\{y_{bt} / 2, y_{ct} / 2\}$. With a lost time of $2L$ per phase, the capacity constraint due to the intersection signal is as given in (7a).

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At the pre-signal, there are separate phases for the right-turning and through-moving vehicles. The latter need $\max\{y_{br}, y_{cr}\}$ to discharge, while the former need $\max\{y_{bt}, y_{ct}\}$. With a lost time of *2L*, the pre-signal yields the capacity constraint in (7b), and the complete set of capacity constraints for the turn box is:

$$\max\{y_{br}/2, y_{cr}/2\} + \max\{y_{bt}/2, y_{ct}/2\} + 2L \le G \tag{7a}$$

$$\max\{y_{br}, y_{cr}\} + \max\{y_{bt}, y_{ct}\} + 2L \le 1 \tag{7b}$$

3.4 Comparisons

We now compare the different segregation strategies to unveil the conditions that make one strategy superior to another. Outcomes can guide future deployments in real settings.

To facilitate an easy-to-interpret, graphical presentation, we shall reduce the degrees of freedom in this question by assuming that the fraction of turns is the same for both modes, so that a combination of inputs is determined by the triple (*y, c, r*); where combined flow $y = y_{cr} + y_{ct} + y_{br} + y_{bt}$, fraction of cars $c = (y_{cr} + y_{ct})/y$, and turning ratio $r = y_{cr}/(y_{cr} + y_{ct}) = y_{br}/(y_{br} + y_{bt})$. Then we shall look for the maximum feasible flows $y_s^*(c, r)$ allowed by each strategy, *S*. This is the solution of the following linear program:

$$(LP) \quad y_s^*(c, r) = \max\{y_{ct} + y_{cr} + y_{bt} + y_{br}\}$$
$$s.t.: \ (4) \text{ or } (5) \text{ or } (6) \text{ or } (7), \text{ depending on the strategy, } S$$
$$y_{ct} = yc(1-r)$$
$$y_{cr} = ycr$$
$$y_{bt} = y(1-c)(1-r)$$
$$y_{br} = y(1-c)r$$
$$0 \le c, r \le 1$$

Figure 7 depicts the four surfaces $y_s^*(c, r)$ obtained using $G = 0.4$ and $L = 0.05$ (where the latter value was estimated from intersections in the city of Chengdu). In these plots, the vertical axis is the combined flow, *y*, and the other two axes are the fraction of cars, *c*, and the right-turning ratio, *r*. Figure 8 shows the combined surface $\max_{S}\{y_s^*(c, r)\}$ in plain view (looking down from the top), and includes contour lines of the combined flow, *y*. The latter figure also unveils the *(c, r)* domain where each strategy is superior. In both figures, the combined flow can exceed 1 because it is aggregated over the four traffic streams. The fine sort strategy performs best (i.e. it produces the largest *y*) when both mode split and turning ratio are even (equal to 0.5). The modified bicycle box performs best when the split between through and right-turning vehicles is even. And the turn box is best when the modal split between cars and bicycles is even. These outcomes are reasonable: if we consider the operation of the modified bicycle box, we see that

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the through and turning vehicles discharge at the same time and that some discharge time is wasted if the split between these movements is not even. A similar argument applies to the turn box, which is well suited for the range of right-turning ratios, but wastes time if the car and bicycle flows are not even.
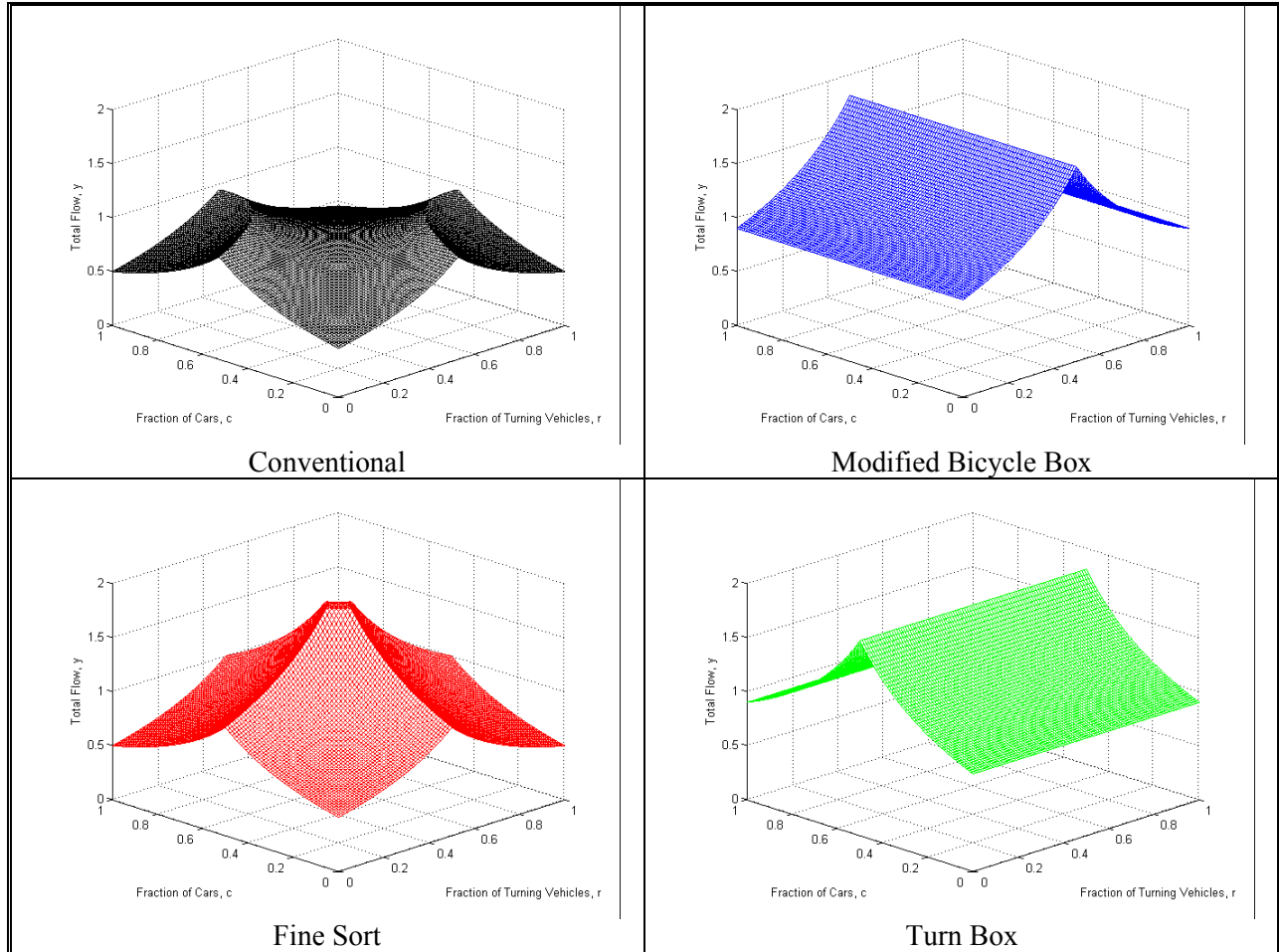
To test the strategies' resilience to variations in demand throughout a day, simulations were run where the temporal changes in demand were dramatic (i.e. the entire *(c,r)* domain was included). The assumption that the turning ratio for bicycles and cars are equal was relaxed, and these turning ratios, along with the mode split are assumed to vary slowly, independently and uniformly between 0 and 1 during the day (using increments of 0.01). Table 2 shows the average flow for each strategy throughout the analysis period. We see that the tandem strategies (modified bicycle box and turn box) are equivalent and the most resilient to time-varying demands; then outperforming the conventional strategy by 55% and the fine sort strategy by 25%.

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Table 2. Comparison Statistics for Different Segregation Strategies

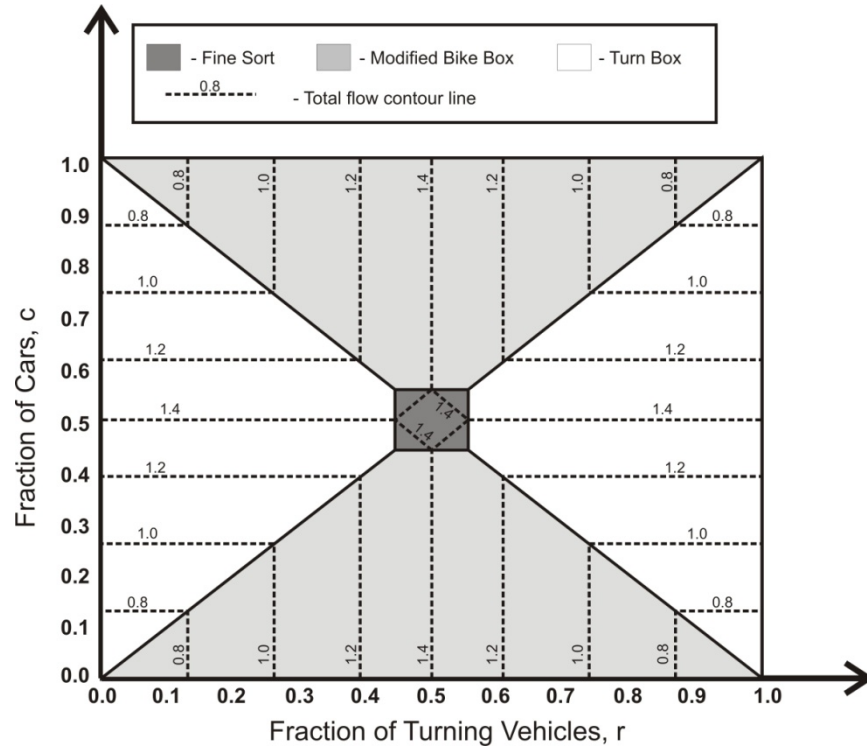|	Conventional	Fine Sort	Mod. Bicycle Box	Turn Box
Average Combined Flow	0.6214	0.7645	0.9678	0.9678

Figure 8. Optimal Segregation Strategies for Given Condition.

3.5 Discussion

Here we extend the ideas to more general intersections, consider other possible segregation strategies, and discuss implementation issues.

3.5.1 More General Intersection Approaches

The simple geometry shown in Figure 5 and assumed throughout this analysis is not a common one. In reality, intersection approaches are often wider and have more than one through-moving car lane. With many lanes, it is possible to allocate them to various streams in proportion to the demand of each stream. The ability to reallocate space to match demand increases with the number of lanes available; the wider the intersection approach, the better off we are. Hypothetical examples are presented in Figure 9.
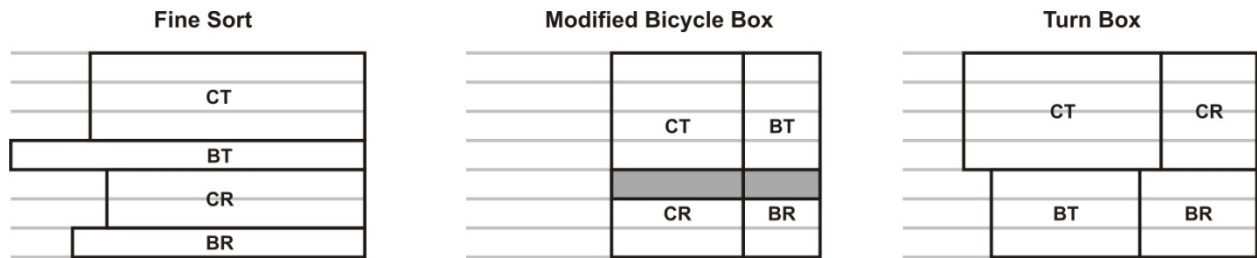
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Figure 9. Reallocation of Space Offered by Wide Approaches.

With the modified bicycle box, it is even possible to use mixed lanes that both through and turning vehicles can use (the shaded area in Figure 9) to further improve combined discharge[4]. In theory, if there are many lanes – or lanes are divisible and the mode split and turning ratio are time-independent – it is possible to divide the lanes in such way that there is no waste at all. In this case, the modified bicycle box can achieve flows, y, close to saturation during the entire green, independent of c and r; i.e., segregation nearly eliminates the effects of intermodal conflict.

We note too that at wide intersection approaches with low bicycle flows, the capacity of the traditional bicycle box with a pre-signal can nearly equal the capacity of the modified bicycle box. When there are few bicycles, the bicycle lane in the traditional implementation can be very narrow as in Figure 2a, such that cars can use nearly the full width of the intersection approach[5].

3.5.2 Other Segregation Strategies

Numerous strategies are available if one removes the restriction of applying the same treatment to both mode and movement; and some are quite realistic. An example is shown in Figure 10. The capacity of this strategy can be easily quantified using the constraints derived in Sections 2 and 3, as was done for the other four-stream strategies. We also know that this strategy is superior to the fine sort, since using tandem segregation (for the turning cars and through-moving bicycles, as shown in the figure) has been shown to be superior to side-by-side segregation. There are other combinations of two-stream treatments that can be used to manage four vehicle streams, and their capacities can be determined using the earlier formulas. However, the feasibility of each strategy may depend on local intersection characteristics, such as geometry or driver compliance.

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[4] Mixed lanes are infeasible with the Turn Box strategy because they would have to be shared by the two very distinct modes, bicycles and cars.

[5] We have performed calculations along the lines of Section 3.3 showing that in the most favorable case, the traditional bicycle box with a pre-signal can achieve nearly 90% of the capacity achieved by the modified bicycle box.
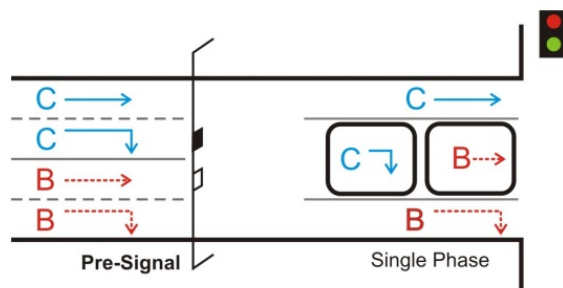
Figure 10. An Example of Strategy that Uses Different Treatments for Movements and Modes

3.5.3 Implementation Considerations

Although this paper has shown that segregating streams in tandem fashion is superior to that of side-by-side, the latter is currently used in many cities. In these cities, bicycle demands are low compared to those of the car such that they can be served via the conventional strategy or the fine sort (without the pre-signal as shown in Figure 1c). However, in locations where bicycle demand is extremely high (e.g. cities in China), these segregation strategies may not have sufficient capacity. In these cases, tandem strategies can provide the most benefit.

Implementation of any of our candidate strategies will require a minimum distance between the intersection and pre-signal to ensure that queue spillovers do not occur. The distance required may depend on the cycle length, number of lanes on the approach, and the jam densities of each traffic stream. Good traffic engineering techniques can be applied to ensure that the chosen distance can accommodate the maximum number of vehicles expected. As is well known, an upper bound to this distance is the space taken at jam density by the number of vehicles that would discharge from one lane in a green phase.

We also assume in this paper that all vehicle queues between the pre-signal and the intersection will completely discharge during each cycle. This may not always be the case due to random disturbances. For the modified bicycle box, this does not present much of a problem: newly arriving bicycles and cars would simply queue behind residual queues and discharge later in the following green. Residual queues can cause operational inefficiencies in the turn box, however, since a separate sub-phase will be used at the intersection to allow turning vehicles to discharge prior to through-moving ones. This sub-phase will restrict the residual through-moving vehicles from discharging, which may create larger residual queues in the next cycle. This can be avoided (at the expense of reduced capacity) by allowing fewer vehicles past the pre-signal than can typically discharge at the intersection.

4   Application to a Real Site

Here we demonstrate that our strategies can significantly improve the capacity of a real intersection. We do so using the site shown in Figure 11a, the eastbound approach to the intersection of First Ring Road and Gaoshengqiao Road in Chengdu. The lane labeled 3 is

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reserved for buses and right-turning cars during much of the day (7:00 – 20:00). Because these vehicles constitute a small percentage of the total traffic that uses the approach, lane 3 is under-saturated. The many left-turning cars that use lane 1 limit its capacity to serve through movements. More through-moving cars thus arrive at the intersection than can be served, and long queues persist in lanes 1 and 2 as a result.
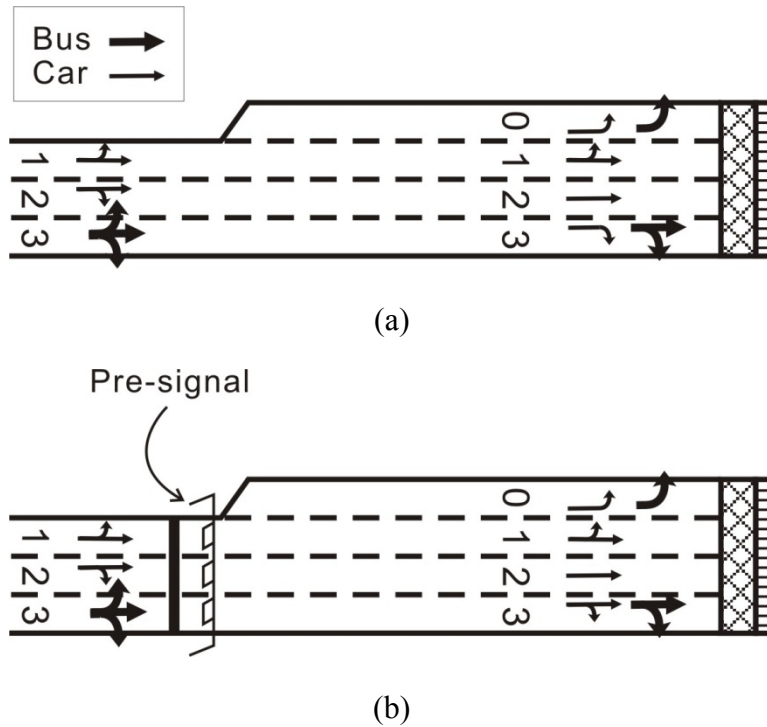

(a)

(b)

Figure 11. Information about the Candidate Intersection Approach.
(a) Current layout; (b) Proposed layout.

4.1 How a Pre-Signal Could Help

The above state of affairs could be improved by deploying a pre-signal, as shown in Figure 11b. We envision a simple strategy in which the pre-signal would sort buses and cars in tandem. Buses would be placed ahead of cars and would use only the outside lanes (0 and 3), as shown. Through-moving cars would now be allowed in lane 3, also as shown.

This control would leave unchanged the queue discharge flows of buses, and of left- and right-turning cars (all these should remain under-saturated). The queue discharge flows of through-moving cars in lanes 1 and 2 would be unchanged as well. The flow of through-moving cars in lane 3, on the other hand, could increase under the pre-signal by as much as $G - (y_{bt} + y_{br} + y_{cr})$, where these y are the dimensionless flows as previously defined, but with the index b now denoting "bus" rather than "bicycle." The increase could be significant.

To see this, refer to the piecewise-linear capacity curves in Figure 12. These unveil the theoretical maximum flows per cycle of: buses and right-turning cars in lane 3 (abscissa) vs through-moving cars in all lanes. These flows are counted as passenger car equivalents (pce's):

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buses are counted as 1.7 cars, since their discharge flows were observed to be: 13 buses/lane/cycle and 22 cars/lane/cycle.[6] Dashed lines show the capacities for the case of no pre-signal, whereby through-moving cars are assumed to use only lane 2; and the solid lines are the capacities when a pre-signal allows these cars to use both lanes 2 and 3. Traffic in lanes 0 and 1 is excluded from this assessment because we assume that the simple strategy used by our pre-signal would have little, if any, effect on these two left-hand lanes. Visual inspection of the curves reveals how a pre-signal can increase the capacity for through-moving cars as demands diminish for buses and right-turning cars.

4.2 Empirical Test

We observe that through-moving cars often utilize lane 3 even though this constitutes a traffic violation. These violators function as if controlled by the pre-signal described above, and thus make the following natural experiment possible.

Table 3. Field Observations.

Signal Cycle #	Signal Cycle Starting Time	Lane #	Through Buses	Right Buses	Through Cars	Right Cars	Required Green Times
1	5:54pm	2	0	0	18	0	43 sec
		3	3	1	4 †	7	38 sec
2	5:59pm	2	0	0	19	0	41 sec
		3	4	1	8 †	4	44 sec
3	6:05pm	2	0	0	19	0	49 sec
		3	4	2	2 †	4	43 sec ‡
4	6:13pm	2	0	0	23	0	49 sec
		3	5	1	4 †	7	53 sec
5	6:16pm	2	0	0	21	0	47 sec
		3	5	0	6 †	1	33 sec ‡
6	6:28pm	2	0	0	25	0	54 sec
		3	3	1	8 †	6	52 sec
7	6:30pm	2	0	0	24	0	51 sec
		3	4	1	5 †	7	50 sec
8	6:33pm	2	0	0	20	0	57 sec
		3	8	0	3 †	11	57 sec
9	6:36pm	2	0	0	18	0	42 sec
		3	2	1	5 †	5	42 sec
10	6:39pm	2	0	0	20	0	49 sec
		3	4	1	9 †	5	49 sec

† violations   ‡ lane empties before green ends

Counts of queued vehicles discharging into the intersection were extracted (from a video) for each of ten signal cycles. These counts were disaggregated by lane, by movement and by vehicle class; see Table 3. Note that through-moving violations (in lane 3) are separately included in the table. Also shown (in the table's right-most column) are the green times that were required to serve the counts.

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[6] Measurements were extracted from a video taken during the evening rush on Thursday, June 11, 2009.

Counts of both vehicle types were proportionally adjusted to obtain equivalent values in a fully saturated green phase;[7] and then combined to obtain a single pce value. The resulting estimates of maximum pce counts per cycle (capacities) are shown by the data points in Figure 12: the x's exclude through-moving cars in lane 3 as would occur in the absence of a pre-signal (and with full driver compliance of traffic regulations); the circles include these cars, which a pre-signal would have allowed. Of course, a legal pre-signal could allow more cars into lane 3, since drivers would not hesitate to use that lane. Thus, the circles are a lower bound on the capacity of through-moving cars.
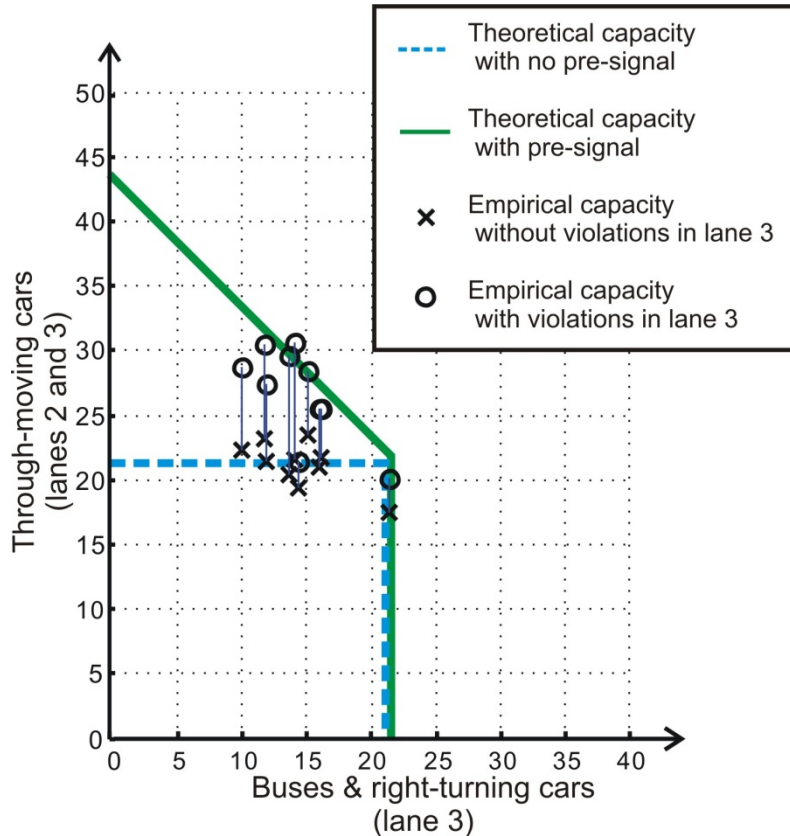

Figure 12. Empirical Validation of the Theoretical Capacity Constraints.

We see from the figure that the x's match the theoretical (dashed) curves quite well. As expected, some of the circles fall below their corresponding (solid, diagonal) curve: these came from cycles in which the through-moving violations were insufficient in number to compensate for the low demand of buses and right-turning cars. In light of this, the agreement between observation (circles) and theory (solid, diagonal curve) seems reasonable.

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[7] The effective green time allocated to these vehicles each cycle was measured to be 50 sec. In some cycles, queues continued to discharge even after the green time had elapsed. The counts in these instances were factored proportionally downward to coincide with our assumption that a queue can discharge for a fraction of the signal cycle not to exceed G.

We see from the cluster of data points in Figure 12 that the flow of buses and right-turning cars in lane 3 ranges from about 10 to 15 pce's per cycle. Thus, the theoretical capacity curves indicate that for the present set of conditions on the approach, a pre-signal could achieve capacity gains of about 25% for lanes 2 and 3 combined.

5   Conclusions and Future Work

This paper has examined new strategies for controlling traffic streams at signalized intersections. After all treatments are enumerated for the two-stream case, we conclude that tandem segregation is superior to segregating streams side-by-side. Extending the analysis to more complicated four-stream cases shows that the conventional strategy is never optimum; a fine sort strategy, for example, outperforms the conventional strategy by a wide margin (and was found to be the easiest strategy to deploy). Two strategies, the modified bicycle box and the turn box, were found to perform even better than the fine sort and to make better use of the entire approach width. Very importantly, simple test indicates that our ideas can produce significant capacity gains in complicated, real-world settings.

Future work is needed, of course: e.g. to explore how factors, such as mode speed and operator aggressiveness, affect signal lost time; and to expand our ideas to address even more complex scenarios, including intersections that serve many (more than two) modes, left-turn movements, etc. Work in these areas is ongoing.

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