MULTIMODAL TRAFFIC AT ISOLATED SIGNALIZED INTERSECTIONS: NEW MANAGEMENT STRATEGIES AND A FRAMEWORK FOR ANALYSIS

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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 various schemes for doing this are systematically enumerated, using as a building block the simple case of an intersection approach on which two movements are in conflict; and a framework is formulated for estimating the capacities that these schemes produce. Findings are extended to more complicated intersection approaches: the case in which two distinct modes make two conflicting movements is examined; ways to apply the ideas to yet other scenarios are described; and practical issues of implementation are discussed. Analysis shows that the proposed schemes produce capacities that consistently and significantly exceed those of conventional intersection treatments, and that the new schemes can reduce travel delays for all modes at an intersection, including those that are greener and more sustainable than the automobile. The work is thus a first step toward realizing more environmentally-friendly ways of managing city traffic.

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 in developing countries like India and China. 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 segregating vehicles on these links, as in the cases of sidewalks, bicycle lanes, and dedicated bus lanes, is beneficial both for safety and efficiency. However, segregation on approach links does not eliminate the conflicts between the modes; the segregated modes still must re-coalesce at intersections to accommodate 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 (*1, 2, 3, 4, 5, 6*) and the bus pre-signal (*7, 8*), 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 implemented, priority treatments may also be Pareto efficient. The second category is sorting, which lets vehicles swap positions laterally at some location at or upstream of the intersection to resolve the intermodal conflict. Treatments of this type include the weaving area (*9*), 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.

To our knowledge, there have been no systematic efforts to estimate how the above treatments affect the capacity of a generic intersection. Thus 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, and proposes strategies to increase these maximum flows for all modes.

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 making a specific movement (e.g. through-moving bicycle 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 their capacities, compare them to see which is superior and discuss more general strategies. Conclusions and future work are discussed in Section 4.

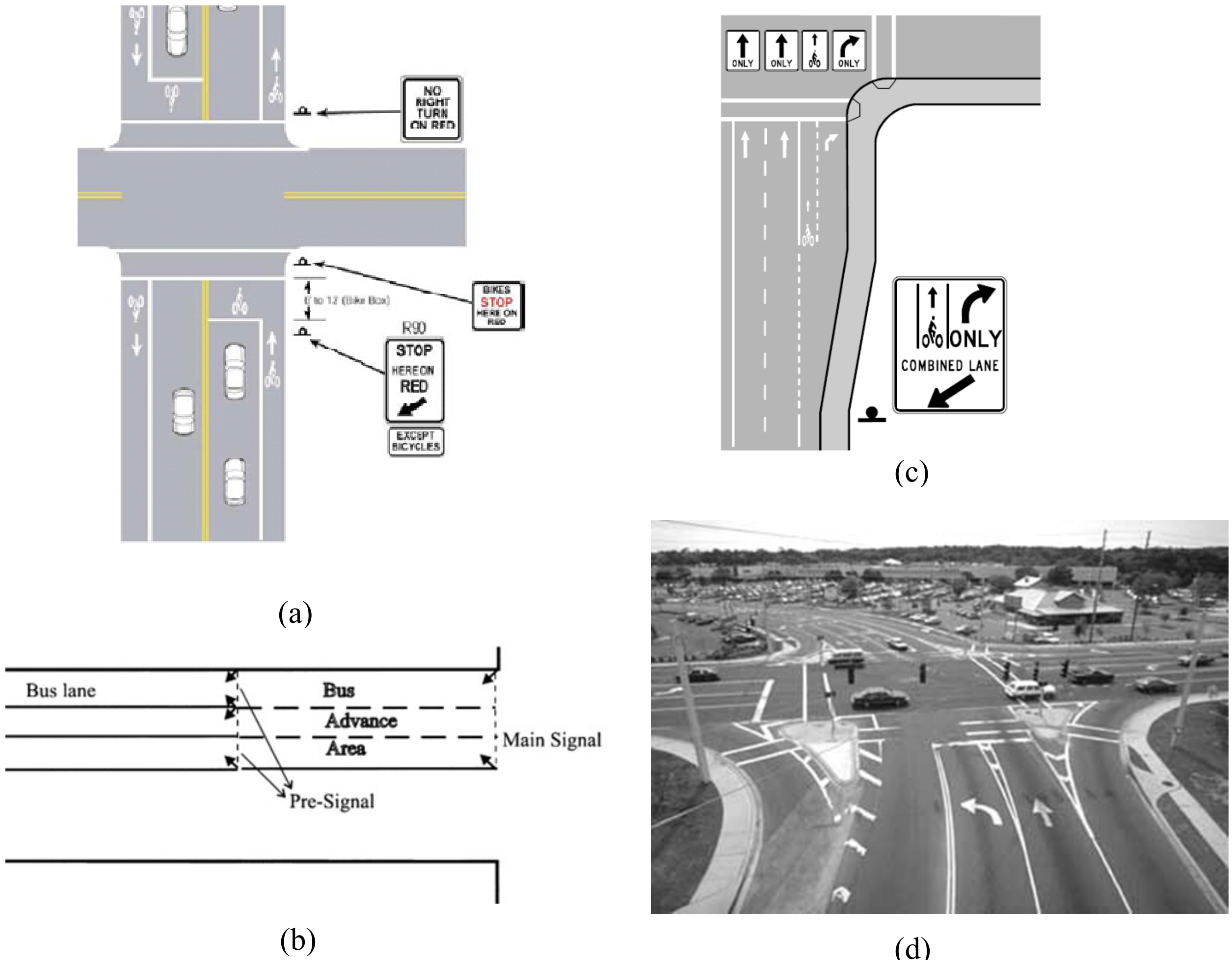


FIGURE 1 Examples of multimodal treatments.
Priority treatments: (a) bicycle box; (b) bus pre-signal.
Upstream sorting: (c) weaving area; (d) refugee island.

2 ANALYSIS OF A TWO-STREAM SCENARIO AS A BASIC BUILDING BLOCK

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

2.1 Segregation Treatments

There are three possible ways to completely segregate two traffic streams with different destinations 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.

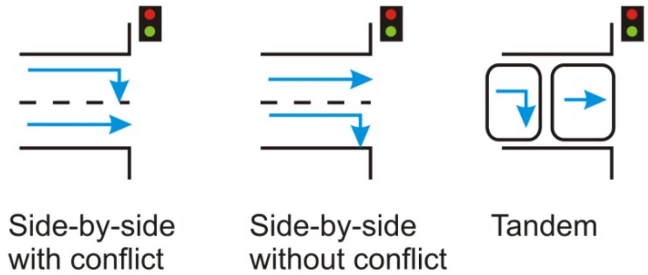


FIGURE 2 Possible ways to segregate two traffic streams at an intersection.

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

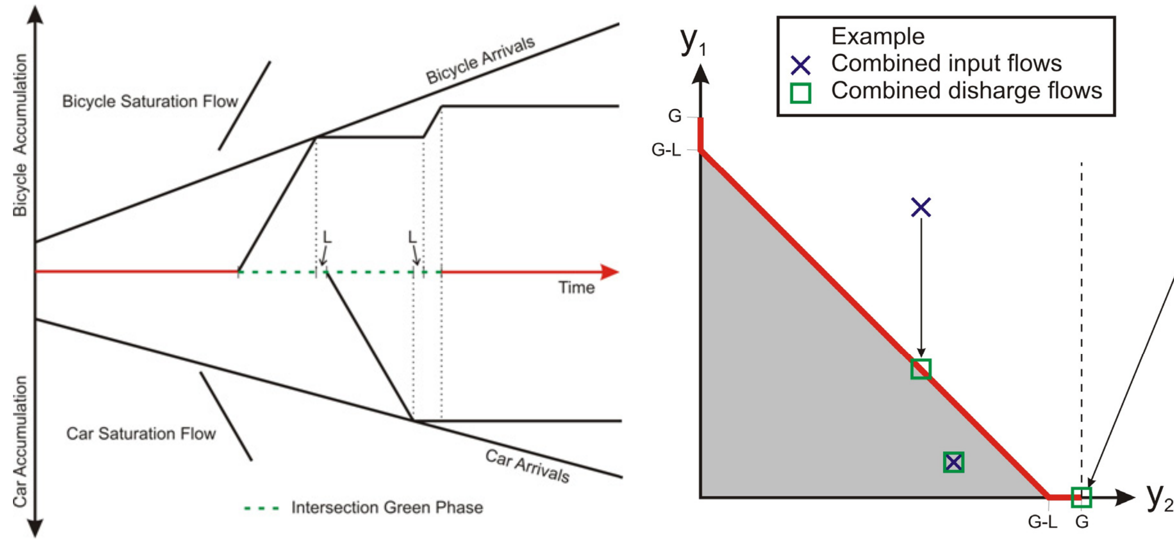
To simplify calculations, we define the cycle length of the intersection's signal as the unit of time; and we define the number of vehicles from each traffic stream (e.g. right-turning bicycles) that can discharge from one lane in one unit of time as the unit of vehicle quantity. With these definitions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

2.2.2 Side-by-side Segregation of Conflicting Streams

Let the right-turning vehicles on the left lane and 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 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 and discharge rates are constant.
3. Through-moving bicycles discharge through the intersection before right-turning cars at the beginning of the green. This assumption is consistent with the literature on bicycle traffic.

FIGURE 3a shows how these rules play out with a cumulative input-output diagram. The main discrepancy with the videos is that queues sometimes switch before they have completely discharged. 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; and (e) is separated from other intersections in the sense that it does not experience spillovers from downstream intersections.



(a) (b)

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 *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 outflow is equal to the inflow, regardless of the initial queues present. For inflows above the curve, outflows 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 green time of the signal, *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:

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

Equation (1) can also be derived analytically. To do this, verify that if the inflows are on the capacity line, then the discharge 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 not enough green time to discharge all the vehicles that arrive during a single cycle and 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 the green time of the intersection, *G*. Thus the capacity constaint becomes:

$$y_1 \leq G, y_2 \leq G \qquad (2)$$

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:

$$y_1/2+y_2/2 \leq G \quad (3)$$

2.3 Comparison and Discussion

The capacity curves for the three methods of segergation 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, when the flows are unbalanced (i.e. $y_1 \neq y_2$) some portion of the green period is wasted when one lane discharges vehicles while the other lane is empty. This does not happen with the tandem approach. Thus tandem segregation is equivalent or superior to the side-by-side segregation strategies.

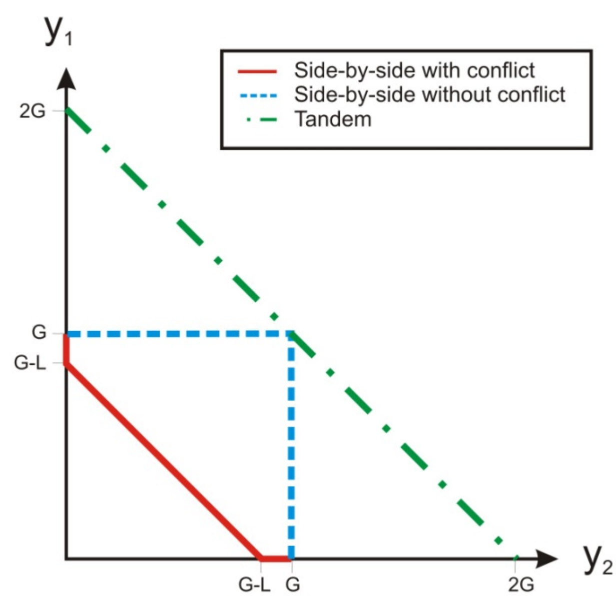


FIGURE 4 Comparison of capacities for the three segregation methods.

The capacity curves shown 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: i.e., far enough that the recurrent queues from the intersection do not back up to the pre-signal. The pre-signal will impose an additional capacity constraint but will 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 the pre-signal and the intersection signal (considering each as a separate intersection) will be able to pass through the entire system. Thus, the capacity of the system is determined by (1), (2), or (3), depending on our choice of segregation treatment, and the control of the pre-signal. Since the pre-signal only needs two phases – one for each traffic stream – the extra constrant is $y_1 + y_2 \le 1 - 2L$, in our units of time and flow.

Note from FIGURE 4 that when $2G \le 1 - 2L$, the pre-signal constraint cannot not be binding; thus the results from FIGURE 4 hold. 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 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.

For the two traffic streams, tandem segregation 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 will 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.

Tandem segregation has an additional advantage over side-by-side segregation in that it can accommodate time-varying demands of the two traffic streams. The simple example presented here assumed that there were 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 the tandem segregation case by allocating space laterally according to the demand. However, side-by-side segregation streams requires that the lanes be marked upstream of the signal. If these markings are permenant but 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

We now expand our analysis to a more complicated situation to gain insights about managing multimodal traffic at more generic intersections. Consider a four-stream scenario involving two modes and two destinations. We assume that the intersection serves only cars and bicycles, and that these vehicles make only through or right-turning movements as shown in the conventional case in FIGURE 5; that each traffic stream has its own lane (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.); and that each lane has the width of a car lane (Wide lanes exist in cities where bicycle traffic is heavy.). The conventional striping creates a conflict between the right-turning cars and through-moving bicycles during the signal's green phase, also as shown in the conventional case in FIGURE 5.

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 the segregation strategies that apply the same treatment to each mode – bicycle or car – and the same treatment to each movement – through-moving or right-turning. With this restriction, the strategies are greatly reduced in number and can be analyzed systematically. Schematic illustrations of the strategies are presented in FIGURE 5.

Vehicles can be segregated by mode and movement 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. The "fine sort" strategy shown in FIGURE 5 is an example of the first way, where both segregation types are side-by-side. The "conventional" strategy also shown in FIGURE 5 is an example of the second way, in which segregations are also side-by-side. The combination of the two ways of sorting, the two treatments for mode, and the two treatments for movement yields 2x2x2 possibilities, and these are summarized in TABLE 1.

Strategies in which traffic streams are segregated in tandem by both mode and movement are ignored in the table because they seem impractical. After all, a turning bicycle 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.

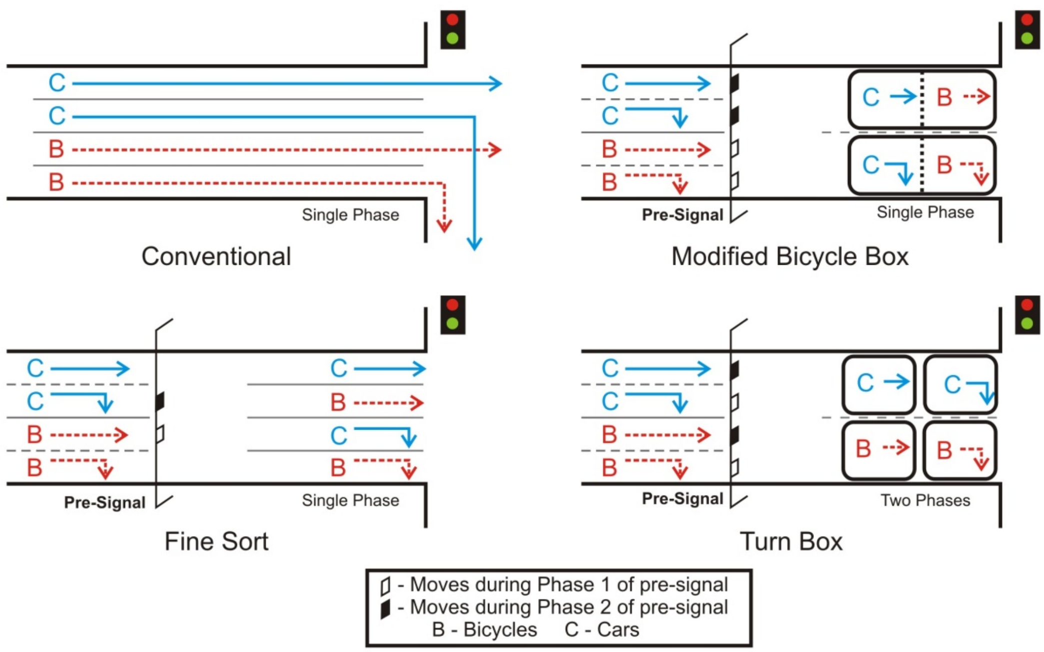


FIGURE 5 Feasible segregation strategies.

TABLE 1 Possible Segregation Strategies

			Segregation of Mode	
Primarily by mode Secondarily by movement			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

3.2 Description of the Strategies

Every strategy, save for the conventional one, requires a pre-signal. The 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 or by movement for the turn box – or the side-by-side sort for the case of the fine sort. For the latter strategy, the pre-signal controls the movement of the middle two lanes only. Pavement markings between the pre-signal and the intersection can be used to guide vehicles through the intersection.

In all cases except for the turn box strategy, the signal at the intersection can be operated as in the conventional strategy, with a single green phase for the approach. In the case of the turn box, through-moving bicycles would be held until the right-turning cars discharge. To improve safety, a separate sub-phase could ban all 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 the latter two strategies to be similar since both use one side-by-side sort and one tandem sort.

3.3 Capacity Analysis

The capacity constraints presented in Section 2 are sufficient for determining the capacity for these 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, these flows are the green times needed to serve them using the set of units defined previously.

3.3.1 Conventional Strategy

Since through-moving cars and right-turning bicycles are not affected by the middle lanes, 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:

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

$$y_{br} \le G , \quad \text{shoulder lane} \tag{4b}$$

$$y_{bt} + y_{cr} \le G - L , \quad \text{middle lanes} \tag{4c}$$

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 the intermodal conflicts can be when treated in the conventional manner.

3.3.2 Fine Sort

Refer back to FIGURE 5. At the intersection, each stream flow 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. In addition, there is a lost time of $2L$ (one L for each phase) per cycle. Thus the capacity constraint due to the pre-signal is the first inequality of (5c), and the complete set of capacity constraints for the fine sort is:

$$y_{ct} \le G , \quad \text{median lane} \tag{5a}$$

$$y_{br} \le G , \quad \text{shoulder lane} \tag{5b}$$

$$\begin{cases} y_{bt} + y_{cr} + 2L \le 1 , \\ y_{bt} \le G, y_{cr} \le G , \end{cases} \quad \text{middle lanes} \tag{5c}$$

3.3.3 Modified Bicycle Box

Again, refer to FIGURE 5. In this case, all traffic streams discharge via two lanes upstream of the intersection (and would also have two lanes downstream for receiving). 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 unit of time), yielding the constraint in (6b), such that the complete set of capacity constraints for the modified bicycle box is:

$$\max\{y_{bt}/2 + y_{ct}/2, y_{br}/2 + y_{cr}/2\} + 2L \le G \tag{6a}$$

$$\max\{y_{bt}, y_{br}\} + \max\{y_{ct}, y_{cr}\} + 2L \le 1 \tag{6b}$$

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 $\max\{y_{bt}/2, y_{ct}/2\}$. Since there is a lost time of $2L$ per phase, the capacity constraint due to the intersection signal is as given in (7a).

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

$$\max\{y_{br}/2, y_{cr}/2\} + \max\{y_{bt}/2, y_{ct}/2\} + 2L \le G \quad \text{(7a)}$$

$$\max\{y_{br}, y_{cr}\} + \max\{y_{bt}, y_{ct}\} + 2L \le 1 \quad \text{(7b)}$$

3.4 Comparisons

We now compare the different segregation strategies to unveil the conditions that make one strategy superior to another. This will suggest how best to deploy the strategies.

To facilitate graphic illustration, 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:

$$\begin{aligned}
(LP) \quad & y_s^*(c,r) = \max\{y_{ct} + y_{cr} + y_{bt} + y_{br}\} \\
& s.t.: \text{ (4) or (5) or (6) or (7), depending on the strategy, } S \\
& y_{ct} = yc(1-r) \\
& y_{cr} = ycr \\
& y_{bt} = y(1-c)(1-r) \\
& y_{br} = y(1-c)r \\
& 0 \le c, r \le 1
\end{aligned} \quad (14)$$

FIGURE 6a – FIGURE 6d depicts the four surfaces $y_S^*(c, r)$ obtained using $G = 0.4$ and $L = 0.05$ (a value 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 6e shows the combined surface $\max_S\{y_S^*(c,r)\}$ looking down from the top, including contour lines of the combined flow, y. The latter figure also shows 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 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.

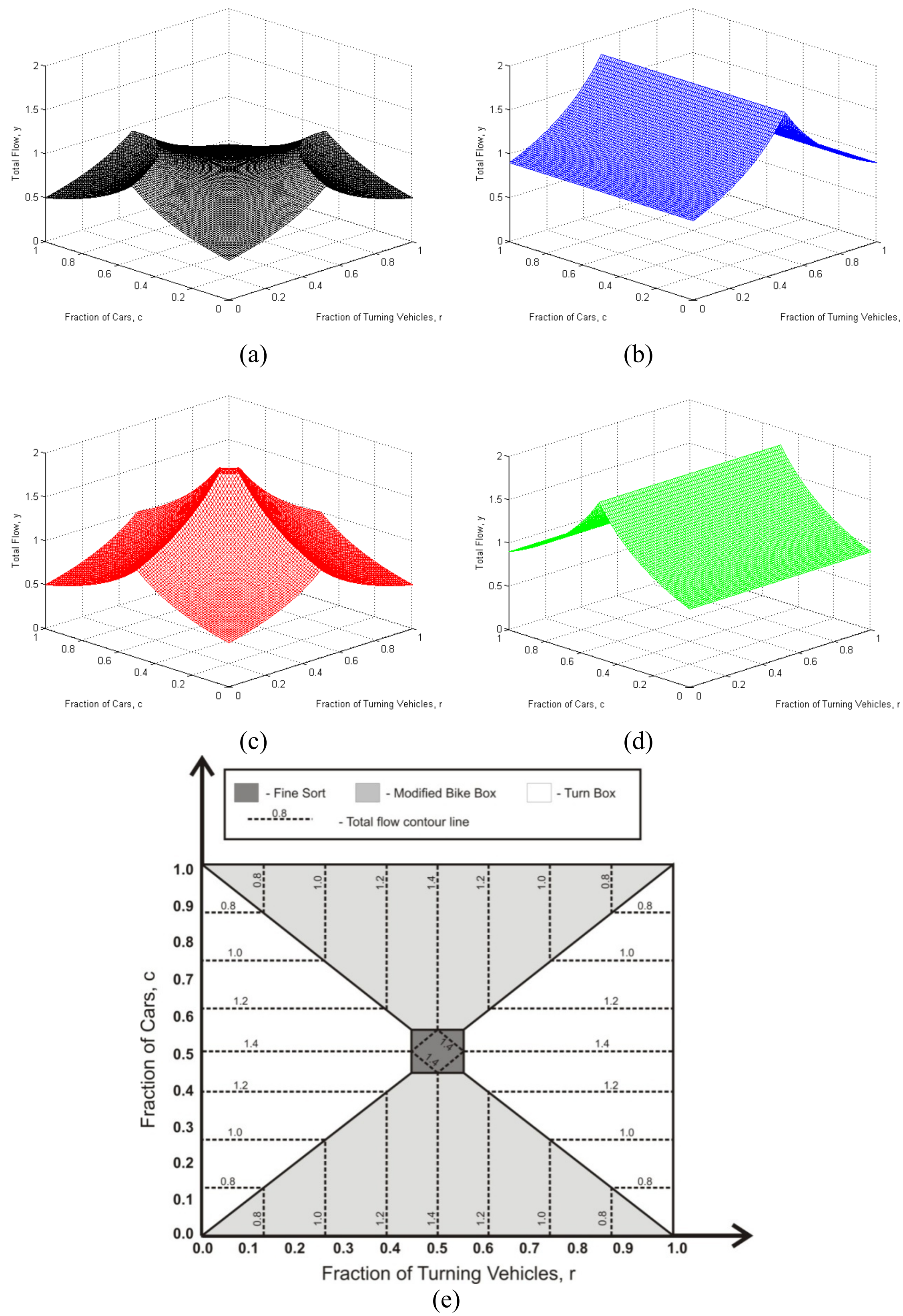


FIGURE 6 Capacity constraints for feasible segregation strategies.
(a) Conventional; (b) Modified bicycle box; (c) Fine sort; (d) Turn box; (e) Best among the four strategies.

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). Throughout the analysis period, the average flow for conventional, fine sort, modified bicycle box and turn box are 0.6214, 0.7645, 0.9678 and 0.9678 respectively. The statistics here were obtained by relaxing the assumption that the turning ratio for bicycles and cars are equal, and by assuming that the turning ratios for bicycles and for cars, and mode split vary slowly, independently and uniformly between 0 and 1 during the day (using increments of 0.01). The result shows that the tandem strategies are equivalent and the most resilient to time-varying demands, outperforming the conventional strategy by 55% and the fine sort strategy by 25%.

3.5 Discussion

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

3.5.1 More General Intersection Approaches

The simple geometry shown in the conventional case in FIGURE 5 and assumed throughout this analysis is not a common one. Instead, intersection approaches are often wider and have more than one through-moving car lane. With many lanes, it is possible to allocate them in proportion to the demand of each stream. Hypothetical examples of this are presented in FIGURE 7a. 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.

With the modified bicycle box, it is even possible to use mixed lanes (the shaded area in FIGURE 7a, representing lanes that both through and turning vehicles can use) to further improve combined discharge. 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. Therefore, modes can be segregated with this strategy almost as well as if they did not interact at all.

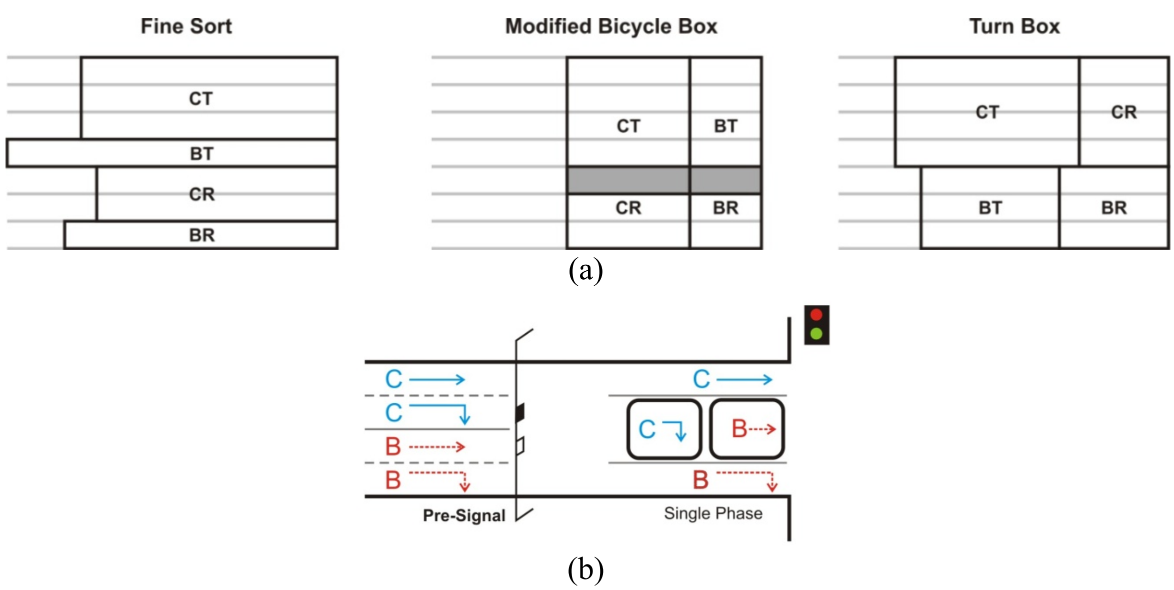


FIGURE 7 More general segregation strategies.
(a) Reallocation of space offered by wide approaches;
(b) An example of strategy that uses different treatments for movements and modes.

3.5.2 Other Segregation Strategies

To simplify discussion, we have restricted ourselves to segregation strategies that apply the same treatment to both modes and the same treatment to both movements. In fact, there are many more strategies available if this restriction is removed; and some are quite realistic. An example is shown in FIGURE 7b. Its capacity of this strategy can be easily quantified using the constraints derived in Sections 2 and 3, as was done for the four-stream strategies. We can also tell that this strategy is superior to the fine sort, since tandem strategy is used instead of side-by-side segregation of non-conflicting streams. 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.

3.5.3 Implementation Considerations

Although this paper has shown that tandem segregation is superior to side-by-side segregation, the latter is currently used in many countries. In these countries, bicycle demands are low compared to those of the car and the conventional design or fine sort (without the pre-signal as shown in FIGURE 1c) both provide capacities large enough to serve the vehicular demand. However, in locations where bicycle demand is extremely high, like China, the side-by-side segregation strategies may not have sufficient capacity. In these locations, 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. This distance 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 distance provided 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 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: residual car queues can discharge during the next green before the newly arriving bicycles and cars. The new arrivals 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 vehicles. The 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 will typically be able to discharge at the intersection.

4 CONCLUSIONS AND FUTURE WORK

This paper has examined simple scenarios consisting of two and four traffic streams at a signalized intersection. After all possible treatments are exhaustively enumerated for the two-stream case, we conclude that tandem segregation is superior to side-by-side segregation of non-conflicting streams, and that the latter is superior to side-by-side segregation of conflicting streams. In the four-stream case, we find that there are only four possible segregation strategies if the same treatment is applied to each mode and to each movement. The conventional strategy is never optimum. A "fine sort" strategy, for example, outperforms it by a wide margin. The fine sort strategy is also the easiest strategy to implement among those proposed. We also find two even better strategies, a "modified bicycle box" and a "turn box", which make better use of the entire approach width.

The analysis showed that there exist designs for multimodal intersection that are more efficient than those that are currently implemented. The new designs can be adapted to any intersection geometry and use a pre-signal to perform the necessary sorts. The pre-signal can also provide safety benefits by resolving intermodal conflicts in an orderly way.

There are some caveats. This analysis assumed that lost time is fixed and the same between all switches. In reality, lost time may depend on many factors, including the speed of a specific mode, the distance traveled to clear sufficient space for another mode, and the aggressiveness of drivers. Further work is required to determine how variable lost time affects intersection capacity.

Finally, the work has also assumed that left turns are prohibited at the intersection and that only two modes are present. As a result, our simplified intersection exhibited only one intermodal conflict. In reality, intersections may include left-turn movements as well as three or more modes, including pedestrians. This increases the number of intermodal conflicts and further reduces capacity. Future work will therefore expand the number of modes and movements, perhaps with modified versions of the strategies presented here. Experimental tests are planned to verify if the theoretical capacity gains seen here can be achieved in reality.

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