Traffic Segregation on Spatial and Temporal Bases: The Experience of Bicycle Traffic Operations in China

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For many years, appropriate techniques for establishing suitable traffic regulations under mixed-traffic conditions in Chinese cities have been explored. Generally, it is considered that the segregation of motorized and nonmotorized traffic by temporal and spatial means is a basic principle for managing and operating mixed traffic on most urban streets. Many Chinese cities, especially large cities, have used this principle in their urban traffic operations and management for a long time. A study of the implementation of this principle on the basis of the experiences of several large cities in China is presented. Traffic operation and management under mixed-traffic conditions from the standpoint of roadway planning, traffic engineering, operation, and various treatment measures to separate mixed traffic, particularly at intersections, are discussed. Detailed examples of intersection traffic operation and unique patterns of interchange are presented with regard to the traffic segregation principle. It is indicated that the mixed-traffic congestion or chaos due to massive use of nonmotorized vehicles could be resolved to a great extent by sound engineering and traffic operation solutions.

The bicycle plays a vital role in urban passenger transportation in virtually all of the cities of China. It offers low-cost private transportation, provides a great deal of flexibility and convenience for short trips in most cities, emits no pollution, and uses renewable energy. It has been recognized that bicycle transportation predominates in urban transportation in China and that bicycles will continue as a major type of private vehicle in most Chinese cities for decades. Recent statistics showed that, in major Chinese cities, bicycle ownership has increased more than 10 percent annually, and the ownership rates are one bicycle per household or more (*1*). Between 1980 and 1988, the number of bicycles in Beijing grew more than 12 percent per year to 7.3 million (*2*).

It is obvious that this massive usage of the bicycle as a passenger transportation mode in urban China has adversely affected the entire urban traffic operation. In Beijing, for example, peak-hour bicycle flow exceeded 20,000 at 14 intersections in 1986 at inner-city areas. By 1989 the number of such intersections increased to more than 20 (*3*). Currently, there are three major problems in urban traffic operations in Chinese cities caused by heavy bicycle traffic:

- On narrow roads or roads where saturated bicycle flow exists, bicycles and motor vehicles compete to occupy the limited road spaces.
- In at-grade intersections, the mingling of bicycles and motor vehicles because of a lack of separation measures causes traffic chaos and a great reduction in traffic capacity.
- There are large numbers of alleys intersecting with roads or streets in inner-city areas. Many bicycles often maneuver suddenly and wantonly turn left on the street to enter or exit the alleys. This situation seriously affects the traffic operation of motor vehicles on the street and greatly reduces the speed of the vehicles.

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It is well known that the mixed traffic of bicycles and motor vehicles is a major characteristic of urban transportation in China, and it has led to serious traffic congestion and recurrent accidents in many cities. For many years, traffic operation and management in Chinese cities have been devoted to exploring appropriate operation methods and to establishing suitable traffic regulations under the mixed-traffic conditions.

Generally, the segregation of motorized and nonmotorized traffic by temporal and spatial means is a basic principle for managing and operating mixed traffic on most urban streets. Many Chinese cities, especially the large cities, have used this principle in their urban traffic operations and management for a long time. This paper presents the results of a study of the implementation of this principle on the basis of the experiences of several large cities in China. It discusses traffic operation and management under mixed-traffic conditions from the standpoint of roadway planning, traffic operation, and various treatment measures to separate mixed traffic, particularly at intersections. The paper explains traffic segregation by means of various engineering and management treatments for different categories of traffic (vehicle types, speeds, etc.) and turning movements of the traffic. These treatment measures outline the basic methods of traffic segregation either by spatial separation at the same time or by temporal separation in the same space.

ALLOCATION OF BICYCLE ROADS

There are two major categories of bicycle roads in Chinese cities. One is the separated bicycle road, in which the bicycle traffic is divided from motorized vehicular traffic by an open space, barrier, or even pavement markings, either within the roadway right-of-way (the most common type in China) or within an independent right-of-way. The other is the mixed bicycle road, in which bicycles share the roadway with motorized vehicular traffic or pedestrian traffic without any physical or nonphysical separations. The separated bicycle road can be further classified according to the extent of the separation between motor traffic and bicycle traffic:

- Exclusive bike paths, mostly positioned on one or both sides of motor vehicle–traveled ways with designed outer separations (these are called "three-slab roads" by Chinese, a vivid description of this type of roadway);
- Independent bike lanes, positioned on one or both sides of motor vehicle lanes with barrier separations; and
- Nonindependent bike lanes, positioned on one or both sides of motor vehicle lanes without physical separation but separated by pavement markings.

The mixed bicycle roads can be further classified according to their mixture compositions. One type is bicycle-pedestrian mixed paths, and the other is bicycle-motor mixed roads.

In a few Chinese cities, so-called special bicycle roads, which are independent of the vehicular road network and dedicated to bicycle use only, are being developed. In some cities, the extensive alley systems provide opportunities for creating bicycle networks while improving traffic operations, as shown in a World Bank project in Shanghai.

The concept of network functional classification used in classifying highways is also applied to planning and designing cycle networks in most Chinese cities. There are two classes of bicycle roads. The first is the city-level bicycle road, which carries citywide or interdistrict bicycle traffic and provides for faster speeds, less interference, and higher capacity. The second is the district-level bicycle road, which mainly serves as a secondary or collector road, functions as a major road for intradistrict and some interdistrict bicycle traffic. Table 1 gives the general relationship between the classifications and the facility types.

According to the concept of traffic segregation, the Chinese experts developed a special evaluation index, separation ratio (SR), for evaluating and determining the levels of service (LOSs) of the bicycle roadway system (*4*). The separation ratio is defined as

$$SR = L_s/R \quad \text{(percent)}$$

where L_s is the length of primary and secondary roads that provide a physical separation between motorized and nonmotorized traffic within a certain area and R is the total length of primary and secondary roads in the area. Table 2 indicates the classifications of the SR.

BICYCLE TRAFFIC OPERATIONS AT INTERSECTIONS

Bicycle traffic operations at Chinese urban intersections are discussed under the typical four-leg crossing intersection conditions. In industrial countries, traffic conflicts between motor vehicles at intersections are the main consideration in traffic analyses and operations. However, the big difference between traffic characteristics in Chinese cities and those of motorized cities is the large amount of bicycle and pedestrian traffic. All traffic conflicts can be classified on the basis of safety concerns as follows (*5*):

- Type A includes crossing conflicts between motor vehicles, motor vehicle and bicycle, and motor vehicle and pedestrian.
- Type B includes merging and diverging conflicts between motor vehicles.
- Type C includes all conflicts between bicycles and between bicycle and pedestrian.

The relationship among these three types of traffic conflicts on the basis of accident severity can be indicated as

$$A > B > C$$

Figure 1 shows all traffic conflict points at a typical signalized crossing at-grade intersection. The related data are given in Table 3.

The bicycle is a flexible but slow and unstable transportation mode. In movement, particularly at intersections, the bicycle is unlike the motor vehicle, which appears in a linear queue and keeps a constant lateral distance, whereas the bicycle shows a "group" movement in which a number of bicycles move close together in a cluster pattern. This unique travel pattern brings traffic conflicts everywhere within the moving area. It virtually increases conflict points to a conflict area at the intersection (Figure 1).

In fact, the bicycle starts moving faster than the motor vehicle. A study done by Chinese experts indicates that a

TABLE 1 Classifications and Facility Types of Bicycle Roads[a]

Classifications		Facility Types			
		Separated Roads			Mixed Roads
		Exclusive	Independent	Non-Independent	
City Level	Large, Medium City	O[b]	O	x[d]	x
District	Large, Medium City	O	O	x	x
Level	Small City	O	O	Δ[c]	Δ

[a]Q.S. Xiao and W.Z. Xu, *Urban Transportation Planning* (in Chinese). People's Transportation Press, Beijing, China, 1990.
[b]O indicates the facility should be built.
[c]Δ indicates the facility may be built depending on the situation.
[d]x indicates unsuitable for building the facility.

TABLE 2 Separation Ratios for Evaluating LOS of Bicycle Roadway Systems (*4*)

Levels	A	B	C	D
SR	> 80	70 - 79	50 - 69	< 50

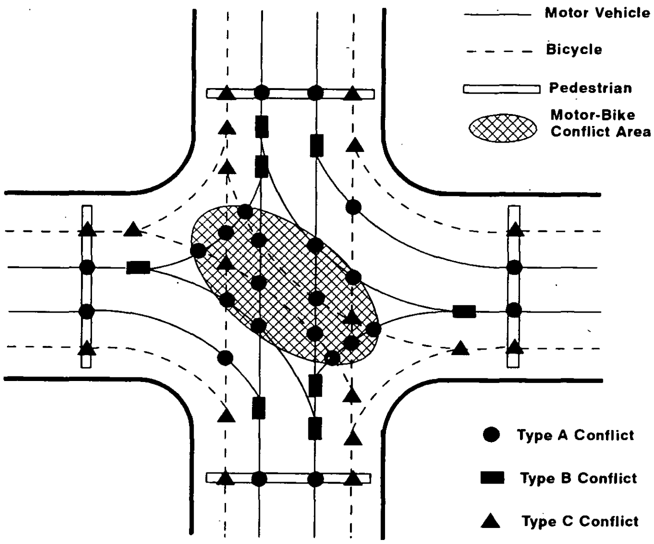

FIGURE 1 Intersection conflicts.

bicycle starts to move more than 1 sec faster than a motor vehicle; however, the motor vehicle has a greater speed afterwards (*6*). Therefore, bicycles start moving promptly when a green signal turns on; when left-turning bicycles reach the middle of the intersection, they encounter through vehicular flow from both the same and opposing directions, which significantly interferes with their movements.

In general, the presence of bicycle traffic at intersections dramatically increases the number of conflict points and the breadth of the conflicting areas at the intersection. Consequently, the pivotal concept is to separate vehicular and bicycle traffic on either a spatial or a temporal basis to reduce the chance of traffic conflicts. On the basis of this concept and the unique characteristic of mixed traffic, several measures have been adopted by Chinese engineers and administrators to alleviate traffic congestion at urban intersections. These measures can be generally categorized as (*a*) pavement marking channelization, (*b*) engineering treatment, and (*c*) regulatory management.

Pavement Marking Channelization

Bicycle Banned Area

As Figure 1 indicates, bicycles appear in a "cluster" move pattern producing a conflict area at the center of the intersection. On the basis of this feature, a square or rectangular space marked at the center of the intersection is enforced as a bicycle banned area (Figure 2). All bicycles are required to travel outside the banned area while motor vehicles maintain their original route. If the gap of through vehicles does not allow left-turning bicycles to pass through the vehicle stream, the bicycles need to wait outside the banned area at Location A until an appropriate gap acceptance exists. As a safety measure, a bike protection pathway may be created at the periphery of the banned area (Figure 2), and cyclists will be given priority if they follow the prescribed pathway.

This method has been implemented in Beijing with very positive results. To evaluate the effectiveness of the method, a before-after study was conducted by the Institute of Beijing Traffic Engineering in 1989 (*3*). It was found that after the bicycle banned area was implemented, the percentage reduction of average travel time at the intersection was 0.1 percent per vehicle for through motor vehicles, 8.3 percent per vehicle for left-turning vehicles, and 15.5 percent per bicycle for left-

TABLE 3 Number of Conflicts for Different Types of Intersection/Interchange[a]

Type of Intersection/ Interchange	Number of Conflicts							Peak Hour Traffic[e]
	Type A				Type B	Type C	Total	
	M-M[b]	M-B[c]	M-P[d]	SUM				
Signal Intersection	2	14	8	24	8	18	50	4202
2-Level Roundabout	4	8	8	20	12	28	60	3885
3-Level Roundabout	0	0	8	8	12	20	40	6201
2-Level Cloverleaf	0	16	8	24	16	20	60	6253
3-Level Cloverleaf	0	0	8	8	16	20	44	7030

[a]Reference 5.
[b]M-M represents conflicts between motor vehicles.
[c]M-B represents conflicts between motor vehicle and bicycle.
[d]M-P represents conflicts between motor vehicle and pedestrian.
[e]Peak hour traffic represents monitoring result on September 9, 1987.

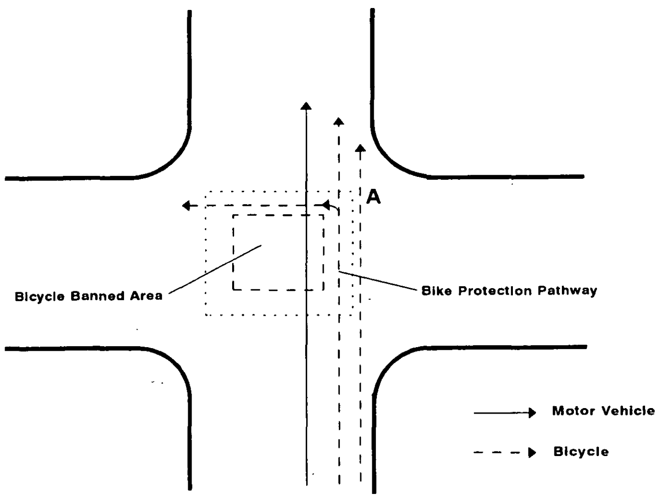

FIGURE 2 Bicycle banned area.

turning bikes. The traffic capacity at the intersection increased about 16.1 percent (passenger car equivalent). The study result also indicated the following:

- The establishment of a bicycle banned area channelizes bicycle traffic at the intersection.
- The bicycle banned area method is more suitable for large intersections.
- Cyclists are willing to accept the bike protection pathway because of the legal endorsement of the priority of bicycles on the pathway.
- The bike protection pathway appears to be more effective at three-slab T-intersections (Figure 3).

The study also found that the major problem in implementing the method is violation of traffic rules by cyclists, so the effectiveness of the measure has not been fully demonstrated.

Second Stop Line at the Intersection

As mentioned earlier, although the bicycle starts moving faster than the motor vehicle, its speed is much lower than that of the motor vehicle afterwards. At wide intersections, when left-turning bicycles move to the place where they start to turn left, the through vehicular flow from the same direction also arrives at the same place and, thus, blocks the left-turning bicycles. Therefore, two stops exist when left-turning bicycles traverse an intersection. The first is at the stop line during a red signal period, and the second occurs while waiting for an acceptable gap in the through vehicular flow during a green signal period. On the basis of this trait, a left-turning bicycle waiting line, the second stop line, can be established to maintain priority for the vehicular traffic in the conflict area, reducing motorized vehicle-bike conflicts and restricting arbitrary movements by cyclists (Figure 4) (7).

Special Waiting Area for Left-Turning Bicycles

At some narrow intersections, because of the bicycle trait of prompt starting speed, a special bike waiting area can be created beyond the approach stop line at the intersection (Figure 5). Bicycles, especially left-turning bicycles, wait in this area during a red signal period. Once a green signal turns on, the bicycles waiting in the area can quickly pass the intersection while the motor vehicles are just starting to move. In this way, bicycles and motor vehicles can be separated on a temporal basis, which will avoid conflicts between them. If the pedestrian crosswalk is not close to the intersection, the bicycle stop line (or the bicycle waiting area) can be positioned close to the center of the intersection (Figure 5, east approach). Therefore, the prompt start trait of bicycles can be used to make left-turning bicycles quickly pass the intersection and avoid conflict with through motor vehicles.

Engineering Treatment

At some intersections, a common engineering measure can be used to expand the width of intersection approaches. In many cases, separate left-turn, through, and right-turn bike lanes can be created. If necessary, a physical barrier can also

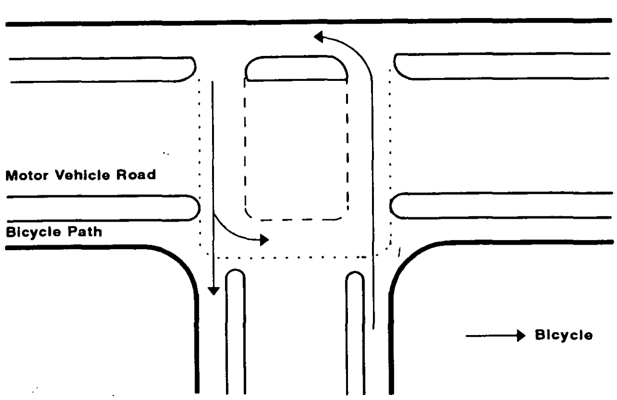

FIGURE 3 Bicycle banned area at T-intersection.

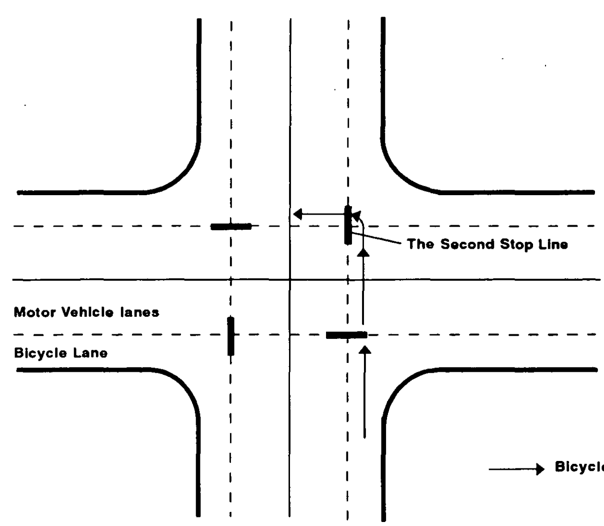

FIGURE 4 Second bicycle stop lines.

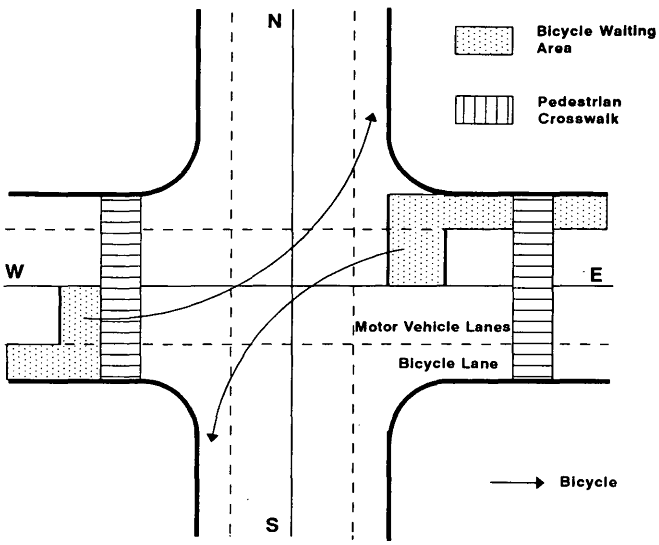

FIGURE 5 Special waiting area for left-turning bicycles.

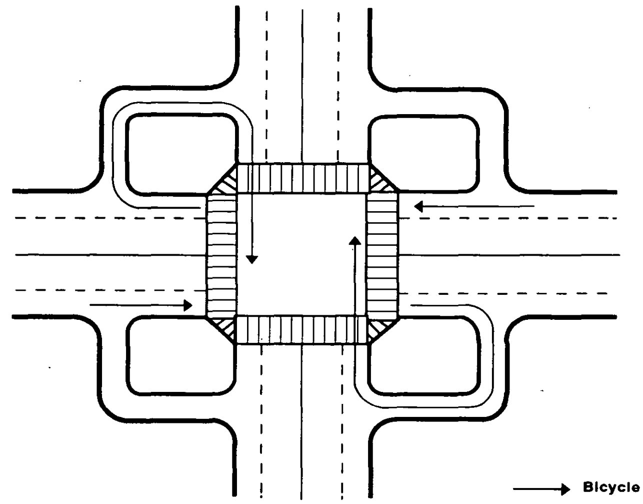

FIGURE 6 Intersection for prohibiting bicycle left turns.

be built to separate right-turning bicycles to prevent right-turn jam. It is believed that this treatment can effectively eliminate conflicts among bike turning movements at an intersection and increase the capacity of the intersection to deal with mixed traffic.

Regulatory Management

One-Way Bicycle Roads

As a part of roadway network planning, a one-way bicycle network can be established on the basis of existing traffic conditions and future traffic demand analyses. At the same time, the public transit routes and stops in the network area may need to be adjusted to best coordinate the one-way bike traffic. A study concluded that, for a particular route, if the bicycles whose O-D points are not located on the linking roads of the route exceed 70 percent and the distance of this route to a parallel route that is able to facilitate bicycle traffic is less than 200 to 300 m, the route can be considered for implementation of one-way bicycle traffic (*8*).

Left-Turn Prohibitions

At intersections where serious congestion exists, prohibiting bicycle left turns is a means of reducing bike-motor conflicts and relieving such congestion. Because the bicycle is propelled by human power, it is not appropriate to force cyclists to make a long detour. In many cases, the alleys near the intersection can be used to make left-turning bikes change to a right-turn travel path (Figure 6). This measure has been tried in Beijing but proved to be unpopular with cyclists.

Changeable Traffic Lanes

In most Chinese cities, urban arterial routes can experience much greater peak-hour bicycle traffic than motor vehicle traffic. In contrast, the off-peak motor traffic is greater than bicycle traffic. With the changeable lane system, one or more lanes are designated for moving bicycles during peak periods and motor vehicles during off-peak periods. The same concept could be applied to bicycle left-turn bans at intersections. It is not necessary to prohibit bicycle left turns at all times to alleviate congestion or accident problems resulting from conflicts produced by turning bicycles. Left-turning movements should be prohibited only during periods when the study data indicate that a congestion or accident problem exists and when a suitable alternative route is available. When part-time changeable lanes or turning restrictions are used, the signs used to notify cyclists and motorists of the action must be carefully designed and placed so that the time of the action is clearly visible.

BICYCLE TRAFFIC OPERATIONS AT INTERCHANGES

The greatest efficiency, safety, and capacity of crossing intersection traffic are attained when intersecting through traffic flows are grade separated by using interchanges. Two types of nonmotor vehicle pathway treatments at interchanges have been built in Chinese cities. One is the mixed-traffic interchange, in which nonmotor and motor traffic flows are at same levels. This type retains conflicts between turning motor vehicles and through and left-turning bicycles. The other type is the divided-traffic interchange, in which nonmotor traffic flows are separated into an independent level of the interchange. Generally, the mixed-traffic interchange is designed with two levels, and the divided-traffic interchange is designed with three levels. Therefore, the latter type of interchange involves more construction work and financial investment than the former. Statistics gathered from interchange constructions in the Beijing area indicate that the cost of a divided-traffic interchange is 30 percent more than that of a mixed-traffic interchange. However, traffic conditions of the divided-traffic interchange are much better than those of the mixed-traffic interchange because the divided-traffic interchange eliminates interference between motorized and nonmotorized traffic. Therefore, the choice between these two types of interchanges must be based on overall cost-effectiveness and long-term development analysis and evaluation.

Two popular patterns of divided-traffic interchanges have been built in Chinese cities, especially in the Beijing metropolitan area: the cloverleaf pattern and the roundabout pattern. Figures 7 and 8 show these two types and indicate their conflict points.

Data concerning the types of conflicts for signalized intersections, cloverleaf interchanges, and roundabout interchanges have been collected and synthesized in Table 3. As indicated, the three-level divided-traffic interchange has the best traffic conditions in terms of traffic separation, because it eliminates crossing conflicts between motor and nonmotor vehicles and only retains merging and diverging conflicts, which have a much lower accident severity. On the basis of many years of experience with interchange operation in the Beijing area, the roundabout interchange produces lower capacity and poorer safety than does the cloverleaf interchange.

In general, divided-traffic interchanges provide the most effective way to separate motorized and nonmotorized traffic regardless of cost. This type of interchange is the most efficient method of applying the concept of spatial separation of traffic and represents a unique contribution for interchange design by Chinese engineers.

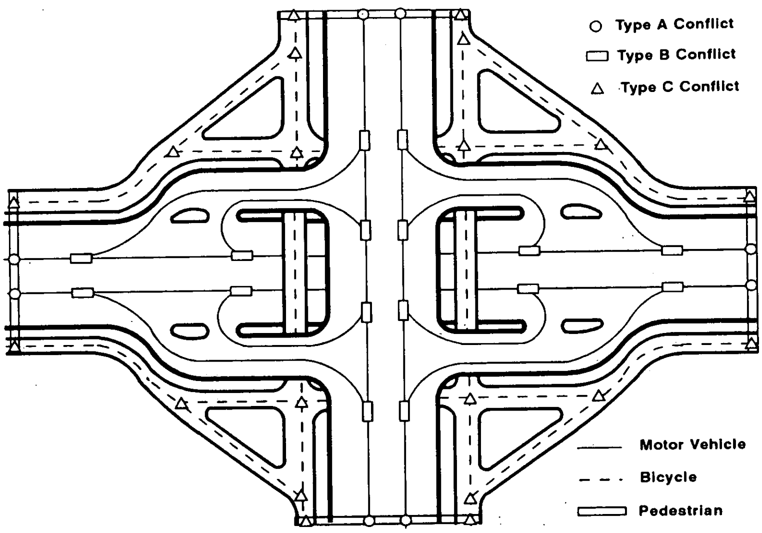

FIGURE 7 Cloverleaf interchange.

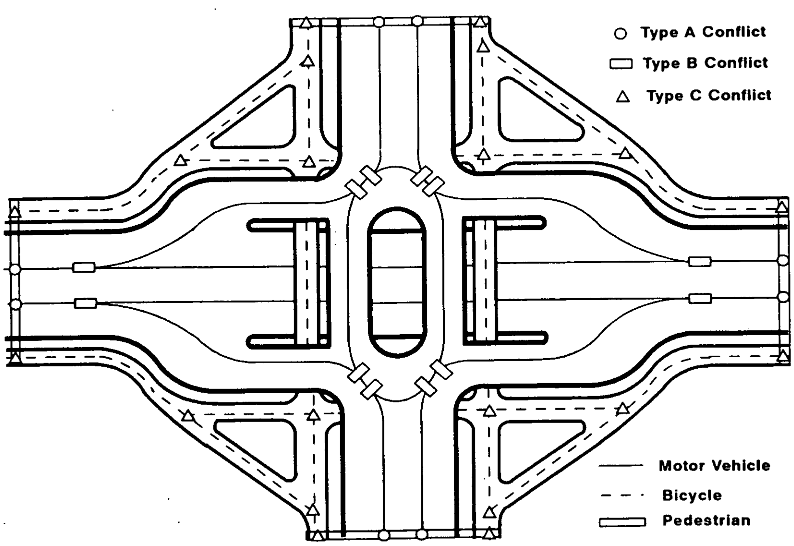

FIGURE 8 Roundabout interchange.

SUMMARY

The guiding principle of mixed-traffic operations is the segregation of motorized and nonmotorized traffic. For bicycle road allocation, an independent bicycle road network provides the most efficient and safe bicycle traffic environment. Traffic operation in at-grade intersections should use the temporal separation principle to reduce conflicts between the two types of vehicles to a minimum. The spatial separation principle can be successfully used in divided-traffic interchanges where motorized and nonmotorized traffic are separated into different physical levels, which eliminates the conflicts between through and left-turning traffic for both types of vehicles.

It is believed that more and more interchanges of all types will be built in many Chinese cities. There are a large number of intersections with congested mixed traffic that need to be improved. However, the current state of research for urban transport under mixed-traffic conditions is far behind the need. Therefore, it is necessary to stimulate more studies of the mixed-traffic transportation system. These studies should focus not only on policy and planning issues but also on detailed engineering and operation solutions.

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