Operational Analysis of Bicycle Interchanges in Beijing, China

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Beijing, a city with more than 10 million residents and nearly 8.4 million registered bicycles, has the highest bicycle ownership in China. In addition, Beijing has more than half a million motor vehicles, and that number is increasing at a rapid rate. To cope with this nonmotorized and motorized traffic, more than 50 interchanges with special facilities to accommodate bicycle traffic were built in Beijing during the last decade—more than half of all the interchanges in China are in Beijing. The operational experience of these bicycle interchanges is presented. The study indicates that a three-level cloverleaf interchange design with an exclusive bicycle facility can accommodate more than 28,000 bicycles per hour. A less sophisticated two-level rotary interchange can accommodate up to 21,500 bicycles per hour. Different adjustment factors were developed after an extensive study of existing bicycle operations in Beijing and other major Chinese cities. It is believed that the operational experience of these high-volume interchanges for nonmotorized transport will be useful to transportation engineers in other countries who are contemplating similar plans.

An interchange is a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways or highways on different levels (*1*). In the United States, most if not all interchanges are designed to accommodate motorized vehicles such as cars or trucks. However, in China, where automobile ownership is not as high and bicycles are relied on heavily for passenger transportation, bicycle traffic is an important consideration in interchange design.

During the last decade, as a result of the economic reform policy in China, the Chinese economy grew rapidly at a two-digit annual rate—nearly twice the international average. The economic boom in China brought more disposable income to its people, and the standard of living increased significantly. In the United States, people buy more and better cars when they have more disposable income; in China, people buy more and better bicycles. For instance, Beijing, the capital, has more than 10 million residents, and nearly 8.4 million bicycles were registered in 1990. Across the urban areas in China, bicycle ownership increased from one bicycle for every three persons in 1982 to one bicycle for every two persons in 1990.

With the bicycle dominating as the single most important mode of transportation for most Chinese urban residents, the ability to accommodate high volumes of bicycle traffic safely and efficiently through intersections becomes a difficult task for Chinese traffic engineers. The greatest efficiency, safety, and capacity are attained when the intersecting through-traffic lanes are separated in grades. The creation of bicycle interchanges has become a reality during the last decade. Bicycle interchange, a unique Chinese traffic engineering design, is defined in this paper as an interchange designed with a special facility to accommodate heavy bicycle traffic. The purpose of this paper is to present this unique bicycle interchange operation in Beijing, China.

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SYSTEMS

More than 60 percent of the residents of Beijing live in urban areas. The population density in the Beijing urban area is about 4,600 people per square kilometer, or 11,800 people per square mile. In addition to the 8.4 million bicycles, more than half a million motor vehicles were also registered in Beijing, as indicated in Table 1. The trend of bicycle ownership in Beijing is shown in Table 2 (*2*). In Beijing, the economic boom in the 1980s nearly tripled the number of registered bicycles in the city, from 2.88 million in 1980 to 8.3 million in 1990. On the basis of a study done in 1986, bicycles accounted for more than half of the passenger trips in Beijing (see Table 3).

To accommodate daily trips generated by nearly 9 million cars and bicycles, there were 51 interchanges in Beijing as of the end of 1991—approximately half of all the interchanges in China. Most of these interchanges are either cloverleaf, rotary, or trumpet-type. A two-level rotary interchange with separated bicycle lane design is shown in Figure 1. The dashed line indicates bicycle traffic, and the solid line represents motorized vehicular flow. A two-level cloverleaf interchange with separated bicycle lane design is shown in Figure 2. In these types of two-level interchange designs, the predominant flow of bicycle traffic is kept at ground level so climbing maneuvers can be eliminated completely. The design for underpasses is such that the minor bicycle flow can negotiate the smooth vertical grades without too much difficulty. *A Policy on Urban Street Design* specifies that the maximum vertical grade design for interchanges with mixed motorized and nonmotorized vehicles should not be more than 2.5 percent.

A three-level rotary interchange with separated bicycle lane design is shown in Figure 3. A three-level cloverleaf interchange with separated bicycle lane design is shown in Figure 4. As in the two-level interchange designs mentioned previously, the predominant flow of bicycle traffic is kept at ground level so climbing maneuvers can be eliminated completely. The design for underpasses is such that the minor bicycle flow can negotiate the smooth vertical grades without too much

TABLE 1 Traffic-Related Statistics for Beijing

	TOTAL	Urban	Suburban
Population (Millions)	10.012	6.142	3.570
Area (sq. km)	16,808	1,333	15,475
Roadway Mileage (km)	11,787	3,400	8,387
Vehicle ownership	500,000 (include 140,000 motorcycles)		

difficulty. In the three-level cloverleaf interchange, the middle level is reserved exclusively for bicycles. Some directional interchanges also have an exclusive level for bicycles. Except for these two, all interchanges have potential turning conflict points between motorized and nonmotorized vehicles.

OPERATIONS

A traffic study of 178 intersections/interchanges in Beijing was conducted in 1986 to collect the relevant bicycle volume data. The study indicated that there were 14 interchanges with peak-hour volume of 20,000 bicycles or more and 42 interchanges/intersections with peak-hour volume between 15,000 and 20,000 bicycles per hour. In addition, 50 intersections were found to have peak-hour volume of 10,000 bicycles or more.

Capacity at Two-Level Cloverleaf Interchange

The equation for calculating nonmotorized vehicle capacity at a two-level cloverleaf interchange design is as follows:

$$N = \sum_{i=1}^{4} N_{iR} + K\sum_{i=1}^{4} (N_{iL} + N_{iT})$$

where

N = number of nonmotorized vehicles per hour;
i = number of approaches, typically four;
N_{iR} = ith approach nonmotorized vehicular right-turn capacity;
K = revision factor depending on motorized vehicular volume (the higher the motorized vehicular volume, the smaller the K value, and vice versa);
N_{iL} = ith approach nonmotorized vehicular left-turn capacity; and
N_{iT} = ith approach nonmotorized vehicular through capacity.

Capacity at Three-Level Cloverleaf Interchange

The equation for calculating nonmotorized vehicle capacity at a three-level cloverleaf interchange design is as follows:

$$N = \sum_{i=1}^{4} n_i * 2{,}000$$

where n_i is the number of bicycle lanes at midlevel (or exclusive bicycle level) for the ith approach and other terms are as defined previously.

Capacity at Two-Level Rotary Interchange

The equation for calculating nonmotorized vehicle capacity at a two-level rotary interchange design is as follows:

$$N = \sum_{i=1}^{4} \mathrm{N}_{iR} + K_1\sum_{j=1}^{2} \mathrm{N}_{jT} + \mathrm{N}_{R1}$$

where

K_1 = revision factor for thoroughfare (underpass street) motorized traffic, depending on the right-turn motorized and nonmotorized vehicular volume (the higher the right-turn traffic volume, the smaller the K value, and vice versa);
N_{jT} = jth approach (underpass thoroughfare) nonmotorized vehicular through capacity; and
N_{R1} = ground-level (rotary) nonmotorized vehicle capacity.

Other terms are as defined previously.

Capacity at Three-Level Rotary Interchange

The equation for calculating nonmotorized vehicle capacity at a three-level rotary interchange design is as follows:

$$N = \sum_{i=1}^{4} N_{iR} + K_1\sum_{j=1}^{2} N_{jT} + N_{R2}$$

where N_{R2} is the midlevel (exclusive level) nonmotorized vehicular capacity (typically, $N_{R2} > N_{R1}$) and other terms are as defined previously.

Observed bicycle volumes at 10 major interchanges in Beijing during the morning peak hour (7:00 to 8:00 a.m.) are given in Table 4. Jiankuomen Interchange is a three-level cloverleaf interchange design. Bicycle capacities for the three different types of interchange are given in Table 5.

TABLE 2 Trend of Bicycle Ownership in Beijing

Trend of Bicycles						
Year	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**
Bikes (Millions)	2.88	3.21	3.77	4.29	4.88	5.51
Year	**1986**	**1987**	**1988**	**1989**	**1990**	
Bikes (Millions)	6.21	6.41	7.32	7.89	8.38	

TABLE 3 Modal Splits for Beijing (1986)

Mass Transit	24.32%
Bicycles	54.03%
Walk	13.76%
Private car	4.35%
Rental car	0.30%
Other	3.25%

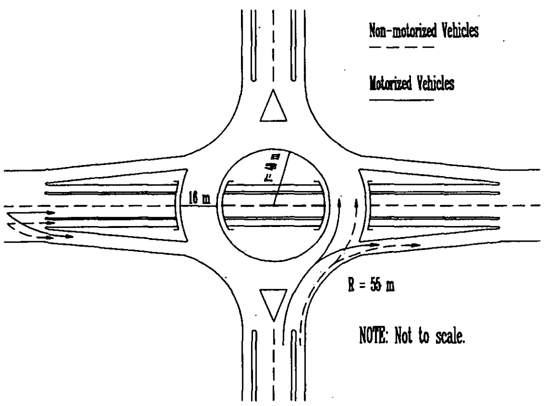

FIGURE 1 Two-level rotary interchange design.

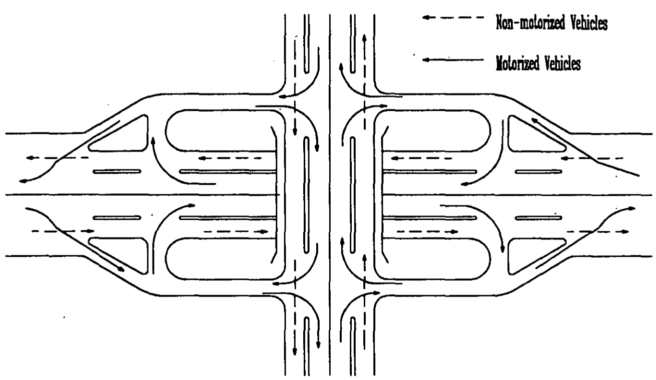

FIGURE 2 Two-level cloverleaf interchange design.

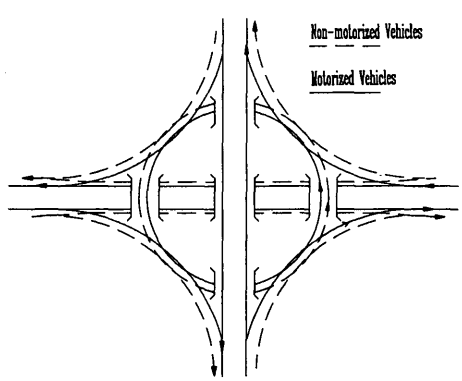

FIGURE 3 Three-level rotary interchange design.

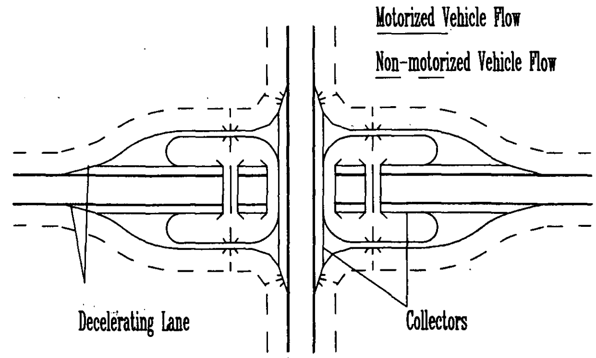

FIGURE 4 Three-level cloverleaf interchange design.

TABLE 4 Observed Bicycle Volumes During Morning Peak Hour (7:00 to 8:00 a.m.) at Major Interchanges in Beijing

Interchange	Volume (veh/peak hour)	Interchange	Volume (veh/peak hour)
Jiankuomen	28,391	Poochanmen	23,040
Chouyangmen	19,037	Tabeiyao	14,603
Tungchimen	22,724	Sanyuan	14,574
Andinmen	16,560	Anchen	11,728
Hsichimen	20,355	Marding	10,398

TABLE 5 Theoretical Bicycle Capacity at Three Interchanges in Beijing

Location of Interchange	Type of Interchange	Bicycle Capacity (vehicles/hour)
Fusingmen	2-level Cloverleaf	28,000
Jiankuomen	3-level Cloverleaf	28,300
Chouyangmen	2-level Rotary	21,500

Capacity Between Intersections

The observed vehicle headway for bicycle traffic at intersections/interchanges typically varies from 1.2 to 2.37 sec (i.e., the observed capacity per bicycle lane varies from 1,500 to 3,000 bicycles per hour). The average headway is about 1.8 sec (i.e., the average bicycle lane capacity is about 2,000 vehicles per hour per lane). On the basis of more than 130,000 observations in China, the headways in several major Chinese cities are given in Table 6. From the observed values in Table 6, bicycle lane capacity was converted to number of bicycles per hour per meter of roadway. Typical bicycle lane capacity in China is as follows: without raised island separating motorized and nonmotorized vehicles, $N = 0.51 * 3{,}600 = 1{,}836$ vehicles per hour per meter; with raised island separating motorized and nonmotorized vehicles, $N = 0.58 * 3{,}600 = 2{,}088$ vehicles per hour per meter.

If the delay at the signalized intersection is to be considered, the intersection adjustment factor based on the field obser-

TABLE 6 Observed Bicycle Volumes at Selected Major Chinese Cities

City	With R.I.	Width of Bike Lane (meters)	Observe Data	Speed km/hour	Volume/ 5 sec.	Volume/ sec./meter
Beijing	No	3.9	12,433	14.23	9.85	0.51
Beijing	Yes	5.5	8,678	16.28	17.91	0.61
Nanjing	Yes	3.3	1,551	14.28	9.39	0.57
Fuchou	Yes	6.5	3,096	13.44	14.5	0.45
Wusi	Yes	3.2	2,976	12.05	10.52	0.66
MEAN	**No**		**12,433**	**14.23**		**0.51**
MEAN	**Yes**		**16,300**	**14.01**		**0.58**

Notes: With R.I. = With Raised Island for separation of motorized and non-motorized traffic.
Speed km/hour = Observed bicycle speed in kilometers per hour.
Volume/5 sec. = Observed bicycle volume in five seconds.
Volume/sec./meter = Observed bicycle volume per second per meter of bicycle lane.

vations is 0.55 (i.e., the capacity has to be adjusted by multiplying by this factor). In addition, if the roadway characteristics are to be considered, the following roadway adjustment factors should be used: for major arterial streets, 0.8; for minor arterials and collectors, 0.9.

The effective bicycle lane capacity between signalized intersections can be calculated as follows:

	Capacity (vehicles per hour per meter)
Without raised island	
Major arterial streets	800
Minor arterials and collectors	900
With raised island	
Major arterial streets	900
Minor arterials and collectors	1,000

However, if interchanges are used, these capacities can easily be doubled. Therefore, along major streets where the intersecting traffic is heavy, the building of appropriate interchanges becomes cost-effective because the road-user costs due to delays at congested at-grade intersections are substantial. Travel time and accidents can be significantly reduced by the building of interchanges in urban areas. In general, interchanges require somewhat more total travel distance than direct crossings at grade. However, the added cost of the extra travel distance is less than the saving in cost brought about by the reduction in stopping and accident costs. In an effort to reduce delays at signalized intersections and improve traffic safety, nearly 50 interchanges in Beijing were built during the last decade. This significant investment has greatly improved traffic flow within the city.

SUMMARY

The bicycle plays a key role in Beijing since it accounts for more than 54 percent of passenger trips. Because of Beijing's ideal geographic and weather conditions, it is the transportation mode of choice for most Beijing residents. As the city with the highest bicycle ownership in China, the building of nearly 50 interchanges in Beijing during the last decade greatly improved the way traffic flows in Beijing. The three-level cloverleaf interchange with its exclusive bicycle level design has been a great success for bicyclists in Beijing. It is hoped that this unique Chinese experiment can benefit transportation engineers in other countries who are contemplating similar plans.

ACKNOWLEDGMENTS

The assistance of Jer-Wei Wu and Christopher Moore is acknowledged and appreciated.

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The statements and opinions expressed in this paper are the sole responsibility of the authors.