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Analysis of Problems in Pedestrian Signal Control at Urban Intersections

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Abstract: Pedestrian traffic is an important component of urban transportation system, accounting for a large proportion of total urban trips. However, during the rapid motorization and urbanization over the past 20 years in China, more attention has been paid on motorized vehicles, while pedestrians' requirements are quite often neglected. This paper analyzes the pedestrian-vehicle conflicts at urban intersections, and points out the deficiencies of pedestrian crossing facilities in planning, design, signal control, as well as related traffic laws and regulations. In terms of pedestrian clearance signal, this paper proposes to use flashing red in China. Finally, the paper proposes several signal control strategies that may be effective under certain conditions to reduce the conflicts between pedestrians and right- and left-turn vehicles. **DOI:** 10.13813/j.cn11-5141/u.2018.0511-en

Keywords: urban street intersection; pedestrian crossing; signal control; pedestrian clearance interval; reduce pedestrian-vehicle conflicts

0 Introduction

Pedestrian traffic, accounting for a large proportion of urban traffic, is a very important part of the urban transportation system, because it is not only an independent short-distance travel mode, but also a necessary travel mode connecting with other modes such as private vehicles and public transport. However, in the process of rapid urbanization in China for more than 20 years, much attention has been paid to the rapid growth of motorized traffic, while pedestrians' requirements are quite often neglected. Whether in the planning and design of urban traffic space, especially the planning and design of pedestrian crossing facilities, or in signal control, pedestrian traffic is far from getting the attention it deserves. This has become an important cause of traffic chaos at urban street intersections, which in turn has seriously affected the passage of motorized vehicles at intersections and even the order of urban road network and the smoothness of traffic flow [1].

In recent years, many cities in China have gradually improved the traffic environment of pedestrian crossing by "giving way to pedestrians at crosswalks", which has reduced the conflicts between pedestrians and motorized traffic to some extent. However, more topics should be put on the agenda, such as how to further analyze the characteristics of pedestrian traffic, understand pedestrian traffic from the psychological and behavioral perspectives, formulate reasonable regulations, and make human-oriented planning, design, management and control.

Based on years of observations, studies and analyses, this paper aims to provide some reference for traffic management departments, experts and engineers so that they can have more discussions and reach some consensus, and finally improve pedestrian safety and comfort in practice.

1 Typical problems of pedestrian crossing and pedestrians' safety perception

1.1 Main situations of pedestrian-vehicle traffic conflicts

Most urban intersections do not have exclusive pedestrian signal phases, and pedestrians generally cross streets in the phase for parallel motorized through traffic. With the increase in pedestrian and motorized vehicle volumes, more conflicts between pedestrians and vehicles occur, which becomes one of the main problems of pedestrian traffic at intersections (see Figure 1). These conflicts can be classified into three situations:

1) The pedestrian signal light turns red before the pedestrians who start to cross in the middle or at the end of the green time reach the other side of the street. Meanwhile, motorized vehicles from conflicting phases start to enter the intersection, and the pedestrians are blocked in the middle of the crosswalk;

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Figure 1 Conflicts between pedestrians and turning vehicles

2) When pedestrians enter the crosswalk at the beginning of the green time, motorized vehicles from the previous phase have not cleared the intersection, which causes conflicts with pedestrians on the crosswalk.

3) Pedestrians and turning vehicles interfere with each other

The causes why pedestrian-vehicle traffic conflicts at traditional signalized intersections lead to traffic chaos and inefficiency lie in as follows:

1) The traffic flow characteristics of pedestrians and motorized vehicles are different.

Pedestrians start fast but go slowly, and motorized vehicles have a loss of speed at start up but drive fast. The setting of traditional traffic signal phase does not fully consider the difference in traffic characteristics between pedestrians and motorized vehicles. It uses one signal phase for pedestrians, non-motorized vehicles and motorized vehicles, which fails to meet their different travel demands.

2) The motorized vehicles seldom yield to pedestrians.

In the conflict of pedestrians and motorized vehicles on a crosswalk, pedestrians are in a weak position and they often yield to motorized vehicles in order to avoid collisions. However, when the speeds of motorized vehicles are low, pedestrians are more likely to walk among vehicles, which leads to low efficiency and accidents.

3) The signal control measures are too simple.

To fit the characteristics of different traffic flows, proper signal control measures should be adopted flexibly. The traditional signal timing usually does not control right-turn motorized vehicles, which leads to serious conflicts between right-turn vehicles and pedestrians, especially in the vicinity of urban commercial districts where pedestrians and right-turn vehicle volumes are high. It also reduces the travel efficiency of right-turn vehicles to a large extent.

In addition, the pedestrian signal also has the following problems. The signal cycle or the pedestrian waiting time/red time is too long, which leads to an increase in illegal crossing behaviors. The definition of the flashing green signal is lacking in traffic laws, and the public does not have a correct understanding of the flashing green signal. The signal timing does not provide enough time for pedestrians and motorized vehicles to clear the intersection. The minimum green time requirements are often violated.

1.2 Survey results of pedestrians' safety perception when crossing a street

A survey of more than 1 000 pedestrians was conducted [2] at 32 crosswalks in Shanghai. The interviewed pedestrians were asked to rate their sense of security when crossing a street on a scale of 1 to 10 with 10 being the securest. According to the time point when pedestrians enter crosswalks, pedestrians can be divided into three categories: Green Walkers (GW) who enter crosswalks on a pedestrian green signal, Red Walkers (RW) who enter crosswalks on a pedestrian red signal, and Late Walkers (LW) who enter crosswalks on a pedestrian flashing green signal. The ratios of these three types of pedestrians are 8:3:1 in this survey. The results show that the safety perception of Late Walkers is mainly concentrated in 5–8 points, while the safety perception of Green Walkers and Red Walkers is mainly concentrated in 7–10 points (see Figure 2). Therefore, the Late Walkers have the worst safety perception. The probability cumulative curves show that Green Walkers and Red Walkers have similar safety perception.

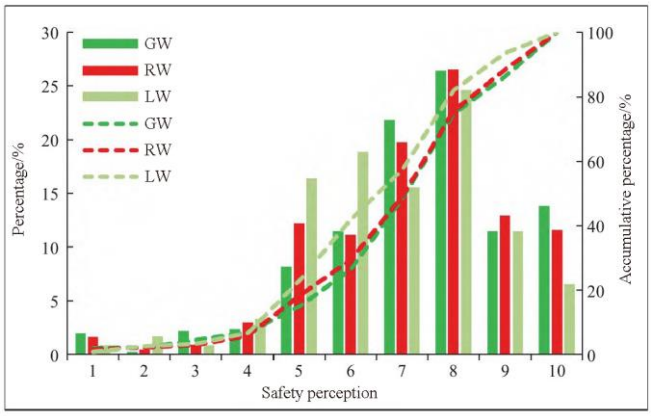


Figure 2 Safety perception of pedestrian crossing

Source: Reference [2].

During a green signal, pedestrians often walk in groups, which makes them feel safer than walk individually. However, after the first group of pedestrians pass the conflict point, the right-turn vehicles or non-motorized vehicles start to pass from the behind or from the front, which increases pedestrians' risks and reduces their safety perception. During a red signal, pedestrians will carefully observe the traffic environment before crossing the road, and they will only cross illegally on a red signal when they feel there are enough gaps in the vehicle flow and they feel safe to cross. Therefore, Red Walkers feel safer instead. The safety perception of Late Walkers is very low because the flashing green time is often insufficient. A more important reason is that pedestrians have great time pressure if they start to cross at the end of the flashing green time, and some unreasonable signal controls even lead to the conflicts of these

pedestrians and vehicles.

2 Regulations about pedestrian crossing in traffic laws and issues to be improved

2.1 Road traffic safety law of the People's Republic of China

Article 26—The traffic signal lamps shall be composed of red light, green light and amber light. The red light means prohibition of passage, and the green light means permission of passage, while the amber light means a warning.

Article 47—A motor vehicle shall slow down when passing a crosswalk; or shall stop to give way when a pedestrian is passing the crosswalk.

When a motor vehicle is passing a road without traffic signal and a pedestrian is crossing the road, it shall give way.

Article 61—Pedestrians shall walk inside the pavement, or walk on the right side of the road if there is no pavement.

Article 62—A pedestrian shall, if passing a road junction or crossing a road, walk the crosswalk or pedestrian crossing facilities; or shall pass a crosswalk with traffic signal lamps according to the indications of the traffic signal lamps; or shall pass a road junction without traffic signal lamps or crosswalk, or cross a road at the road section without pedestrian crossing facilities after making sure that it is safe.

2.2 Regulation on the Implementation of the Road Traffic Safety Law of the People's Republic of China

Article 38—The motor vehicle signal lamps and non-motor vehicle signal lamps may give signals by

1) green light, which means that vehicles are allowed to proceed, but the making-a-turn vehicles shall not interfere with the movement of the straight-moving vehicles and pedestrians that are allowed to pass;

2) yellow light, which means that the vehicles across the stop line may keep on driving;

3) red light, which means that vehicles are prohibited from passing.

With regard to a cross without non-motor-vehicle signal lamps and pedestrian crosswalk signal lamps, the non-motor vehicles and pedestrians shall pass the cross by following the motor vehicle signal light.

At red light, the right-turn vehicles may proceed without interfering with the movement of the vehicles and pedestrians that are allowed to pass.

Article 39—The pedestrian crosswalk signal lamps may give signals by

green light, which means that the pedestrians are allowed to pass the crosswalk;

red light, which means that the pedestrians are prohibited from entering crosswalk, but those have entered it may go on passing or wait on the midline of the road.

2.3 Issues to be addressed to improve current traffic laws

The above laws and regulations define the basic right of way between pedestrians crossing the street and motorized vehicles, but pedestrian signals commonly used in cities of China do not match these laws and regulations. The *Regulation on the Implementation of the Road Traffic Safety Law of the People's Republic of China* only defines the green and red signals for pedestrians, but not the flashing green signal. Based on the statement of "red light, which means that the pedestrians are prohibited from entering crosswalk, but those have entered it may go on passing or wait on the midline of the road", a red light should be used for the pedestrian clearance time. The source of the flashing green signal of pedestrians was apparently before the promulgation of *Road Traffic Safety Law of the People's Republic of China*. The *Road Traffic Management Regulations of the People's Republic of China*, promulgated by the State Council on March 9, 1988, regulates:

Article 10—Command signal light:

1) green light, which means that vehicles and pedestrians are allowed to proceed, but the making-a-turn vehicles shall not interfere with the movement of the straight-moving vehicles and pedestrians that are allowed to pass;

2) yellow light, which means that vehicles and pedestrians are prohibited from passing, but vehicles which have passed the stop line and pedestrians who have entered crosswalk may go on passing;

3) red light, which means that vehicles and pedestrians are prohibited from passing.

Article 12—The pedestrian crosswalk signal lamps:

1) green light, which means that pedestrians are allowed to proceed;

2) flashing green light, which means that the pedestrians are prohibited from entering crosswalk, but those have entered it may go on passing or wait on the midline of the road;

3) red light, which means that the pedestrians are prohibited from entering crosswalk.

These regulations should have been abolished after the promulgation of *Road Traffic Safety Law of the People's Republic of China*. However, the reality is that they are abolished but the implementation of these regulations is not stopped. Additionally, there is no definition of the pedestrian transition signal in the newly promulgated *Road Traffic Safety Law of the People's Republic of China* and the *Regulation on the Implementation of the Road Traffic Safety Law of the People's Republic of China*, which are currently in effect. Therefore, the flashing green signal commonly used in practice is not defined in current traffic laws or regulations, so almost no one can understand this signal and the pedestrian flashing green signal is essentially ineffective.

According to the above analysis, the clearance signal for pedestrian crossing at urban intersections in China needs scientific and reasonable regulations urgently.

3 Suggestions on the pedestrian clearance signal

3.1 Pedestrian clearance signal and clearance time in foreign countries

Developed countries such as European countries and the United States set a long enough pedestrian clearance time using the pedestrian transition signal to ensure the safety of pedestrian crossing. The United States, the United Kingdom, and Australia use flashing red signals. Germany uses steady red signals, and some cities in Switzerland use yellow signals, as shown in Table 1. None of the developed countries use flashing green signals for pedestrian clearance.

3.2 Suggestion to use flashing red as the pedestrian clearance signal in China

From the psychological analysis, people have been educated to "stop on red and go on green". Pedestrians' basic understanding of the flashing green signal is to continue, not to stop. Most pedestrians will enter the crosswalk from the sidewalk even after the pedestrian green signal starts flashing, so it is difficult to clear pedestrians at intersections with the flashing green signal. Most developed countries use flashing red as the clearance signal, which is worth learning, because the perception of red is to stop. *Code for Signal Control of Intersections on Urban Roads* (DB 34/T 2423—2015) in Anhui Province, China, proposed the use of flashing red for pedestrian clearance for the first time [3], which should be promoted nationwide.

The use of flashing red for pedestrian clearance prohibits pedestrians who have not entered the crosswalk from crossing, which is easy for pedestrians to understand and accept and is also easy to enforce. Once a dispute or even an accident occurs, it is easy to define their respective responsibilities. This improvement seems to be minor, but can greatly improve the order of pedestrian traffic at urban intersections, and will have a very big effect on improving the status of urban traffic in China. In addition, this improvement basically requires no additional investment in facilities, so it can achieve more with less.

4 Strategies to solve pedestrian-vehicle conflicts at urban intersections

4.1 Solutions to conflicts between right-turn vehicles and pedestrians

The conflicts between right-turn vehicles and pedestrians are more serious under certain conditions. However, according to the actual situation of the intersection, adopting a reasonable signal control strategy can alleviate or even solve this thorny problem.

4.1.1 Conflict types and the analysis of right-turn vehicle passing time

There are three main types of conflicts between pedestrians and right-turn vehicles [4]. The first type occurs when right-turn vehicles and pedestrians are released in the same phase, and then right-turn vehicles will conflict with pedestrians. As shown in Figure 3, at the south approach of the intersection, right-turn vehicles conflict with the pedestrians walking in the south–north direction. The second type is the conflict between the pedestrians who start to cross the street at the end of the green time or pedestrians with slower pace and the right-turn vehicles in the next phase. As shown in Figure 3, at the east approach, right-turn vehicles conflict with the pedestrians crossing in the south–north direction. The third type occurs when vehicles make a permissive right turn on a red light, and right-turn vehicles conflict with the pedestrians crossing the street. As shown in Figure 3, at the west approach, right-turn vehicles conflict with the pedestrians crossing in the south–north direction.

Table 1 Definition and value range of pedestrian clearance intervals in western countries

Country	Pedestrian clearance signal	Pedestrian clearance time	Pedestrian walking speed used for clearance timing
The United States	Flashing red	Ensure that pedestrians can complete crossing or arrive at the refuge island	3.5 feet•s^{-1} (1.07m•s^{-1}) in general, but at locations with pedestrian push buttons, it can be 4 feet•s^{-1} (1.22m•s^{-1})
The United Kingdom	Flashing red	5–35 s	1.2 m·s^{-1}
Australia	Flashing red	Ensure that pedestrians can complete crossing or arrive at the refuge island	1.2 m·s^{-1}
Switzerland	Yellow	Ensure that pedestrians can complete crossing or arrive at the refuge island	1.2 m·s^{-1}
Germany	Steady red	Ensure that pedestrians can complete crossing or arrive at the refuge island	1.2~1.5 m·s^{-1}

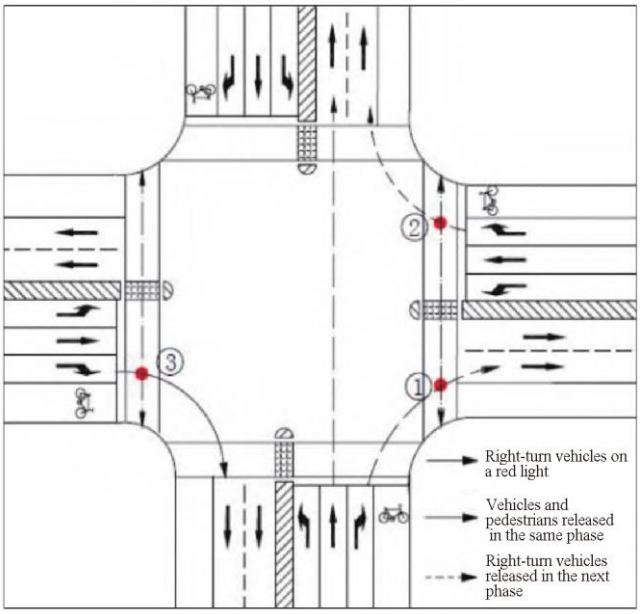


Figure 3 Conflict types between pedestrians and right-turn vehicles

Source: Reference [4].

The second type of conflict can be solved by setting enough time between green signals or by constructing refuge islands. The other two types of conflicts should be treated differently for intersections with four-phase control and non-four-phase control. For intersections with the ordinary four-phase signal control and with a refuge island in the middle of the crosswalk, right-turn vehicles can pass in phases for through vehicles, as well as in the two phases for left-turn vehicles. In this case, the passing time is relatively sufficient, so pedestrians and vehicles can be completely separated. However, for intersections with the normal two-phase signal control, no matter in which phase the right-turn vehicles are released, they will conflict with pedestrians. Other than setting an exclusive pedestrian phase, it is difficult to separate vehicles and pedestrians.

4.1.2 The strategy of "right-turn vehicles shall yield to pedestrians"

When the pedestrian green signal starts, right-turn vehicles must yield to pedestrians before they can pass. This control strategy allows vehicles to use acceptable gap among pedestrians to cross the crosswalk. It is only applicable when pedestrian volume and right-turn vehicle volume are low. The implementation of this control strategy requires a matching traffic design. As shown in Figure 4, a waiting space is reserved for right-turn vehicles at the corner of the intersection, so right-turn vehicles waiting to turn right do not block the vehicles behind them. In Figure 4, l should not be less than 6 m [5].

In order to ensure pedestrian safety while taking into account the efficiency of intersections, it is recommended to use appropriate signs or signals when implementing the

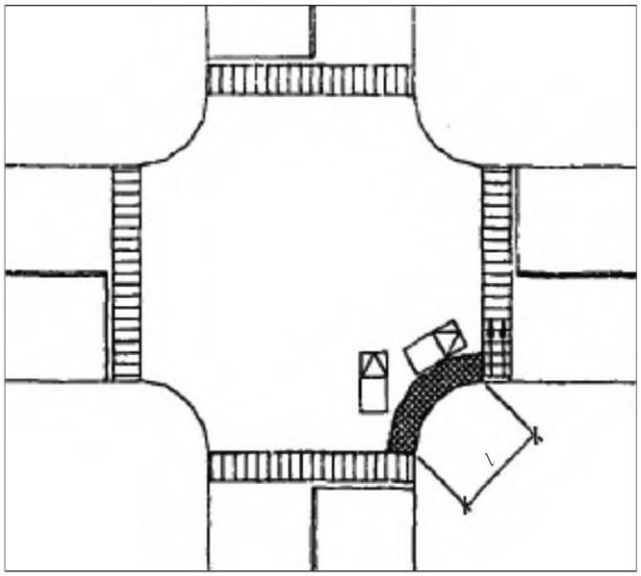


Figure 4 Yield space of right-turn vehicles

Source: Reference [5].

strategy of "right-turn vehicles shall yield to pedestrians". For example, a flashing yellow arrow signal can be used to alert right-turn vehicles to yield to pedestrians, and signs such as "YIELD TO PEDESTRIANS" can be used to indicate that pedestrians have priority.

4.1.3 The strategy to signalize the right-turn movement

1) The red arrow signal to control right-turn vehicles

A right-turn arrow light that only shows red or yellow can be installed next to the round signal lights for through vehicles (see Figure 5). When the right-turn red light is on, right-turn vehicles are prohibited from turning right. In other intervals, the right-turn arrow light is dark, and right-turn vehicles may proceed following the corresponding traffic rules if they would not affect other traffic flows. The yellow arrow signal should be used as a transition between allowing passage and prohibiting passage.

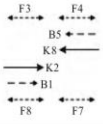
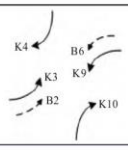
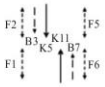
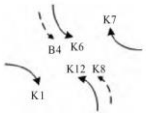
This control strategy can control traffic flows flexibly based on the volumes of right-turn vehicles, pedestrians and non-motorized vehicles and their conflict situations. It can effectively avoid the conflicts between right-turn vehicles and non-motorized vehicles and pedestrians, and can also provide enough time for right-turn vehicles to find gaps and turn right.

(2) The arrow light specifically for right-turn vehicles

A traffic signal head with red, yellow and green arrow lights (see Figure 6) can be used to control right-turn vehicles. Right-turn vehicles are allowed to pass only when the green arrow light is on. When the red arrow light is on, right-turn vehicles are prohibited from proceeding. Since right-turn vehicles absolutely have the right of way when the green arrow is on, this type of control completely separates right-turn vehicles from pedestrians and non-motorized vehicles in time.

Figure 5 Arrow signal for right-turn vehicles (red and yellow arrow only)

Figure 6 Arrow signal for right-turn vehicles

Phase number	1	2	3	4
Logical light group	K2, K8 B1, B5 F3, F4, F7, F8	K3, K4, K9, K10 B2, B6	K5, K11 B3, B7 F1, F2, F5, F6	K1, K6, K7, K12 B4, B8
Phase design				

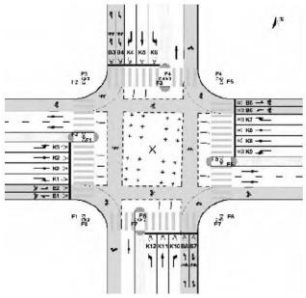


Figure 7 Phase of arrow signal for right-turn vehicles

This control strategy clarifies the right of way for right-turn vehicles and completely avoids the conflict between right-turn vehicles and other traffic flows. It is more effective when the volumes of right-turn vehicles, pedestrians and non-motorized vehicles are high. This strategy will improve the operational efficiency of intersections and the safety of pedestrians and non-motorized vehicles. It is only applicable to the four-phase control mode as shown in Figure 7.

(3) The leading pedestrian signal

When the conflict between pedestrians and right-turn vehicles in the same phase is not very serious, a leading pedestrian signal can be implemented. In general, pedestrians waiting to cross the street during the red light interval accounts for a large proportion of pedestrians crossing the street. With the leading pedestrian signal, these pedestrians can arrive at the conflict point before right-turn vehicles, and it is easier for right-turn vehicles to notice pedestrians on the crosswalk and take appropriate actions to yield to them.

4.2 Solutions to the conflict between left-turn vehicles and pedestrians

Compared with right-turn vehicles, conflicts between pedestrians and left-turn vehicles may be more serious under certain circumstances. The reason is that left-turn vehicles are far away from pedestrians when they start to enter the intersection, and their positions and angles are difficult to be observed. It is often difficult for pedestrians to notice and predict left-turn vehicles in time. When there is no protected phase for left-turn vehicles, the traffic situation faced by left-turn vehicle drivers is more complicated. After crossing the through vehicle flow, left-turn vehicles will often speed up and neglect pedestrians. At a larger intersection, the left-turn radius is larger and left-turn vehicles have higher speeds.

At typical four-phase intersections, the conflict between pedestrians and left-turn vehicles is easy to be separated by signalization. Therefore, this paper focuses on the method to reduce the conflict between pedestrians and left-turn vehicles at two-phase and three-phase intersections.

4.2.1 Solution to the conflict between pedestrians and left-turn vehicles at two-phase intersections

Generally, at two-phase intersections, the volume of motorized vehicles is relatively low, and pedestrians and non-motorized vehicles become the main part of the traffic. The conflict among left-turn vehicles, pedestrians and non-motorized vehicles is a major safety hazard for pedestrian crossing. Therefore, it is the first priority to ensure the safety and efficiency of pedestrians and non-motorized vehicles crossing the street when designing street intersections. An integrated design method should be adopted to integrate pedestrians and non-motorized vehicles, which should be treated together as a part of the non-motorized transportation system.

1) When the traffic volumes of motorized vehicles and pedestrians are both low, the pedestrian phase can start before or after the start of the motorized vehicle phase.

The essence of this method is to properly stagger the release time of the phase for left-turn vehicles and the phase for pedestrians and non-motorized vehicles to mitigate conflicts. When the pedestrian phase starts late, it should be ensured that left-turn vehicles can pass the conflict point before pedestrians who are closest to the conflict point. When the pedestrian phase starts early, it should be ensured that pedestrians who are farthest from the conflict point can pass the conflict point before left-turn vehicles. These two strategies are applicable when left-turn vehicles tend to pass through at the beginning and at the end of the green interval, respectively. Detailed traffic conditions should be considered to determine which one is better.

2) At a two-phase intersection with low motorized vehicle volume and high pedestrian volume, an exclusive pedestrian phase can be added between the phases for motorized vehicles to ensure pedestrian crossing.

An exclusive pedestrian phase can be added between the phases for motorized vehicles to serve both pedestrians and non-motorized vehicles, and the phase for motorized vehicles can stop early to ensure the demand of pedestrian crossing. The phase sequence diagram is shown in Figure 8. This control strategy will greatly reduce the traffic capacity of motorized vehicles, which is only applicable where the motorized vehicle volume is low and the pedestrian volume is high. With this control strategy, diagonal crosswalks and corresponding pedestrian signals can be considered based on detailed traffic situations.

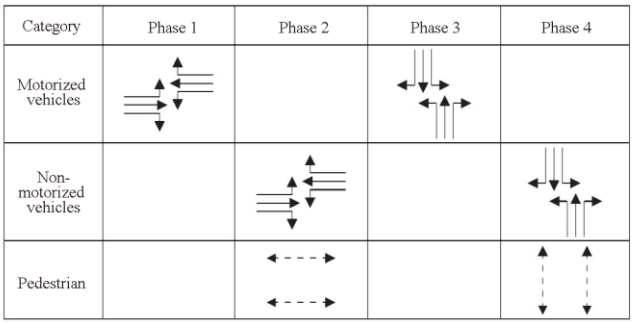
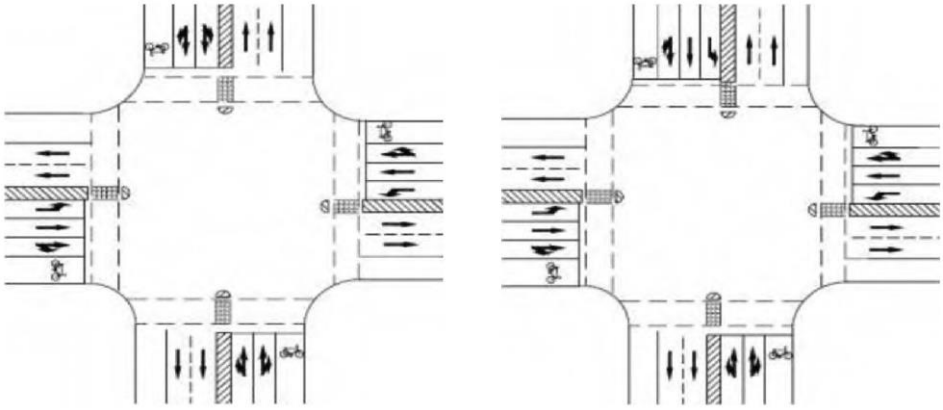


Figure 8 Phase sequence design to reduce conflicts between pedestrians and left-turn vehicles

The two methods described above must meet the requirement of the minimum green time and the intergreen time, especially the intergreen time between the motorized vehicle phase and the pedestrian phase. Pedestrian signal timing should meet the requirement of the minimum green time and the clearance time, and the red interval should not be longer than the acceptable waiting time.

4.2.2 Solution to the conflict between pedestrians and left-turn vehicles at three-phase intersections

The two channelization options usually used for three-phase intersections are shown in Figure 9. When the through and left-turn phase at the east and the west approaches release vehicles separately, left-turn vehicles will not conflict with pedestrians. If both the south and the north approach have no left-turn only lanes (see Figure 9a), the pedestrian phase should start earlier so that the pedestrians stopped by the red light (accounting for a large portion of pedestrian flows) can pass the conflict point before left-turn vehicles. If there is a left-turn only lane (see Figure 9b), the



a South and north entrance without left-turning traffic lane　　b Only south entrance without left-turning traffic lane

Figure 9 Channelized intersection design option for three phase signals

left-turn and through phase at the north approach should start earlier. After most of the queued left-turn vehicles pass through the intersection, the left-turn phase at the north approach should stop. Then the motorized vehicles at the south approach, the through vehicles at the north approach, and pedestrians traveling in the south–north direction should be allowed to pass the intersection. At that moment, the conflict between pedestrians and the left-turn vehicles from the south approach still exists, but it is relatively weak. The traffic sign of "LEFT TURN YIELD TO PEDESTRIANS" can be used to warn left-turn vehicles to slow down or even stop to yield to pedestrians.

5 Conclusions

Pedestrian traffic seems like a small problem, but it involves everyone, every region, and even every trip. The frequent conflicts among motorized vehicles, pedestrians and non-motorized vehicles are the main reasons for poor traffic order, frequent accidents and low efficiency of urban street intersections in China. The specific influencing factors are numerous, and the situation varies greatly from place to place. Therefore, it is difficult to find one measure to fit all situations. Based on observations, analyses and practical attempts, this paper suggests to use flashing red as the pedestrian clearance signal. Regarding conflicts between pedestrians and turning vehicles, some signal control strategies that may be effective under certain conditions are proposed, which provide some ideas to the analysis and solution of the problems. At the same time, it is hoped that this research would attract attentions and discussions so that in the field of theoretical research and practice, practical and effective methods could be proposed to guide practical applications in various situations and conditions.

How pedestrian traffic is treated in a city reflects the degree of urban civilization. In the process of rapid urbanization and motorization, Chinese cities have a lot of pedestrian traffic problems, and now it is time to solve them. A safe and comfortable pedestrian traffic environment helps improve overall urban traffic safety, order and efficiency, and enhance urban transportation civilization.

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