Traffic flow interaction mechanism and Facility design at signalized intersections

HeKun\textsuperscript{1,a}, Zhenzhou Yuan\textsuperscript{1,b*}

\textsuperscript{1}Beijing Jiaotong University, School of Traffic and Transportation, Beijing, China
\textsuperscript{a}e-mail: 19120819@bjtu.edu.cn, \textsuperscript{*}Corresponding author: bzyuan@bjtu.edu.cn

Abstract. In China’s urban traffic, mixed traffic is a basic feature. Especially at urban intersections, the phenomenon of non-mixed traffic is more serious. At many intersections in our country, due to the different characteristics of traffic flow, there are various interactions between motor vehicle traffic flow and non-motor vehicle traffic flow. This paper analyzes the interaction principle between motor vehicles and non-motor vehicles at intersections. It is found that the expansion characteristics of non-motor vehicles at intersections have a certain influence on the straight-going non-motor vehicles, and the interference degree is defined as an index to measure the influence of non-motor vehicle on motor vehicle. Finally, the paper proposes corresponding solutions to improve the safety and operation efficiency of intersections.

1. Introduction

With the improvement of China’s economic development level, China’s social demand for transportation is increasing day by day. In recent years, the bike-sharing industry has developed rapidly in all parts of China, and non-motor vehicles have become a major mode of urban transportation. With the increase of urban motor vehicle and non-motor vehicle traffic, the competition for resources between different types of traffic flows in urban traffic becomes increasingly serious, which leads to traffic disorder at intersections and the decrease of safety at intersections. Therefore, the traffic control and traffic design of urban intersections become the key and difficult problems.

In the study of motor vehicle and non-motor vehicle traffic flows, Yang Peikun, Peng Rui et al. have extensively studied various basic characteristics of non-motor vehicle traffic flows on road sections [1-3]. Wu Jianping et al. studied the micro-crossing behavior model of non-motor vehicles at intersections [4]. In his doctoral thesis, Winai Raksuntorn builds a simulation model of motor vehicle and non-motor vehicle mixing based on two different intersections, and simulates the non-motor vehicle behavior at intersections[5]. Lu Huapu and Shi Qixin studied and analyzed the defects of the traditional design methods of urban intersections, and established the micro-simulation system of urban signalized intersections based on the vehicle following model, and qualitatively analyzed the mechanism of traffic congestion in Beijing and other large cities by comparing with Tokyo in Japan [6-7]. Based on the situation of signalized intersections, Jing Chunguang and Wang Dianhai qualitatively analyzed the influencing factors of urban signals on the traffic capacity of intersections, and put forward solutions such as setting the left-turn phase of non-motor vehicles[8]. This paper mainly analyzes the interaction mechanism between motor vehicles and non-motor vehicles to guide the traffic control and design of urban intersections, so as to improve the traffic efficiency and safety of intersections.

2. data

The data cited in the article comes from surveys. The investigation took place at the intersection of
Huizhou Avenue and Wuhu Road and the survey was conducted during the morning peak period from 6:00 to 8:00, and during the normal peak period from 9:00 to 10:00.

The intersection’s east and west approach roads consist of two straight lanes, a left turn lane and a right turn lane. The east exit and the west exit consist of two roads. The intersection’s south and north approach roads consist of three straight lanes, one left turn lane and one right turn lane. The south exit and the north exit are composed of three roads.

The main objects of the investigation are the traffic flow, traffic composition and timing scheme of signal control of motor and non-motor vehicles.

3. Methodology

3.1. The properties of agglomeration, dissipation, and expansion

At the signalized intersection, non-motor vehicles arriving at the intersection during the red light will queue up. At the beginning of the green light, they will start to pass through the intersection in groups, showing an obvious phenomenon of agglomeration and dissipation.

Through investigation and literature reading, it is found that there are two clustering characteristics of non-motor vehicles at intersections: One, the number of non-motor vehicles at intersections is small during the flat peak period. Non-motorized vehicles will slow down in advance and eventually stop in front of the stop line, rarely crossing the stop line, which has little impact on right-turning vehicles. Two, there are more non-motor vehicles at the intersection during peak hours. When the red light starts, non-motor vehicles arriving at the intersection wait in front of the stop line. A small number of non-motor vehicles will pass through the stop line. With the increase of the number of non-motor vehicles, a group of non-motor vehicles will gradually form, and the rear non-motor vehicles will continue to look for gaps. Finally, non-motor vehicles occupy the position of the right-turning motor vehicle driving area, causing serious traffic conflicts and greatly reducing the capacity of intersections.

During a red light at a signalized intersection, non-motor vehicles line up behind the stop line, forming a dense swarm of non-motor vehicles. When the green light turns on, the cars in line start and accelerate out of the stop line. The lateral spacing of non-motor vehicle queuing is very small. After driving, in order to ensure safety, the requirement of lateral spacing increases, which is the expansion phenomenon of queuing vehicles. The expanding non-motor vehicle traffic encroachment on part of the motor vehicle lanes has a great impact on the straight-going motor vehicles, and the safety of non-motor vehicle traffic cannot be guaranteed.

![Figure 1: Expansive properties](image-url)
3.2. Expansion width and number of expanded non-motor vehicles

Non-motor vehicles will encroach on the space resources on both sides of the non-motorized lane when they run at the beginning of the green light at the intersection. The expansion width is defined as the extension width of one side of the non-motorized lane.

The expansion width can be calculated from the following formula:

\[ w_p = \frac{DN - w}{2} \]  

(1)

Where:
- \( w_p \) is the expansion width of non-motor vehicle;
- \( w \) is the width of non-motorized lane;
- \( D \) is the width of the road occupied by non-motor vehicles during running, usually 1.012m;
- \( N \) is the horizontal parallel number when a non-motor vehicle is running.

Ideally, the horizontal parallel quantity of non-motor vehicles in operation is equal to that of non-motor vehicles in the inlet queue [9].

\[ N = \rho wl \]  

(2)

Where: \( \rho \) is the queuing density of non-motor vehicles at the entrance of the intersection (vehicles/m²); \( l \) is the length of a lane occupied by a non-motor vehicle while queuing at an intersection.

The number of non-motor vehicles within the expansion width can be calculated from the following formula:

\[ Q_p = \frac{S_3}{S_1 + S_2 + S_3} \cdot q_c = \frac{w_p - w_b}{DN} \cdot q_c \]  

(3)

Where: \( Q_p \) is the number of non-motor vehicles in the expansion area; \( S_1, S_2, S_3 \) are the area of the region \( D_1, D_2, D_3 \); \( w_b \) is the width of the separation belt between motor vehicles and non-motor vehicles; \( q_c \) is the number of non-motor vehicles queuing (vehicles/cycle).

3.3. The degree of interference

In the safety evaluation of urban intersection, traffic conflict is defined as: under the condition of the observable, two or more than two road users at the same time and space close to each other, if one party take abnormal traffic behavior, like suddenly stop, unless the other party also take evasive action accordingly, otherwise, will be a collision. This phenomenon is called traffic conflict.

From the above definition, it can be seen that traffic conflict technology is mainly applied to road traffic safety. In practice, the motor vehicles and non-motor vehicles at the intersection are in the state of mutual influence in most cases, rather than collision, resulting in traffic accidents. Therefore, it is
more accurate to use the word "interference" to describe the interaction between motor vehicles and non-motor vehicles at intersections. Both motorized and non-motorized traffic flows are understood as a regular curve, and the intersection of curves is considered as a point of conflict. However, in practice, the traffic flow tends to be multi-flow in parallel, especially under the condition of mixed traffic of motor vehicles and non-motor vehicles, the traffic flow has become a traffic section composed of several irregular moving traffic flows, and the resulting interference and conflict are often an area. Taking the mutual interference between right-turning motor vehicles and straight-going non-motor vehicles as an example, the area enclosed by right-turning motor vehicle lane extension line, parking line and intersection curb arc is defined as the interference area as shown in FIG.3. When right-turning motor vehicles and straight-going non-motor vehicles enter this area, they begin to be interfered with each other, and the interference ends when they leave the interference area.

![Figure 3: Interference region](image)

After the green light at the signal intersection, there is a certain disturbance between right-turning motor vehicles and straight-going non-motor vehicles, which causes traffic delay. The degree of interference is defined to evaluate the phenomenon of interference.

$$k = \frac{t_d - t_n}{t_n}$$

Where: $k$ is the degree of interference; $t_d$ is the passage time in the case of interference; $t_n$ is the passage time without interference.

4. Results AND Discussion

4.1. The interaction between straight motor vehicle and straight non-motor vehicle

By analyzing the average time headway of each vehicle and the queue position when the vehicle headway reaches saturation after the green light is turned on at different periods of time at the intersection, we can know the influence degree of non-motor traffic flow on motor traffic flow. The following table shows the average headway and queue positions of motor vehicles at the intersection of Huizhou Avenue and Wuhu Road in Hefei at different time periods.
Figure 4: Average time headway in different time periods

It can be seen from the figure 4 that the flat peak period ends at the red light, and after the green light starts, the headway of the straight-going motor vehicle is about 2 seconds when the fifth motor vehicle reaches saturation. In peak hours, the straight-going motor vehicles reach saturation headway around the eighth motor vehicle, and the queuing position is extended when the traffic flow reaches saturation. The expansion characteristics of non-motor vehicles have significant interference effect on the operation of motor vehicles.

From formula (3), it can be seen that with the increase of non-motor vehicle flow, the more non-motor vehicles in the expansion width are, the greater the disturbance to the straight-going motor vehicles will be. The larger the width of the separation belt between motor vehicles and non-motor vehicles, the less the number of non-motor vehicles in the expansion width, and the less the interference to the straight-going motor vehicles.

4.2. The interaction between right-turning motor vehicle and straight-going non-motor vehicle

The following table shows the degree of interference between right-turning motor vehicles and non-motor vehicles at the intersection of Huizhou Avenue and Wuhu Road.

Table 1 mainly shows the relationship among right-turning motor vehicle speed, travel time and interference degree under different non-motor vehicle interference environments. From the table we can see that there is a significant difference in the influence of non-motor vehicle interference on the speed of right-turning motor vehicles. When a group of straight non-motor vehicles pass through the intersection, the disturbance degree to right-turning motor vehicles reaches 2.25, and the

| The traffic environment | The degree of interference | The average velocity (m/s) | The passage of time (s) |
|-------------------------|---------------------------|---------------------------|------------------------|
| No interference         | 0                         | 3.198                     | 4                      |
| Single non-motor vehicle interference | 0.75                     | 1.924                     | 7                      |
| Non-motor vehicle group interference | 2.25                     | 1.091                     | 13                     |

Table 2: Degree of disturbance caused by right-turning motor vehicle to non-motor vehicle

| The traffic environment | The degree of interference | The average velocity (m/s) | The passage of time (s) |
|-------------------------|---------------------------|---------------------------|------------------------|
| Single non-motor vehicle | Non-interference by motor vehicle | 0                         | 3.21                   | 2.98                   |
average speed of right-turning motor vehicles is 1.091m/s. When there are fewer non-motor vehicles going straight, the gap between non-motor vehicles is larger and the impact on right-turning vehicles is much smaller. At this time, the disturbance degree is 0.75 and the average speed is 1.924m/s. When the straight non-motor vehicle is at the red light, the right-turn motor vehicle is free to pass through the interference zone, and the average speed of the right-turn motor vehicle is the maximum.

Under different interference conditions, the time for right-turning non-motor vehicles to pass through the intersection is also different. The delay caused by non-motor vehicles group for right-turning motor vehicles is the largest, followed by a single non-motor vehicle. When there is no interference, the time for right-turning motor vehicles to pass through the intersection is the shortest and the delay is the smallest.

Table 2 shows the interference of right-turning motor vehicles on straight-going non-motor vehicles. Right-turning motor vehicles have different effects on a single non-motor vehicle and a group of motor vehicles. In the case of no interference, the speed of a single non-motor vehicle is greater than that of a group of bicycles, because there is mutual interference between non-motor vehicle groups, which hinders the operation of non-motor vehicles. In the case of interference, the interference degree of a single non-motor vehicle is 0.49, but greater than that of a group of non-motor vehicles is 0.19. This is because a group of non-motor vehicles usually occurs at the beginning of the green light. At this time, straight lines have the priority, and right-turn vehicles will mostly choose to avoid the passage of non-motor vehicles. At the middle and late stage of the green light, the number of non-motor vehicles is relatively small. At this time, right-turning motor vehicles will choose the appropriate clearance to pass through the interference zone, and the interference to non-motor vehicles is greater than that to the non-motor vehicles.

5. Conclusions
From the analysis in the previous section, it can be seen that the expansion effect of straight-going non-motor vehicles hinders the operation of straight-going non-motor vehicles, resulting in low efficiency and some potential safety hazards at the intersection.

It is necessary to design the separation zone between motor vehicle and non-motor vehicle at the intersection in view of the expansion characteristic of straight-going non-motor vehicle. It can be seen from formula (3) that a certain width of separation belt can effectively reduce the influence of non-motor vehicles on motor vehicles. When setting space belt, we should do a good job of traffic flow survey, so as to choose a reasonable width of space belt. In addition, highlighting non-motorized lanes inside intersections helps cyclists better follow the rules of the road.

As for the interaction between right-turning motor vehicles and non-motor vehicles, it can be found that the group of non-motor vehicles has a greater influence on right-turning motor vehicles, and right-turning motor vehicles also have a greater influence on a single non-motor vehicle. To solve this problem, we can set the special phase of right-turning motor vehicle to separate the interference between motor vehicle and non-motor vehicle in time. Spatially, the stop line of the non-motorized lane is advanced, and the right-turn channelization island is set up to separate the right-turn motorized traffic flow from the straight-going non-motorized traffic flow.

This paper analyzes the interaction mechanism between motor vehicles and non-motor vehicles, obtains the mutual interference factors of different urban traffic flows, and puts forward practical Suggestions for the design of urban intersections. It improves the operation efficiency of the intersection and guarantees the safety of traffic participants. This paper has certain practical guiding significance.
Acknowledgement
The research work presented in this paper was supported by Beijing Jiaotong University. The authors would like to thank Zhenzhou Yuan for his assistance in data collation. The contents of this paper reflect the views of the authors.

References
[1] Peng Rui. Theory of non-motorized traffic flow [D]. Shanghai: Doctoral thesis of Tongji University, 1994.
[2] Yang Peikun. (1994) Research on non-motor vehicle traffic flow model. China Traffic Engineering, (3): 3-5.
[3] Peng rui, Yang peikun. (1993) Basic model of bicycle traffic flow. Journal of Tongji University(Natural Science), (4): 463-468.
[4] Wu jian ping, Huang ling, Zhao jian li. (2004) The Behavior of Cyclists and Pedestrians at Signalized intersections in Beijing. Journal of Transportation Systems Engineering and Information Technology, (2): 105-114.
[5] Dean Brantely Talor. Contributions to Bicycle-Automobile Mixed-Traffic Science: Behavioral Models and Engineering Applications[D]. The University of Texas at Austin, 1998.
[6] Lu Huapu, Shi Qixin. (1996) The development trend and enlightenment of intelligent transportation system research. Science & Technology Review, (10): 26-30.
[7] Lu Huapu, Zhu Yin. (2003) Intelligent transportation system in the 21st century -- the fusion of modern technology. Journal of Transportation Engineering and Information, (2): 28-33.
[8] Jing Chunguang, Wang Dianhai. (2004) Analysis and treatment of the mixed traffic conflict at typical intersections. China Civil Engineering Journal, (6): 97-100.
[9] Sun Mingzheng, Yang Xiaoguang. (2008) Feature model of traffic flow at signal-controlled intersections. Urban Transport of China, (2): 92–96