Journal of Information Hiding and Privacy Protection
DOI:10.32604/jihpp.2020.09759
Article

Research on the Optimization Design of Intersections for Safe Operation of Large Trucks

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Received: 12 August 2020; Accepted: 29 September 2020

Abstract: When big trucks are running at urban road intersections, they are easy to interfere with other motor vehicles, and the turning big trucks are easy to have conflicts with non-motor vehicles and pedestrians, which will affect the safety of intersections. This paper first studied the intersection of trucks to the running trajectory, on this basis, through the establishment of mathematical model analysis of large truck steering conditions inside the wheel, and the influence of blind area to the driver. In the research of intersection safety design, the safety design is divided into three parts: Entrance road, internal operation and signal control. At the same time, the design method of the entrance road, the interior of the intersection and the signal control is given, which improves the safety of the truck driving at the intersection. Finally, the intersection of Jungong road and Zhoujiazui road in Yangpu district of Shanghai was selected as a case, and the optimal design of the intersection for large trucks was carried out through the investigation and analysis of actual data. The evaluation and analysis were carried out by using the multi-index matter-element model. The results show that the comprehensive safety correlation degree of the intersection is reduced to 0.42, and the safety level of is improved by one level.

Keywords: Large truck; city road intersection; safety design; safety operation; inner wheel difference; blind area

1 Introduction

According to the statistics in 2016, the number of large trucks accounted for 12.28 percent of the total number of cars in China, but the number of deaths caused by large trucks accounted for 48.23 percent of the total number of traffic accidents. Among them, due to the incomplete safety facilities at the intersection, blind area in the driver's right turn and other factors, the death rate of large trucks in the turning of the intersection is about 30% [1]. Due to its long body, large volume, overspeed, overload, long braking distance and other driving characteristics, traffic accidents have serious consequences, greater safety hazards.

Malte Ahrholdt studied the impact of trucks on the safety of pedestrians and non-motor vehicle users at the intersection, and demonstrated the solution of right turn of large trucks through the cross safety application [2]. The study of vehicle driving safety from the perspective of vehicle warning can help drivers reduce the blind area of turning at the intersection, and improve the safety of vehicle running [3]. Babkov based on the statistics of the road width and traffic accident rate of some countries such as the United States, Germany, Britain and the former Soviet union, found that the traffic accident rate decreased with the increase of the road width [4]. In 2014, Chai C. analyzed the relationship between right-turn truck and traffic conflict through cellular automata model, and found that right-turn truck had a significant impact on signal control and right-turn lane design [5]. The collected data of pedestrian and right-turn vehicle collision behavior at 8 signalized intersections in India, obtained the influencing factors of human-vehicle collision, and established a collision index model to evaluate pedestrian safety at intersections through k-means clustering method [6]. Said et al. explored the influence of highway geometric design characteristics on vehicle track and steering wheel Angle by using test vehicles. It provided different reference directions for the consistency evaluation of flat curve design and road design [7]. Domestic aspects: Xu proposed the crossing probability by studying the right-turn vehicle crossing pedestrians and the critical crossing gap of the vehicle, so as to reduce the collision accident between pedestrians and right-turn vehicles [8]. Wang established the track model of right turn of freight car based on the formation mechanism of right turn blind area of freight car driver, and proposed the calculation method of blind area. In terms of driving track [9]. Xu introduced the traffic flow track of the intersection to analyze the conflict points at intersection, and began to use the vehicle track to study the design of the intersection [10]. Pang et al. established the cellular automata model of mixed traffic flow to study the design parameters of the intersection of the turning direction of large trucks, so as to determine the reasonable length of the entrance road of intersection and the turning radius [11]. Hao obtained the turning radius of the double-hung train by graphical method, and gave the passing scheme of double-hung train on China's roads from the perspective of vehicle design [12]. Yao proposed a power function-based signal recovery transition optimization model of emergency traffic [13]. Zheng proposed the SRSSVM tracking method has low computational cost like the traditional linear SSVM tracker while can significantly improve the robustness of the discriminative classifier [14].

2 Analysis of Safe Operation and Influencing Factors of Large Trucks at Intersections

2.1 Analysis on the Steering Track of Large Truck at the Intersection

2.1.1 Steering Characteristic Analysis

According to the design size of the truck and the minimum turning radius, the radius of the most lane curb at the intersection can be obtained as shown in formula (1). The steering track plane of the truck is shown in Fig. 1.

$$r_0 = \sqrt{r^2 - d^2} - b - x \tag{1}$$

r_0 is the minimum turning radius; r is the Minimum truck turning radius; d is the the distance between the front and rear wheels; b is the distance between the rear wheels; x is the he safe distance between the vehicle and the kerb is generally 0.5 m.

2.1.2 Influence of Kerbstone Radii on Turning Process of Truck

Different kerbstone radii have great influence on the right turning process of large truck. When the minimum radius of the kerbstone required for turning is set (R = 2.4 m), the large truck will occupy other lanes in the intersection to turn right, or even the entire intersection to turn right. When the kerbstone is set with the minimum kerbstone radius (R = 5 m) required by the truck to turn, the truck will still occupy other lanes to complete the right turn. When the kerb radius is 10m, the wheel track of the big truck turning right Narrows, which has little influence on other lanes in the intersection. When the kerb radius is 20 m, the right turn of the large truck will hardly affect the operation of vehicles on other lanes. as shown in Fig. 1.

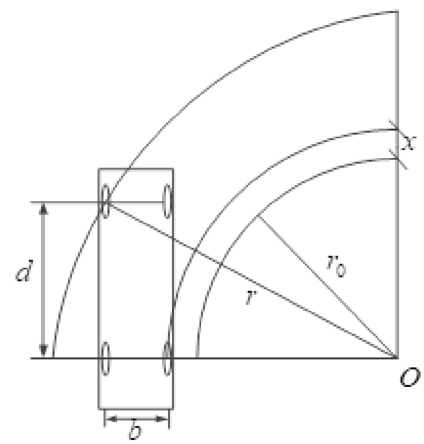

Figure 1: Right turn track of freight car

2.2 The Analysis of the Inner Wheel Difference of Large Truck's Turning Track at the Intersection

2.2.1 Definition of Inner Wheel Difference

When the vehicle is turning, the running track of the rear wheel and the front wheel is not consistent, which will produce deviation. The deviation of the outer wheel has little impact on the safety of the large truck, and the deviation of the inner wheel has great impact on the driving of the vehicle. Therefore, the deviation of the research vehicle is the inner wheel difference. Different types of large trucks have different sizes, different turning radius and different inner wheel differences.

2.2.2 The Model of Inner Wheel Difference of the Large Trucks

When the truck turns at the intersection, it is assumed that the running track of the front and rear wheels is circular, and a mathematical model is established for the running track, as shown in Fig. 2.

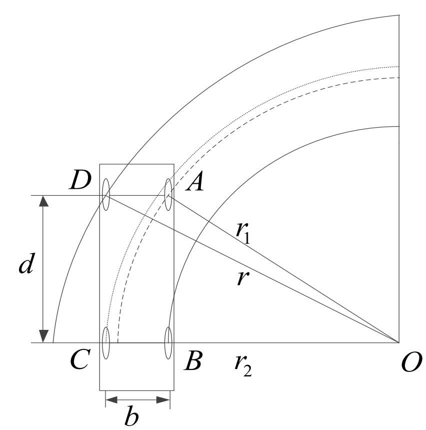

Figure 2: The model of inner wheel difference of the large trucks

r_1 is the turning radius of front wheel; r_2 is the turning radius of rear wheel.

The calculation method of inner wheel difference L is shown in formula 2:

$$L=\sqrt{\left(\sqrt{r^2-d^2}-b\right)^2+d^2}-\sqrt{r^2-d^2}+b \tag{2}$$

The inner wheel difference of the truck turning right at the intersection is shown in Fig. 3.

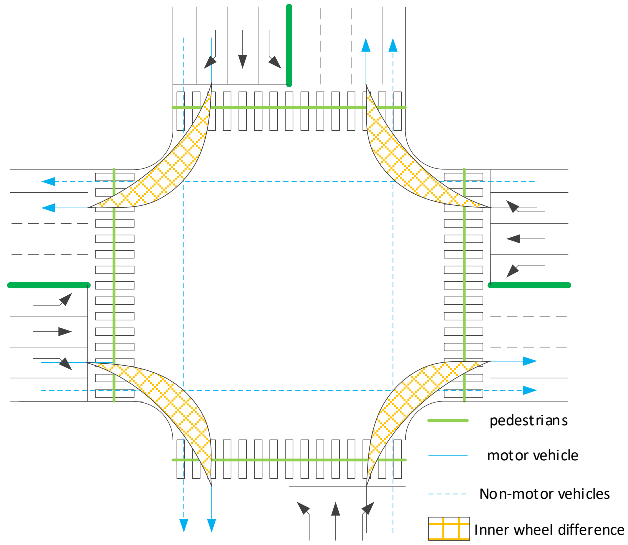

Figure 3: The inner wheel difference of the truck turning right at the intersection

When the Angle of turn decreases, the difference between the inner wheel and the turning wheel decreases. When the Angle of turn increases, the difference between the inside wheels of the truck in the turn increases.

2.3 Analysis of Blind Area of Sight for Truck Drivers at Intersections

In general, the blind area produced by freight cars is divided into six parts: the blind area at the front of the car, the blind area at the left and right front doors, the blind area at the AB pillar, the blind area at the left rear-view mirror, the blind area at the right rear-view mirror and the blind area at the rear of the car. The blind area at the front and both sides of the door is caused by the over height of the truck body. The blind area of the AB column is caused by the shielding of the AB column. The blind area of the left and right rear-view mirrors is caused by driver's inability to observe through the rear-view mirrors. The rear and rear wheels of large trucks are often in the driver's blind area, as shown in Fig. 4.

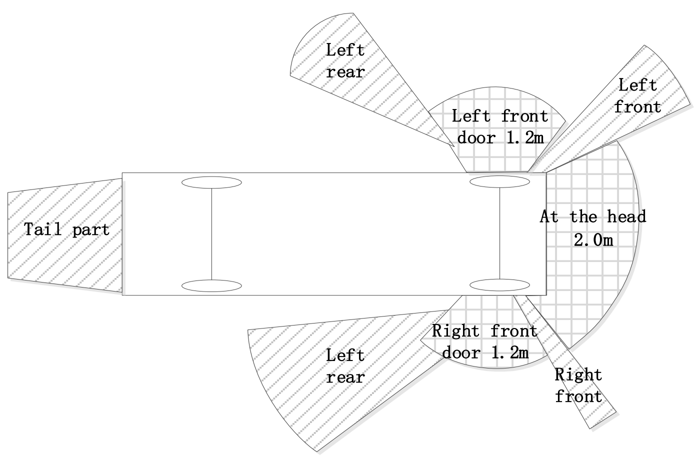

Figure 4: Blind area of large trucks

The blind area at the front of the truck is due to the truck body is high, which can only see the vision beyond the front distance through the front window, and the vision is blocked by the car body near the car body; the blind area near the left front door and the right front door is because the truck body is high, the driver can only see part of the vision through the left and right windows, and the vision is blocked by the car body near the car body The blind area of a and B pillars is the blind area caused by occlusion at the front left and right of the truck; the blind area at the rear of the truck because it is a closed box, and the driver cannot see the information at the rear of the truck through the devices such as the rear-view mirror.

3 Safety Optimization Design of Intersections for Large Trucks

For the safety optimization design of the large truck intersection, this section carries out the optimization design from the three aspects: The entrance road, the interior of the intersection and the signal control.

3.1 The Design of the Entrance Road of the Intersection

3.1.1 Lane Distribution

In order to minimize the impact of the inner wheel difference and blind area of the turning of large trucks, it is necessary to increase the turning radius of large trucks as much as possible at the intersection with a large number of large trucks, and separate the mixed traffic of right turning large trucks. The lane distribution of the intersection is designed according to four modes, as shown in Fig. 5.

Mode I: The left turning lane of large trucks and the turning lane share the same lane, and are set inside the entrance lane.

Mode II: The left turning lane of large trucks is shared with the turning lane, which is set outside the entrance lane.

Mode III: The turning lane and left turning lane of large trucks are set separately, the turning lane is set outside the entrance lane.

Mode IV: The turning lane of large trucks is shared with the right turning lane, and is set at the outermost side of the intersection.

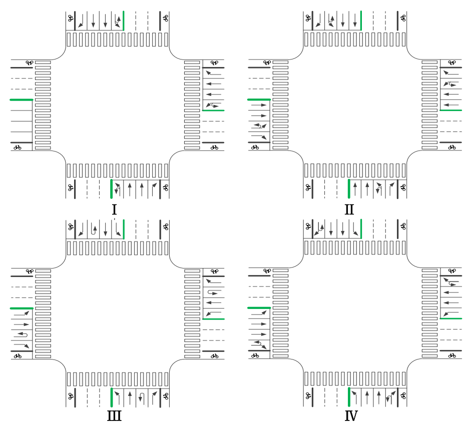

Figure 5: Lane distribution

3.1.2 Lane Width Determination

According to the “code for design of urban roads” (cjj37-90), when calculating the lane width, the body width of large vehicles is 2.5 m, and the limit speed of large vehicles and mixed lanes is 40 km/h according to the urban traffic management rules. According to the above calculation process and design speed, the width of mixed lanes of large trucks can be obtained as shown in Tab. 1.

Table 1: Calculation table of lane width of different types

Lane width composition	Model and location	Speed (km/h)	Land width (m)
$W = c + a + 0.5d$	Innermost mixed Lane	$v = 40$	3.73
$W = 0.5d + a + 0.5d$	Intermediate Lane	$v = 40$	3.68
$W = c + a + 0.5d$	Outermost mixed Lane	$v = 40$	3.73

W is lane width; c is transverse safety distance between car body edge and separation belt; a is body width; d is a safe distance between vehicles. At present, the width of large trucks is generally 2.5 m, and the recommended width of lanes at intersections facing large trucks is shown in Tab. 2.

Table 2: Recommended lane width at intersections

Speed / Vehicle Lane	10 km	20 km	30 km	40 km	50 km
Intermediate lane (m)	3.31	3.39	3.46	3.52	3.58
Outside lane (m)	3.42	3.53	3.63	3.73	3.81

Therefore, the lane width of truck turning lane can be set as 3.4–3.8 m, and the lane width of through lane can be set as 3.25–3.60 m.

3.2 Interior Design of Intersections for Large Trucks

3.2.1 Design of Right Turn Lane for Large Trucks at Intersections

In view of the safety of pedestrian and non-motor vehicle traffic at intersections, more vehicles turn right at intersections with large trucks and adopt rigid isolation with non-motor vehicles. There are two types of specific design: Using barrier or setting right turn separation lane, as shown in Fig. 6 and Fig. 7.

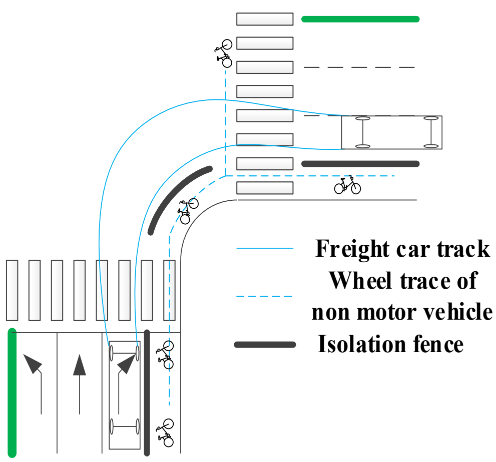

Figure 6: Using barrier

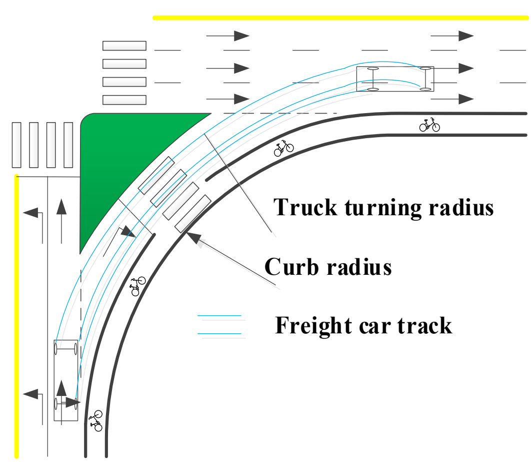

Figure 7: Setting right turn separation lane

3.2.2 Design of Turning Lane for Truck at Intersection

The turning radius, the width of median, the number of lanes and the width of lanes are the factors that determine whether a truck can turn around at an intersection. The larger the minimum turning radius of large trucks is, the more difficult it is to turn around at the intersection; the wider the central dividing belt is, the easier it is to turn around at the intersection; the narrower the lane at the intersection is, the more unfavorable it is for the large trucks to turn around, as shown in Fig. 8.

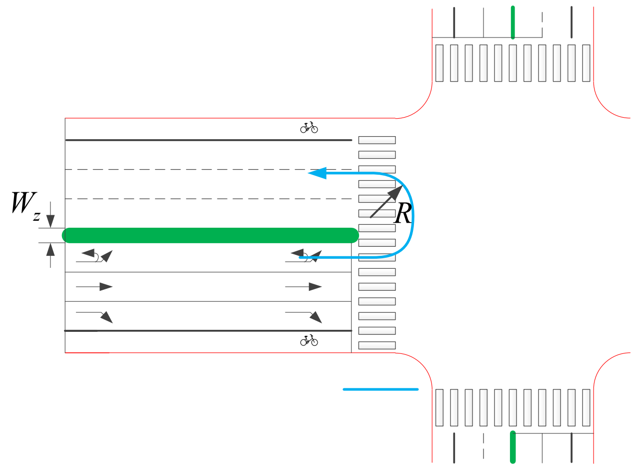

Figure 8: Turn around diagram of intersection

The number of lanes the truck needs to cross to turn around is shown in formula (3):

$$n = \left(2R - W_z\right) / W \tag{3}$$

n is the number of lanes the truck needs to cross to turn around; W_z is the width of median; R is the minimum turning radius; W is the lane width.

In the case of different width of the median, the number of lanes that the truck needs to cross for turning is shown in Tab. 3.

Table 3: Number of lanes the truck needs to cross for turning

The width of median (m)	0.3–3.8	3.8–7.3	7.3–10.8	10.5–14.3
Number of lanes the truck needs to cross for turning	7	6	5	4

If the number of exit lanes is greater than or equal to the number of lanes to be crossed, the truck lane can be set inside the entrance lane. When the number of lanes at the exit is less than the number of lanes to be crossed, it is necessary to move the turning lane to the outside of the entrance to meet the turning radius requirements, and the truck can turn around at the intersection.

3.2.3 Design of Non-Motor Lane

At urban road intersections, bicycle lanes and motorways are adjacent to each other. The separation fence between motor vehicles and non-motor vehicles is not enough to provide the right turning radius of large trucks. Large trucks must use bicycle lanes to complete the right turning. At the same time, riders do not consider the right turning of motor vehicles at intersections. In the process of right turning of large trucks, in most cases, they will continue to parallel with large trucks so that they fall into the blind area of driver's vision. Entering into the area of wheel difference in freight cars, and there is a left turn signal shared by motor and non motor vehicles in the intersection, which increases the occurrence of motor and non-motor vehicle mixed traffic, and aggravates the conflict between large freight cars and non-motor vehicles. The most effective way to solve the conflict between large trucks and non-motor vehicles is to isolate them in space and avoid the blind area of vision of drivers and riders. The separation of trucks and non-motor vehicles by barriers at intersections can avoid the parallel occurrence of cyclists and large trucks during right turning, as shown in Fig. 9.

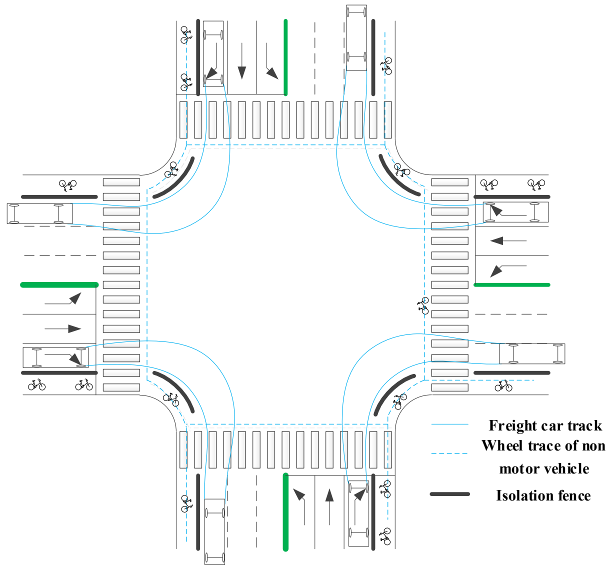

Figure 9: Channelization design of non motorway

3.3 Signal Control Design for Large Trucks

For general urban road intersections, in order to further separate traffic flow and reduce traffic conflict, signal control is used for intersections. Generally, there are two phases, three phases and four phases, as shown in Figs. 10–12.

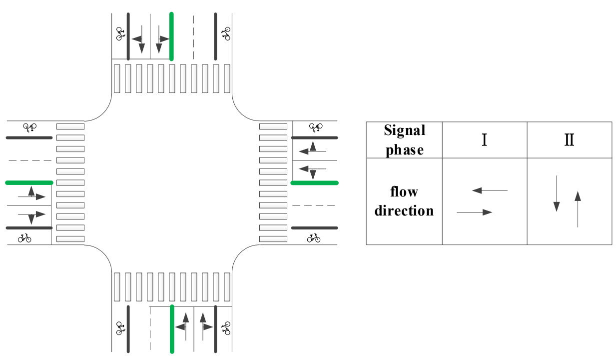

Figure 10: Two phases signal design

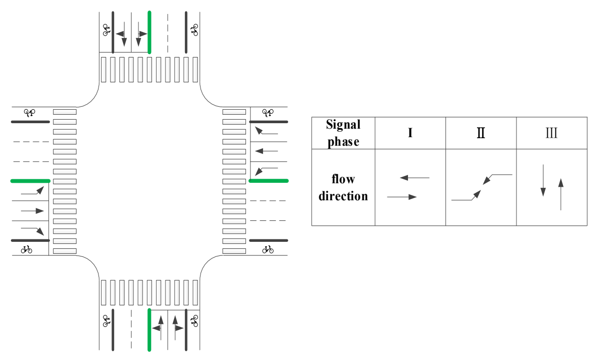

Figure 11: Three phases signal design

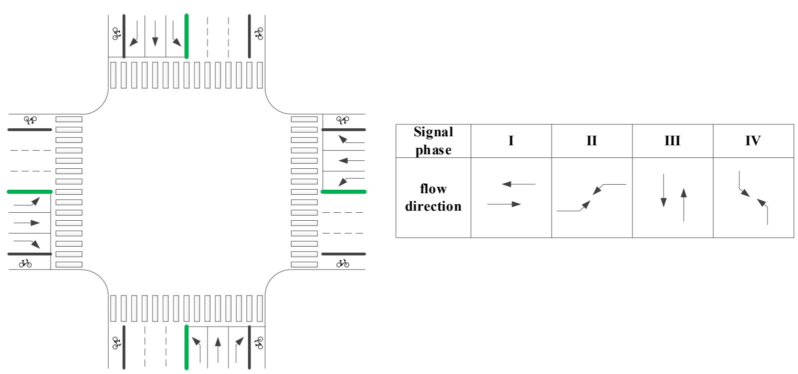

Figure 12: Four phases signal design

4 Case Analysis and Verification

The intersection of Jungong road and Zhoujiazui road in Yangpu District, Shanghai city is a T-shaped intersection. Jungong road is located in the north-south direction, with outer ring elevated road, Zhoujiazui road in the east-west direction, and school gate in the East. Jungong road is of three plate structure, with seven entrance roads in the south, six in the north and four in the West. Because the traffic flow of Zhoujiazui Road intersection is large, and there are many pedestrians and non-motor vehicles. According to situation, the optimization design of the intersection is carried out, so that the design of the intersection entrance can reduce the influence of the inner wheel difference and blind area of the large trucks. It can reduce the possibility of conflict between the large trucks and other traffic flows.

4.1 Design Optimization of Intersections for Large Trucks

4.1.1 Design Optimization of Intersection Entrance

For the west entrance lane, there are many left turn, turn around and right turn traffic of large trucks. The design of lane should meet the traffic capacity of intersection and improve the safety level as much as possible. The width of the west entrance road is 17 m. On the basis of the current situation, isolation fence can be set to isolate the large trucks from the non-motor vehicles. The width of the non-motor vehicle lane is 2.5 m, and the width of the mixed lane is 3.6 m, as shown in Fig. 13.

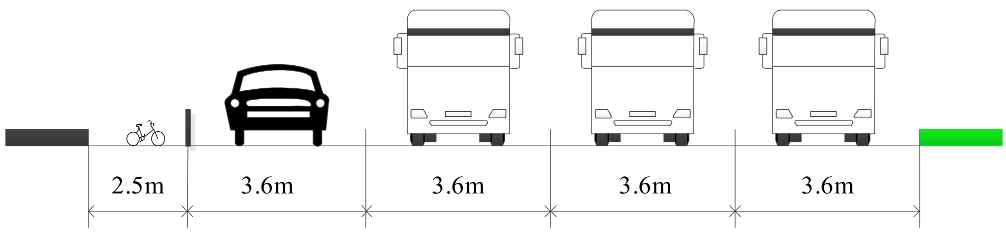

Figure 13: West entrance lane design

For the north entrance lane, there are many large trucks that go straight and turn right, and the traffic volume of motor vehicles is large and the speed is fast, which has a great impact on the safety of motor vehicles and pedestrians. In order to improve the safety of the north entrance, it is necessary to restrict the speed of cars through lane width design, and increase the safety of large trucks at intersections. The north entrance road is affected by the outer ring viaduct, with a channelized width of 15.5 m, two right turn lanes and two through lanes. Therefore, the width of the non-motor vehicle lane is 2 m, the width of the car road is 3.25 m, and the width of the mixed lane is 3.6 m, as shown in Fig. 14.

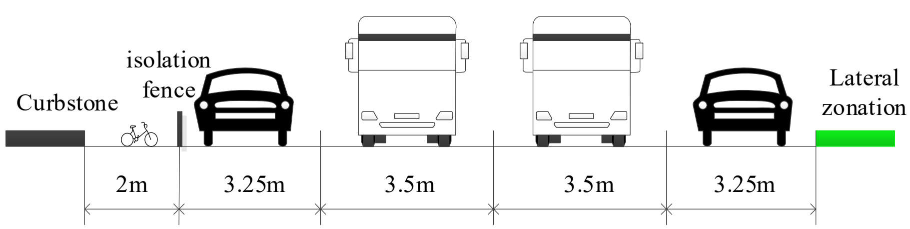

Figure 14: North entrance lane design

4.1.2 Interior Design Optimization of Intersections

Due to the large inner wheel difference and blind area of large trucks at Zhoujiazui Road intersection of military industry road, it is necessary to ensure the safety of turning of large trucks during the internal design. In addition to increasing the lane width of turning large trucks, appropriately increasing the width of non motorized lane, and setting up the secondary left turning crossing of non motorized vehicles. At the same time, a hard barrier is set at the corner of the intersection to increase the intersection angle of the non motor vehicle and the large truck, reduce the blind area of vision when the driver and the non motor vehicle user turn, and ensure the internal operation safety of the intersection through the separation of the motor and the non motor vehicle.

For the inner wheel difference of large trucks at the intersection, it cannot be completely eliminated through internal design at the intersection corner. In order to improve the safety of turning of large trucks, the warning area of inner wheel difference of large trucks is marked near the intersection corner with color to make drivers and pedestrians more alert when driving at the intersection. The warning area of inner wheel difference is shown in Fig. 15.

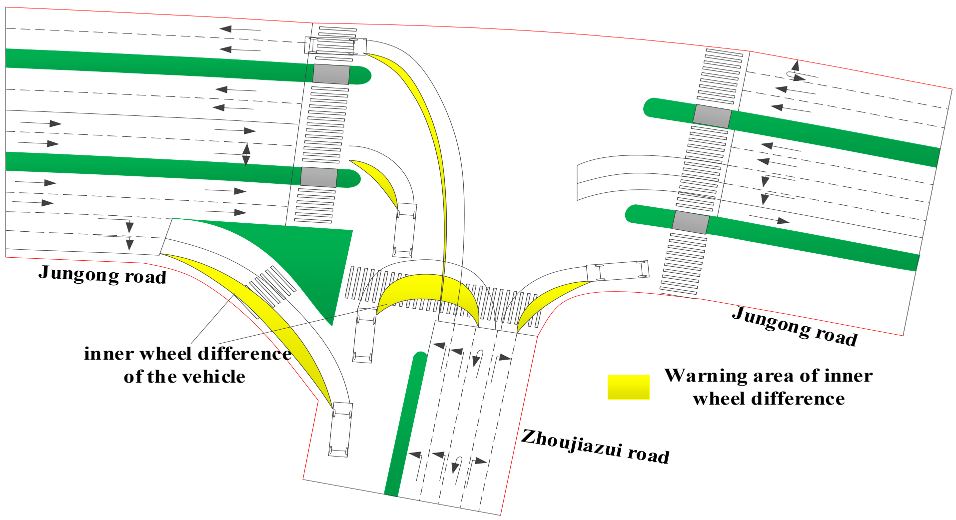

Figure 15: Warning area of inner wheel difference

Isolation fence shall be set at the corner of the intersection to organize the secondary crossing of non motor vehicles. As shown in Fig. 16, the blind area of vision for drivers and non motor vehicle users is reduced, so as to reduce traffic conflicts and traffic accidents.

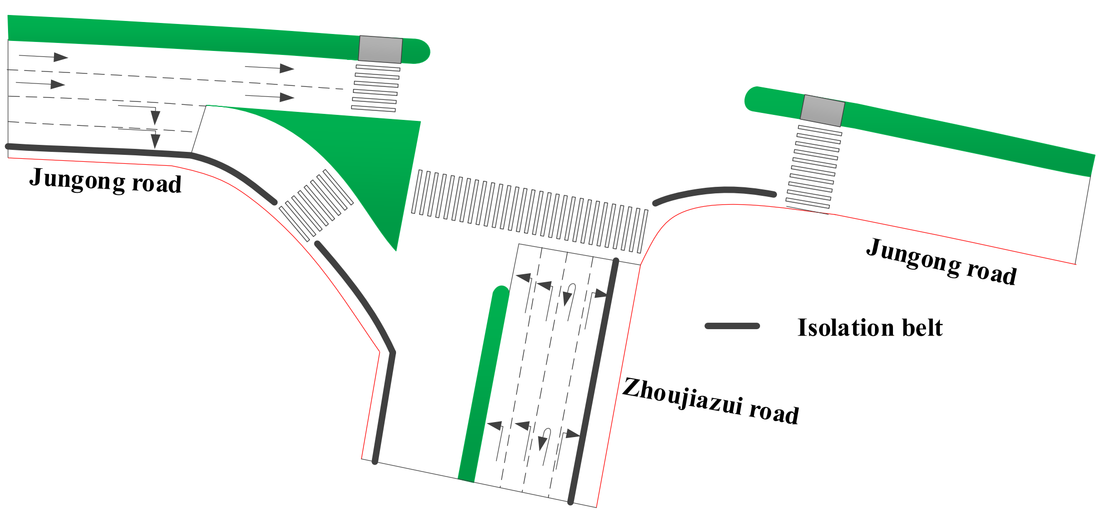

Figure 16: Setting of isolation belts for motor vehicles and non motor vehicles

4.1.3 Design Optimization of Intersection Signal Control

Through the analysis of the traffic volume of the case intersection, there are many right turning trucks at the north and West entrances, which cause serious interference. Without changing the signal cycle, the signal phase of the intersection is still designed as four phases, and the signal is designed for the right turning lanes at the north and West entrances. The signal timing diagram at this time is shown in Fig. 17.

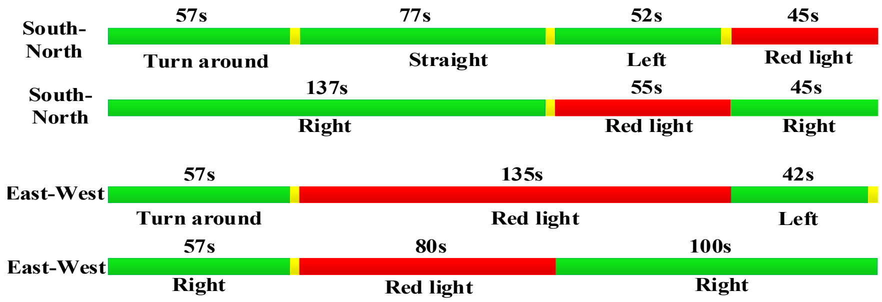

Figure 17: Optimized signal timing diagram

4.2 Safety Evaluation of Large Trucks Running at Intersections

Through the reconstruction of intersection infrastructure and the analysis of multi index matter-element model [15], the change of index value before and after the improvement is shown in Tab. 4.

Table 4: Evaluation form of traffic safety index of improved intersection

Evaluation system	Evaluating indicator	C	Unit	Present value	Improvement value	Improvement rate
Intersection infrastructure	Mandatory Signs	C_1	min	85	88	0.035
	Warning signs	C_2	min	86	89	0.035
	Other signs	C_3	min	85	87	0.024
Intersection service level	Intersection delay	C_4	/s	132	112	0.152
	Queue length at intersections	C_5	m	124	116	0.065
Influencing factors of large trucks	Pedestrian	C_6	-	37	26	0.297
	Non-Motor Vehicle	C_7	-	26	15	0.423
	Cars	C_8	-	25	18	0.280

It can be seen from Tab. 4 that the correlation function value of the improved intersection has changed compared with present value, among which the indicator signs, warning signs, other signs, the number of conflicts between large trucks and pedestrians, the number of conflicts between large trucks and non-motor vehicles and the number of conflicts between large trucks and small cars have all been improved. Among them, the number of conflicts between trucks and non-motor vehicles has been improved most significantly, with an improvement rate of 0.423, and the number of conflicts between trucks and pedestrians has been improved. The comprehensive correlation degree of intersection safety level is 0.42, which is very safe.

5 Conclusions

Starting from the operation characteristics of large trucks, this paper studies the influence of the characteristics of the inner wheel difference of large trucks and the driver blind area on the safety of non motor vehicles, pedestrians and motor vehicles at intersections. In this paper, the feasibility of turning trucks to traffic and turning traffic at different intersections is considered from the perspective of space, and the traffic channelization mode that satisfies the safety of trucks and other traffic flows through the design of spatial geometric conditions of intersections is studied, and its rationality and scientificity are analyzed from the perspective of overall safety of intersections, so as to provide reference for relevant theoretical research and engineering practice.

Acknowledgments: We would like to thank the Ministry of education of Shanghai Philosophy and Social Science Project. It provides support for this work. We would like to thank the reviewers and editors. We successfully completed the format requirements of the manuscript with their helpful advice and comments.

Funding Statement: This study was supported by the Ministry of education of Shanghai Philosophy and Social Science Project (Project No. 2020BGL013).

Conflicts of Internet: The authors declare that they have no conflicts of interest to report regarding the present study.

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