Research Article

A Simulation-Based Comprehensive Analysis for Traffic Efficiency and Spatial Distribution of Risks in Short Weaving Area of Municipal Interchange

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The weaving area is an important junction that affects the efficiency and traffic safety at the municipal interchanges. To explore the factors affecting traffic efficiency and the spatial distribution characteristics of traffic risks in the weaving areas of municipal interchanges, this study employed a microscopic traffic software of Vissim to construct a simulation model of weaving areas and evaluate the impact of road and traffic design parameters in the short weaving on traffic efficiency and risks, which includes ramp delay, mainline through lane (TL) traffic delay, average ramp speed, TL average speed, and collision rate. Through variance analysis via a large number of simulation scenarios, the weaving length is identified as the most important factor affecting traffic efficiency and risks in the short weaving area. Subsequently, three different types of weaving lengths with 350 m, 450 m, and 550 m were set to conduct the sensitivity analysis based on four performance indexes of mean acceleration and deceleration, acceleration range, deceleration range, and speed standard deviation as the representative variables of spatial risk distribution. The simulation results illustrate that a shorter weaving length has a significant influence on risk distribution, especially the highest risk probability at the positions after three-quarters of the inner and outer lanes in the short weaving area at the municipal interchange. Finally, this study verified the traffic risk reduction method of having traffic safety facilities and traffic organization at the complex interchange with double-entry and single-exit weaving areas in the city of Guangzhou, China. The research proposed a method to analyze the influence of the design parameters in the short weaving area on traffic efficiency and safety and provided a reference for the risk spatial distribution analysis and improvement in the short weaving area.

1. Introduction

At municipal interchanges, merge and diverge weaving areas are usually dense and concentrated where one of the most important purposes is to protect ecological land and save land capital. However, around the short weaving areas of this kind of municipal interchanges, the frequent vehicle lane-changing affects traffic efficiency and safety, leading to traffic flow disorder and increased risk of traffic accidents. The short weaving area has gradually become an accident-prone one with concentrated risk at municipal interchanges. Nowadays, many researchers are mainly focused on the impact of traffic characteristics on the risk and identification of hazardous segments in weaving areas. However, few researchers reported the spatial distribution characteristics

of traffic risks in the short weaving areas of municipal interchanges.

Therefore, this study will analyze the distribution characteristics of traffic efficiency and risks around the short weaving areas of the typical municipal interchange with three main lanes and an auxiliary lane, double-ramp entry, and single exit. Firstly, the popular traffic microsimulation software of Vissim is used to research traffic efficiency and risk at the short weaving areas. Taking four parameters (i.e., weaving area length, traffic volume, interweaving traffic ratio, and interweaving ratio) as design variables, this study analyzes their respective influences on traffic efficiency and risk. Also, the sequence of five influencing factors (i.e., mean acceleration, mean deceleration, acceleration range, deceleration range, and speed standard deviation) is obtained by

variance analysis. On this basis, the spatial distribution characteristics of risk in weaving areas are further recognized under three weaving lengths: 350, 450, and 550 m. Furthermore, the corresponding traffic optimization method scheme of traffic safety facilities and traffic organization is put forward to improve traffic safety in the short weaving areas of municipal interchanges.

2. Literature Review

If two adjacent ramps are close to each other on an expressway, the motorized vehicles need to merge or diverge on a single ramp, which will have an impact on the vehicles in the TL and adjacent ramps. Therefore, these two ramps and the weaving area between them should be considered as a whole.

There have been many research studies in the design of short weaving areas on highways. Chen [1] used the Traffic Software Integrated System (TSIS) to build a model for the combination of ramps. Li [2] discussed a conventional arrangement method of entrances and exits, the layout method of auxiliary lanes, and the advantages and disadvantages of the method of scissors arrangement in the elevated expressway. Huang and Chen [3] calculated weaving length with a calculation method of traffic capacity in the weaving area, analyzing the running characteristics of vehicles. The minimum distance required for acceleration and deceleration of vehicles was researched from the principles of dynamics. Thus, the calculation model of the minimum distance between connecting parts of a ramp was constructed. Pan [4] put forward the treatment plan for traffic and civil engineering when researching the design of entrances and exits in new expressway projects. These research studies provided a reference for the parameter selection of the short weaving area.

So far, HCM 2010 [5] and China's norms [6] are not enough to analyze the efficiency and safety of short weaving areas. HCM2010 has collected mature research results on the traffic flow operation state, operation influencing factors, and traffic capacity analysis in the weaving area. However, there are few studies on its application in the field of traffic safety in the weaving area because it often only considers the limited factors such as ramp form and traffic volume or makes a relatively rough analysis of the weaving area as part of the overall safety evaluation model of the interchange. In contrast, the analysis of the weaving area in China's norms still uses speed consistency to evaluate safety.

Currently, some researchers studying weaving area safety and traffic efficiency mainly concentrate on the impact of traffic characteristics on the weaving area risk and traffic efficiency characteristics. Collecting freeway crash records, geometric design data, and weather data, Wang et al. [7] proposed a multistage Bayesian logistic regression model for collision in the freeway weaving segment, using the Microwave Vehicle Detection System (MVDS). Abdel-Aty and Wang [8] tested several variable-speed-limit strategies after calibration and verification in microsimulation. Wang et al. [9] established a lane-changing conflict model and used a statistical analysis method to study the vehicle running

characteristics and lane-changing process in the weaving area of expressways, classifying lane-change conflicts into four different levels. Li et al. [10] determined the optimal weaving scheme under different combination designs of lanes in weaving areas by taking the traffic conflict rate as the safety evaluation index. Yuan et al. [11] discussed the impact of weaving length, traffic conditions, and drivers' characteristics on drivers' behavior of forced lane changing from the perspective of safety using a driving simulator. Hao et al. [12] explored the proposed models of the vehicle lane-changing process of highway weaving areas from the driver's level and provided the safety for CAV vehicle to change lane recognition in the weaving area. Kim and Park [13] studied the collision-rate distribution in highway weaving segments and buffer-separated high-occupancy lanes. Cai et al. [14] comprehensively studied the safety impact of different lengths after each lane change on the weaving segments of the general lane close to entrances and exits using VISSIM microsimulation and a driving simulator. Dong et al. [15] used a mixed logit model to examine the difference of SV and MV accident probability and found traffic, road, surface characteristics are the main influencing factors of SV and MV accident possibility. Selecting a representative ramp exit of an expressway in Changchun, China, Liang et al. [16] analyzed characteristics of traffic conflicts, traffic flow, and traffic density and built a model to study the relationship between the number of traffic conflicts and traffic flow and density.

At the same time, some other research studies have reported the dangerous segment identification of the short weaving area and the overall optimization method for the traffic efficiency and safety of the short weaving area. Lord and Bonneson [17] found that there were more crashes on crossroad off-ramps than crossroad on-ramps by a ratio of 1.5, and non-free-flow ramps had twice as many crashes as other ramp types. Kusuma et al. [18, 19] analyzed the two weaving segments between junctions 41 and 43 of the M1 motorway, and results showed that approximately 1/4 of the interweaving behaviors occurred 50–100 m before the junction. Chi and He [20] took the comprehensive risk index of traffic conflict as an evaluation index and determined the overall evaluation level by using the gray clustering evaluation method, based on the types and severity of conflicts, and concluded that the outer lane in the weaving area is the most dangerous of all lanes. Chen et al. [21] proposed a micro-traffic-simulation method to analyze the influence of bus lanes on the traffic capacity of weaving areas. Rakha and Zhang [22] determined 34 different configurations of weaving and used INTEGRATION software to model weaving length and travel-demand distribution in maximum-capacity conditions. Tanaka et al. [23] developed a vehicle control algorithm to avoid the conflicts of weaving segments while improving traffic capacity. He [24] used a cellular automaton to build a weaving-area discrete model of a multilane urban expressway by analyzing vehicle characteristics. Tilg et al. [25] studied how to improve traffic capacity in weaving areas with automated vehicle technology. Cai et al. [26] obtained traffic capacity by different simulation models of weaving areas and put forward a model

of traffic capacity in weaving areas that is appropriate for urban roads in mountainous areas. Ma et al. [27] proposed a traffic equilibrium organization method based on a lane-changing constraint in neighboring weaving areas, aiming at improving traffic efficiency and safety in weaving areas. Based on the analysis of the characteristics of safety in weaving areas, Xie et al. [28] established a collaborative control framework for the traffic in weaving areas and the areas they affect that considers control strategies of ramps and TLs. Li et al. [29] analyzed lane-changing behavior and optimized the lane-changing strategies in the upstream segments to improve road safety and capacity of the ramp areas.

However, research on spatial distribution characteristics of risk and internal optimization in municipal interchange short weaving areas is rare. This study will present an optimization method of the facilities and traffic organization in the short weaving areas of municipal interchanges.

3. Risk and Traffic Efficiency Parameters

When vehicles in a weaving area experience traffic conflicts due to lane changing, both the capacity and traffic risk of the weaving area are affected. Therefore, this paper focuses on identifying the distribution characteristics of traffic efficiency and risk in the weaving areas and presenting the corresponding improvement methods.

3.1. Traffic Risk Indicator. When evaluating the safety of the weaving area, traffic conflicts are usually used, namely, the ratio of the number of conflicts to the equivalent of mixed traffic. This indicator and its evaluation criteria are based on the analysis of level intersections. It is not appropriate to use the above indicators into the analysis of traffic efficiency of weaving areas. The ratio of the number of conflicts to traffic volume and weaving length is proposed on this basis, which is called the vehicle-kilometer conflicts number [30], to objectively reflect traffic safety in weaving areas:

$$f(V_r, VR) = \frac{TC(L, V_T, V_R, V_r, VR)}{(V_T + V_R) \cdot T} \times 1000, \quad (1)$$

where $f(V_r, VR)$ are the number of traffic conflicts per kilometer in different interweaving traffic ratio VR and interweaving ratio V_r (times/vehicle-km); $TC(L, V_T, V_R, V_r, VR)$ is the total number of traffic conflicts per kilometer per hour in the different weaving length T ; V_T and V_R denote the traffic volumes on the upstream mainline and entrance ramp per hour (pcu/h), respectively; VR is interweaving traffic ratio; V_r is interweaving ratio; and T is the weaving length (m).

In Figure 1, traffic volumes from the upstream mainline to the downstream mainline and the exit ramp are set to V_{FF} and V_{FR} , respectively, and the volumes from the upstream entrance ramp to mainline through movement and the downstream exit ramp are called V_{RF} and V_{RR} , respectively. The total interweaving traffic volume is equal to the summation of V_{FR} and V_{RF} in this study. Thus, the interweaving traffic ratio refers to the ratio of the interweaving

traffic volume to the total traffic volume on the upstream mainline and the upstream entrance ramp, and the interweaving ratio refers to the ratio of the smaller side to the larger side of V_{FR} and V_{RF} .

3.2. Traffic Efficiency Indicators. Traffic delay and average weaving-area speed are selected as traffic efficiency indicators in weaving areas in this study. Delays are divided into vehicle delays on the mainline through lanes (TLs) and vehicle delays from the through lanes to the diverge lane, that is, TL delays and ramp delays. The average speed is divided into the average speed on the through lanes and that from the through lanes to the diverge lane with the corresponding to TL average speed and ramp average speed.

In summary, the risk- and traffic-efficiency-characterization parameters of weaving areas are selected as shown in Table 1.

4. Experiments

PTV-VISSIM is a microscopic simulation tool based on the time interval and driving behavior, which is often used for modelling urban traffic and public transportation operations. This study established the selected weaving-area model via the VISSIM interface to set traffic parameters (e.g., the proposed traffic volume, expected speed, and traffic volume composition, entered to simulate the traffic flow operations under specific conditions in the weaving area) and further obtain the conflict rate, delay, and average speed, as well as other data used to develop research on the influence of various parameters on the risk and traffic efficiency characteristics of weaving areas.

4.1. Simulation Parameters. To study the traffic flow characteristics of weaving areas under different road conditions, input values of the simulation parameters should be selected. After the simulation parameters are determined, traffic simulation is used to combine different influencing factors, and then the law of traffic flow operation and risk characteristics in the weaving area of the interchange section is analyzed. Based on the common municipal short-weaving-area configuration, one can select the typical scenario of having the three-lane single-side weaving of the TL and the double-entry and single-exit form of the ramp entrance and exit to construct a model for traffic simulation.

4.1.1. Weaving Length. In this study, the length of the weaving area borrows the maximum weaving length formula proposed in the United States Highway Capacity Manual (HCM 2010). Based on it, the calculation shows that the maximum length is 750 m; meanwhile, the minimum weaving zone length determined by Wang et al. [31] research is set to 150 m.

4.1.2. Traffic Volume. As usual, the traffic volume can be predicted after collecting and sorting the historical data, which is used to carry out a series of analysis experiments

FIGURE 1: The layout of the weaving area.

TABLE 1: List of risk and traffic efficiency index settings of weaving areas.

Detection index	Index explanation
Vehicle-kilometer conflicts	The ratio of the number of conflicts to throughput and weaving length
Ramp delay	Delay time from TL to diverge lane
TL delay	Delay time on TL
Average ramp speed	Weaving length/travel time from TL to diverge lane
Average TL speed	Weaving length/travel time on TL

and improvements. Chen et al. [32–34] proposed a prediction method for traffic volume and shipped type based on the neural network model, which is referred to the design capacity of TL lanes and ramps specified in relevant codes [35], as shown in Tables 2 and 3. In this study, the design capacity in the code is selected as the intermediate value of the simulation test group. The selected range of the traffic volume on the two-lane ramp at 60 km/h is 2100–2500 vehs/h and the step length is set to 100 vehs/h; the traffic volume of the three-lane TL at 80 km/h is selected in the range 2700–3900 vehs/h and the step length is 300 vehs/h. The simulation experiment results show that the weaving phenomenon in the weaving area is serious under the above-mentioned traffic volume parameter settings. To prevent the occurrence of traffic congestion, while taking into account the influence of the proportion of large vehicles, the selected value and step length of the traffic volume of the ramp and TL are further reduced to 2/3 of the original design. It was determined in this study that the 60 km/h two-lane ramp traffic range is 1400–1680 vehs/h and the step length is 70 vehs/h; the 80 km/h three-lane through-line traffic volume is 1800–2600 vehs/h and the step length is 200 vehs/h. The simulation tests show that some sections of the weaving area still exhibit traffic congestion. After more in-depth debugging and optimization selections, the final selection of the TL traffic volume is 1800 vehs/h and the ramp traffic volume is 1400 vehs/h as the fixed traffic volume parameters in the final simulation experiment.

4.1.3. Interweaving Traffic Ratio. The applicable interlaced flow ratios of each interlaced configuration are different, and a wide range of values may exceed capacity and cause traffic congestion. So, the value in this study is 0.1–0.3 with a step size of 0.05.

4.1.4. Interweaving Ratio. Dia [36] found that the change of the interweaving ratio has no significant impact on the

TABLE 2: Design capacity of basic ramp sections.

Ramp design speed (km/h)	80	70	60	50	40	35	30
Single lane	1500	1400	1300	1200	1000	900	800
Double lane	2900	2600	2300	2000	1700	1500	1300

operating efficiency and safety of the weaving area, so the interweaving ratio is fixed at 0.5.

4.2. Variance Analysis of Influencing Factors. In order to evaluate the impact of the fluctuation of the experimental data on the results, this study employs the analysis of variance method to test the degree of influence of the respective variables on the results and to determine the main influencing factors. SPSS 12.0 software was used as the data-processing method of variance analysis, and the characteristics of the influence of various factors on the indicators are obtained as shown in Figure 2.

From Figure 2, one can find that the weaving length has the greatest impact on traffic safety and efficiency and has a significant impact on the conflict rate, ramp delays, and average speed of the mainline and ramp traffic; ramp traffic has a greater impact on traffic safety and efficiency and has a significant impact on ramp delay. The interweaving traffic ratio and through-movement traffic volume have less impact on traffic safety, and the through-movement traffic volume has a greater impact on traffic efficiency than the interweaving traffic ratio. According to the analysis results, the sequence of the importance degree of each influencing factor is as shown in Table 4.

4.3. Risk Spatial Distribution of Weaving Areas. The results of the above experiment show that ramp length and ramp capacity have the greatest influence on driving risk and traffic efficiency. Further, the distribution characteristics of traffic risk are analyzed for different weaving-segment

TABLE 3: Traffic volume threshold on single-lane expressway under level-of-service (LOS).

Ramp design speed (km/h)	120	100	80
Traffic volume upperbound under the 2nd grade of LOS	1200	1150	1100
Traffic volume upperbound under the 3rd grade of LOS	1650	1600	1500

FIGURE 2: Analysis of variance.

TABLE 4: The sequence of the importance degree of each influencing factor on traffic safety and efficiency under the analysis of variance.

Rank	Vehicle-kilometer conflicts	Number of conflicts	TL delay	Ramp delay	TL average speed	Ramp average speed
Weaving length	1	1	1	1	1	1
Ramp traffic	2	2	2	2	2	2
TL traffic	4	3	3	3	3	3
Weaved traffic ratio	3	4	4	4	4	4

lengths in municipal interchanges. If the length of the weaving segment is too short, the lane-change behavior is prone to congestion, and the internal risk cannot be reflected by the speed and acceleration. Meanwhile, the longer the length of the short interweaving area is, the less the concentration of risk will become because there are much more opportunities and options for drivers to change lanes. In our experiments, the weaving lengths are set to 350, 450, and 550 m. According to the design requirements of Tables 2 and 3 and simulation experiment debugging, the traffic volume of the TL is 1800 vehs/h, while the traffic volume of the ramp is set as 1400 vehs/h. The locations of detection devices to collect traffic parameters are shown in Figure 3.

The mean acceleration and deceleration, acceleration range, deceleration range, and speed standard deviation of each lane and section are selected as the characteristic parameters in the experiments. Among them, the mean acceleration and deceleration can reflect the fluctuation of acceleration and deceleration at the detection location. The larger the mean value, the greater the speed variation range and the greater the corresponding risk [37]. The greater the speed range of addition and subtraction, the greater the probability of traffic collision. The speed standard deviation can reflect the dispersion degree of vehicle speed at the particular section. Generally speaking, the greater the degree

of dispersion, the lower the safety of the location. Those five performance indexes are shown in Figures 4–8.

As can be seen in Figure 4, the mean acceleration in the inner and middle lanes is stable below 0.4 m/s^2 . The mean acceleration reaches a maximum at the merge and diverge sections, while travel speed in the outer lane fluctuates greatly. The mean acceleration exceeds 0.4 m/s^2 , reaching up to 0.66 m/s^2 at the entrance of the outer lane when the weaving length is 550 m. Because the vehicle speed in the auxiliary lane is lower than one in the mainline through movement when the ramp traffic flows into the downstream mainline, the mean acceleration in the auxiliary lane is smaller than one in the outer lane. Also, the mean acceleration of each lane section in the exit ramp increases significantly, indicating that the risk in the exit part of the weaving area increases similarly.

As can be seen in Figure 5, the mean deceleration of each lane section is maintained at 0.2 m/s^2 . At the 3/4 section of the weaving area, the peak value of the mean deceleration appears. When the length of the weaving section is 350 m, the mean deceleration reaches 1.365 m/s^2 . The value in the auxiliary lane remains at a low level from the entrance to the 3/4 section and is stable below 0.2 m/s^2 . However, it significantly increases at the segment from the 3/4 section to the exit, mainly due to differences in traffic speeds between the

FIGURE 3: Diagram of the location setting of detection to collect test data.

FIGURE 4: Distribution diagram of mean acceleration at sections of each lane.

FIGURE 5: Distribution diagram of mean deceleration at different positions.

FIGURE 6: Distribution diagram of acceleration and deceleration ranges at different positions. (a) The acceleration range. (b) The deceleration range.

outer and auxiliary lanes causing the design speeds of the ramp and downstream mainline to be different, as well as to frequent braking during lane changing. The mean deceleration in the diverge area under various lengths decreases. Thus, it can be seen that the deceleration behavior is mainly concentrated in the 3/4 section, which should be regarded as an important area of risk control.

Similarly, one can find that the difference between the acceleration range and deceleration range is large at the different section belonging to different lanes in Figure 6. In

general, the range in the diverge area is larger than one at the other sections. The vehicles entering the lane leave at a high acceleration, which forms the acceleration difference between themselves and the vehicles ahead that has reached a certain speed. The acceleration range between the inner and auxiliary lanes before the 3/4 section generally reaches a low level. The inner lane is less disturbed, while the low acceleration demand of the segment before the 3/4 section occurs in the auxiliary lane. The vehicles move smoothly and braking is less related to lane-changing behavior.

FIGURE 7: Distribution diagram of speed standard deviation at different positions.

FIGURE 8: Continued.

FIGURE 8: Distribution diagram of five characteristic parameters at the overall section.

Figure 7 shows that the peak of speed standard deviation appears at the similar location regardless of the weaving length, which is mainly concentrated in the middle and outer lanes. When the vehicle is in the middle lane, the driver can change lanes to the inside or outside, which may easily lead to acceleration and deceleration to change lanes safely. However, when the vehicle is in the outside lane, lane-changing to the auxiliary lane is facilitated, and then the vehicle can safely drive off the mainline to the ramp, which will also lead to a large speed deviation in the auxiliary lane.

According to the overall section of Figure 8, the peak of previous five parameters is high at the section which is from the entrance and 3/4 sections in the main weaving segment to the exit section, including the exit in the auxiliary lane. Regarding the 1/4, 1/2, and 3/4 sections, the speed standard deviation of vehicles in the weaving area is quite large because of traffic speed difference.

Referring to the above analysis, the indicators of the downstream segment in the 350 m-long weaving areas are generally larger than ones in weaving areas of other lengths, illustrating that short weaving lengths have a certain influence on risk distribution. In short weaving areas of municipal interchanges, the probability of risk occurrence is the highest in the 3/4 section and exit position of the outer lane. Near to the exit, drivers would decide to slow down to complete lane changing, causing vehicle drivers behind those in front to also slow down to complete lane changing to avoid collisions. Meanwhile, some drivers change lanes only when approaching the exit, which increases risk at the exit section or in its immediate vicinity. Thus, the 3/4 and exit sections of the outer lane should be regarded as the critical control point of risk reduction. The fluctuation of the mean acceleration and acceleration range in the auxiliary lane is not significant, which is caused by low-speed vehicles entering the weaving area. As a result, the two indexes above are smaller than those in other lanes, which reduces the probability of risk conflicts. However, in short, risk control measures should be adopted in the diverge-lane segment of the auxiliary lane.

5. Optimal Method

According to the aforementioned simulation analysis, the conflict risk in the mainline is concentrated in the 3/4 section and exit in the outer lane. The risk reduction optimal method is proposed and is simulated for different weaving lengths in Guangdong Province, China. Referring to method requirements of traffic marking of entrances and exits for highways in Guangdong Province, a solid-lane line shall be set between the inside and middle lanes or between the middle and outer lanes. The length of the solid-lane line should not be less than the distance from the start point of the transition region to the tip of the barrier. Meanwhile, the solid-lane line of the inner and middle lanes should be extended forward for a certain length.

Kang and Huang [38] reported that a certain lane-change length is required when a vehicle is changing lanes. It is assumed that the vehicle enters the middle lane when the driver changes lanes before the beginning of the solid-lane line. The length that can ensure that a vehicle can successfully change lanes into the outer lane should be no larger than L . This length includes the length matched by vehicle speed as it accelerates and the lengths that the driver can confirm and import into the middle lane, which are denoted as l_1 and l_2 . If it is assumed that vehicles in the inner and middle lanes drive at the same speed, the length l_1 matched by vehicle speed as it accelerates is equal to 0. Also, the driver's reaction time will change with the transformation of traffic environment complexity. The total response time of drivers is approximately 0.5–4.0 s, but the complexity of a municipal interchange connection is lower, so 2 s is taken.

The travel distance for such a reaction time can be represented by

$$L = l_1 + l_2 = l_2 = \frac{v_1^2 - v_0^2}{2a} + \frac{V}{3.6}t, \quad (2)$$

where v_0 is vehicle speed in the inner lane of the downstream mainline (m/s); v_1 is the speed at which the vehicle accelerates from the inner lane to the middle lane (m/s); a denotes the acceleration (m/s²); V is the design speed in the

FIGURE 9: Diagram of optimal method in weaving area.

downstream mainline (m/s); and t represents the response time of drivers (s).

Therefore, it is calculated that $L = l_1 + l_2 = 0 + 44.44 = 44.44$ m, and $L = 50$ m is used to ensure safety. When the length of the solid-lane line is set between the middle and outer lanes as $1/4$ of the length of the weaving segment, the calculation shows that the ratio of the solid line between the middle lane and the inner lane to the weaving segment is too high, especially the length of the weaving segment is shorter, such as $T=150$ m. Meanwhile, it is necessary to ensure that there is enough length for vehicles to complete lane changing. It is thus more appropriate to set the length of the solid-lane line as $1/5 (T - L)$. The driving conditions in the middle and inside lanes are better than those in the outer and auxiliary lanes. Also, when researching the risk in short weaving areas, vehicles should be allowed to change from the outer to the middle lane or from the middle to the inner lane. The optimal method is shown in Figure 9.

It is calculated that the lengths of the solid-lane line between the middle and outer lanes are 60, 80, and 100 m when the weaving lengths are 350, 450, and 550 m, respectively. The model simulation was carried out for the optimization, and the rationality and applicability of design were analyzed by the mean acceleration, acceleration range, and speed standard deviation. The analysis results are shown in Figures 10–12.

One can find that the acceleration of mean absolute from the entrance to the $1/2$ section fluctuates within 0.05 m/s^2 , within a small fluctuation range in Figure 10. However, there is also a good case that the index decreases by 0.1 m/s^2 in the model in which the weaving length is 350 m. From the $3/4$ section to the exit in the outer lane, the change range of the index fluctuates within 0.05 m/s^2 . At $3/4$ section, the average acceleration indicator of the model with the weaving length of 350 m and 550 m produced a decrease of more than 0.1 and 0.3 m/s^2 , respectively, which significantly reduces the probability of risk. At the exit, however, the mean acceleration increases by approximately no more than 0.1 and 0.2 m/s^2 , respectively, while the mean acceleration decreases by approximately no more than 0.15 m/s^2 in the model in which the weaving length is 450 m. At the $3/4$ section in which the risk is concentrated, vehicles in the inside and middle lanes are forbidden to be driven to the outside lane, which reduces the chance of weaving and the probability of risk. However, because vehicles in the outer and auxiliary lanes are allowed to merge into the middle and inner lanes, with better traffic conditions in the middle and inner lanes, it is equivalent to balancing risks in the entire weaving area and reducing the risk concentration.

Correspondingly, Figure 11 shows that the acceleration range from the entrance to the $1/4$ section fluctuates within 1 m/s^2 , within a small fluctuation range. Since the optimal traffic setting is concentrated in the $3/4$ section to the exit, it has little influence on this segment. An increase of not more than 2 m/s^2 of the acceleration range was generated in the inner and middle lanes at the $1/2$ section. For different weaving lengths, the range of $2\text{--}6 \text{ m/s}^2$ decreases for the acceleration range, which reduces the acceleration range at the risk-concentration position. This indicator has a different degree of decline in each lane, especially at the $3/4$ section. For the weaving areas of 350 m and 550 m lengths, the performance index shows a large decrease of more than 2 and 5 m/s^2 , respectively. Furthermore, the acceleration range at the exit does not have a range of more than 4 m/s^2 , and the variation value fluctuates slightly within the range of 2 m/s^2 . The main reason is that after traffic optimization, vehicles in the inner and middle lanes are prohibited from changing into the outer lane at the $3/4$ section where high risk exists, reducing weaving and the probability of risk.

Subsequently, Figure 12 shows that the speed standard deviation of other models changes by no more than 0.2 m/s from the entrance to the $1/2$ section, except for the outer lane of the 350 m-length weaving area. Due to traffic optimization, drivers in the inner lane and the middle lane will take measures to change lanes in advance, which leads to the increase of speed standard deviation. At the $3/4$ section, the speed standard deviation is mainly decreased, especially in the outside lane. Under the 550 m-length weaving scenario, the decrease of speed standard deviation reaches a maximum in this section, i.e., by more than 0.5 m/s . At the same time, the speed standard deviation at the exit in different models presents a downward trend for the most part. The decrease of the outer lane with a length of 450 m is greater than 0.8 m/s . This is the result of banning lane changing in the inside and middle lane, which leads to fewer vehicles merging into the weaving area, thus ensuring the safety of exiting in the outside lane. Also, the increase of the speed standard deviation in the outer lane under the 550 m-length weaving scenario is greater than 0.6 m/s , which should be caused by the weaving of vehicles in the outer and auxiliary lanes.

To summarize, the optimization scheme transfers the risk to the segment with good driving conditions and low risk, which has a good risk-reduction effect for the risk-concentration segments from the $3/4$ section to the exit in the outer and auxiliary lanes. This is beneficial to improve traffic safety in the short weaving areas of municipal interchanges.

FIGURE 10: The acceleration of mean absolute difference between two schemes.

FIGURE 11: The acceleration range difference between the two schemes.

FIGURE 12: The speed standard deviation difference between the two schemes.

6. Conclusions and Recommendations

Quite a few problems in the construction and operation of municipal interchanges could lead to reduced traffic efficiency and increased risks, especially in weaving areas. To ensure traffic efficiency and safety in the weaving areas of municipal interchanges, the typical double-entrance and single-exit weaving areas in municipal interchanges are taken as the research object in this paper. The conflict rate, ramp delay, TL travel delay, ramp average, and TL average are selected to quantitatively describe traffic efficiency, and then the main influencing factors are recognized. Subsequently, further analysis of risk distribution shows that a short length of weaving areas would increase risk probability. The comprehensive analysis shows that the risk probability is highest at the 3/4 and downstream sections in the outer lane inside municipal interchange short weaving areas, and so these two sections in the outer lane should be regarded as the critical control point of risk reduction. Besides, risk-control measures should also be applied to auxiliary lane exits to ensure vehicle safety. Finally, an optimal method for the high-risk segments in weaving areas is carried out to verify the developed risk distribution characteristics and optimal method. The results can provide a reference for the optimization method of facilities and traffic organization in municipal interchange short weaving areas.

The factors affecting traffic efficiency and spatial distribution characteristics of risks in complex municipal interchanges are explored in this paper. However, the effect of the optimization method is based on the increase or decrease of the detection section index value, and so this study only focuses on the location of risk concentration without recognizing the probability of risk occurrence and distribution

of other detection sections after optimization. In the future, it is necessary to collect field data to validate the reliability and effectiveness of the proposed method under various geometric configurations and traffic demand patterns in urban short weaving areas and estimate the probability of traffic accident occurrence.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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