

Active lane management for intelligent connected vehicles in weaving areas of urban expressway

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Abstract

Purpose – This paper aims to use active fine lane management methods to solve the problem of congestion in a weaving area and provide theoretical and technical support for traffic control under the environment of intelligent connected vehicles (ICVs) in the future.

Design/methodology/approach – By analyzing the traffic capacities and traffic behaviors of domestic and foreign weaving areas and combining them with field investigation, the paper proposes the active and fine lane management methods for ICVs to optimal driving behavior in a weaving area. The VISSIM simulation of traffic flow vehicle driving behavior in weaving areas of urban expressways was performed using research data. The influence of lane-changing in advance on the weaving area was evaluated and a conflict avoidance area was established in the weaving area. The active fine lane management methods applied to a weaving area were verified for different scenarios.

Findings – The results of the study indicate that ICVs complete their lane changes before they reach a weaving area, their time in the weaving area does not exceed the specified time and the delay of vehicles that pass through the weaving area decreases.

Originality/value – Based on the vehicle group behavior, this paper conducts a simulation study on the active traffic management control-oriented to ICVs. The research results can optimize the management of lanes, improve the traffic capacity of a weaving area and mitigate traffic congestion on expressways.

Keywords Active-lane management, Intelligent connected vehicles, Lane-changing behavior, Urban expressway, Weaving area

Paper type Research paper

1. Introduction

As the main road networks in large cities, expressways provide services for long-distance and rapid traffic in cities. With the rapid economic development and accelerating process of urbanization, the number of motor vehicles and traffic demand has increased, congestion on expressways has become a significant concern, especially during morning and evening peak hours. Currently, weaving areas have become one of the major bottlenecks in urban expressways traffic. The main reason for traffic congestion in weaving areas consists of the non-standard, irrational and non-optimized behaviors of the traffic participants. Random and disorderly lane-changing behaviors have significantly hampered the realization of the maximum design capacities of expressways. In particular, the actual running speeds of vehicles in a weaving area are significantly lower than the design speed and their actual traffic capacities often fail to attain the design capacity. With the

continuous development of intelligent connected vehicle (ICV) technology, it is possible to solve the traffic congestion in expressway weaving areas via the new perspective of the initiative for fine lane management.

In recent years, many researchers have shifted their research focus to urban expressway weaving areas. [Chen et al. \(2016\)](#) presented an in-depth analysis of the interweaving behaviors of a weaving area using an analytical model developed by a microscopic simulation method. [Wang et al. \(2015\)](#) presented a multi-level Bayesian logistic regression model to study the risk of crashes using real-time crash data and an intelligent transportation system (ITS) to reduce the risk of crashes in

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weaving areas. The crash risk for the following 510 min of weaving segments related to the mainline speed at the beginning of a weaving segment, the speed difference at the beginning and end of a weaving segment and the volume logarithm were analyzed. The proposed model combined with ITS enhanced the security of the weaving segments in real-time via ramp metering, dynamic message signs and high-friction surface treatments. Wang *et al.* (2021) took conservative and radical driving behaviors into consideration to conduct quantitative analysis and evaluation on the confluence behavior of freeway on-ramp congested traffic. Based on the analysis of actual data, it is concluded that the interactive decision-making among autonomous vehicles should consider the social preferences of surrounding vehicles and filter out irrelevant information to improve its performance.

Xie *et al.* (2012) analyzed the relationships among lane-changing, speeds and densities of different lanes in an urban expressway weaving area for given traffic conditions and level of service two. The effects of lane change factors between a series of recommended models and existing models were examined. Tanaka *et al.* (2017) developed vehicle control algorithms that were implemented into a microscopic traffic simulation model to evaluate the effectiveness of the algorithms. Statistics on the throughput of the downstream segment of a weaving area and the lane-changing position of individual vehicles were compiled. The result showed that the total throughput decreased as the weaving ratio increased. Abdel and Wang (Abdel-Aty and Wang, 2017) used VISSIM simulation software to test several variable speed limit (VSL) strategies using collision probability and collision counts to evaluate the impact of VSL strategies on traffic safety. The VSL that was installed upstream of a weaving segment was determined to be safer than the VSL that was installed downstream of the weaving segment. Sun *et al.* (2016) established models for total crashes, non-congested-flow crashes and congested-flow crashes based on the real-time traffic conditions of each collision. The spatial correlation was considered to establish relevant spatial and distance-related spatial models and a Bayesian method was used as an evaluation parameter. Four factors – congestion index, merger ratio, ramp density and daily average traffic volume – significantly affected the collision frequency. Han *et al.* (2016) investigated the traffic flow parameters of the upstream and downstream wave sources, analyzed them and obtained the parameters of the wave characteristics. They provided response strategies for traffic management departments by abnormal changes in traffic fluctuations. Zhao *et al.* (Zhao and Xu, 2017; Zhao *et al.*, 2016) presented an integrated design model to eliminate traffic weaving and to maximize the section's overall capacity. The mixed-integer non-linear programming model was used to optimize the motion selection, interval layout and signal timing of the pre-signal control in a unified framework. The results showed that the proposed integrated model was effective in improving traffic capacity under various geometric configurations and traffic demand pattern scenarios. An *et al.* (2019) established a cellular automaton model, in which three different lane changing rules were considered to match the driving behaviors in lane assignment.

Suzuki *et al.* (2016) evaluated the collision risk using the surrogate safety measure and collision with urgent deceleration (PICUD) index to analyze the collision risk. Their findings indicated that the location of the conflict was related to the traffic volume. Using sensitivity analysis to study

countermeasures for reducing the collision risk, the service level index of the rear-end collision risk level was proposed. Zhang *et al.* (2013) explored the relationship between environmental- and traffic-related accidents and urban expressways. Using a generalized estimating equations procedure, the time-correlation of collision events was greater than the time-related disability of collision events. The disability rate had a significant relationship with rainfall and temperature and the risk of vehicle disability was high for traffic-intensive and low-speed conditions. Yun *et al.* (2017) investigated the effect of the lane-changing behaviors of an urban expressway and concluded that the traffic flow density and the time at which vehicle navigation provided information affected the lane-changing behaviors. Zhao *et al.* (2016) presented an integrated optimization model for a one-side weaving segment and a mixed-integer-non-linear program that two optimization strategies and combinations of lane assignment and on-ramp signal control would be considered. The results showed that the model could improve the capacity of a weaving segment. Cheng *et al.* (2015) proposed an automatic incident detection method using loop detector data for urban expressways and a detection logic based on density difference fluctuation mode. Li *et al.* (2016) verified an extended generalized filter algorithm through the data collected on the expressway section of Beijing. Sun and Sun (2016) based on the crashes data and traffic flow detection data of Shanghai expressways, a hybrid model combining a support vector machine model with a k-means clustering algorithm was presented to predict the possibility of crashes. The results showed that the accuracy of the accident prediction model could reach 78%. Previous scholars focused on the weaving behaviors of expressway weaving areas, on traffic flow of on-ramp and off-ramp and crash risk assessment by models and algorithms. However, there was little research on the active lane management in the weaving areas and its influence on driving behaviors.

To study lane-changing behaviors, Vechione *et al.* (2018) comparatively analyzed the behaviors of mandatory and random lane changes, expressed the difference between the subject vehicle and the surrounding vehicles by the lane changes decision variable and compared the lane changes of the mandatory and the free by the Kolmogorov-Smirnov test to the cumulative distribution. Park *et al.* (2018) proposed the lane-changing risk index to evaluate a new method of vehicle lane-changing collision risk using a fault tree analysis as the evaluation framework, which combined the exposure time and the expected collision severity of a potential collision and obtained traffic and streaming vehicle trajectory data. Keyvan *et al.* (Keyvan-Ekbatani *et al.*, 2016) investigated the decision-making process of lane change maneuvers of various drivers based on a two-stage test drive. The results concluded that the choice of lane-changing was related to vehicle speed. A new lane-changing model was developed. Atagoziyev *et al.* (2016) developed an algorithm that enabled a single vehicle to perform lane changes in the shortest time and used various scenarios to illustrate the algorithm. Pan *et al.* (2016) proposed a novel mesoscopic multi-lane mode that captured actual multi-lane traffic dynamics by simulating forced and autonomous lane-changing behaviors and identifying different priorities based on different lane-changing motivations and corresponding urgency. Sulejic *et al.* (2017) proposed an algorithm to optimize

the distribution of lane-changing, which evaluated the optimized lane transformation using the microscopic simulation of the weaving segments of the one-sided motorized lane and introduced the problem of lane-changing in the weaving segments. Shiomi *et al.* (2015) developed a multi-lane first-order traffic flow model to represent the dynamics of lane changes and to balance the traffic flow allocation to improve the traffic throughput of bottleneck segments. Gong and Du (2016) proposed a lane change warning model to solve the lack of optimal positioning of the existing technology. This model could determine the best location, set an early compulsory lane change warning near an exit and minimize the traffic delay caused by the lane changes. Zheng (2014) commented on the progress of the model of lane-changing behavior and discussed the characteristics of the lane change model. Zhou and Itoh (2016) modeled the lane change decision based on a case study and collected lane-changing data, which revealed that a driver tended to prefer the time to the collision to the time headway to the rear vehicle. Kuo and Tang (2011) developed a new modified link-labeling Dijkstra algorithm to find the shortest path considering lane-changing. Mai *et al.* (2016) applied the microscopic simulation in AIMSUN to evaluate the effectiveness of the proposed strategy in a one-sided ramp weave. This research investigated a lane-changing distribution advisory application based on cooperative intelligent transport systems for weaving vehicles in weaving sections. Talebpour *et al.* (2015) proposed a lane-changing model based on a game-theoretical approach. The model considered the information flow in the connected vehicle environment from an endogenous point of view. Previous studies on lane-changing behaviors mostly used algorithms and models to analyze lane-changing, lane-changing models were carried out in different ways to predict the risk index and influence of lane-changing behaviors. Zhang *et al.* (2020) introduced a Bayesian non-parametric method, which used continuous (i.e. Gaussian processes) and discrete (i.e. Dirichlet processes) stochastic processes to reveal the potential interaction mode between ego vehicle and adjacent vehicles and verified the effectiveness of the method based on actual data in highway lane change scenarios. However, there was no in-depth study on the active and guided lane changes in weaving areas of expressways. There was little research on the fine lane management in weaving areas. In terms of behaviors, the study of lane-changing guidance was hardly involved.

Currently, domestic and international research on urban expressway weaving areas primarily focuses on weaving areas with the capacity, the evaluation of the service level and the analysis of the operating characteristics. However, few studies address the active fine lane management for weaving areas of expressways. With the development of intelligent transportation, the concept of active traffic management and control becomes more and more mature. To meet the new trend of vehicle autonomous driving in the ICV environment, this paper comprehensively analyzes the vehicle behaviors in different weaving areas and the causes of congestion proposes a method for fine lane management in weaving areas and builds a microscopic traffic model that is oriented to the weaving areas of expressways based on survey data. The simulation scenarios verify the fine lane management method and propose constructive opinions and future research. The objective of the

research is to improve the capacity of expressway weaving areas by guiding and constraining the vehicles' lane-changing behaviors.

2. Lane-changing behaviors analysis of a weaving area

A weaving area is an important part of an urban expressway system. The weaving flows in a weaving area affect the non-weaving flows in a weaving area, which causes fluctuation and turbulent and complex flow of traffic between weaving areas. Frequent lane-changing of weaving vehicles has caused the weaving area to be a major bottleneck, which reduces the operating efficiency of the urban expressway system. Bottlenecks in weaving areas should be reduced and eliminated to improve the capacity and service level of a road system.

The lane changes during the operation of a weaving area have an unfavorable influence on the traffic flow conditions in the weaving area. During the weaving process, geometric features, such as the number of entrance lanes and exit lanes and the relative positions of the lanes and weaving lanes of the weaving vehicles, are closely-related. The geometric features form different weaving area configurations. Figure 1 shows a simplified schematic of weaving traffic.

When a vehicle is driving on an expressway, the vehicle must change lanes in the weaving area because the vehicle leaves the mainline or the ramp vehicle enters the mainline. Drivers may also change lanes according to their wishes, driving needs and driving safety. This section analyzes the lane-changing behaviors in different traffic directions in a weaving area.

Figure 2 shows a section of an expressway weaving area, which contains the four directions of the weaving area. The four demand flows are described as follows: A to B, mainline to mainline, the flow rate is Q_{AB} ; A to D, mainline to the ramp, the flow rate is Q_{AD} ; C to B, ramp to the mainline, the flow rate is Q_{CB} ; and C to D, from ramp to ramp, traffic is expressed as Q_{CD} . The capacity of a weaving area is affected by the length of

Figure 1 Traffic weaving schematic in the weaving area

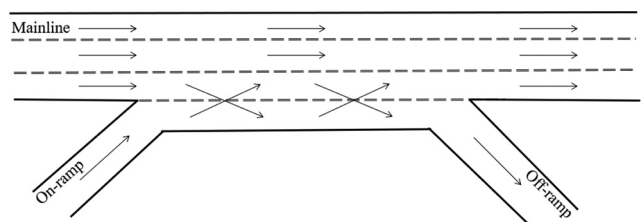
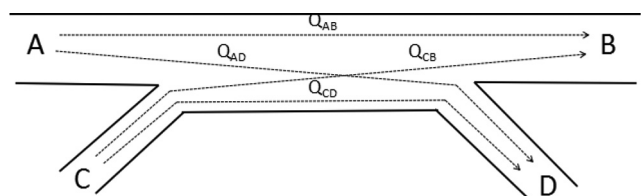


Figure 2 Composition of the weaving segment and the flow direction of the traffic flow



weaving, the ratio of weaving traffic and the number of weaving lanes.

2.1 Two lanes with different flow directions in the weaving area

The single lane of the mainline and a ramp form a simple two-lane weaving area. Each flow-direction traffic stream presents a simple weaving lane-changing behavior in the weaving area. As shown in Figure 3, the lane-changing behaviors of the vehicles in different directions are given. For the main-line to main-line flow, the mainline-driving vehicles generally continue to move in the original direction and weaving behaviors do not occur in the weaving area. Vehicles can maintain the expected speed throughout the weaving area. If the traffic volume is large and congestion occurs in the weaving area, the vehicles on the mainline will inevitably decelerate or stop to exit safely. Although these cases differ to a driver's freedom of driving, the mainline will be oriented in a straight direction. Vehicles move in the original direction and do not make lane changes. For the on-ramp to off-ramp flow, the vehicles are generally similar to the vehicles on the mainline. Weaving lane changes do not occur in the weaving area. Vehicles travel along with the outer lane and exit the ramp. If the traffic volume in the weaving area is large, a driver's freedom of driving is affected and restricted. If the distance between the weaving areas is short, the proportion of vehicles that enter the ramp via the weaving area and then exit the same ramp is very small and almost negligible. In this case, the on-ramp to off-ramp flow can be disregarded. For mainline to off-ramp flow, vehicles generally enter the weaving area and look for opportunities to change lanes to the right lane and then exit along with the right lane to the exit ramp. In this case, a vehicle will interweave with the ramp-to-mainline vehicle in the weaving area to change lanes to their

respective lane. When congestion occurs in the weaving area, the mainline outbound vehicles may continue to travel straight until they approach the exit to change lanes. Drivers will inevitably need to slow down or even stop to complete their lane-changing, which will cause vehicles to take corresponding measures to ensure the safety of their vehicles. The out-of-the-road vehicles that have completed their lane-changing will decelerate or stop and wait for other vehicles to change lanes and exit the ramp. As a result, the capacity of the weaving area is significantly lower than the designed capacity. For the on-ramp to mainline flow, the route is similar to the mainline exit route. The drivers will seek an opportunity to change lanes to the inside lanes as soon as they enter the weaving area. If the weaving area is congested, the vehicles of mainline lanes into the exit lane will reroute to the inner lanes, which inevitably affects the flow of other vehicles and increases the delay in the weaving area.

2.2 Three or more lanes with different flow directions in the weaving area

For the situation in which the weaving area is a minimum of three lanes, without a loss of generality, this paper selects four lanes as an example to illustrate the flow direction change. The remainder of the situation is similar to the four-lane lane-changing in the weaving area and will not be repeated. The lane-changing of the four lanes in the weaving area is shown in Figure 4. For mainline straight-driving vehicles in the weaving area, the majority of the vehicles continue to travel in the original direction but some drivers will attempt to change lanes to the inboard lanes to satisfy their driving experience. Due to less interference from the mainline to vehicles, a driver can freely change lanes in the inner three lanes of the weaving area base on his driving needs. Vehicles of the on-ramp to off-ramp

Figure 3 Behavior of two lanes with different flow directions in the weaving area

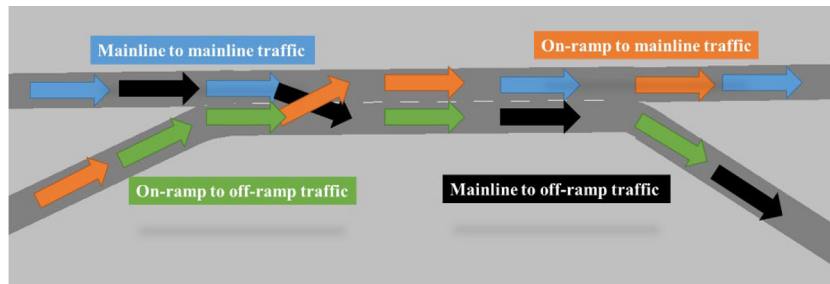
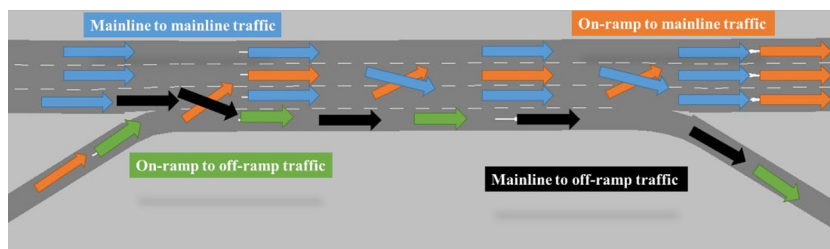
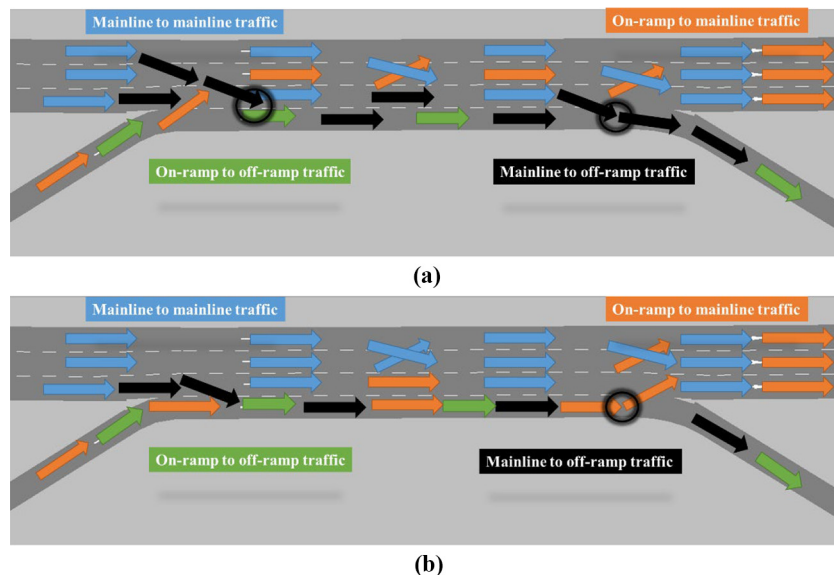


Figure 4 Four-lane lane-changing in weaving area



flow continue to exit the ramp along with the right lane in normal conditions. Weaving does not occur in the weaving area. Generally, the proportion of vehicles that enter the ramp via the weaving area and then exit the ramp and the impact on the lane-changing in the weaving area are relatively small. Main lane exit vehicles will change lanes in advance in the front area of the weaving area. As soon as a driver enters the ramp, he will seek opportunities to change lanes to the right lane of the weaving area and then access the off-ramp along with the right lane. However, some of the outbound vehicles start to change lanes from the inner lanes after entering the weaving area, which will cause interference with the vehicles on the mainline of vehicles that had completed lane-changing. Due to irregular driving habits, some drivers continue to travel straight in the original direction in the weaving area but do not change lanes to the right lane in advance. They do not begin to change lanes until they approach the exit ramp, which will not only affect the mainline vehicles but also interfere with the vehicles that had completed lane-changing. These non-standard lane-changing behaviors caused by drivers' decisions can reduce the speeds of traveling vehicles and the capacity of a weaving area, as shown in Figure 5(a). On route to the mainline vehicles, a vehicle will change lanes to the inside lanes when entering the weaving area to quickly enter the mainline via the weaving area. After completing the lane-changing, the vehicles will travel straight to the main lane and freely change lanes according to their needs in the weaving area. When traffic in the weaving area is heavy, vehicles will drive along with the original lane to reduce mutual interference. Drivers on the mainline may drive along with the right-most lane of the ramp until they change lanes near the exit to achieve the purpose of entering the mainline. If the weaving area is congested, these vehicles will significantly interfere with the other three-flow vehicles. The flow of vehicles has aggravated the congestion in the weaving area, as shown in Figure 5(b).

Figure 5 Irregular lane-changing behavior in the weaving area



Notes: (a) Off-ramp vehicles; (b) on-ramp vehicles

2.3 Weaving area causes of congestion

Bottlenecks in a weaving area must be reduced or eliminated to improve the capacity and service level of an entire road system. Some causes of congestion in the weaving area are described as follows:

- The parameters of the weaving area (interleaving length and interlacing ratio) are unreasonable as follows: the traffic flow is heavy and the interleaving length sections are short, which causes the majority of vehicles to gather in the weaving area, significantly affecting the speeds of vehicles and possibly causing traffic accidents. The capacity of the road declines and is not influenced by the effect of traffic;
- If the distance between two intersections is too short, all lane-changing operations of a vehicle should be completed within the weaving area. If the interval between the two intersections is too short, the length of lane change required by the vehicle cannot be satisfied and the interwoven traffic flow cannot occur in a shorter area. After the weaving is completed, vehicles will accumulate in large numbers in the weaving area and the entrance lanes of the intersections, which causes congestion in the weaving area and affects the capacity and efficiency of the intersections;
- For the weaving area, the lane function division cannot satisfy the actual traffic flow operating characteristics, which will cause a certain degree of congestion. The road traffic signs and markings, especially the lane direction markings, are uncertain or unclear, which causes a certain degree of misjudgment by a driver. As a result, the driver may temporarily change lanes, make a U-turn or make a sudden stop, which may cause congestion, even in the case of a relatively serious traffic accident in which high speeds are involved;
- A driver's uncivil driving behavior can cause the formation and intensification of congestion in a weaving area. When

the mainline-driving vehicles exit a ramp, changing lanes in advance to the outer lane to the off-ramp is generally necessary. However, many drivers will start changing lanes near the off-ramp. To ensure that vehicles can smoothly exit the ramp, the drivers will randomly and frequently change lanes in the weaving area. Vehicles park near the off-ramp and use the lanes of the weaving area, which reduces the speeds of mainline-driving vehicles and affects the acceleration process when vehicles enter the main road;

- When the on-ramp vehicles satisfy the import conditions, the drivers are not confident in their driving skills or their judgment of the import conditions is inaccurate, which causes drivers to hesitate when entering the mainline. The mainline-driving vehicles consider the entry of the incoming vehicles and then decelerate, which causes a general decline in the speeds of converging traffic and reduces the utilization rate of these lanes; and
- Because a driver did not obtain route information promptly due to distractions, the driver can only drive away from the mainline across multiple lanes in the weaving area to smoothly exit the weaving area. His lane-changing is large and will affect other vehicles.

Due to the unreasonable design of the road or drivers' non-standard driving behaviors, these situations can cause congestion in the weaving area and wasted road resources.

2.4 Investigation and analysis of typical behaviors

The typical Shuangjingqiao North weaving area near Beijing Dongsanhuan Middle Road Guomao Bridge is selected as an example to analyze the lane-changing behaviors of vehicles in a weaving area. The Shuangjingqiao North weaving area connects to a side road of Dongsanhuan Middle Road. The side road vehicles enter via the entrance ramp and the mainline vehicles exit via the off-ramp. The entrance ramp connects the four lanes of the weaving area; the C length is approximately 120 m. The weaving area shown on the Baidu map is shown in Figure 6.

From an on-the-spot investigation, the straight-driving traffic flow on the mainline of the Shuangjingqiao North weaving area is relatively large, the drivers' driving freedom is low and drivers can only decelerate. Off-ramp vehicles do not complete their lane changes before entering the weaving area. To smoothly exit the off-ramp, the vehicles can only frequently change lanes during weaving, which will inevitably interfere with other vehicles and make other vehicles decelerate in the weaving area. As shown in Figure 7, the vehicle in the circle must exit the mainline and change lanes from the innermost lane in the weaving area. As a result, the following straight-driving vehicles can only decelerate or stop while waiting for their exit; they occupy the straight lanes. To avoid collision with the vehicles that enter the ramp, the vehicles park in the outside lane to ensure driving safety and space in multiple lanes in the weaving area. The lanes are not fully used, which causes congestion on the mainline.

If all vehicles that drive away from the mainline can complete their lane-changing before the weaving area, mainline straight-driving vehicles will continue to drive in the original direction. The outbound mainline vehicles will pass through the weaving

area in the right lane, which significantly increases the capacity, service level of the weaving area and the speeds of vehicles. Figure 8 shows the traffic situation in the weaving area after changing lanes in advance. The taxi in the circle is looking for opportunities to change lanes to the outside lane when it enters the weaving area. The vehicles in the weaving area are driving in an orderly manner, which significantly improves the capacity of the weaving area.

3. Fine-lane management approach of a weaving area

With the continuous development of intelligent net-connected vehicle technology, it is possible to implement active refined

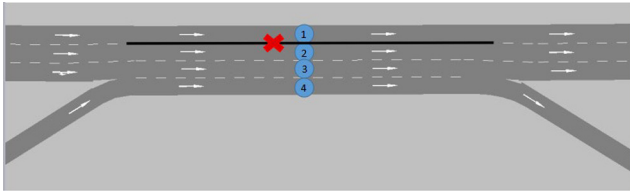
Figure 6 Typical weaving area on Baidu map



Figure 7 Non-standard lane change vehicles in the weaving area



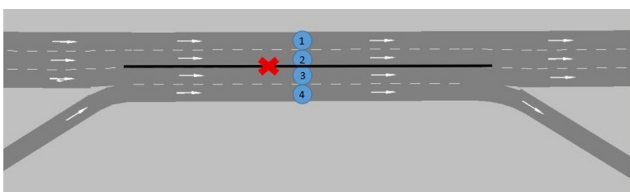
Figure 10 Lane-changing isolation scheme for weaving area (Scenario III)



weaving area but cannot change lanes to the first lane. These vehicles will be affected by other vehicles due to high interference. Thus, the speeds of the vehicles generally decrease. As the off-ramp vehicles have changed lanes to the right-most lane, they will find opportunities to change lanes to the fourth lane as soon as they enter the weaving area and smoothly depart from the ramp with less delay through the weaving area. In this case, the vehicles in the first lane are the mainline straight-driving vehicles and these vehicles' speeds are generally high. In the second lane and the third lane, the remaining straight-driving and on-ramp vehicles will interweave and change lanes between the two lanes to satisfy the drivers' driving needs and all vehicles in the fourth lane will be off-ramp vehicles that have changed lanes. As shown in Figure 11 (Scenario IV), the separation between the second lane and the third lane prohibits lane changes. Most of the mainline vehicles will change lanes by guiding lane-changing before entering the weaving area. Then, the vehicles will continue along with the original direction in the first lane and the second lane; the weaving behaviors of most of the straight-driving vehicles and other flow vehicles in the weaving area are avoided and the safety of vehicles in the weaving area is improved. A very small portion of straight-driving vehicles and mainline off-ramp vehicles that have not changed lanes are driven in the outer lanes of the mainline. These straight-driving vehicles will pass through the third lane of the weaving area with the vehicles on the mainline due to the interference of the on-ramp vehicles. The speeds of the straight-through vehicles relative to the first and second two lanes of vehicles will decrease and the main-line off-ramp vehicles will seek opportunities to change lanes to the fourth lane when entering the weaving area and then smoothly proceed.

By guiding lane-changing in advance and adopting the lane-changing isolation approach, the problem of congestion in the weaving area can be effectively alleviated or even solved. In the practical application, we can choose the appropriate driving behavior guidance methods according to the actual road conditions and guide the vehicles to change lanes in advance

Figure 11 Lane-changing isolation scheme for weaving area (Scenario IV)



before entering the weaving area. The lane separation is implemented by drawing white solid lines at the corresponding lane position of the weaving area, to prevent the vehicles from changing lanes. Straight-line and off-ramp vehicles change lanes in advance of the weaving area, avoid or reduce interference with other flow vehicles. This occurrence can ensure the running speeds of the straight-line and off-ramp vehicles in the weaving area, reduce the delay of vehicles that pass through the weaving area and increase the safety of vehicles. The weaving area is lane-separated and lane-changing is prohibited between the corresponding lanes. This situation will avoid the interference of on-ramp vehicles that enter the main lane to the straight-driving vehicles and ensure the speeds of straight-through vehicles. When a large volume of traffic exists on the mainline, many vehicles exist on the off-ramp and fewer vehicles exist on the on-ramp, guiding lane-changing in advance and adopting the weaving area lane isolation approach can effectively solve the congestion problem and improve the efficiency and safety for the weaving area of an urban expressway.

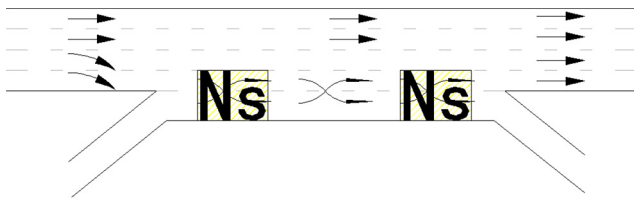
3.2 Lane-changing in advance with conflict avoidance area strategy

A conflict avoidance area, which is also known as a conflict avoidance N-second (Ns) area, uses the concept of the basketball's 3 s area, that is, the preset traffic conflict avoidance area in certain key areas or locations (such as weaving area, signalized intersection and on-ramp link) in the traffic network. In a conflict avoidance area, the time occupied by a vehicle cannot exceed the preset time threshold Ns. Specifically, the preset time threshold is determined according to the traffic volume, the size of the road and the lane coverage. If the occupancy time of a vehicle in the preset traffic conflict area exceeds the preset time threshold, the vehicle is considered to violate a regulation, the driver of the vehicle will be fined. Thus, to reduce the vehicle stopping or waiting time in the critical area, avoid occupying the conflict avoidance area for a long time.

According to the driving state information of the vehicle in the conflict avoidance area, when it is determined that the occupation time of the vehicle in the preset traffic conflict area exceeds a preset time threshold, the violation information of the vehicle is generated. According to the vehicle information, the violation information is transmitted to the communication terminal of the vehicle. As the purpose of this section is only to propose a conflict avoidance area strategy, specific types of equipment and other issues will not be discussed in detail in this section. The conflict avoidance area can effectively improve the capacity of roads, reduce traffic delays in key areas, ensure the safety of vehicles and effectively improve the efficiency and capacity of key areas. A possible arrangement of the Ns area in the weaving area is shown in Figure 12.

As the previous section detailed how to guide lane-changing in advance, this discussion will not be repeated here. Based on the guiding early lane-changing management approach, to mitigate congestion in the weaving area, a conflict avoidance area can be established in the corresponding key areas or locations of the weaving area and a corresponding time threshold value can be selected according to the traffic flow conditions to prohibit vehicles from occupying the time in the conflict avoidance area that exceeds the set time threshold.

Figure 12 Possible arrangement of conflict avoidance area in the weaving area



Note: Ns in Figure 12 means N-second area

Otherwise, drivers will be punished. When the traffic volume in the weaving area is small, the drivers can successfully pass through the conflict avoidance area and will not be limited by the time threshold. When the traffic volume is large, especially when the off-ramp has become congested, the vehicles on the mainline will be affected. After the conflict avoidance area is established, when congestion occurs, the key conflict avoidance area can be vacated in the weaving area, which enables the on-ramp vehicles to smoothly merge with the mainline vehicles and the off-ramp vehicles can sequentially exit the ramp. The total delay of the weaving area can be reduced, which is significant for solving the congestion problem in the weaving area.

The off-ramp in the throat area between the urban expressway and the normal road is a typical traffic bottleneck. Vehicles are often lined up to the off-ramp at the intersection where the off-ramp and the road network are connected. This bottleneck restricts the exit of vehicles on the off-ramp, coupled with the drivers' uncivil driving behaviors. Some drivers approach the off-ramp and forcibly enter the off-ramp. These behaviors have aggravated the queuing on the outer lane. Vehicles that occupy the ramp lane on the side road exacerbate the queues on the ramp and other factors that prevent vehicles on the ramp from clearing. The vehicles on the ramp occupy the outer lane of the weaving area and spread to the mainline and on-ramp vehicles cannot be imported. This situation causes congestion in the entire weaving area and collapses of the entire expressway system. After the conflict avoidance area is established in the weaving area, the mainline vehicles observe that vehicles in the right lane of the weaving area have lined up to the rear and will allow the conflict avoidance area to be vacated for the passage of vehicles that enter the mainline to avoid the impact of queued vehicles of the off-ramp on the on-ramp vehicles. Because the vehicles on the off-ramp are waiting for parking, the vehicles will not continuously flow into the exit. The queuing pressure on the off-ramp has been eased and the queuing phenomenon will begin to slowly dissipate. By early lane-changing guidance and the establishment of a conflict avoidance area in the weaving area, the straight vehicles of the mainline continue to move forward along with the inner lanes and the off-ramp vehicles change to the outer lane in advance, avoiding the impact on the main-line and on-ramp vehicles. The conflict avoidance area provides space for on-ramp vehicles to enter the mainline and relieves the pressure of off-ramp queuing, then the problem of congestion on the off-ramp is perfectly resolved. Although a certain delay to the off-ramp vehicles on the mainline may occur, the total congestion of the on-ramp and weaving area can be alleviated.

4. Modeling and simulation

Based on the actual survey data, VISSIM sets up the simulation scenarios by establishing the corresponding traffic parameters in the simulation area to simulate the traffic flow near the weaving area. The total length of the simulated road comprises approximately 120 m of the weaving area, approximately 350 m in front of the weaving area and approximately 300 m after the weaving area. The total number of lanes is based on the actual survey as follows: the mainline has three lanes, the weaving area has four lanes, the on-ramp and the off-ramp consist of one lane separately, the weaving area side road consists of two lanes and the other area side road comprises three lanes.

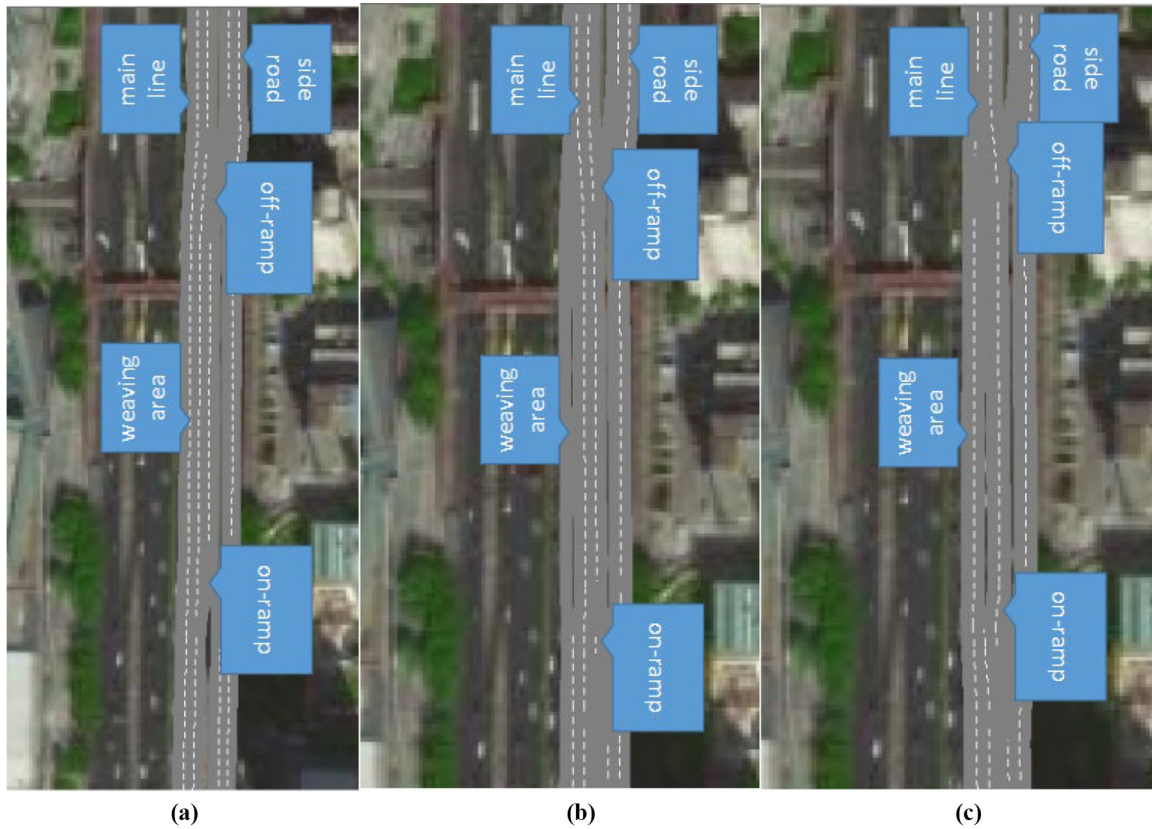
4.1 Simulation of the current situation and lane separation management approach

According to an actual investigation, the urban expressway is primarily based on small passenger cars. The traffic flow is unified as an equivalent traffic volume, the mainline flow is 3,750 pcu/h, the speed limit is 80 km/h; the side road flow is 2,000 pcu/h/lane, the speed limit is 60 km/h; the proportion of the mainline vehicles exit is 20%, the proportion of the side road vehicles that enter into the mainline is 45% and the speed limit on the on-ramp and off-ramp is 40 km/h. The research data are imported into VISSIM and serve as the basic data. The data are combined with actual conditions to establish the current status and the weaving area is isolated with lane-changing in different scenarios in the simulation.

To effectively reflect the operational status of the traffic flow in the weaving area and facilitate a comparative analysis of the simulation results of the fine lane management approach, travel time detectors are installed to detect the average delay of the vehicles that pass through two sections in the statistical period. Four travel time detectors are used in the current simulation scenario; they detect the average delay from mainline to mainline, mainline to the ramp, side road to mainline and side road to side road. The starting point is set to 350 m before the mainline and the side road, the ending point is set to 300 m downstream of the mainline and the off-ramp of the side road.

Based on this road network, basic data and simulation parameters, the simulation scenarios run 3,600 s, the delay indicator is output and the current simulation result is obtained. To eliminate the influence of VISSIM's randomness on the results, different seeds were used to simulate the scenarios for many times (more than 10 times) and the results were averaged.

Based on the current road network, lane isolation is performed between the lanes of the weaving area. Two cases are considered. The first case is the separation between the first lane and the second lane and the second case is the separation between the second lane and the third lane, that is, Scenarios I and II. In VISSIM, to achieve the effect of lane separation, the target lane is painted separately. These two simulation scenarios are each run for 1 h. The delay is also used as an indicator to output the simulation results of Scenarios I and II. The simulation scenario is shown in Figure 13 as follows: the output delays of three different simulation scenarios, including average delay, off-ramp delay and on-ramp delay. The results are listed in Table 1.

Figure 13 Traffic simulation in different scenarios**Notes:** (a) Scenario 0; (b) Scenario I; (c) Scenario II**Table 1** Average delays in different simulation scenarios

Scenario	Average delay (s)	Off-ramp delay (s)	On-ramp delay (s)
Scenario 0	3.4	7.3	7.3
Scenario I	3.2	4.9	2.9
Scenario II	3.3	6.6	1.6

4.2 Simulation of lane-changing in advance with lane separation management approach

Based on the status road network and combined with actual survey data, simulations of lane-changing in advance and lane-separation in the weaving area are performed. The simulation scenarios are based on the current situation simulation. To achieve the effect of an early guided lane change in VISSIM, the three lanes of the mainline are, respectively, input into the flow from left to right. Different ratios are given for different lanes of vehicles on the outbound ramp. The two scenarios of the forbidden lane-changing regarding the first lane and the second lane of lane changes (Scenario III) and the second lane and the third lane of lane changes (Scenario IV) in the weaving area are simulated. In Scenario III, the traffic volumes of the three lanes from the left lane to the right lane are 1,300 pcu/h, 1,250 pcu/h and 1,200 pcu/h. The innermost lane of the mainline contains straight-through vehicles that pass through the first lane of the weaving area; 95% of the straight-driving vehicles in the middle

lane of the mainline pass through the second lane and the third lane of the weaving area. The remaining 5% of the vehicles comprise the vehicles of mainline to the off-ramp. They drive through the lanes of the weaving area. In total, 15% of the straight-through vehicles and 85% of the ramp vehicles are allocated to the right lane of the mainline. In Scenario IV, the flow volume for each lane of the mainline is 1,250 pcu/h and the inside two lanes of the mainline contain straight-driving vehicles. These vehicles pass through the first lane and the second lane of the weaving area. In total, 25% of straight-driving vehicles and 75% of off-ramp vehicles are allocated to the right-most lane of the mainline.

Except for the different ratios of flow distribution and path selection in each lane of the mainline, the simulation scenarios are identical to the other parameters and the status simulation. It should be pointed out that the ICV environment is the foundation of this paper and assumes that all vehicles are subject to the active fine lane management method proposed in

this paper. However, the traffic flow environment constructed in this paper does not consider the real-time dynamic communication between vehicles. Fortunately, The VISSIM software supports setting the path of vehicle groups, which enables VISSIM to depict the traffic flow characteristics required by the ICV environment, thus studying the effect of fine lane management approaches under the ICV environment.

Different scenarios run for 1 h, the output once every 600 s and the corresponding delay indicators are obtained. The simulation output results for the different scenarios are compared with the current situation. The output simulation delays are shown in Table 2.

4.3 Simulation of lane-changing in advance with conflict avoidance area strategy

The main purpose of establishing a conflict avoidance area is to resolve congestion on the off-ramps, especially when queues for the off-ramp are traced to the mainline and significantly affect the entry of on-ramp vehicles on the mainline and to test whether the establishment of the conflict avoidance area is effective in relieving congestion in the weaving area and whether it can solve the problem of queuing on the off-ramp. Based on the original road network, this paper will build a simulation scenario in which vehicles on the off-ramp queue back to the mainline due to an increase in the traffic volume and the expected speeds on the off-ramp decrease and apply this scenario as the current situation in a repeated simulation (Scenario 0-CA). A comparison among the new current situation simulation, the conflict avoidance area simulation, the advanced-guided lane-changing and the weaving area setting conflict avoidance area simulation is performed to test the effectiveness of the lane management approach in the weaving area.

The VISSIM simulation software does not easily implement the concept of a conflict avoidance area and cannot completely

express the idea that the vehicles do not occupy more than N_s in the conflict avoidance area. Therefore, a short cycle signal can only be set at the outside two lanes of on-ramp areas in VISSIM. The method for controlling the signal cycle and green time is convenient for reflecting the management concept of a conflict avoidance area. Based on the situation without a conflict avoidance area, the simulation of the conflict avoidance area in the weaving area is performed by adjusting the signal cycle and green time (Scenario V). Table 3 lists the output delay indicators after 1 h of simulation of the conflict avoidance area for different signal cycles and green times. As the purpose of the conflict avoidance area is to alleviate the congestion in the weaving area, the scheme with the minimum delay in the following table is taken as the final signal timing plan. Simulate for 1 h using this signal cycle and green time to obtain the delay indicators as the simulation result output for establishing the conflict avoidance area.

Scenario VI is based on Scenario V, which refines the traffic volume per lane of the mainline, re-plans the proportion of route selection and forms a simulation environment for guiding the lane-changing in advance. Based on guiding lane-changing in advance and adding a simulation scene of the conflict avoidance area, this scenario is simulated for 3,600 s and the output delay indicators are compared with the output delay of the first two simulation scenarios.

In addition to dividing the traffic flow volume by lane, resetting the path ratios and providing a traffic signal to simulate the conflict avoidance area, the simulation scenario and other parameters are identical to the newly established current situation of the simulation. By the current situation, guiding lane-changing in advance and establishing a conflict avoidance area, two scenarios will be simulated and run for 3,600 s. Then, the corresponding delay indicators will be

Table 2 Delay output of guiding lane changes in advance and change lane separation in the weaving area

Time interval	Scenario III			Scenario IV		
	Average delay (s)	Off-ramp delay (s)	On-ramp delay (s)	Average delay (s)	Off-ramp delay (s)	On-ramp delay (s)
600 s	1.2	2.2	1.1	0.5	0.7	0.9
1,200 s	1.3	1.6	1.6	1.4	1.9	3.1
1,800 s	1.1	1.2	1.3	0.8	0.9	1.3
2,400 s	1.6	2.7	2.8	0.6	0.6	1.3
3,000 s	1.2	1.8	1.1	1.0	1.2	2.1
3,600 s	1.2	1.6	1.5	0.9	1.7	1.4
Average	1.3	1.9	1.6	0.9	1.2	1.7

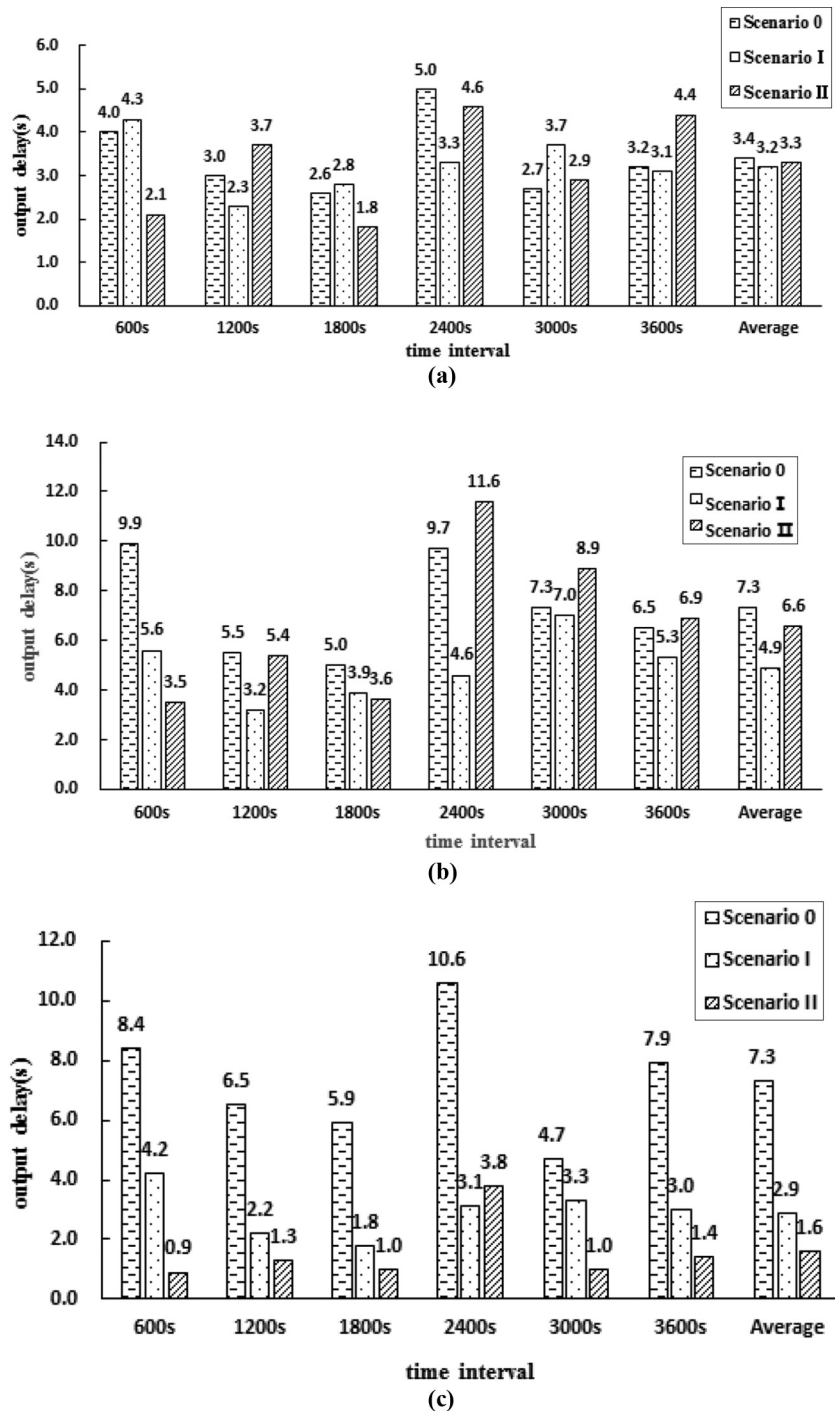
Table 3 Summary of different signal cycle delays of Scenario V

(Signal cycle; Green time)	Average delay (s)	Off-ramp delay (s)	On-ramp delay (s)
(40;20)	62.4	110.4	15.0
(40;25)	65.5	123.6	46.9
(50;25)	59.9	105.8	12.6
(50;30)	74.4	139.6	69.5
(50;35)	77.6	139.7	69.5
(60;30)	61.1	106.2	13.1
(60;35)	70.9	130.2	29.7
(60;40)	87.7	157.5	69.2

Table 4 Delay output comparison results after setting the conflict avoidance area

Scenario	Average delay (s)	Off-ramp delay (s)	On-ramp delay (s)
Scenario 0-CA	99.0	140.7	190.2
Scenario V	55.3	103.8	9.2
Scenario VI	48.8	103.1	9.0

Figure 14 Delay output histogram for Scenarios 0, I and II



Notes: (a) Average delay; (b) off-ramp delay; (c) on-ramp delay

obtained. The simulation output indicators are used to verify whether the fine lane management approach in the weaving area is effective. The delay comparison results are shown in Table 4.

5. Results and analysis

5.1 Simulation results and analysis of Scenarios 0, I and II

Figure 14 is a histogram of the output results for the current situation of Scenario 0, the first lane and the second lane isolation simulation of Scenario I and the second lane and the third lane isolation simulation of Scenario II. Three types of delays – average delay, off-ramp delay and on-ramp delay – in the weaving area serve as the basis for comparison. Each simulation scenario runs for 3,600 s, the output results for each of the three indicators are output every 600 s and the average delay after 3,600 s for all vehicles is output.

From the average delay histogram of the weaving area in Figure 14(a), the weaving area only has a lane-changing separation and the total delay of the weaving area cannot be improved if no-measure is taken. The current status does not have any measure, the average delay in Scenario 0 is 3.4 s, the average delay in the Scenario I is 3.2 s, the average delay in Scenario II is 3.3 s and the delay error among the three scenarios is negligible. Only lane-changing isolation of the weaving area, whether the isolation between the first lane and the second lane or between the second lane and the third lane, these two situations cannot achieve acceptable results in resolving congestion in the weaving area. At some point, the change in lane-changing isolation will cause greater delay than the current status, which aggravates the congestion in the weaving area. Figure 14(b) shows that the delay of the mainline exits for three scenarios. In Scenario I, relative to Scenario II, the delay of the mainline outbound vehicles has been reduced. In different scenarios, the difference between the delay of the vehicles does not significantly differ. In Figure 14(c), after lane-changing isolation measures are taken, the delay in entering the mainline of the ramp is significantly reduced and Scenario II is more effective than the Scenario I in relieving congestion in the weaving area. Generally speaking, the only way of lane separation is not good for the congestion alleviation of the weaving area.

Although the lane-changing isolation measures have a certain effect on reducing the delay of vehicles on the ramp when entering the mainline, the total average delay in the weaving area will not cause a significant effect. Scenarios I and II have a different effects on off-ramp vehicles and on-ramp vehicles. Solving traffic congestion in the weaving area by lane-changing isolation and without taking other measures is meaningless.

5.2 Simulation results and analysis of Scenarios 0, III and IV

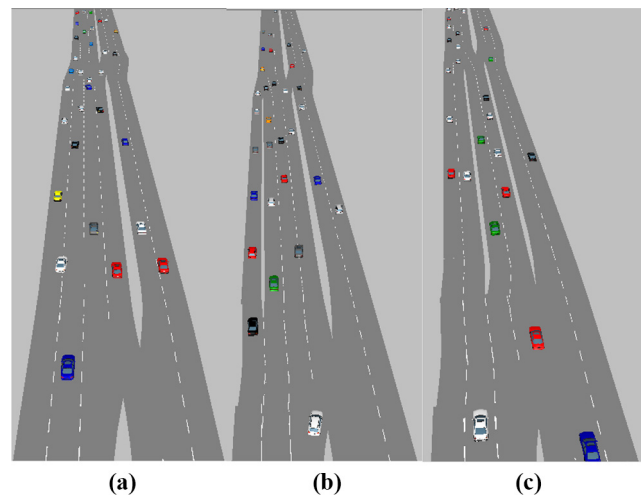
Figure 15 shows the traffic flow statuses of simulation for different simulation scenarios in the weaving area at 1,800 s. From left to right, Scenarios 0, III and IV.

For the simulation scenarios of 1,800 s, we observe that the traffic volume in the weaving area is not very different. The current weaving area is intertwined with a slight disorder. The individual vehicles that enter the mainline change lanes in the vicinity of the off-ramp, which renders traffic in the weaving area confusing. If no-measure is taken on the lane, the weaving

area during the morning and evening peak periods is in a congested state. At the time, the traffic operation is chaotic, which exacerbates the congestion problem in the weaving area. The lane-changing is guided in advance and a lane separation measure is taken in the weaving area. In Scenarios III or IV, vehicles travel in their directions and do not interfere with each other. The traffic operation is conducted in an orderly manner. For the two scenarios, even congestion occurs in the weaving area, vehicles in the weaving area will travel in their direction and the congestion can also dissipate in a short time. This finding is compared with the current situation; the capacity of the weaving area has been significantly improved.

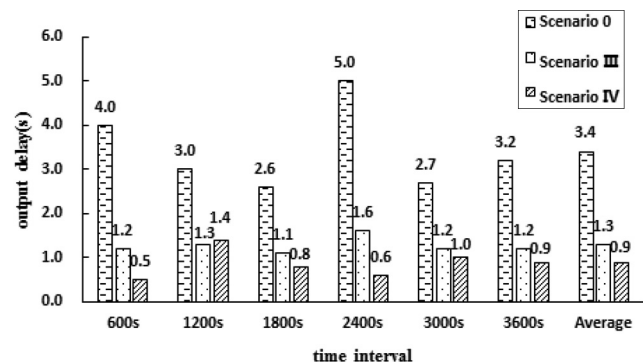
Figure 16 shows the output delay histogram after 3,600 s for Scenarios 0, III and IV. By guiding the lane-changing in advance and adopting a lane-changing isolation measure in the weaving area, the total average delay in the weaving area can be significantly reduced. The delay for Scenario III is slightly greater than the delay for Scenario IV; however, the total difference for Scenario III is less than the total difference for Scenario IV. Using the simulation delay evaluation index,

Figure 15 Traffic flow statuses of different scenarios in the weaving area at 1,800 s



Notes: (a) Scenario 0; (b) Scenario III; (c) Scenario IV

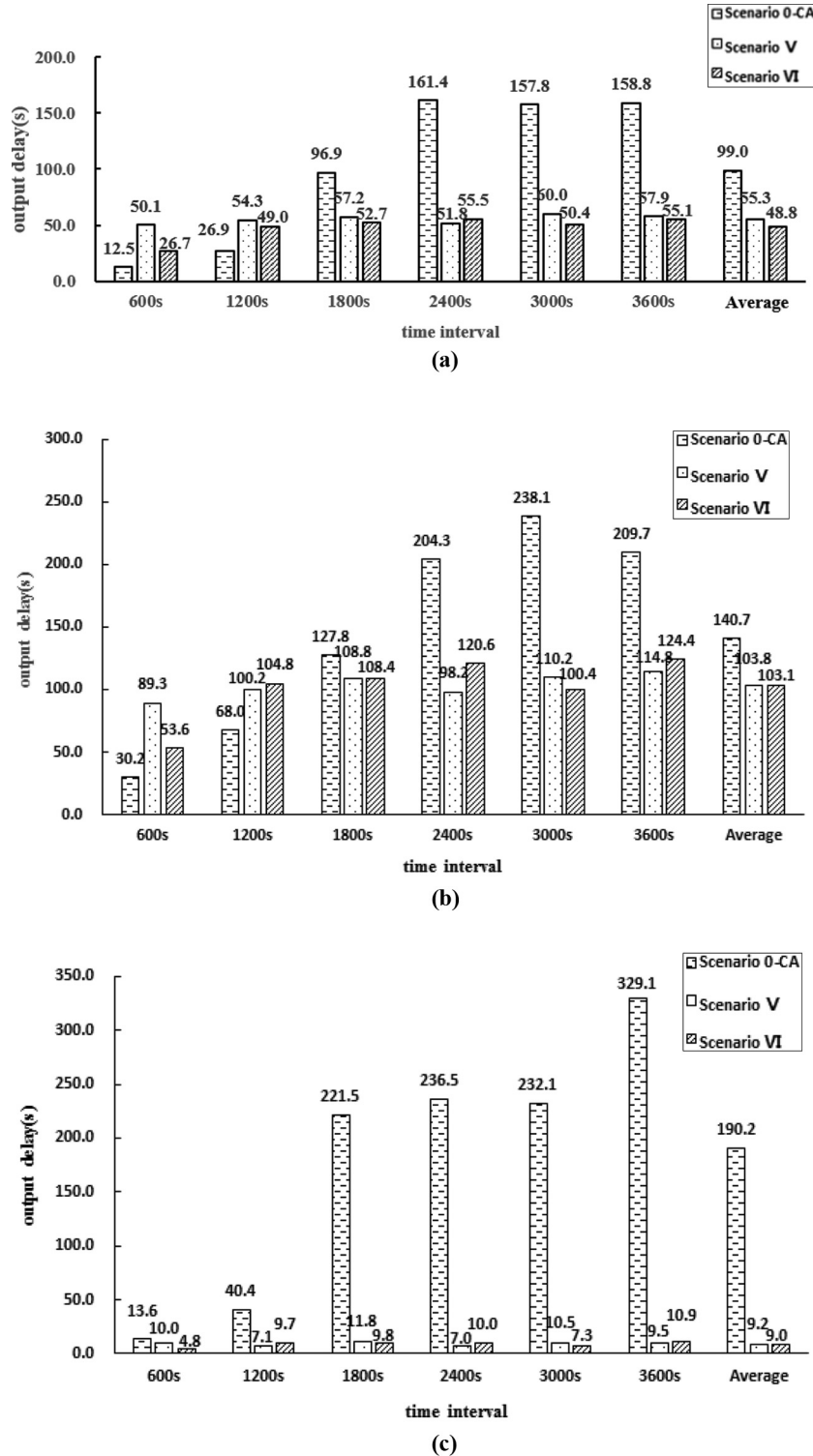
Figure 16 Average delay of current status and fine lane management simulation



guiding the lane-changing in advance and adopting a lane-changing isolation measure in the weaving area can alleviate or even solve the congestion of a weaving area and can achieve significant results with these measures. Applying this lane

management approach to an entire urban expressway network, the total urban traffic delay will be significantly reduced, the road resource utilization will be maximized and the problem of expressway traffic congestion can be fundamentally resolved.

Figure 17 Delays of the current status of Scenario 0-CA, Scenario V and Scenario VI



Notes: (a) Average delay; (b) off-ramp delay; (c) on-ramp delay

5.3 Simulation results and analysis of Scenarios 0-CA, V and VI

Figure 17 displays histograms of the delay output for Scenarios 0-CA, V and VI with total average delay, delay of off-ramp and delay of the on-ramp. As demonstrated by many simulation operations, the first 1,200 s on the off-ramp does not form a congestion situation. When analyzing the simulation results, the results of the previous 1,200 s will not be analyzed. These histograms show that the delay is from approximately 1,800 s–3,000 s of the current status, which exceeds 90 s, whereas the average delay of these vehicles is 99 s, the average delay of off-ramp vehicles is 140.7 s and the average delay of on-ramp vehicles is 190.2 s. After establishing a conflict avoidance area, the average delay and the delays of the off-ramp and on-ramp vehicles have been significantly reduced. In particular, the delay in entering the mainline of the ramp has been reduced. The conflict avoidance area and the conflict avoidance area with fine management are set up, the total average delay of the weaving area is reduced by 44.1% and 50.7%, respectively and the weaving area system slowly recovers from the crashed state. In particular, the impact of establishing the conflict avoidance area is even greater for the vehicles of the off-ramp; the delay after establishing the conflict avoidance area decreases from 190.2 s to 9.2 s and the delay is directly reduced by 95.2%. The establishment of the conflict avoidance area plays an important role in relieving congestion of the weaving area and it can change from the break state to the stable state in the weaving area. The on-ramp vehicles, which may be parked on the entrance ramp, can only wait for the opportunity to pass through the weaving area. After the conflict avoidance area is set up, a certain area is set aside for these vehicles to smoothly enter the weaving area, which significantly reduces the delay.

The establishment of a conflict avoidance area is particularly effective for resolving the problem of delay on an off-ramp, especially for on-ramp vehicles. The results of the simulation indicate that the total delay in the conflict avoidance area of the weaving area is reduced, the congestion of off-ramp vehicles due to the conflict avoidance area is relieved and the influence of the on-ramp vehicles after establishing the conflict avoidance area is far-reaching. Establishing a conflict avoidance area is important for solving the situation of traffic collapse in a weaving area. The blocked traffic can be relieved and the conflict avoidance area occupancy time threshold is also used to solve the congestion problem in a weaving area. Leading the lane-changing in advance and establishing a conflict avoidance area can successfully resolve the congestion of the off-ramp and the mainline, which addresses the traffic system on the verge of collapse in the weaving area. The traffic capacity of the weaving area is significantly improved.

6. Conclusions

This paper oriented to ICVs and explores the influence of two fine lane management approaches on each traffic flow in the weaving area. The first fine lane management approach is to guide lane-changing in advance and lane-changing separation and the second fine lane management approach is to guide lane-changing in advance and establish a conflict avoidance area. We verify whether the delays of different flow vehicles can be reduced after adopting management measures. By combining the investigation of the field weaving area on Beijing Dongsanhuan Middle Road, the characteristics and lane-

changing behaviors of different flow vehicles in a weaving area of an urban expressway are analyzed. Based on the actual survey data, the model and simulation of the weaving area of the urban expressway are conducted to simulate the effect of different lane management approaches on the weaving area, so as to provide support for the active management of intelligent networked vehicles.

Guiding lane-changing in advance enables drivers to complete their lane-changing when entering a weaving area, prevents vehicles from interfering with each other in the weaving area, avoids random and frequent lane-changing and improves the safety and efficiency of vehicles. The road capacity of the weaving area can be improved by guiding lane-changing maneuvers. The lane-changing isolation in the weaving area can ensure the speeds of the inside straight-driving vehicles and reduce the occurrence of traffic accidents. Establishing a conflict avoidance area and reasonable value occupation time threshold can fundamentally solve the problem of blocked traffic on an off-ramp. Fine lane management approaches not only improve the safety of road traffic but also significantly reduce the delay in an entire weaving area.

Based on the research results of this paper, it can be applied to traffic control under the environment of ICVs. At the same time, the following aspects of applications are expected:

- Provide relevant management approaches for solving congestion in weaving areas;
- Provide selection and design references for regional and time thresholds established in the conflict avoidance area of an urban expressway; and
- Provide a basis for analyzing lane-changing behaviors constraints in a weaving area.

In the later research, in-depth research can be carried out from the following three aspects:

- Study the traffic flow lane-changing rules of the on-ramp under the environment of ICVs and refine the constraints of lane-changing;
- Comparative study of vehicle behavior differences before and after strategy action and vehicle group behavior optimization characteristics under strategy action; and
- Study the location selection and time thresholds of conflict avoidance areas in different scenarios.

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