

Research Article

VISSIM-Based Simulation and Analysis of Upstream Segments in Ramp Areas for Optimizing Vehicle Group Lane-Changing Behaviors

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The traffic congestion in ramp areas is becoming increasingly prominent. In the upstream segments of ramp areas, effective management and control of lane-changing behaviors can improve the road capacity and make full use of the existing road resource. With the continuous development and application of connected vehicle technologies, lane-changing behaviors can be performed by vehicle groups. Under a connected vehicle environment, the lane-changing behaviors by vehicle groups are controlled in the upstream segment in a ramp area, and the lane-changing behaviors can be completed prior to entering the ramp area. Finally, lane-changing strategies are optimized and identified. VISSIM simulates these proposed strategies. This paper considers the delay as the output index for analyzing and comparing various strategies. The results demonstrate that the delays of different lane-changing strategies are also different. If the delays of ramp areas are to be substantially reduced, it is necessary to continuously optimize the lane-changing strategies by vehicle groups in the upstream segments. This optimization of lane-changing strategies will effectively regulate drivers' lane-changing behaviors, improve road safety, and increase traffic capacity.

1. Introduction

Traffic congestion has been a common problem all over the world and must be solved urgently in recent years. Ramp areas have become severe traffic congestion bottlenecks. Scholars at home and abroad seek to solve traffic congestion of ramp areas. With the application of advanced traffic control technologies and the progress of connected vehicle technologies, emerging technology has become one of the most effective ways of reducing traffic congestion in ramp areas. The main reason for the congestion in ramp areas is that the vehicles fail to change lanes in time. This causes the vehicles to change lanes only when they are close to the ramp area, which affects the normal operation of other vehicles. In

the ramp area upstream segment, based on the study of vehicle group lane-changing behaviors, this paper continuously optimizes the lane-changing strategies of vehicle groups. At the same time, effective optimization models of ramp areas are established for reducing traffic congestion. These lane-changing strategies by vehicle groups will reduce vehicle delays and increase the capacity in ramp areas.

The gap acceptance theory was the basis of most previous lane-changing models, which shows whether a gap is accepted for lane-changing [1, 2]. The lane-changing behaviors of vehicles can separate into three types at ramp merges: free lane-changing, cooperative lane-changing, and forced lane-changing [3, 4]. Learning through lane-changing behaviors, the impacts of lane-changing on surrounding vehicles are

identified. A lane-changing model is proposed for estimating the capacities of weaving segments [5]. Wang et al. [6] studied a hidden Markov model (HMM) method for the two-stage lane-changing model to more accurately indicate the forced lane-changing behaviors in urban arterials. The model is parameterized and evaluated on detailed vehicle trajectory data of next-generation simulation (NGSIM). Arbis and Dixit [7] employed a quantum response equilibrium framework to simulate the lane-changing maneuvers while considering conflict risks and estimated the model parameters based on a freeway on-ramp lane-changing data using the NGSIM dataset. It was determined that the likelihood of conflict could be substantially reduced to add longer acceleration lanes to reduce on-ramps speed limits. Deng and Feng [8] proposed a lane-changing decision model of multiattribute that is focused on an analytic hierarchy process and then presented a newly improved multilane traffic cellular automata model. According to numerical simulations under various traffic densities, the variations in the lane-line-markings affected the lane-changing cause chances and the lane-changing success chances. Zhou et al. [9] introduced a hyperbolic-tangent lane-changing trajectory model that is given a large number of reference angle data. The model is evaluated on real data and via simulations. The results demonstrate that drivers' lane-changing trajectories could successfully be described based on the proposed lane-change trajectory model.

In recent years, connected vehicle technologies have been widely valued by scholars all over the world. The application of connected vehicle technologies in the field of transportation has had a substantial impact on vehicle driving behaviors. The University of Maryland focused on Traffic View, which is a traffic monitoring device that is based on vehicular ad hoc networks. Using mobile ad hoc networks and car-to-car communication, a vehicle communication platform was used to collect and to publish traffic information to improve traffic safety and efficiency [10]. Collaborative adaptive cruise control (CACC) at the University of California contributed to the improvement of connected vehicle technologies. The stability and speed of traffic flow in platoon form were realized; acceleration and spacing information was transmitted in real time. It required the fleet to establish a complete communication system and required improvements to the existing vehicle longitudinal control algorithm [11]. Sharma et al. [12] incorporated driver compliance behavior into a connected vehicle driving strategy (CVDS). The driver obedience was modeled based on prospect theory (PT) and the connected vehicle trajectory data were utilized to correct CVDS, which was combined with an intellectual driver model. The demarcated results showed that drivers could drive safely and efficiently under the connected environment. Ye and Yamamoto [13] presented the distributions of acceleration and velocity difference in mixed traffic flow. It was determined that the dynamics of mixed traffic flow evolve with the increase of the penetration rate of connected and autonomous vehicles (CAV). The results demonstrated that with the increase of the CAV popularization rate, traffic safety had been significantly improved. Dai et al. [14]

studied the connection between a traffic system performance and the driver's path choice under a connected vehicle environment. The dynamic travel of commuter's daily path choice in the connected vehicle environment was investigated. At the same time, real-time information and driving experience were regarded. Yao et al. [15–17] focused on dynamic platoon discrete models in the traffic detection environment of a cross section. The model can forecast the arrival of vehicles and optimize traffic signals continuously. The effectiveness of the proposed method was verified by modeling the actual road network in VISSIM. Li et al. [18] presented a new car-following model for platoon control of a multivehicle system under a V2V/V2I communication environment. Qi et al. [19, 20] described the cell transmission model of traffic flow based on urban road networks. The results could be used to estimate the impact of driving behaviors on traffic delay and to perfect the role of the state in the prevention of urban traffic congestion accidents. As our previous work, Li et al. [21] used VISSIM to simulate six scenarios to obtain the optimal vehicle group lane-changing behaviors for upstream traffic flow in off-ramp areas. As the complexity and multiformity of vehicle group lane-changing behaviors, more scenarios and parameters should be tested.

Ramp area and weaving area control strategies have been deeply and continuously researched by scholars at home and abroad. The study of ramp areas has mainly followed three stages [22]. Early studies focused on improving transport facilities and the traffic organization was optimized via reasonable channelization [23]. The second stage was based on research on the dynamic management of variable information boards or other systems, which could reduce the mainline delay by controlling the ramp traffic flow [24]. In the third state, car-road coordination was investigated to realize vehicle active intervention measures to improve the operational efficiency of ramp areas and weaving areas. A control strategy for ramps was proposed in the scenario of both intelligent vehicles and ordinary vehicles [25]. Marinescu et al. [26] presented a slot-driven merging algorithm. The results demonstrated that the algorithm realized low delay and very high volume on an on-ramp. Sivaraman et al. [27] used an automotive tested instrument with sensors to monitor key areas around the vehicle. The system recommended the suitable acceleration or deceleration to merge into the neighboring lane and assigned when and how to merge. Tanaka et al. [28] proposed vehicle control algorithms to prevent weaving conflicts from happening. A microscopic traffic simulation model achieved developed algorithms. The results demonstrated that the total throughput decreased slowly with the increase of the weaving ratio. Huang et al. [29] studied the relationship between off-ramp lane-changing spacing and traffic congestions on urban expressways and tested the impact of different densities of traffic and off-ramp ratios on the congestion. The results showed that with the increase of density of traffic and the proportion of off-ramp vehicles, the required lane-changing spacing should be increased accordingly. Zhao et al. [30, 31] presented a comprehensive design model to remove weaving and to maximize the

enhancement of the capacity of the section. An et al. [32] established a cellular automata model considering three different regulations of lane-changing to mate with the driving behaviors in lane distribution.

Currently, the research on-ramps modeling at home and abroad mainly was based on the specific traffic environment and lane-changing behaviors of independent vehicles. There are few studies on the lane-changing behavior of vehicle groups. With the realization of connected vehicle technologies, the ramp traffic model can be based on the studies of the lane-changing behavior of vehicle groups. In a connected vehicle environment, it is necessary to conduct suitable modeling and analysis of ramp areas. Therefore, this paper studies the behaviors of vehicle group lane-changing in the upstream sections of ramps. The simulation results are validated by VISSIM. By leading and restricting the vehicle group lane-changing behaviors, the ramp capacities are improved.

2. Modeling and Method

With the continuous improvement of the connected vehicle technologies, drivers can obtain real-time traffic information for surrounding roads in a connected vehicle environment, including the state data of adjacent vehicles, the environment, and road facilities, for conducting vehicle trajectory planning and safety early warning for vehicle groups and for realizing lane-changing driving. Based on a connected vehicle environment, this paper establishes lane-changing of vehicle group models and strategies in the upstream sections of ramp areas. The optimal lane-changing strategy is obtained by continuously optimizing the lane-changing strategies of vehicle groups: the uniform distribution of off-ramp vehicles in each lane in the initial stage. Through connected vehicle technologies, the vehicles change lanes in groups. At the end of the lane-changing of vehicle groups, the off-ramp vehicles change lanes in the outermost lane.

This paper considers three lanes as an example for the vehicle group lane-changing behaviors study in the upstream section in a ramp area. The uniform distribution of vehicles in each lane is assumed initially. Under this assumption, according to the off-ramp ratio of each lane, in the lane-changing space of the ramp area, the vehicle group lane-changing behaviors, it is realized that vehicles complete lane-changing in the form of vehicle groups in the upstream segment based on connected vehicle technologies. Under an environment of connected vehicles, based on lane-changing orders, the off-ramp vehicles in each lane form a vehicle group. Under the limited space of lane-changing, the vehicle groups perform lane-changing behaviors at various stages. Figure 1 is a schematic diagram of the vehicle group lane-changing behaviors in the upstream section in the ramp area. “S” represents the lane-changing space of the vehicles and “S₁” and “S₂” represent the lane-changing space of different lane-changing stages, respectively.

The vehicle group lane-changing behaviors in the upstream section in the ramp area are illustrated in Figure 2(a). As shown in Figure 2(a), the off-ramp vehicles change lanes

in the lane-changing space to the outside lane according to their off-ramp ratios, and the other vehicles go on running ahead. q_1 , q_2 , and q_3 represent the initial traffic flows in the three lanes. The through-moving vehicles and a proportion of the off-ramp vehicles are evenly distributed in each lane. The off-ramp ratios of the inside lane to the outside lane are expressed as r_1 , r_2 , and r_3 , respectively. Among the first lane vehicles of the off-ramp, some change lanes to the third lane. The proportion of these vehicles relative to all first lane vehicles of off-ramp is p . “ p ” represents the ratio of off-ramp vehicles changing lanes from the first lane to the third lane, and the ratio of the rest lane-changing to the second lane “ $1 - p$.” Different values of “ p ” lead to different choices of lane-changing paths. The remaining off-ramp vehicles change lanes to the second lane and the third lane. All vehicles of off-ramp concentrate on the outermost lane after changing lanes in the space of lane-changing. Then, the outer lane includes all vehicles of off-ramp or the vehicles of original through-moving, while the through-moving vehicles include all vehicles in the inner lane. After changing lanes, q'_1 , q'_2 and q'_3 express the traffic flows in the three lanes. The uniform distribution of the vehicles is still in each lane. Compared with the original traffic volume of the corresponding lane, the traffic volume of each lane after lane-changing is unchanged.

Figure 2(b) illustrates the path selections in lane-changing behaviors in the space of lane-changing. According to Figure 2(a), in the lane-changing space, these vehicles in the inner lanes of the off-ramp have to complete lane-changing to the outside lane, the path selections of lane-changing behaviors depend on the value of p . To keep the equilibrium among the lanes, the outside through-moving vehicles are obliged to change lanes into the inside lanes. Via this approach, vehicles in the upstream segment of the ramp area have completed lane-changing ahead of time within the space of lane-changing. Vehicles only need to travel along their respective lanes when entering the ramp areas, thereby exiting the ramp areas smoothly, avoiding frequent lane-changing and weaving, reducing the delay of vehicles, and increasing the road capacity.

As illustrated in Figure 2(b), in the lane-changing space, the vehicles of lane-changing behaviors in the three lanes are enumerated. Some of the first-lane vehicles change to the third lane, and the remainder of the vehicles of off-ramp change to the second lane initially and subsequently find a suitable opportunity to change to the third lane. Originally, the through-moving vehicles continued along their lanes. Similarly, vehicles in the second lane continue to drive straight along the lane, while all off-ramp vehicles change lanes to the third lane. To keep the equilibrium among the lanes, the original through-moving vehicles in the third lane change to inner lanes. In the formula, “from lane” indicates that the vehicles for lane-changing come from the lane. For example, “from lane 2” means that the vehicles for lane-changing come from the second lane. Balancing requirements for lanes, before and after the completion of lane-changing, the traffic flow relationship among lanes is as follows:

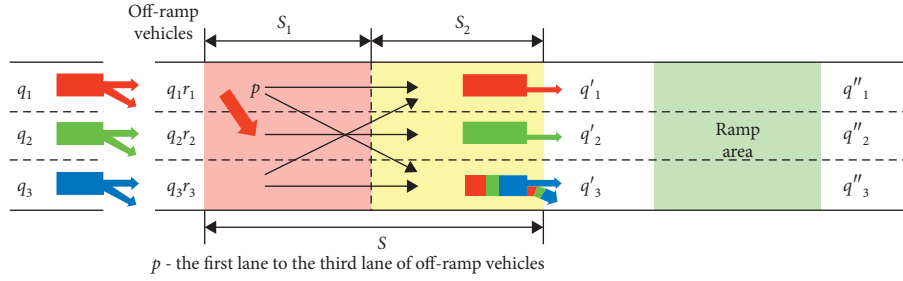


FIGURE 1: Vehicle group lane-changing behaviors in the upstream section in a ramp area.

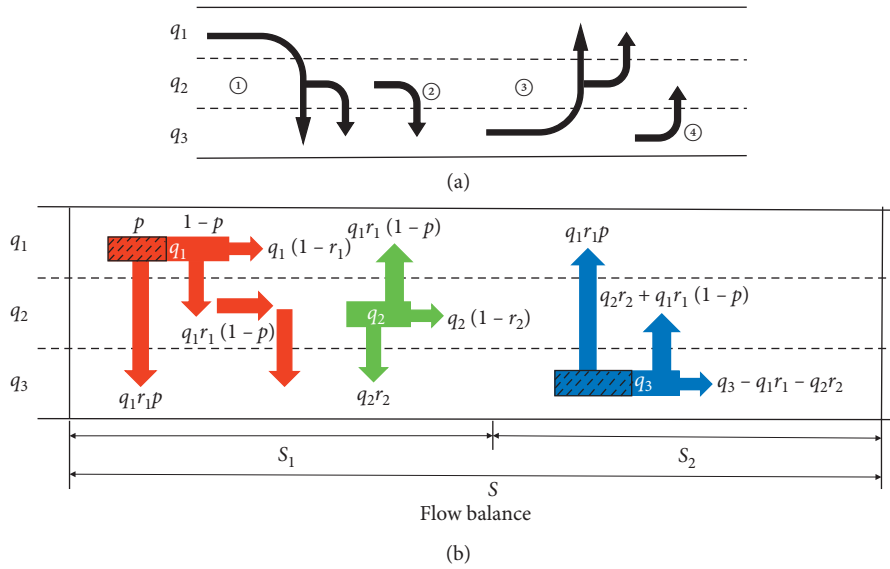


FIGURE 2: Lane-changing behaviors in three lanes: (a) path selections in lane-changing behaviors in the space of lane-changing and (b) schematic diagram of lane-changing behaviors in three lanes.

$$q_{\text{out}} = q_1 r_1 + q_2 r_2 + q_3 r_3,$$

$$q'_1 = q_1,$$

$$q'_1 = q_1 - q_1 r_1 p - q_1 r_1 (1 - p) + q_1 r_1 (1 - p) \{\text{from lane 2}\} + q_1 r_1 p \{\text{from lane 3}\},$$

$$q'_2 = q_2,$$

$$q'_2 = q_2 - q_1 r_1 (1 - p) - q_2 r_2 + (q_2 r_2 + q_1 r_1 (1 - p)) \{\text{from lane 3}\},$$

$$q'_3 = q_3,$$

$$q'_3 = q_3 - q_1 r_1 p - q_2 r_2 - q_1 r_1 (1 - p) + q_1 r_1 \{\text{from lane 1}\} + q_2 r_2 \{\text{from lane 2}\}.$$

According to its value, p can be divided into three cases: $p = 0$, $p = 1$, and $0 < p < 1$. If $p = 0$ or $p = 1$, there are 4 lane-changing paths of vehicles. If $0 < p < 1$, there are 6 lane-changing paths of vehicles. Figures 3(a)–3(c) illustrate a part of path selections in the lane-changing behaviors for $p = 0$, $p = 1$, and $0 < p < 1$, respectively.

2.1. The Unified Lane-Changing of Vehicle Group Strategies. Based on the unified vehicle group lane-changing behaviors,

the vehicle groups must change lanes in the lane-changing space. According to the “ p ” values, the lane-changing behaviors of the vehicle groups in each lane are adjusted to keep the equilibrium of the traffic volume with the lanes. In an environment of connected vehicles, each vehicle group that has the same lane-changing path is based on a unified order for changing lanes to outside. This paper uses the common three-lane section to study the unified lane-changing strategies of vehicle groups in the upstream section in a ramp area.

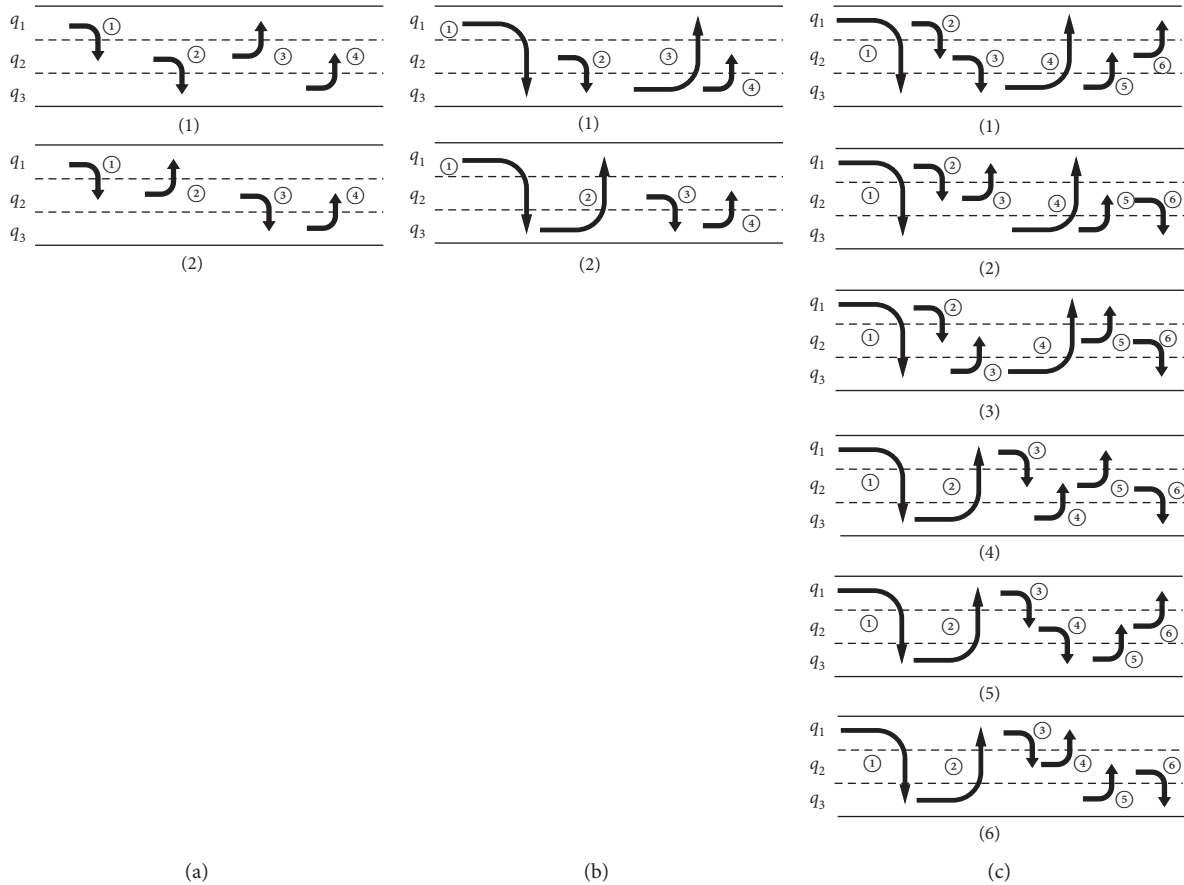


FIGURE 3: Path selections of lane-changing behaviors: (a) $p = 0$; (b) $p = 1$; and (c) $0 < p < 1$.

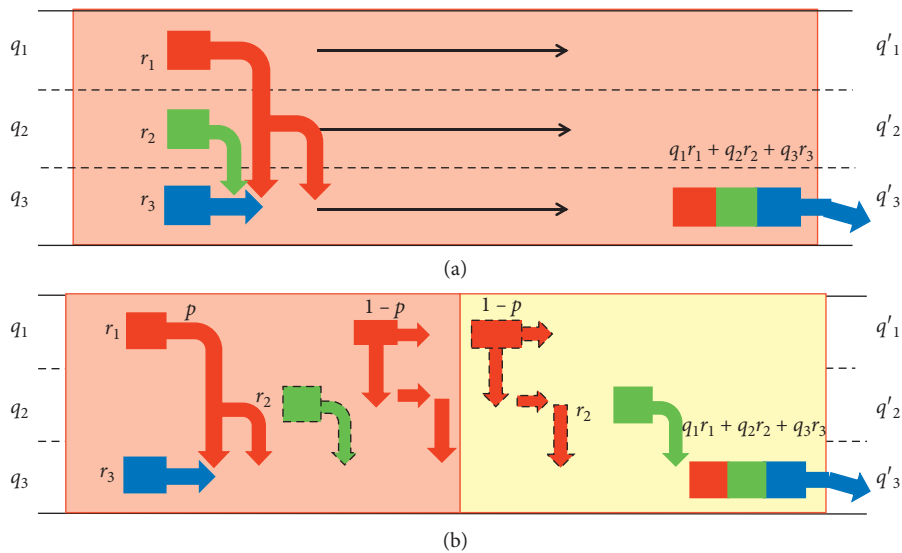


FIGURE 4: A lane-changing schematic diagram in a segment: (a) unified lane-changing and (b) stepped lane-changing.

Figure 4(a) shows that in a certain lane-changing space, according to the unified order, the vehicle groups change lanes to outside. The vehicles in the inner lanes change lanes to the outside within the lane-changing space. There is no

restriction on the order of lane-changing for these vehicles. Vehicles change lanes and eventually all vehicles of off-ramp concentrate in the outside lane. Similarly, to reduce the congestion that is caused by excessive traffic pressure in the

outer lane, the original through-moving vehicles change to inner lanes as vehicle groups to keep the equilibrium among the lanes. In the upstream section in the ramp area, vehicles of off-ramp change lanes in advance. After entering the ramp area, these vehicles can exit the ramp smoothly, thereby avoiding affecting the vehicles of the mainline.

2.2. The Stepped Lane-Changing of Vehicle Group Strategies.

In an environment of connected vehicles, in addition to the unified lane-changing strategies of vehicle groups, stepped lane-changing strategies are utilized by vehicle groups. Within the lane-changing space, all vehicles of off-ramp change lanes at different stages. For simplicity, in the lane-changing space, we assume that the process of lane-changing separates into two stages. The lane-changing paths of vehicle groups will differ according to their “ p ” values. The off-ramp vehicles of lane-changing between lanes will also be carried out in stages. Typically, the first lane of off-ramp vehicles change lanes; some change to the third lane and others to the second lane. The second lane of vehicles with lane-changing demands are allowed to complete lane-changing to the outside lane. Vehicles on the off-ramp of the third lane run along the lane without lanes change. Under a special circumstance, the off-ramp vehicles in the first lane go to the second or the third lane. At the same time, to keep the equilibrium among the lanes, the original through-moving vehicles will also change lanes to inner.

Figure 4(b) shows the strategies of vehicle group for stepped lane-changing. The first lane-changing stage is carried out in the pink area on the left side. The off-ramp vehicles in the first lane complete lane-changing to the second or the third lane. In the area, the off-ramp vehicles in the second lane may change to the third lane. After completing the first lane-changing stage, the second lane-changing stage will be carried out on the yellow area on the right side. In the first lane, if off-ramp vehicles of the first lane do not change to the third lane, then these vehicles in the second stage will continue to change lanes. Therefore, a lane-changing second-step mode is formed. As shown in the solid-line part of Figure 4(b), in the first stage, some of the off-ramp vehicles of the first lane change lane to the second lane, while the remaining vehicles continue to change to the second lane within the second stage. As shown in the dashed-line part of Figure 4(b), the vehicles after lane-changing continue to drive along the second lane and, in the second stage, these vehicles will change lane to the third lane. If these through-moving vehicles drive along the first lane in the first stage, the lane-changing behaviors are completed in the second stage, and the vehicles change to the second lane and then to the outside lane.

3. Simulation and Analysis

The lane-changing strategies of vehicle groups that are described above are simulated by VISSIM. The output indicators are used to compare the strategies and the optimal

vehicle group lane-changing strategy is identified. In the upstream section in the ramp area, a three-lane road network is established under a simulation environment. In VISSIM, the parameters of basic traffic facilities are set, and the corresponding detectors including traffic flow and delay are used as evaluation indexes. By continuously adjusting parameters in the lane-changing space, the optimum lane-changing strategy is obtained. As an evaluation index, the delay can fully and accurately reflect the traffic conditions. Therefore, the delay is used as an indicator of the lane-changing strategies comparison and analysis.

The road length (m), the lane-changing length (m), the traffic volume (pcu), the lane-changing space (m), the lane-changing ratio (%), and the lane-changing path are taken as simulation parameters.

Under the unified lane-changing mode, when implementing the vehicle group lane-changing strategies based on VISSIM, the path selection settings for all “ p ” values in the VISSIM simulation are the same. Therefore, within the same lane-changing space and lane-changing decision space, the vehicle group lane-changing strategies under the unified lane-changing mode are unified into a plan for various “ p ” values.

3.1. Parameter Input and Detector Settings. In VISSIM, enter the basic parameters. The simulation section is basic three lanes and the width of each lane is 3.5 m. Traffic volumes of 1400 pcu/h/lane, 1200 pcu/h/lane, and 1000 pcu/h/lane are simulated and compared. In the simulation scenario, there are two kinds of traffic detectors put up: traffic volume detectors, which can measure the traffic flow volume of the corresponding section in the statistical period and travel time detectors, which are used to check the mean vehicles delay passing through two specified segments within the statistical time interval.

3.2. Simulation Analysis of Segment. To evaluate the performances of the proposed strategies, VISSIM is used to output the corresponding evaluation indicators and to conduct a comparative analysis. Taking the three-lane section conduct as the research target, in unified lane-changing spaces of lengths 400 m, 600 m, and 800 m and stepped lane-changing space of length 800 m, several scenarios are simulated. The effect of the space of lane-changing on unified lane-changing is studied. The simulated lane-changing plans are listed in Table 1. Table 2 presents the lane-changing schematic diagrams of simulation plans.

The corresponding lane-changing strategies in all simulation scenarios are listed in Table 1 and Table 2 presents schematic diagrams that correspond to Table 1. An off-ramp ratio 20% is used for all lane-changing plans. The lane-changing paths for vehicle lane-changing are determined by the “ p ” value. In the schematic diagram column of Table 2, the corresponding lane-changing space is shown in color, in which the slant filling of the area

TABLE 1: Lane-changing simulation plans.

Number	Space	Decision space	ρ	Number of paths
A1	400 m	400 m	1	4
A2	600 m	400 m	1	4
A3	800 m	400 m	1	4
A4	800 m	800 m	1	4
A5				
A6	(400 + 400) m	400 m	1	4
A7				
A8				
A9				
A10	(400 + 400) m	400 m	0.5	6
A11				
A12				

TABLE 2: Schematic diagrams of the lane-changing simulation plans.

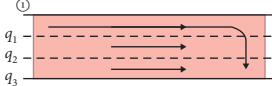
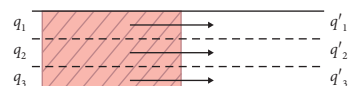
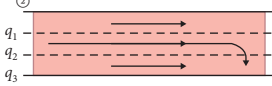
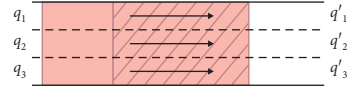
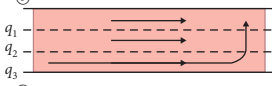

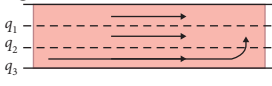
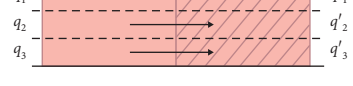
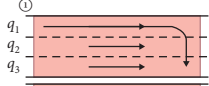
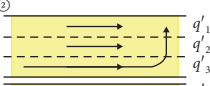

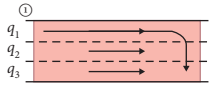
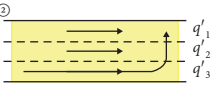

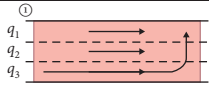
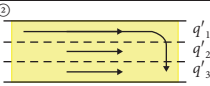
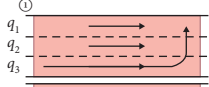
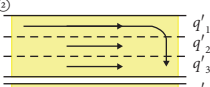
Number	Space	Decision space	Sectional lane-changing	Schematic diagram
A1	400 m	400 m	① 	
A2	600 m	400 m	② 	
A3	800 m	400 m	③ 	
A4	800 m	800 m	④ 	
A5			①  ② 	
A6	(400 + 400) m	400 m	①  ② 	
A7			①  ② 	
A8	—	—	①  ② 	—

TABLE 2: Continued.

Number	Space	Decision space	Sectional lane-changing	Schematic diagram
A9				
A10	(400 + 400) m	400 m		
A11				
A12	—	—		—

represents the lane-changing decision space with the plan. The oblique filling in the region represents the lane-changing decision space in the scheme. The schematic diagrams differ among plans due to differences according to the lane-changing decision space and the lane-changing space.

4. Results and Discussion

According to the above plans, single-lane traffic volumes of 1400 pcu/h/lane, 1200 pcu/h/lane, and 1000 pcu/h/lane are simulated. Under various simulation conditions, each simulation scenario is simulated for 3600 s and the output indices are obtained. The detectors output delay index and the traffic flow index. Table 3 is the summary of output results. To eliminate the influence of accidental factors, each scenario is simulated many times, and the average value of the results is taken. When the traffic volume output does not satisfy the requirement, these results will not be used as the basis for analysis; the best plan of output value is marked in bold in Table 3.

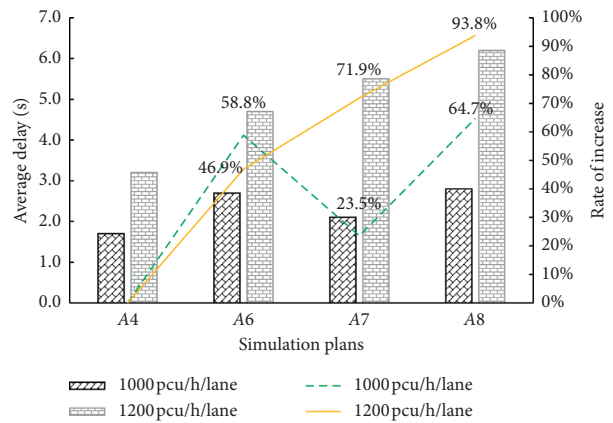
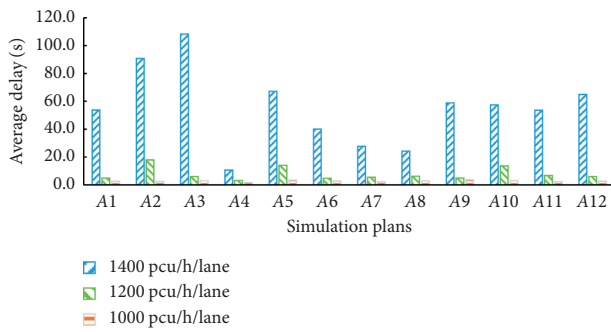
According to the simulation plans that are shown in Table 1, the simulation results are presented in Table 3. From Table 3, when the traffic volume is 1400 pcu/h/lane, only plan A4 satisfies the traffic flow requirement; namely,

the space of lane-changing and the decision space of lane-changing both exceed 800 m. The output flows of the other plans with a traffic flow of 1400 pcu/h/lane do not satisfy this requirement; therefore, the other plans are not analyzed. Figure 5(a) is a histogram of the delay results that correspond to Table 3. Plan A4 is the optimum simulation results and the mean delay value is the smallest among all plans. If the traffic flow requirement is satisfied, according to the comparison of plans A1 to A4 with flows of 1000 pcu/h/lane and 1200 pcu/h/lane, only increasing the lane-changing space without lane-changing in advance has no effect on reducing the delay; instead, it increases it. If the lane-changing space is increased, vehicles should be guided to complete lane-changing as quickly as possible so as to change lanes ahead of the off-ramp, which will substantially reduce the vehicle delay and alleviate the traffic congestion.

To compare the effects of unified lane-changing and stepped lane-changing in terms of the vehicle group lane-changing behaviors, in the condition of meeting the traffic outputs, plan A4 is selected for comparison with plans A6, A7, and A8 at flows of 1000 pcu/h/lane and 1200 pcu/h/lane. According to Figure 5(b), under the identical space of lane-changing, unified lane-changing outperforms stepped lane-changing. The delay that is caused by unified lane-changing

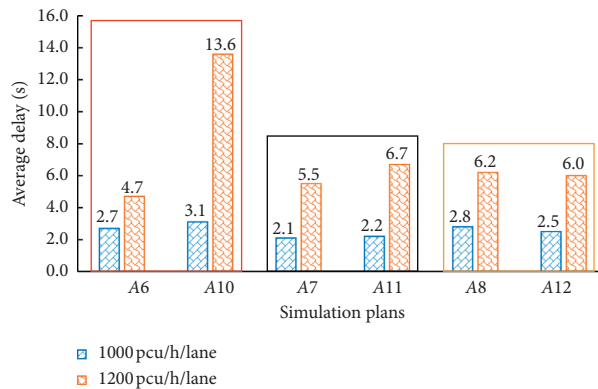
TABLE 3: Results of lane-changing simulation plans.

Index	1400		1200		1000	
	Volume (pcu)	Average delay (s)	Volume (pcu)	Average delay (s)	Volume (pcu)	Average delay (s)
A1	3696	53.8	3560	4.8	2948	2.5
A2	3435	90.9	3560	17.9	2948	2.3
A3	3693	108.3	3560	6.0	2948	3.0
A4	4159	10.6	3560	3.2	2948	1.7
A5	3700	67.2	3490	14.1	2948	3.5
A6	3870	40.1	3560	4.7	2948	2.7
A7	4078	37.7	3560	5.5	2948	2.1
A8	3903	24.2	3560	6.2	2948	2.8
A9	4020	58.9	3560	4.8	2948	3.7
A10	3733	57.4	3560	13.6	2948	3.1
A11	4003	53.6	3560	6.7	2948	2.2
A12	3609	65.0	3560	6.0	2948	2.5



(a)

(b)



(c)

FIGURE 5: Results comparison among lane-changing plans: (a) the twelve lane-changing plans, (b) unified lane-changing and stepped lane-changing, and (c) lane-changing paths with flows of 1000 pcu/h/lane and 1200 pcu/h/lane.

is less than that caused by stepped lane-changing. Under the same lane-changing space of 800 m, the delay of stepped lane-changing increases at least 23.5% than that of unified lane-changing. In plan A8, when the traffic volume reaches 1200 pcu/h/lane, the delay increases by 93.8% compared

with plan A4. Hence unified lane-changing should be chosen instead of stepped lane-changing.

Figure 5 shows a comparison of various plans in the condition of satisfying the flow outputs under various lane-changing path choices. Figure 5(c) compares the

results with traffic flows of 1000 pcu/h/lane and 1200 pcu/h/lane, respectively. During the stepped lane-changing process, the routes differ among lane-changing strategies and lane-changing stages. In the identical lane-changing stage, vehicles in different lanes change lanes by crossing the lane-changing space. The delay increases with the number of lane-changing paths. However, if vehicles in different lanes change lanes synchronously at the same lane-changing stage, as the number of lane-changing paths increases, the delay decreases.

5. Conclusions

To improve the capacity of the road and to alleviate the ramp area congestion, this paper studies the vehicle group lane-changing in the upstream sections of ramps. By optimizing the vehicle group lane-changing strategies, vehicles can be guided to pass ramp areas quickly and smoothly. With the continuous improvement of technologies of connected vehicles, lane-changing behavior coordination of vehicle group can be able to guide and restrain driving behaviors; then, congestion and delays have been effectively reduced in ramp areas. In an environment of connected vehicles, this paper proposes lane-changing strategies of vehicle groups and simulates the proposed strategies via VISSIM. Finally, the optimum lane-changing strategy is determined. This paper studies the vehicle group lane-changing behaviors in the upstream section of a ramp area; it provides an efficacious managerial approach to solve the problem of traffic congestion in ramp areas. In addition, it provides a basis for using the collaborative constraint method to analyze the vehicle group lane-changing behaviors in ramp areas.

According to the research results of this paper, the following research focuses are as follows: (1) the simulation and modeling of vehicle group lane-changing behaviors in weaving areas and (2) the practicability of vehicle group coordination and organization under different traffic conditions.

Data Availability

The data in this paper are shown in Figures and Tables.

Conflicts of Interest

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

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