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Modeling and simulation of vehicle group lane-changing behaviors in upstream segment of ramp areas under a connected vehicle environment

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Abstract

Purpose – The purpose of this study is to effectively optimize vehicle lane-changing behavior and alleviate traffic congestion in ramp area through the study of vehicle lane-changing behaviors in upstream segment of ramp areas.

Design/methodology/approach – In the upstream segment of ramp areas under a connected vehicle environment, different strategies of vehicle group lane-changing behaviors are modeled to obtain the best group lane-changing strategy. The traffic capacity of roads can be improved by controlling group lane-changing behavior and continuously optimizing lane-changing strategy through connected vehicle technologies. This paper constructs vehicle group lane-changing strategies in upstream segment of ramp areas under a connected vehicle environment. The proposed strategies are simulated by VISSIM.

Findings – The results show that different lane-changing strategies are modeled through vehicle group in the upstream segment of ramp areas, which can greatly reduce the delay of ramp areas.

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Originality/value – The simulation results verify the validity and rationality of the corresponding vehicle group lane-changing behavior model strategies, effectively standardize the driver's lane-changing behavior, and improve road safety and capacity.

Keywords A connected vehicle environment, Ramp area, Upstream segment, Vehicle group lane-changing behavior

Paper type Research paper

1. Introduction

With the rapid economic development of society and the accelerating process of urbanization, the number of motor vehicles and the traffic demand are increasing. Traffic congestion has become the main traffic problem in China. In ramp bottleneck areas, the merging and the diverging vehicles form strong traffic flows, which reduce the speed of the main line. The poor lane-changing behaviors of vehicles have a substantial impact on the speed of the main-line vehicles. The reduced speed will be transmitted upstream in the form of waves, thereby resulting in decline of the road capacity. Therefore, it is of high importance to study lane-changing behaviors of vehicles in upstream segment of ramp areas for alleviating traffic congestion and for increasing the speeds of vehicles. Our country has a satisfactory industrial foundation in connected vehicle and communication technologies that is keeping pace with the international development trend, and some innovative Chinese businesses are at the forefront of the world. Connected vehicle technologies are the inevitable development trend for realizing intelligent transportation in China. The control of vehicle group behaviors is gradually being realized. By controlling the lane-changing behaviors of vehicle groups, lane-changing strategies can be continuously optimized to improve the road capacity and to reduce the vehicle delays. Traffic flow in platoon form can be realized via vehicle-to-vehicle communication and a cooperative vehicle infrastructure system. An information transmission mechanism can realize driving safety and traffic flow smoothness under a connected vehicle environment. The action mode of connected vehicle information is illustrated in Figure 1.

The lane changing feasibility is represented by a gap acceptance model. There are two types of gap acceptance models ,namely, gap acceptance critical clearance model, such as the MITSIM model (Lee, 2006), the SITRAS model (Hidas, 2002), and the AIMSUN model (Boxill *et al.*, 2000), and the gap acceptance probability model (Jeon and Choi, 2001), in which the probability of lane changing obeys the binary logit model. To study lane-changing behaviors, Vechione *et al.* (2018) comparatively analyzed mandatory and random lane-changing behaviors. The differences in the lane-changing decision variables were expressed among the subject vehicle and the surrounding vehicles. The Kolmogorov–Smirnov test was used to compare the effects of the mandatory lane changing and the free lane changing on the cumulative distribution. Wang *et al.* (2014) estimated the capacity for weaving segments using a lane-changing model. A linear optimization problem

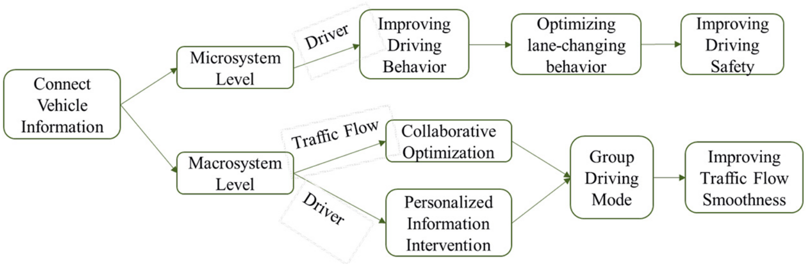

Figure 1. Action mode of connected vehicle information

was defined for solving the weaving capacity, and a lane-changing model was established. The proposed model for capacity estimation was calibrated using the highway capacity manual 2010 model and field observations. Roncoli *et al.* (2017) proposed a lane-changing feedback control for lane assignment at a bottleneck. The throughput of the bottleneck location was maximized by optimizing the lane assignments of the upstream vehicles with bottlenecks. The total density of bottleneck areas was distributed over lanes according to the specified strategy. Keyvan-Ekbatani *et al.* (2016) investigated the decision-making process of lane-changing maneuvers of various drivers based on a two-stage test drive. The results demonstrated that the choices regarding lane changing were related to the speed. A new lane-changing model was developed. Atagoziyev *et al.* (2016) developed an algorithm that enabled a single vehicle to perform lane changing in the shortest time. The algorithm was demonstrated by employing various scenarios. Sulejic *et al.* (2017) proposed an algorithm for optimizing the distribution of lane-changing behaviors, which evaluated the optimized lane transformation using the microscopic simulation of weaving segments of the one-sided motorized lane. The lane-changing behaviors were introduced into the weaving segments. Zhou and Itoh (2016) modeled the lane-changing decision based on a case study and collected lane-changing data, according to which drivers tended to prefer the time to collision to the time headway to the rear vehicle. Gong and Du (2016) overcame the lack of rigorous methods for optimally issuing advance warnings for lane changing. The downstream area of advance warning included two zones – the green zone and the yellow zone. An optimization model was proposed for searching for the optimal green and yellow zones.

With the development of connected vehicle technologies, the collaborative behaviors of vehicle groups have been studied in recent years. Driving information has an important impact on drivers' behaviors. Wang *et al.* (2011) showed that drivers would pay attention to the most important traffic information under various traffic conditions and use this information to correct their driving behaviors timely. Chun *et al.* (2013) found that the connected vehicles could effectively avoid collisions on roads by sharing a series of information, such as their locations, energy consumptions and routes. Based on the obtained information, it was possible to reduce the occurrence of traffic congestion, increase the capacity of roads and improve traffic safety. Caveney (2010) showed that communication between vehicles was highly important for collision detections. The vehicles positions, orientation and speed information that was transmitted between connected vehicles was helpful in drivers' driving processes. Andrews (2012) found that vehicles could cope with danger ahead in a timely manner by transmitting information about the positions, speeds and power statuses of the leader and the follower. Then these vehicles maintained the most effective distance. Therefore, it was possible to increase the road traffic capacity and reduce the frequency of traffic accidents. Roncoli and Papageorgiou (2014) and Roncoli *et al.* (2015a, 2015b, 2015c) obtained accurate information regarding the use of vehicle automation and communication systems and it to assign to each vehicle suitable control tasks, via their proposed novel first-order multi-lane macroscopic traffic flow model for motorways. The motorway traffic congestion was alleviated by implementing suitable traffic control strategies.

Scholars at home and abroad have conducted a substantial amount of research on the modeling of ramp areas and weaving areas. Sun *et al.* (2014) developed and compared five discrete choice models (two multinomial logit and three nested logit) with empirical data to analyze merging behaviors at on-ramp bottlenecks. The results demonstrated that the two-level nested logit model was the most suitable for describing merging behaviors. Wang *et al.* (2014) evaluated a lane-changing model with field data from two weaving segments. The proposed model was applied to estimate the real-time maximum discharge flow rate. Liu *et al.* (2015) introduced and modified an improved control model that integrated ramps and the mainstream on multi-lane roadways. The simulation results demonstrated that the improved model had the best control effect on alleviating multi-lane roadway congestion. Ye *et al.* (2017) used a

Bayesian network model to investigate the association between breakdowns and parameters prior to breakdowns at on-ramp bottlenecks. Liu *et al.* (2016) presented a second-order partial differential equation model for simulating compulsory lane-changing behaviors and free lane-changing behaviors. A form of this model that focuses on compulsory lane changing that is caused by off-ramp areas is derived. Huang *et al.* (2019) developed the relationship of lane-changing spacing intervals provided by off-ramp facilities and traffic flow conditions. Smart lane management was implemented to optimize lane-changing spacing intervals via VISSIM.

Domestic and international research on the modeling of ramp areas primarily considers traditional traffic environments, and lane-changing behaviors are modeled based on individual vehicles. Few studies address the lane-changing behaviors of vehicle groups. With the development of connected vehicle technologies, the traditional ramps traffic models are no longer applicable. Therefore, this paper establishes a vehicle group lane-changing model in the upstream segments of ramp areas under a connected vehicle environment. The model is evaluated via VISSIM simulation. The objective of the study is to improve the capacity of ramp areas by guiding and constraining the lane-changing behaviors of vehicle groups.

2. Modeling and method

Typically, vehicles are evenly distributed in each lane. When the traffic volume is low, vehicles can change lanes freely, which has less impact on the nearby vehicles. However, when the traffic volume is large, lane-changing behaviors of vehicles are limited. If vehicles change lanes only when they are close to an off-ramp, this will inevitably reduce the utilization rate of the lane space. Furthermore, it will affect other main-line vehicles and increase the delays among vehicles. It can also lead to congestion in severe cases. To avoid this scenario, the vehicles should complete lane changing in the upstream segments of ramp areas. In this paper, via modeling of vehicle group lane-changing strategies, the lane-changing strategies of vehicle groups are continuously optimized to obtain the best lane-changing strategy for a connected vehicle environment in the upstream segments of ramp areas. Off-ramp vehicles are initially evenly distributed in each lane and vehicle groups change lanes by connected vehicle technologies. After the vehicle groups change lanes through the lane-changing space, the vehicles complete lane changing such that the off-ramp vehicles are distributed in the outermost lane.

Based on connected vehicle technologies, vehicles evenly distribute in each lane and change lanes in the upstream segments of ramp areas according to various off-ramp ratios. To leave ramp areas smoothly, vehicles must complete lane changing in the corresponding lane-changing space. Under a connected vehicle environment, various lane-changing instructions are issued to vehicle groups, which enable vehicle groups to conduct lane-changing behaviors at various stages in the limited lane-changing space. Figure 2 illustrates that the off-ramp vehicles complete lane-changing in the space under various lane-changing proportions, while the remaining vehicles continue to move forward. To better explain the problem, this paper considers three lanes.

Figure 2 illustrates the lane-changing behaviors of vehicle groups in the upstream segment of a ramp area. The straight-driving vehicles and the off-ramp vehicles are evenly distributed in each lane, and the original traffic volumes in the three lanes are q_1, q_2 and q_3; of these volumes, the off-ramp vehicles correspond to volumes of q_{out1}, q_{out2} and q_{out3}, and the corresponding off-ramp ratios are r_1, r_2 and r_3. The probability of off-ramp moving vehicles from the first lane to the third lane is p. In the lane-changing space, after completing lane changing of vehicles in each lane, all off-ramp vehicles are concentrated in the outermost lane. Finally, the vehicles in inner lanes are all straight-driving, whereas in the outermost lane, straight-driving vehicles and off-ramp vehicles are distributed. After changing lanes, these vehicles remain evenly distributed in each lane, and the traffic volumes of the three lanes become q_1', q_2' and q_3'. The traffic volume of each lane is equal to the original traffic volume of the corresponding lanes after the completion of lane changing.

$$q_{out1} = q_1 r_1 \tag{1}$$

$$q_{out2} = q_2 r_2 \tag{2}$$

$$q_{out3} = q_3 r_3 \tag{3}$$

In the upstream segments of ramp areas, the off-ramp vehicle groups must change to the outside lane in advance by connected vehicle technologies. To balance the traffic pressure among the lanes, the outer straight-driving vehicles must change to the inside lanes. The off-ramp vehicles in the inner lanes need to change lanes to the outermost lane in advance within the lane-changing space. The outermost straight-driving vehicles must change to the inner lanes at the same time in a critical proportion. Figure 3 is a schematic of four lane-changing paths in the lane-changing space.

Figure 4 is a diagram of lane-changing behaviors for each lane. The off-ramp vehicles in the first lane are proportionally guaranteed to change lanes directly to the third lane, while the remaining off-ramp vehicles are buffered through the second lane before changing to the third lane. The straight-driving vehicles continue to drive along the lane. For the vehicles in the second lane, the straight-driving vehicles continue to move forward, while the off-ramp vehicles complete the process of lane changing in the lane-changing space. The straight-driving vehicles in the third lane must change lanes to the first lane and the second lane in

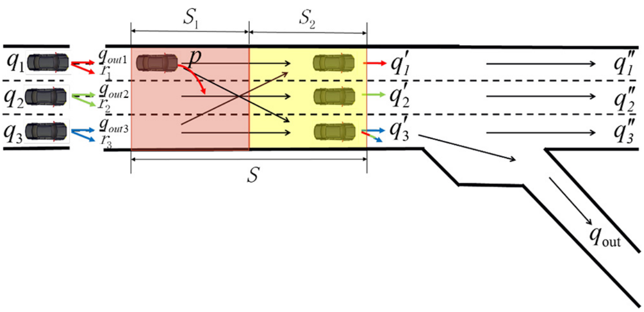

Figure 2. Vehicle group lane-changing behaviors in the upstream segment of a ramp area

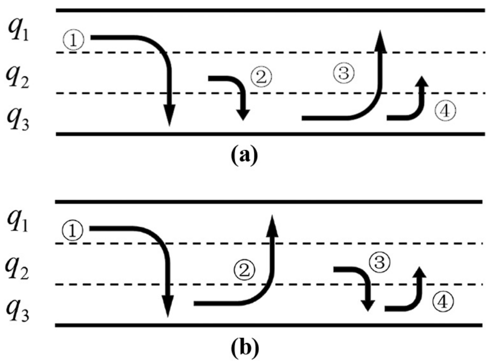

Figure 3. Schematic of four lane-changing paths in the lane-changing space (a) synchronized lane changing and (b) cross lane changing

accordance with the corresponding proportion to balance the traffic pressure among the lane. The remaining straight-driving vehicles and the vehicles with off-ramp demand continue to drive along the third lane. The relationship of traffic volume among lanes before and after lane changing is expressed as follows:

$$q_{\mathrm{out}} = q_{out1} + q_{out2} + q_{out3} \tag{4}$$

$$q_1' = q_1 \tag{5}$$

$$q_1' = q_1 - q_{out1}p - q_{out1}(1-p) + q_{out1}\{\text{from line3}\} \tag{6}$$

$$q_2' = q_2 \tag{7}$$

$$q_2' = q_2 - q_{out2}\{\text{from line2}\} + q_{out2}\{\text{from line3}\} \tag{8}$$

$$q_3' = q_3 \tag{9}$$

$$q_3' = q_3 - q_{out1}\{\text{from line3}\} - q_{out2}\{\text{from line3}\} + q_{out1}\{\text{from line1}\} + q_{out2}\{\text{from line2}\} \tag{10}$$

2.1 Vehicle group strategies for unified lane changing

In a connected vehicle environment, the vehicle groups obey a unified lane-changing command to complete lane-changing behaviors in the space, to realize the unified lane-changing strategies. The unified lane-changing strategies are implemented in the upstream segments of ramp areas. In the common three-lane segment, based on connected vehicle technologies, the vehicle groups can issue unified lane-changing orders and then change lanes to the outside lane in the lane-changing space.

As illustrated in Figure 6, within the designated lane-changing space, the vehicle groups change to the outside lane based on the unified instructions. The vehicles in the first lane and the second lane change to the third lane in the lane-changing space, and the sequence of lane-changing is not limited. All off-ramp vehicles complete lane-changing behaviors within the lane-changing space, and these vehicles eventually concentrate in the third lane. In the upstream segments of ramp areas, the off-ramp vehicles complete lane changing in advance of entering ramp areas, so that these vehicle groups can leave ramps smoothly, thereby avoiding impact on the main-line vehicles.

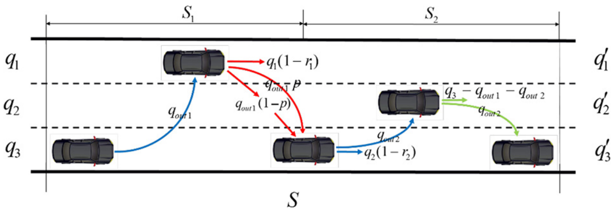

Figure 4.
Schematic of lane-changing behaviors in three lanes

2.2 Vehicle group strategies for stepped lane changing

Under a connected vehicle environment, in the lane-changing space of the upstream segments of ramp areas, all vehicles with lane-changing demand complete lane changing in the space. To avoid conflicts with lane-changing vehicles in other lanes, the lane-changing behaviors of vehicle groups are simplified. It is assumed that the process of lane changing can be divided into two stages in the lane-changing space. In the first stage, some of the off-ramp vehicles in the first lane change directly to the third lane and these remaining vehicles change to the second lane. In the second stage, vehicles with lane-changing demand in the second lane can change to the third lane. After completing the above lane-changing process, all off-ramp vehicles drive along in the third lane without changing lanes.

The vehicle group strategies for stepped lane-changing are illustrated in Figure 7. The first lane-changing stage is conducted in the pink area, and the off-ramp vehicles in the first lane can change to the second lane or to the third lane. The off-ramp vehicles in the second lane may complete the process of lane changing to the third lane in the area. The second lane-changing stage is conducted in the yellow area, and the off-ramp vehicles that have not completed lane changing to the third lane in the first stage will change in the second stage, thereby forming a second-step lane-changing mode. A proportion of the off-ramp vehicles in the first lane changes to the second lane in the first stage or in the second stage. In the first stage, the lane-changing behaviors that are

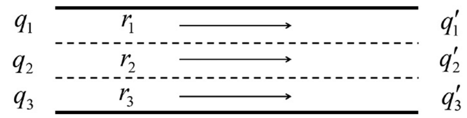

Figure 5.
Common segment before lane changing of vehicles

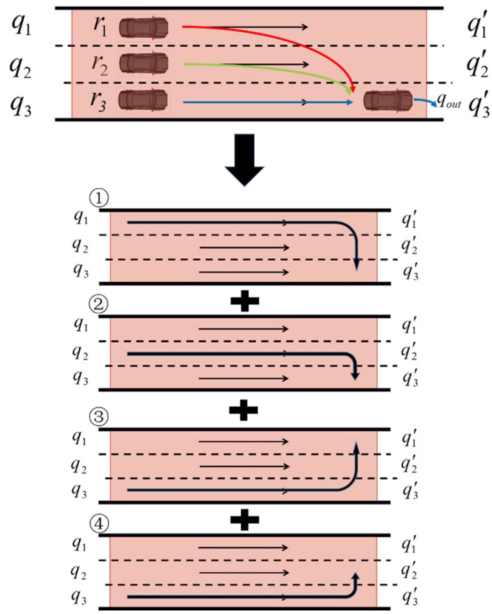

Figure 6.
Schematic of unified lane changing in a segment

described above are completed as illustrated in the solid-line section of Figure 7. After completing the first lane-changing stage, these vehicles continue along the second lane and change to the third lane in the second stage. If these lane-changing behaviors take place in the second stage as illustrated in the dashed-line section of Figure 7, these vehicles drive along the first lane in the first stage and, subsequently, change to the second lane and the third lane in the second stage.

3. Simulation and analysis

Based on VISSIM simulation, it is demonstrated that the collaboration model of vehicle groups that was proposed in the previous chapter is reasonable. The traffic flow in the upstream segment of a ramp area is simulated by building a road network under a simulation environment. In this paper, a three-lane road segment is studied. The basic parameters are set in VISSIM, and the evaluation indices are collected by using the traffic flow detectors and the delay detectors. The optimal lane-changing strategy is identified by continuously debugging parameters various simulation scenarios.

The delay, as an evaluation index, can fully reflect the traffic flow in the road segments. The simulation results that are obtained from the output of the delay detectors are used to compare and analyze the various lane-changing strategies of vehicle groups. The delay is defined as the difference between the actual travel time and the expected travel time of drivers (Hamiel, 2010).

Based on VISSIM simulation, special parameters can be obtained, which include the road length (m), the traffic volume (pcu), the lane-changing length (m), the lane-changing ratio (per cent), the lane-changing space (m) and the lane-changing path.

3.1 Parameters input and detector settings

The basic parameters are input into VISSIM, and the whole segment has three lanes. Each lane is of width 3.5 m, and the lanes have traffic volumes of 1,400, 1,200 and 1,000 pcu/h/lane. In the simulation scenarios, there are two detectors, namely, delay detectors and traffic flow detectors. The detectors are initially located 95 m upstream of the road entrance, and the end position of the detectors is located downstream at the end of the road. The total length of the region that is covered by the detectors is 855 m. The locations of the detectors are specified in Figure 8.

3.2 Segment simulation analysis

VISSIM is used to simulate the proposed lane-changing strategies. Considering a three-lane segment as the research object, various scenarios are simulated by combining the lane-

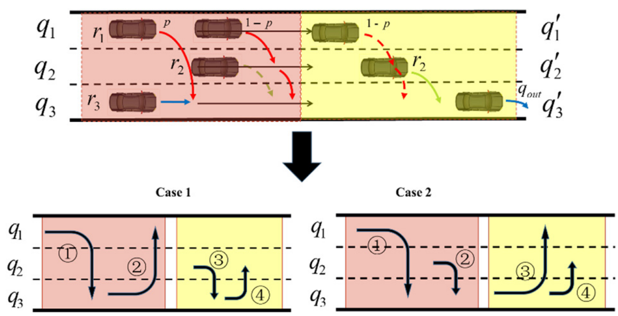

Figure 7.
Schematic of stepped lane changing in a segment

changing space at 200, 400, 600, 800 m and four lane-changing paths. The impacts of unified lane changing and stepped lane changing on the lane-changing behaviors of vehicle groups are compared. Table I lists the simulation plans of lane changing. Figure 9 summarizes schematics of the plans in Table I.

For all lane-changing plans, a 20 per cent off-ramp ratio is used for changing to the outside lane in the simulation scenarios. These off-ramp vehicles consider four lane-changing paths for changing lanes in the lane-changing space. In the schematic representations of Figure 9, the colored regions represent the corresponding lane-changing space, and the oblique filled lines in the region represent the lane-changing decision space in the plans. The schematics differ in terms of the lane-changing space.

4. Results and discussions

Based on the simulations of various plans that are described above, the driving conditions under single-lane traffic volumes of 1,400, 1,200 and 1,000 pcu/h are simulated, and each scenario is simulated for 3,600 s. The delay index and the traffic flow index are exported by the detectors, and the output results are summarized in Table II. The simulation results demonstrate that the volume output cannot satisfy the requirement, which is presented in bold in Table II; hence, the corresponding value will not be analyzed. Figure 10 shows the simulation process of lane changing.

Under the condition that the volume outputs are satisfied, Plans A4, A5 and A6 at traffic volumes of 1,000 and 1,200 pcu/h/lane with unified lane changing and stepped lane changing are compared. The comparison results are presented in Figure 11. According to Figure 12, the delays of unified lane changing are much shorter than those of stepped lane changing. In the scenarios of 1,200 pcu/h/lane, the delay may be more than three times longer using stepped lane changing. Therefore, unified lane changing should be selected over stepped lane changing.

Figure 12 presents the comparison results between the lane-changing space and the lane-changing decision space that are based on satisfying the volume output. With the expansion of the lane-changing space, the difficulty of realizing lane changing increases in practice. Meanwhile, with the expansion of the lane-changing decision space, vehicles that must change lanes must execute the changes as early as possible. When the lane-changing space and the lane-changing decision space are sufficiently large, vehicles will complete lane-

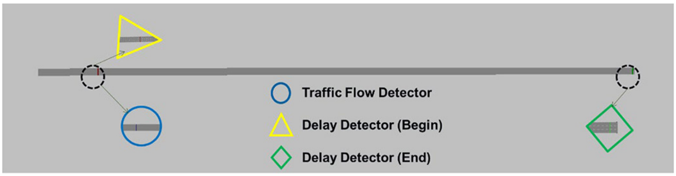

Figure 8. Distribution of the traffic detectors

No.	Space	Decision space	Ratio (%)	No. of paths
A1	200 m	200 m	20	4
A2	400 m	400 m	20	4
A3	800 m	400 m	20	4
A4	800 m	800 m	20	4
A5	(400 + 400) m	400 m	20	4
A6	(400 + 400) m	400 m	20	4

Table I. Simulation plans of lane changing

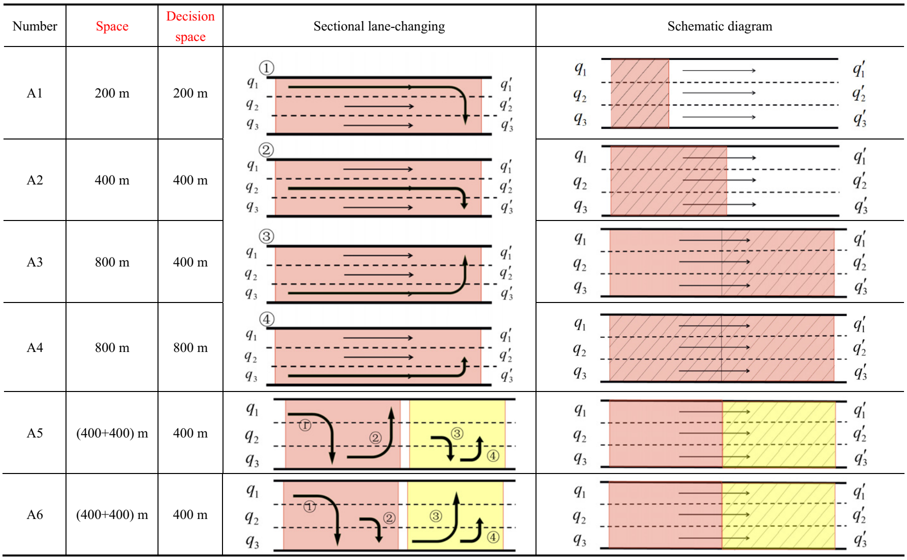

Figure 9.
Schematics of the lane-changing simulation plans

Table II.
Simulation results of different lane-changing plans

Single lane traffic volume (pcu/h)	Index	A1	A2	A3	A4	A5	A6
1,400	Average delay (s)	39.7	53.8	108.3	*10.6*	61.5	67.2
	Volume (pcu)	3,168	3,696	3,693	4,159	3,529	3,700
1,200	Average delay (s)	31.7	4.8	6.0	*3.2*	4.3	14.1
	Volume (pcu)	3,219	3,560	3,560	3,560	3,560	3,490
1,000	Average delay (s)	4.2	2.5	3.0	*1.7*	2.2	3.5
	Volume (pcu)	2,948	2,948	2,948	2,948	2,948	2,948

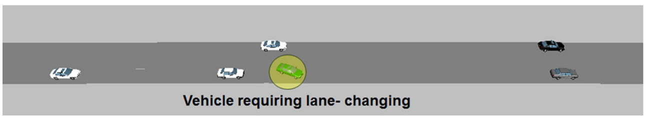

Figure 10.
Vehicle that requires lane changing during the simulation process

changing behaviors prior to leaving lane-changing space, and the delays will be substantially reduced. The lane-changing space and the lane-changing decision space of size 200 m are compared with spaces of sizes 400 and 800 m, and the delays are reduced by 40.5 and 59.5 per cent.

According to Table II, the larger the lane-changing decision space, the shorter the delays under a fixed road segment lengths. Under the condition of satisfying the traffic flow, the lane-changing paths choices have an impact on the delays. Meanwhile, unified lane changing outperforms stepped lane changing, which can effectively reduce the traffic congestion in the upstream segment of the ramp area. As shown in Figure 13, the lane-changing strategy of Plan A4 realizes the best simulation performance, and the average delay values of the output results are the smallest.

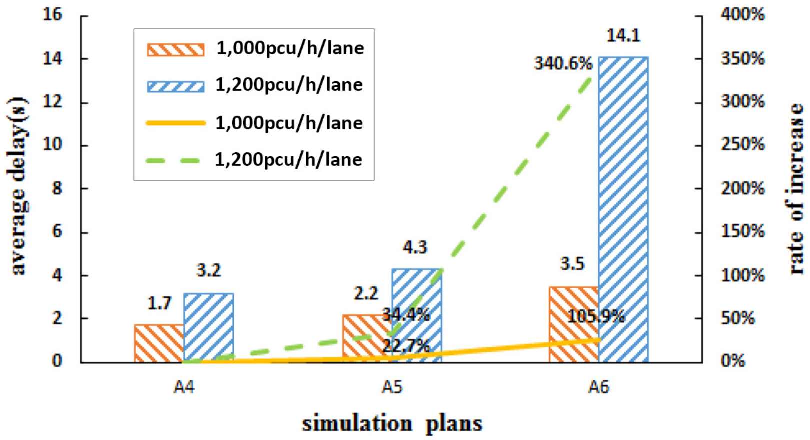

Figure 11. Comparison results between unified lane changing and stepped lane changing

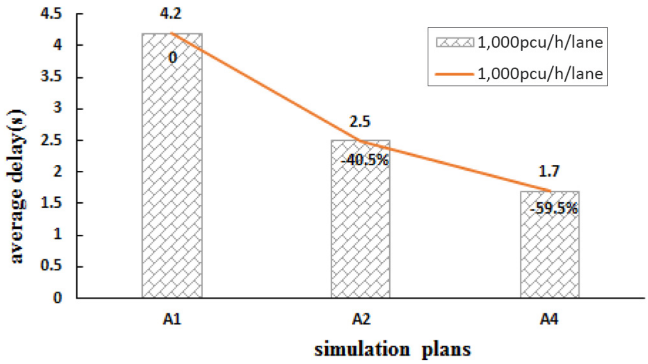

Figure 12. Comparison results between the lane-changing space and the lane-changing decision space

5. Conclusions

Vehicles pass through ramp areas quickly and smoothly, which is of substantial importance for improving the road capacity and alleviating congestion in ramp areas. Via the study of lane-changing behaviors of vehicle groups in the upstream segments of ramp areas, the lane-changing strategies of vehicle groups can be optimized and the vehicle groups can be guided to pass through ramp areas quickly. With the development of connected vehicle technologies, the congestion and the delays in ramp areas can be effectively reduced by guiding and restraining cooperative vehicle group lane changing. In this paper, a vehicle group lane-changing model is proposed under a connected vehicle environment, which includes the strategies of unified lane changing and stepped lane changing, which are based on group collaboration. The proposed strategies are simulated via VISSIM, and six plans are evaluated. Finally, the optimal lane-changing strategy of vehicle groups is identified, which provides a useful management method for reducing the congestion of ramp areas and a theoretical basis for analyzing the cooperative constraint method of vehicle groups.

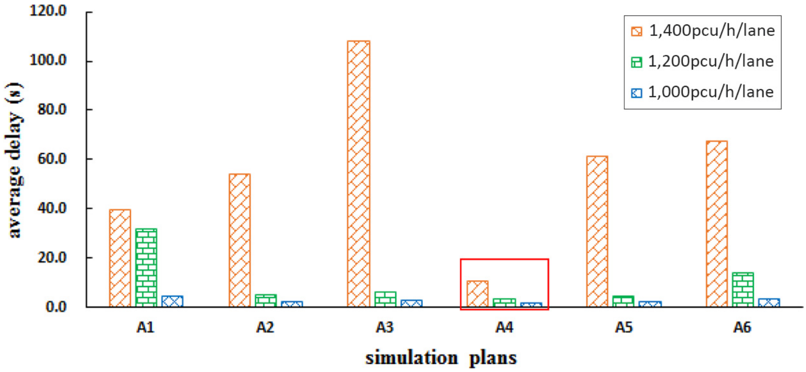

Figure 13.
Output histogram of the six lane-changing plans

Based on the results of this study, future research should focus on the following:

- the modeling and simulation of lane-changing behaviors of vehicle groups in weaving areas; and
- the feasibility of vehicle cooperative organization strategies under various road conditions.

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