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Modeling and Simulation of Lane-Changing Management Strategies at on-Ramp and off-Ramp Pair Areas Based on Cellular Automaton

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ABSTRACT In urban expressways, when an on-ramp and off-ramp pair are closely spaced, the operational condition of the downstream diverge area influences that of the adjacent upstream merge area because of the weaving movement and queuing. Although lane-changing management schemes have often been used in practice, the quantification effect of specific management schemes has not been studied in detail. In this paper, a new cellular automaton model that fits in an on-ramp and off-ramp pair area was established, in which three types of lane change behaviors and eight types of lane-changing management schemes are considered. Sensitivity analysis of the simulation results was conducted to validate the effectiveness of the lane-changing management schemes, from which the optimal schemes under various geometric and traffic conditions are recommended. Results show forcing the off-ramp vehicles to change lanes in advance by using lane markings results in higher operational efficiency in most cases.

INDEX TERMS Cellular automaton model, lane-changing management, freeway, operational simulation.

I. INTRODUCTION

The urban expressway is the skeleton that connects the main parts of the city. It plays a highly important role in dealing with large amounts of traffic in the city [1]. On-ramp merge areas and off-ramp diverge areas are basic components of the urban expressway. Due to the limitation of the land use, the on-ramp and off-ramp pair is in close proximity in some cases. The operational condition becomes more complex because of the weaving movement and queuing. In order to reduce the congestion at the on-ramp merge areas and off-ramp diverge areas, various management and control strategies were proposed, including ramp metering (RM) [2]–[4], variable speed limit (VSL) [5], [6], integrated RM and VSL [7], [8], high-occupancy/toll lanes [9]–[12], route guidance [13]–[15], and lane-changing management [16]–[21].

Among these strategies, lane-changing management is a method for improving the running order of the urban expressway, which could force vehicles to change lanes only where allowed. Daganzo *et al.* [16] proposed the use of a lane assignment strategy at the off-ramp, which shows assigning multiple lanes to exit traffic can alleviate the queuing from affected upstream ramps. Wang *et al.* [22] expanded the use of the lane assignment strategy to freeway weaving areas. An optimal lane assignment model was proposed for one-sided freeway weaving areas to reduce the disturbance between weaving and non-weaving traffic streams. Zhao *et al.* [23] proposed an integrated optimization model for the weaving areas, in which the lane allocation and on-ramp signal control are combined. An *et al.* [24] further explore the effect of operational efficiency at weaving areas and considered three different

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lane-changing rules to match the driving behavior using the cellular automaton model.

The traffic flow model is widely used to analyze various complex traffic phenomena on the expressway. Pan *et al.* [25] divided lane-changing behaviors into mandatory and discretionary lane-changing behaviors, and proposed an algorithm to estimate the dynamic mandatory and discretionary lane-changing demands; they calibrated the proposed mesoscopic multilane cell transmission model and validated the model on a complex weaving section of the State Route 241 freeway in Orange County, California, showing both the positive and negative impact of lane-changing maneuvers. Gong et al [26] proposed an optimization model to search for the optimal position of advance warning for a lane change. Experimental results indicate that the proposed optimization model can identify the optimal location to set the advance mandatory lane change warning near an off-ramp so that the traffic delay resulting from lane change maneuvers is minimized, and the corresponding capacity drop and traffic oscillation can be efficiently mitigated.

Among many traffic flow models, the cellular automaton (CA) model is a commonly used modeling method that can simulate the evolution of dynamic systems by discretizing time and space [27]. With the maturity of the CA model in the field of traffic flow in recent years, the model has seen a series of developments [28]–[35]. For the road segment, Wang, *et al.* [36] investigated the effects of passing lanes on traffic flow on a single-lane highway based on a CA model. The traffic flow conditions under different flow rates and different operating lengths were analyzed. Mei, *et al.* [37] set three-lane changing rules for different road sections to study the traffic of urban expressway systems with on-off-ramps and accessory roads; results show that a higher on-ramp rate easily produces traffic jams on main roads, on-ramps, and their upstream sections; a higher off-ramp rate easily leads to conflict with the inflow of accessory roads. In order to more realistically reflect real-world vehicular movement, Lv, *et al.* [38] extended the continuous single-lane models to simulate lane-changing behavior on an urban roadway that consists of three lanes. The effects of the lane-changing behavior on the distribution of vehicles, velocity, flow, and headway were investigated. Rassafi, *et al.* [39] modeled a drivers' behavior on a basic freeway by nesting the logit model simulation rules into the CA model. The existing systems showed that focused drivers select their next position in accordance with the maximum safe speed. Habel and Schreckenberg [40] used the CA model as essential to extended asymmetric lane change rules. The presented ruleset was then verified in simulations of two-lane and three-lane highways. Yang, *et al.* [41] focused on the mixed traffic flow of manual and automated vehicles, they improved the existing CA model to analyze the characteristic variations in the mixed traffic flow, and they found that with the proportional increment of automated vehicles, lane change frequency decreases significantly. For the ramps, Li, *et al.* [42] studied the dynamics of traffic flow around an on-ramp with an acceleration lane. the lower acceleration rate of a vehicle was described by the refined CA model. Kang and Yang [43] proposed a CA model with sensitive lane change, in which the driving behavior under the guidance of traffic signs at ramp was considered Shang, *et al.* [44] established a multiple CA model to describe the queue jump behavior and the traffic spillback near expressway off-ramp. The queue-jump rules are incorporated into the car-following and lane changing logics in the model Hua, *et al.* [45] simulated the traffic flow with the effect of adaptive cruise control (ACC) vehicles and on-ramps. A car-following model with constant headway is used for ACC vehicles, while an CA model is proposed for manual vehicles Kong, *et al.* [46] analyzed the influence of heavy vehicles the on-ramp system based on CA model. The differences of driving behavior in different vehicle combinations was considered in the forward motion, while the aggressive behavior was considered in the lane changing motion. Dong, *et al.* [47] analyzed the effect of intelligent vehicles on the traffic flow at off-ramp diverge segment based on CA model. The future behaviors of intelligent vehicles are reflected by the discretionary and mandatory lane-change model.

According to the literature review, the existing studies on lane-changing management are mainly focusing on weaving areas. However, compared to the weaving areas, the length of the on-ramp and off-ramp pair areas can be longer. Therefore, different lane-changing management strategies can be combined used according to the traffic pattern and geometric conditions. It makes the operational condition more complex. This paper aims to analyze the effect of lane-changing management on operational efficiency at on-ramp and off-ramp pair areas. A cellular automaton model is proposed to investigate the effect. A detailed analysis of the operational efficiency of eight lane-changing management strategies is conducted under different traffic and geometric conditions. The application conditions of these strategies can be drawn.

The rest of this paper is organized as follows. In Section 2, the cellular automaton model that fits in an on-ramp and off-ramp pair area with the con lane-changing management strategies is described in detail. Section 3 presents the simulation results and analyzes the effectiveness of the proposed strategies under various geometric and traffic conditions. Conclusions and recommendations are provided at the end.

II. MODEL DESCRIPTION

In this section, a CA model for the merge and diverge area with the consideration of different lane-changing management schemes are established. Two kinds of behaviors, namely car-following and lane-changing, are built into this model.

The reasons we choose CA model are two-fold: (1) Lots of relevant works have been conducted based on CA model as mentioned in the literature review. (2) In our study, numerous numerical simulations (86400) were tested, which make us to consider the balance between the simulation granularity and efficiency.

A. LANE-CHANGING MANAGEMENT SCHEMES AT AN ON-RAMP AND OFF-RAMP PAIR AREA

On-ramp merge areas and off-ramp diverge areas are basic components of the urban expressway, as shown in Fig. 1 (a) and (b), respectively. If an on-ramp and off-ramp pair is in close proximity, the operational conditions of the downstream diverge area influence that of the adjacent upstream merge area because of the weaving movement and queuing. To ensure that the traffic stream at the on-ramp and off-ramp pairs operate smoothly, the lane-changing behavior is controlled by lane-changing management strategies. As shown in Fig. 1 (c), the permission of the lane changing between two adjacent lanes can be divided three types by setting a one-direction or two-direction no-passing zone: (1) lane changes are permitted for the two adjacent lanes when they are separated by a broken line; (2) lane changes are prohibited for the two adjacent lanes when they are separated by a solid line; (3) lane changing is permitted only for the traffic traveling adjacent to the broken line when a broken line and a solid line are both used, which can be further divided into two sub-types. Different lane markings on a contiguous merge area and diverge area will have different effects. Eight lane-changing management schemes are considered, as shown in Table 1. Please note that the lane-changing behaviors will be directed affected by the lane markings between lane 2 and 3. Moreover, the traffic flow of the entire on-ramp and off-ramp pair area will also be affected correspondingly.

The CA model is described using cells. Each cell has two running conditions: empty or occupied. At each simulation time, one vehicle can occupy only one cell, and one cell can be occupied by only one vehicle. A cellular description of an on-ramp and off-ramp pair is shown in Fig. 2. According to Table 1, eight lane-changing management schemes are considered. They have similar cell composition with different behaviors for lane-changing. Without loss of generality, using scheme 34 as an example (see Fig. 2), the vehicles from the on-ramp can make a lane change from lane 3 to lane 2 at the merge area, but the lane change from lane 2 to lane 3 is prohibited. Moreover, the vehicles going to the off-ramp can make a lane change from lane 2 to lane 3 at the diverge area, but a lane change from lane 3 to lane 2 is prohibited.

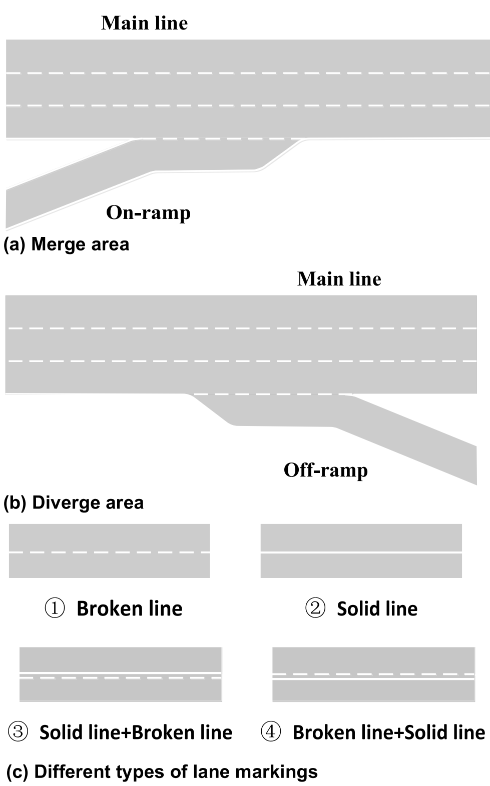


FIGURE 1. On-ramp merge areas and off-ramp diverge areas.

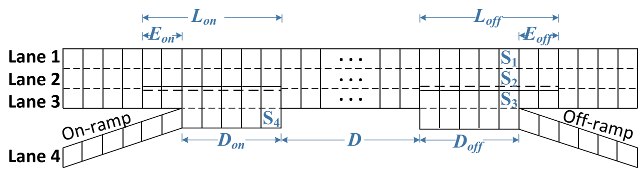


FIGURE 2. Cellular description of on-ramp and off-ramp pair.

TABLE 1. Lane-changing management schemes.

Schemes	Lane markings On ramp	Lane markings Off ramp	Schemes	Lane markings On ramp	Lane markings Off ramp
Scheme 11	①	①	Scheme 31	③	①
Scheme 22	②	②	Scheme 41	④	①
Scheme 34	③	④	Scheme 13	①	③
Scheme 43	④	③	Scheme 14	①	④

Note: ①, ②, ③, and ④ represent a broken line, solid line, solid line + broken line, and broken line + solid line, respectively.

Note: D is the distance between the on-ramp and off-ramp; D_{on} is the length of the merge area; D_{off} is the length of the diverge area; E_{on} is the extended length of the on-ramp lane marking at the beginning of the merge area; E_{off} is the extended length of the off-ramp lane marking at the ending of the diverge area; L_{on} is the length of the on-ramp lane marking; L_{off} is the length of the off-ramp lane marking; and S_1, S_2, S_3 and S_4 are the end cells for the on-ramp and off-ramp cars to change lanes.

B. BEHAVIORS FOR THE CELLULAR AUTOMATON MODEL

According to real-life driving habits, the operational behaviors for the CA model can be divided into two parts: car-following and lane-changing. Car-following behaviors are for vehicles running in a straight line on a single lane, and the lane changing behaviors are for vehicles that want to change to adjacent lanes with different goals.

1) CAR-FOLLOWING BEHAVIORS

In this model, car-following behaviors come from the Nagel-Schreekenberg (NS) model (*29*). The state of each vehicle is represented by its speed and position, which will be updated based on the cells/time step. All vehicles in the system will be generated at the first cell position and will leave the system after driving to the last cell position. At the inlet, vehicles will appear randomly if the inlet cells are not occupied. Otherwise, vehicles will wait until inlet cells have a vacancy. At the outlet, vehicles can always leave freely. The vehicular speed, which is expressed by the number of cells that the vehicle is moving forward, can be determined by the following two steps. Step 1 determines the possible maximum speed of vehicles, as shown in Eq. (1). It contains three conditions according to the relationship between the vehicular speed in step t-1, the number of empty cells ahead, and the maximum speed limitation, as shown in Fig. 3. Step 2 randomly decelerates the vehicle with a certain probability (p) to simulate the cautious driving behavior and obtain the running speed of each vehicle, as shown in Eq. (2).

$$v_{n\max}(t) = \begin{cases} v_n(t-1)+1 & v_n(t-1) < V, v_n(t-1) < g_n(t) \\ v_n(t-1), & v_n(t-1) = V \le g_n(t) \\ g_n(t), & g_n(t) \le v_n(t-1) \end{cases} \quad (1)$$

where $v_{n_{\max}}(t)$ is the nth car's possible maximum speed at time step t, the unit is the number of cells per time step; $v_n(t$-1) is the nth car's speed at time step t-1, the unit is the number of cells per time step; and V is the maximum speed, the unit is the number of cells per time step; $g_n(t)$ is the gap in the number of cells between the nth car and the car in front of it at time step t.

$$v_n(t) = \begin{cases} v_{n\max}(t), & random[0,1] > p \\ v_{n\max}(t)-1, & random[0,1] \le p \end{cases} \quad (2)$$

where $v_n(t)$ is the nth car's running speed at time step t, the unit is the number of cells per time step; p is a fixed probability value; random [0,1] is a random value between 0 and 1.

The vehicular position is updated according to the speed determined by Eq. (2), as shown in Eq. (3). In other words, the two steps of speed determination are conducted in a time step.

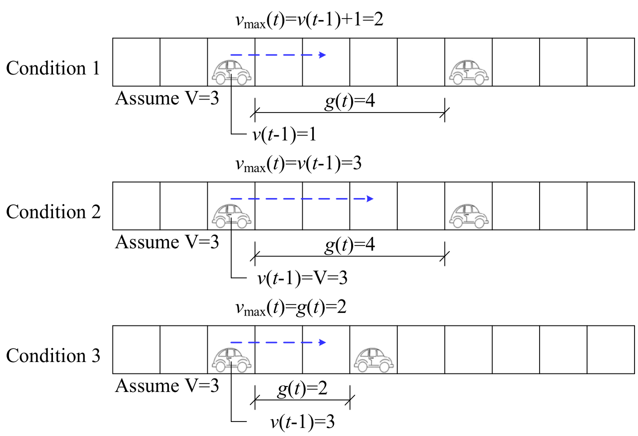


FIGURE 3. The possible maximum speed of vehicles.

Please note, since vehicles move based on the lattices in the CA model, it may result in the unreasonable acceleration and deceleration.

$$x_n(t) = x_n(t-1) + v_n(t) \quad (3)$$

where $x_n(t)$ is the nth vehicle position at time step t; $x_n(t$-1) is the nth vehicle position at time step t-1.

2) LANE CHANGING BEHAVIORS

Three kinds of lane changing behaviors for on-ramp and off-ramp vehicles are proposed according to the degree of the lane changing demand in different areas: strong-demand, middle-demand, and weak-demand. At the merge and diverge areas, on-ramp and off-ramp vehicles have the strong lane changing demand because they must change lanes immediately. At a short distance before a diverging area, vehicles that need to get off the expressway have middle lane changing demand because they are preparing to leave the mainline. In other areas, vehicles have weak lane changing demand because they change lanes to achieve higher speeds but not necessary. The models of the lane changing behaviors that are shown in Eqs. (4)-(9) under the strong-demand, middle-demand, and weak-demand are presented in the following paragraphs in that order.

Eqs. (4)-(6) are used for vehicles having an urgent need to change to their target lanes. Eq. (4) indicates that the car cannot perform the lane change if the cell in the target lane directly beside the vehicle is occupied. Eq. (5) indicates that the car does not consider the conditions and other cars. If there is enough empty space before it on the target lane, the formula is satisfied. Eq. (6) indicates that if there is enough empty space after the car on the target lane, the formula is satisfied. When all three conditions (Eqs. (4)-(6)) are satisfied, the car will change to the target lane. It will not perform the lane change if any condition is not met. If it always cannot satisfy the formulas, the car will wait at the end of the on-ramp cell or at the beginning of the off-ramp cell (the S_1 to S_4 cells in Fig. 2).

$$\delta_n(t) = 0 \quad (4)$$

$$g_n^+(t) \ge g_n(t) \text{ or } g_n^+(t) \ge 1 \quad (5)$$

$$g_n^-(t) \ge g_n(t) \text{ or } g_n^-(t) \ge 1 \quad (6)$$

where $\delta_n(t)$ is the statue of the cell in the target lane directly beside the vehicle n at time step t, 0-empty and 1-occupied; $g_n(t)$ is the number of empty cells between the car n and the front car on the same lane at time step t; $g_n^+(t)$ is the number of empty cells between the car n and the front car on the target lane at time step t; and $g_n^-(t)$ is the number of empty cells between the car n and the car behind it on the target lane at time step t.

For cars that have middle demand, they need to guarantee they do not disturb other cars behind them, and have safe empty cells before them on the target lane. Even though they do not have an urgent demand in this area, they still need to change lanes actively to prepare for an on-ramp or off-ramp.

Eq. (7) means that the empty cells are sufficient for the car behind it on the target lane to drive after the lane change. Eq. (5) is used to control the driving conditions before the car, while Eq. (7) is used to control the driving condition behind the car. Eq. (4) is used to ensure the cell in the target lane directly beside the vehicle is empty. When Eqs. (4), (5), and (7) are satisfied, the car will change to the target lane. It will not perform the lane change if any condition is not met.

$$g_n^-(t) \geq \min\left\{v_n^-(t)+1, V\right\} \tag{7}$$

where $v_n^-(t)$ is the speed of the car behind at time step t.

Cars need to ensure they do not disturb others and get higher speed when they change lanes. This kind of lane-changing behavior has weak demand, so they will change lanes with a probability. Eq. (8) means the empty cells are sufficient for the car to drive ahead after a change to the target lane. Eq. (9) means the empty cells are not sufficient before changing lanes. Eq. (7) is used to control the driving condition behind the car, and Eq. (8) is used to control the driving condition before the car on the target lane; and Eq. (9) is used to control the car itself. If the car wants to change lanes, it must satisfy Eqs. (7)-(9); then, it will change with probability p_c. Eq. (4) is used to ensure the cell in the target lane directly beside the vehicle is empty. When Eqs. (4), and (7)-(9) are satisfied, the car will change to the target lane with probability p_c. It will not perform the lane change if any condition is not met.

$$g_n^+(t) \geq \min\left\{v_n(t)+1, V\right\} \tag{8}$$

$$g_n(t) < \min\left\{v_n(t)+1, V\right\} \tag{9}$$

These behaviors should work together with different lane allocation scheme designs because they fit different areas. The whole operational procedure structure of the expressway CA model is shown in Fig. 4. Please note that a vehicle will first update the lane-changing behavior then the car-following. It is due to the fact that drivers care more about the lane-changing in the studied area.

III. SIMULATIONS AND SENSITIVITY ANALYSES

Based on the proposed CA model, this section aims to explore the effectiveness of these schemes in various traffic and geometric scenarios. The changing tendency of the performance of eight lane-changing management schemes is illustrated. Then, the application conditions of these strategies can be drawn.

The simulation evaluation indicators include average driving speed on one lane, average travel time of the four paths (from main-line to off-ramp, from on-ramp to mainline, from main-line to main-line, and from on-ramp to off-ramp), and the number of lane changes. The basic input of the simulation is shown as follows. The number of cells in each area is shown in Table 2. The update time interval is set to be 0.5 seconds. The random proportion p is 0.3; the week demand lane changing proportion p_c is 0.2; the maximum driving speed V is 3 cells/step; the traffic volume on each lane Q is 400 veh/ln; the proportion of on-ramp vehicles α_c is 0.2; and the proportion of off-ramp vehicles α_d is 0.2. The average result of 50 times simulation is used.

The following sensitivity analysis was conducted from three aspects: the influence of the traffic volume, the on-ramp and off-ramp proportion, and the distance between the on-ramp and off-ramp.

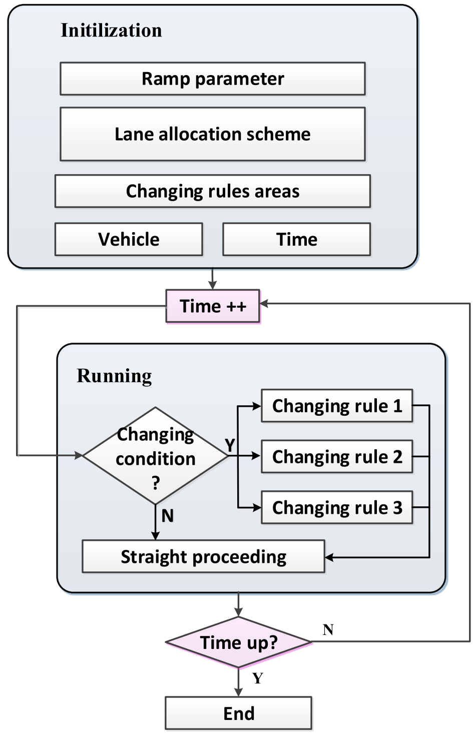


FIGURE 4. Computational procedure of expressway CA model.

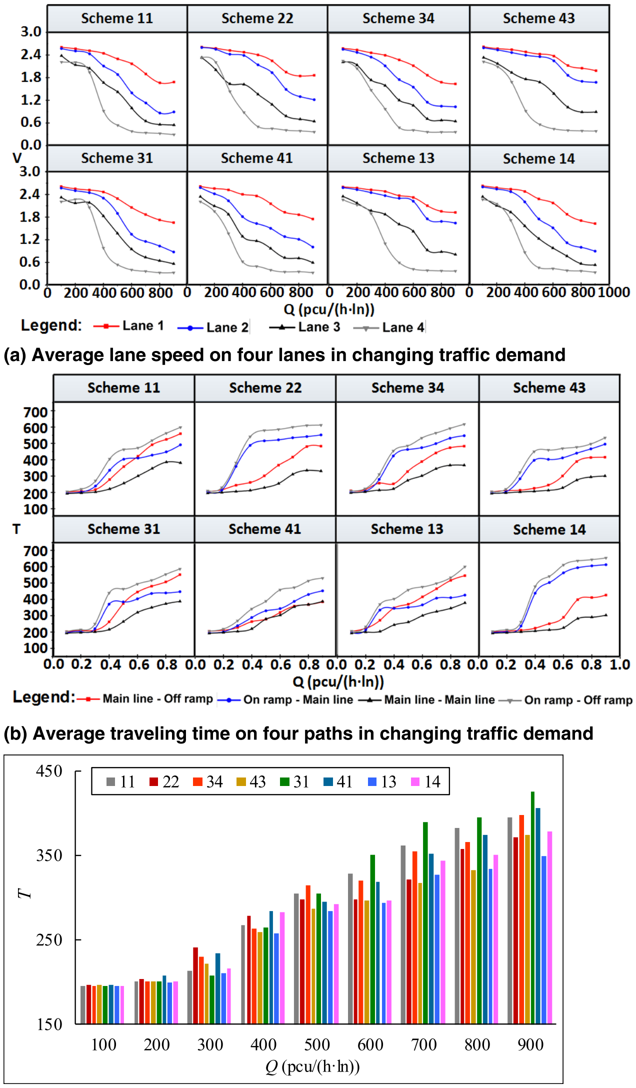
TABLE 2. Simulation geometry at each area.

Area	Length		Width	
	Size (m)	Number of Cells	Size (m)	Number of Cells
Single Cell	5	1	3.5	1
Entire area	2500	500	14	4
Merge area	75	15	7	2
Diverge area	75	15	7	2
Area used for data collection	1500	300	14	4
Extend of lane marking at the beginning of merge area	25	5	3.5	1
Extend of lane marking at the ending of diverge area	25	5	3.5	1
Total on-ramp lane marking	100	20	-	-
Total off-ramp lane marking	100	20	-	-
Distance between on-ramp and off-ramp	150	30	-	-

Note: The merge and diverge area includes lane 3 and lane 4.

A. INFLUENCE OF TRAFFIC DEMAND

The input traffic demand on a traffic lane (Q) was changed from 100 veh/ln to 900 veh/ln to explore the effect of traffic demand on the eight schemes. The comparison results of the four lanes' average speed (V), the four paths' average travel time (T), and the average travel time of all the vehicles are shown in Fig. 5(a), (b), and (c), respectively.



(a) Average lane speed on four lanes in changing traffic demand

(b) Average traveling time on four paths in changing traffic demand

(c) Average travel time of all the vehicles in changing traffic demand

FIGURE 5. **Effect of the traffic demand.**

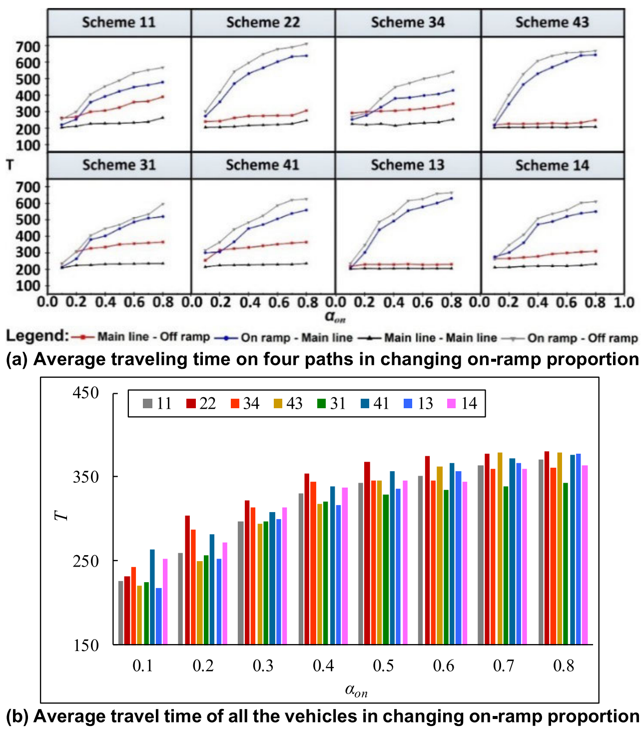
Overall, with the increase of single-lane traffic demand, the average speed on all four lanes decreases, and the average travel time on four paths increase in all eight strategies. The most influenced lane is lane 4, whereas the least influenced lane is lane 1. The most influenced path is from on-ramp to off-ramp, whereas the least influenced path is from main line to main line.

The eight schemes perform similarly when the demand is less than 300 veh/(h·ln). With the increase in traffic demand, Schemes 43 and 13 show the advantage gradually. Schemes 43 and 13 limits the lane-changing of off-ramp vehicles, while they allow vehicles to change lanes to the main line. They can keep lane 1 and lane 2 at a high speed when the traffic flow increases. Therefore, schemes 43 and 13 can increase the travel speed on lanes 1 and 2, and decrease the average travel time of vehicles coming from the main line.

The average travel time of all the vehicles is shown in Fig. 5(c). The lane-changing management schemes do not always outperform the original no lane-changing limitation scheme (scheme 11). Therefore, the selection of the lane-changing management scheme is important for the operation of the on-ramp and off-ramp pair area. In this case, the optimal scheme (scheme 13) is stable under various traffic demand conditions. With respect to scheme 11 as a benchmark, scheme 13 can decrease the average travel time by 11.4%.

B. INFLUENCE OF ON-RAMP AND OFF-RAMP VOLUME PROPORTIONS

The input on-ramp volume proportion (α_{on}) and off-ramp volume proportion (α_{off}) were changed from 0.1 to 0.8 to explore the effect of lane-changing proportion on eight schemes. The comparison results of the four paths' average travel time (T), and the average travel time of all the vehicles with changing α_{on} are shown in Fig. 6(a) and (b), respectively. The four paths' average travel time (T) and the average travel time with changing α_{off} are shown in Fig. 7(a) and (b), respectively.

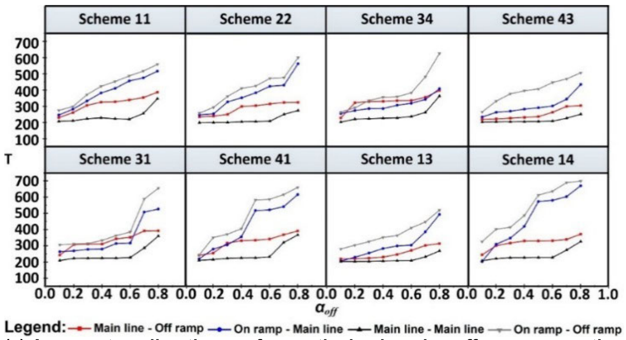


(a) Average traveling time on four paths in changing on-ramp proportion

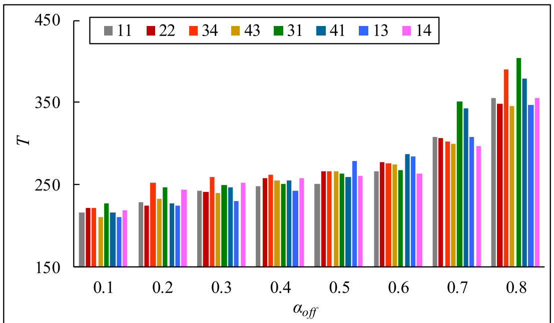
(b) Average travel time of all the vehicles in changing on-ramp proportion

FIGURE 6. **Effect of the on-ramp proportion.**

With respect to on-ramp proportion, overall, as the proportion of on-ramp flow increases, the travel time of the four paths increases in the eight schemes. The path of the main road is less affected than the path of the on-ramp. In addition, the on-ramp vehicles are highly sensitive and are greatly

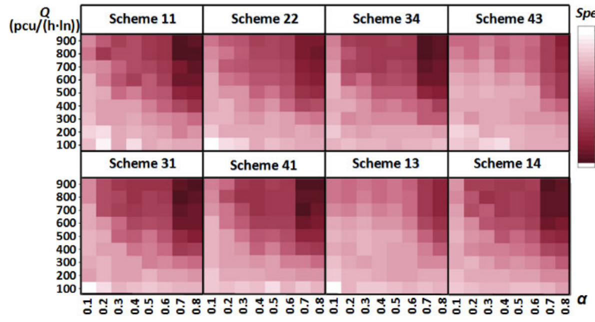


(a) Average traveling time on four paths in changing off-ramp proportion

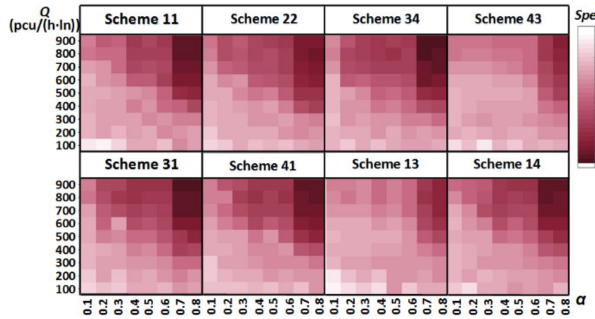


(b) Average travel time of all the vehicles in changing off-ramp proportion

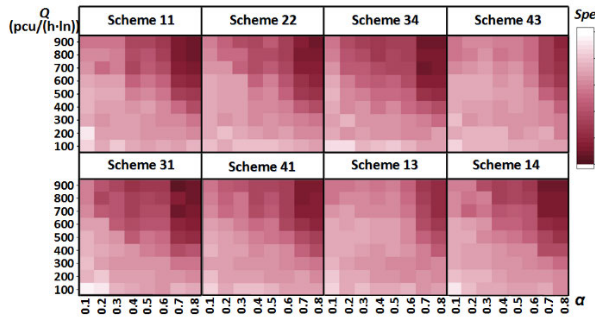
FIGURE 7. Effect of the off-ramp proportion.



(a) Congestion index under different conditions when *D* is 30 cells



(b) Congestion index under different conditions when *D* is 60 cells



(c) Congestion index under different conditions when *D* is 90 cells

FIGURE 8. Congestion index for different distances between on-ramp and off-ramp.

affected by the proportion of on-ramp flow. With the increase of α_{on}, different schemes show highly different effects.

Comparing the performance among schemes (see Fig. 6(b)) shows that schemes 34 and 31 can keep on-ramp cars running smoothly and maintain a low travel time when on-ramp volume proportion is higher than 0.4 because they give the on-ramp cars priority. They have a better performance in the travel time under high on-ramp volume proportion condition. About 9% reduction in travel time can be obtained. Therefore, schemes 34 and 31 can decrease the average travel time of on-ramp vehicles, and will not have a negative impact on the main line vehicles.

With respect to off-ramp proportion, overall, with the increase of off-ramp proportion, the travel time of cars in the four paths exhibited a stable increase in all eight schemes. However, in comparison to the on-ramp proportion, the effect of average travel time changes gently with increasing off-ramp proportion. This indicates that the travel time is more sensitive to the on-ramp proportion. The most influenced path is from on-ramp to off-ramp, whereas the least influenced path is from main line to main line.

The eight schemes perform similarly when the proportion of off-ramp vehicles is less than 0.6. Schemes 13 and 43 can keep the main lanes at a high speed when α_{off} increases. They can decrease the average travel time of vehicles coming from the main line. When the off-ramp volume proportion is under 0.6, scheme 13 is the best management scheme; when the proportion is higher than 0.6, scheme 43 is the best management strategy.

Fig. 7(b) shows that the lane-changing management schemes are superior to the original scheme 11 when α_{off} is higher than 0.6. In this case, it is found that the optimal scheme (scheme 43) is stable under different traffic volume conditions. With respect to scheme 11 as a benchmark, scheme 43 can decrease the average travel time by 7.1%.

C. INFLUENCE OF DISTANCE BETWEEN ON-RAMP AND OFF-RAMP

In order to investigate the influence that the diverge area has on the merge area, three distances between on-ramp and off-ramp were chosen: a short distance for which the diverge area can be considered to have a strong influence on the merge area, a middle distance for which the diverge area can be considered to have a medium influence on the merge area, and a long-distance that can be considered to have no relation. Fig. 8(a) shows the system average speed under different conditions when *D* is 30 cells (150 m); in Fig. 8(b), *D* is 60 cells (300 m); and in Fig. 8(c), *D* is 90 cells (450 m).

Overall, the average speed V increases with the increase of D. It indicates that with the increase in D, the influence of the diverge area on the merge area is smaller, and the crowding in the merge area is digested more easily. In general, the least congested situation is when D is 90 cells; the most condition is when D is 30 cells.

Comparing the performances among schemes shows that the effects of the eight schemes are similar when the indicators of α and Q are low. Schemes 43 and 13 can improve congested conditions in almost all parameters, especially when α is between 0.2 and 0.8 and Q is between 300 veh/ln and 900 veh/ln. When D is 90 cells, the different schemes do not have significant differences. Therefore, the optimization effect of the optimal scheme is minimal when D is 90 cells.

With respect to scheme 11 as a benchmark, when D is 30 cells, Scheme 43 is generally the optimal solution. It has highly stable optimization effects. When D is 60 cells and 90 cells, scheme 13 is the optimal solution under different ramp proportions on these two conditions. When the distance between the on-ramp and off-ramp increases, using free lane-changing management for the merge area effectively increases the average speed of the system and has a better mitigation effect on congestion.

D. PROPOSAL OF OPTIMAL LANE-CHANGING MANAGEMENT STRATEGIES

Based on the results of the simulations described above, the optimal schemes under different traffic conditions can be recommended. On average, a reduction of 10% in travel time can be obtained with respect to scheme 11 as a benchmark. With single-lane traffic flow (Q), ramp volume proportion (α), and the distance between on-ramp and off-ramp (D) as three independent variables, the optimal schemes under different conditions are shown in Table 3.

Overall, schemes 43 and 13 are generally optimized management schemes that have the best results in most cases. As the distance between on-ramp and off-ramp grows, the situation in which scheme 13 applies moves down overall, and the applicable situation becomes more extreme.

Table 3 shows that when D is 30 cells, scheme 43 is more advantageous, especially under extreme conditions. However, scheme 13 is more suitable for more moderate conditions. When D is 60 cells and 90 cells, scheme 13 becomes more advantageous, and it is better than scheme 43 in more cases. When the distance reaches 90 cells, the original scheme (scheme 11) is applicable in more cases. It can be concluded that prohibiting lane changes in the divergent area is a useful lane management scheme, which can significantly improve traffic efficiency.

TABLE 3. Optimal schemes under different conditions.

α	Q (veh/ln)								
	100	200	300	400	500	600	700	800	900
D = 30 cells									
0.1	11	11	11	11	11	11	11	43	43
0.2	11	11	43	43	43	43	43	43	43
0.3	11	43	43	13	13	13	43	43	43
0.4	11	43	13	13	13	13	13	13	43
0.5	43	43	13	13	13	13	13	13	43
0.6	43	43	13	13	13	13	13	13	43
0.7	43	43	43	43	43	43	43	43	43
0.8	43	43	43	43	43	43	43	43	43
D = 60 cells									
0.1	11	11	11	11	11	11	11	13	13
0.2	11	11	11	11	11	43	13	13	13
0.3	11	11	43	43	43	43	13	13	13
0.4	11	43	43	43	43	43	13	13	13
0.5	11	43	43	43	43	43	43	13	13
0.6	43	13	13	13	13	13	13	13	13
0.7	43	13	13	13	13	13	13	13	13
0.8	43	13	13	13	13	13	13	13	13
D = 90 cells									
0.1	11	11	11	11	11	11	11	43	43
0.2	11	11	11	11	11	11	43	43	43
0.3	11	11	11	11	43	13	43	43	43
0.4	11	11	43	43	13	13	13	13	43
0.5	11	11	43	43	13	13	13	13	43
0.6	11	43	43	13	13	13	13	13	43
0.7	43	43	13	13	13	13	13	13	13
0.8	43	43	13	13	13	13	13	13	13

Note: The numbers correspond to the eight schemes in Table 1.

IV. CASE STUDY

In this section, a segment from Yonghe Road to Lingshi Road on the North-South Elevated Road in Shanghai, China, is used to validate and evaluate the effectiveness of the proposed approach, as shown in Fig. 9. There are two main lanes with two on-ramp lanes at the merging area, and three main lanes with two off-ramp lanes at the diverging area. The management scheme 11 is used in this study site in reality, in which the broken lines have been set at both merge and diverge areas. The distance between the on-ramp and off-ramp D is 350 m, which is measured by 70 cells in the CA model (5m for each cell); the lane-changing distance for on-ramp cars D_{on} is 90 m (18 cells); the lane-changing distance for off-ramp cars D_{off} is 70 m (14 cells); the length of on-ramp lane marking L_{on} is 28 cells; the length of off-ramp lane marking L_{off} is 24 cells.

The traffic operation data, including traffic volume, travel speed, and lane-changing movements, from 7:00 to 14:00 were collected by traffic monitoring video. Statistics show that during peak hours, the average on-ramp proportion α_{on} is 0.39; the average off-ramp proportion α_{off} is 0.21. The number of the passing vehicles and the average speed (the speed 1 in the simulation is equal to 10 m/s) is used as the indicate to validate the accuracy of the proposed model, as illustrated in Fig.10(a). The data was aggregated in every 20 minutes. The proposed model could cause an error under 5.0% and 8.0% for the number of passing vehicles and the average speed, respectively, in all statistical intervals. Moreover, the paired T-test shows the difference between the measured data and the result of the model simulation is not significant (p = 0.326 and 0.21 for the number of

FIGURE 9. Location and geometric condition of the case study.

passing vehicles and the average speed, respectively, which are larger than 0.05), which shows the accuracy of the proposed method is acceptable. Then several lane-changing management schemes are tested using the proposed model. The comparison results are shown in Fig.10(b).

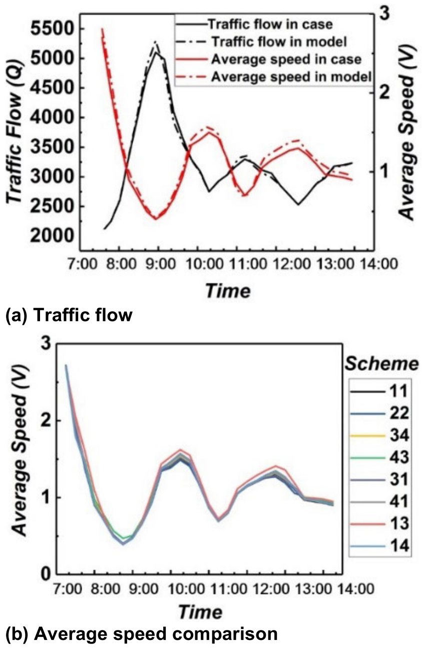


FIGURE 10. Simulation results.

From Fig.10, scheme 11 can be considered as the benchmark. When the average speed of this system is extremely high or extremely low, the effects of the eight schemes are similar. It indicates that lane-change management schemes cannot work if the road is particularly smooth or severely blocked. During the morning peak hour, scheme 43 has the greatest optimization effect, which indicates that scheme 43 is suitable for use in situations with large traffic flows, but scheme 43 is not optimal all the time. During the off-peak hours, when traffic flow is moderate, the effect of scheme 13 is most prominent. Especially after 9:00, the effect of optimization is most obvious. In general, scheme 13 can increase the average speed by more than 10%. It is efficient to relieve congestion when the traffic flow is moderate. Scheme 13 forbids off-ramp cars changing lanes to the main line in diverge area, ensuring that the main lane cars are unhindered. The result is in line with the recommended scheme of the previous optimal lane-changing management, which indicates the feasibility of the study.

V. CONCLUSION

This paper explored the effect of lane-changing management on operational efficiency at on-ramp and off-ramp pair areas. A CA simulation model was established in which the lane-changing behavior was divided into three categories according to the degree of the lane changing demand in different areas: strong-demand, middle-demand, and weak-demand. Based on numerous numerical simulations (86400), the effectiveness of eight lane-changing management strategies was compared. The following conclusions can be drawn.

(1) The main function of the lane-changing management strategy is to reduce the amount of irrational lane-changing.

(2) On average, a reduction in travel time of 10% can be obtained by setting the optimal lane-changing scheme.

(3) Forcing the off-ramp vehicles to change lanes in advance is a useful lane-changing management strategy in most cases. Scheme 43 is the best when the distance between on-ramp and off-ramp is around 150 m; Scheme 13 is the best when the distance is more than 300 m.

It is assumed that all the vehicles obey the lane-changing management rules. More detailed driving behavior analysis, i.e., the possibility of the lane-changing violation and its effect on the traffic flow, can be the direction of future study.

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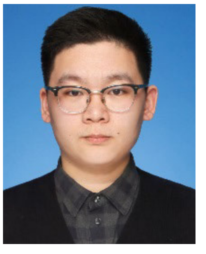

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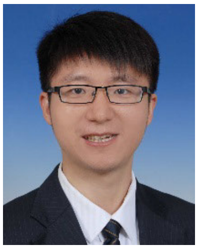

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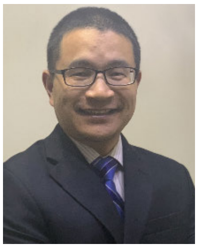

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