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Research Article

Cooperative U-Turn Merging Behaviors and Their Impacts on Road Traffic in CVIS Environment

Wenjing Wu,[1] **Renchao Sun**,[1] **Yongxing Li**,[2] **and Runchao Chen**[1]

[1]*School of Transportation, Jilin University, Changchun 130000, Jilin, China*
[2]*School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*

Correspondence should be addressed to Yongxing Li; liyx219@163.com

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U-turn behavior of vehicle is one of the main causes of urban traffic congestion and accidents. A collaborative U-turn merging control algorithm is studied with collision avoidance and delay minimization for vehicles under Cooperative Vehicle Infrastructure System (CVIS) environment. Two control strategies, zip merging and platoon merging control, are proposed. The applicability of these two strategies is compared from the perspective of efficiency and driving comfort. The cellular automaton simulation system composed of a two-way four-lane traffic flow with a U-turn facility in middle of road is established with cooperative control algorithm imbedded. The influence of cooperative U-turn merging behaviors on traffic performance is evaluated by analyzing the arrival rates of main lane and U-turn vehicles and their relationship between one another. The simulation results show that the arrival rate of vehicles on target lane has a great impact on traffic delay. The cooperative control can improve the traffic flow only in the condition that the arrival rate of vehicles on target lane is less than 0.7. It provides some practical references for transportation agencies to meet efficiency requirements of the U-turn section when they apply cooperative control strategy.

1. Introduction

U-turn facilities are used as open areas for two-way traffic flow on the road, often set at the entrance of intersection or the middle of road section. U-turn behaviors of vehicles have significant impacts on the traffic performances [1–5]. In theory, straight vehicles should get priority to U-turn vehicles all the time. However, the conflicts between U-turn vehicles and incoming vehicles are common especially when the U-turn vehicles are in a long queue, or reach the endurance waiting limit of drivers, or the incoming vehicles are reluctant to yield. The traffic managers guide the vehicles by means of speed limit, traffic signs, or traffic line marking. However, the responses to these guidance strategies are different because of the different driving abilities, characteristics, and driving styles. So, the implementation effects of those measures are not obvious. The advent of new technologies in transportation, known as Cooperative Vehicle Infrastructure System technology (CVIS), and their introduction into daily city traffic has become a major focus for car manufacturers, road authorities, traffic operators, and researchers. The CVIS provides a new solution for the safety control and traffic management of U-turn traffic problem.

U-turn traffic is one of the vehicle-merging problems for two vehicle streams. The most common merging behaviors happen on ramps and unsignalized intersections. The control strategy of merging in CVIS environment has attracted extensive attentions. Wu et al. [6] developed a game theory-based description of drivers' interactions in U-turn scene, and the game model was imbedded into a cellular automaton model for identifying the effect of U-turn vehicle on traffic performance. In [7, 8], the collaborative control models for ramp merging of freeway in CVIS environment are proposed. In [9], an adaptive traffic signal control method based on traffic flow conditions to reduce conflicts and delays at signal intersections is proposed. In [10, 11], respectively, a rolling optimization control model and an improved centralized control model to optimize the organizational form of the intersection were constructed. In [12], a vehicle operation model at intersection based on

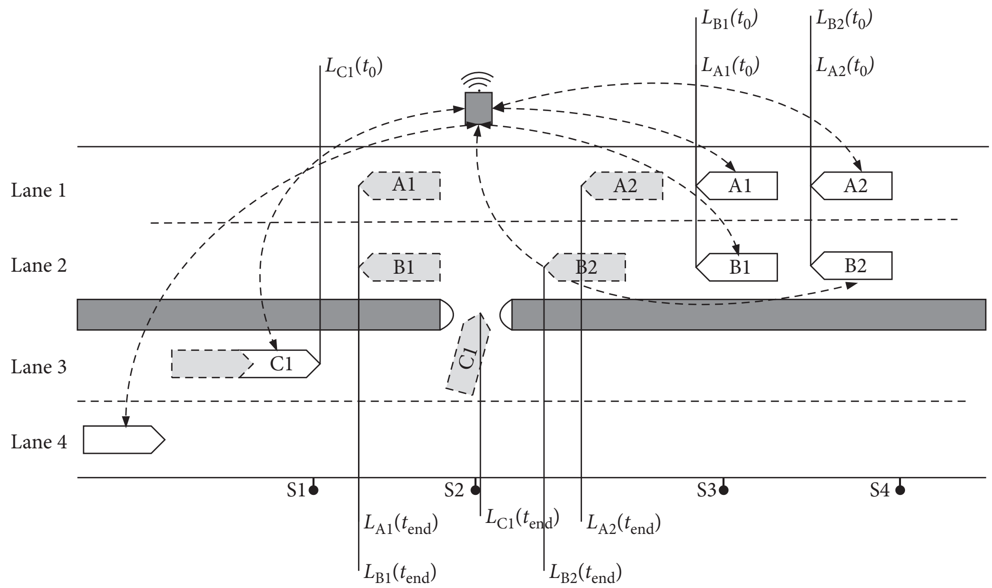

Figure 1: Vehicle cooperative control framework in U-turn zone.

model predictive control theory is proposed. In [13, 14], the turning behavior of vehicles in the CVIS environment was studied and the U-turn behavior of automated vehicles was evaluated. Zha et al. [15] studied the judgement method of troubled areas timely and used signal control to reduce the conflicts in troubled areas.

The proposed algorithms for cooperative merging can be classified from many aspects, such as the control method can be divided into centralized and decentralized [16–18]. All the vehicles are controlled automated or only partial vehicles can communicate between each other [19–24]. The vehicles on mainstream and on-ramp lane are coordinated controlled or only controlled for one stream of vehicles [25–27]. The optimal criteria can be divided into the view of safety, passenger comfort, flow efficiency, fuel consumption and emissions, time delay, etc. [28, 29]. Otherwise, the differences of the layout of networks or the location of the control and the type of communication type between vehicles [30, 31] are also included.

The purpose of this paper is the development of a centralized control algorithm between the U-turn vehicle streams and incoming vehicle streams in the middle of road section (Figure 1). All the vehicles are assumed to be automatic under control. The aim of the control is collaborative U-turn merging behaviors of vehicles with collision avoidance and maximum speeds. Different from the control algorithms applied before, the merging algorithm in this work consists of the two control steps in order to be consistent with the real operation of U-turn vehicles. U-turn vehicles should firstly decelerate to finish the turning operation, then accelerate, and choose the proper gap of the target lane at the right time.

This paper makes two contributions. The first is designing a coordinated control strategy to meet the requirements of zip merging or platoon merging in the CVIS environment as well as exploring the threshold of application of these two strategies through comparing the driver comfort and delay. The second is evaluating the impacts of U-turn vehicles on the lane-based traffic performance considering the influence of the arrival rate of incoming vehicles under cooperative control and no control environment as well as exploring the trigger of cooperative control strategy application, which would be helpful for transportation agencies to meet time-cost and comfort needs of the drivers to manage the U-turn traffic.

The work is organized as follows. The U-turn merging control framework is proposed and the control algorithms composed of zip merging and platoon merging are constructed in Section 2. The vehicles trajectories of zip control and platoon control are compared by simulation experiment, and the applicability of these two strategies is discussed in Section 3. The cellular automata system with U-turn cooperative control model embedded is constructed in Section 4, and the efficiency of control strategy is studied by traffic performance analysis. Section 5 presents the conclusion.

2. U-Turn Merging Control Framework and Algorithm

2.1. Merging Control Framework. It is assumed that vehicles are all automatic and obey the instructions issued by the Traffic Manage Center. Figure 1 shows the scenario. There is a two-way 4-lane road with U-turn section in middle, incoming vehicles A1 and A2 on lane 1, B1 and B2 on lane 2, and a U-turn vehicle C1 on the opposite direction lane 3. We assume that C1 starting from lane 3 would cross from lane 2 to lane 1. Because the middle isolate zone set in this work is not wide enough to meet the requirement of vehicles turning operation, C1 cannot turn directly from lane 3 to lane 2. Otherwise, we do not consider the lane-change process of U-turn vehicles from lane 4 to lane 3, only U-turn vehicles on lane 3 are selected as research objects. There are three cases of merging situations:

Scenario 1: vehicle C1 would merge behind the platoon vehicles A1 and A2 on the main lane.

Scenario 2: vehicle C1 would merge before the platoon vehicles A1 and A2 on the main lane.

Scenario 3: vehicle C1 would merge in between the vehicles A1 and A2 on the main lane.

The first and the second scenarios are the special forms of the third scenario. All merging control problems can be solved if merging control of the scenario 3 has been formulated, so this work chooses the third scenario as the research situation.

Set the road segments S1–S4 as the cooperative control regions. The point S2 is the merging point. All U-turn vehicles coming from the lane 3 are enforced to merge at this point. Under the CVIS environment, U-turn vehicles and main lane vehicles would exchange information with the Traffic Management Center. When the C1 approaches the point S2, it will scan the merging target lane 1 and lane 2 for the possible intervals. Once the interval is selected, the C1 would adjust the speed of the vehicle to align with the target gap accordingly in segment S1-S2. Otherwise, the A1, A2 and B1, B2 on main lanes will adjust their speeds on segment S3-S4 to produce the available gaps for C1 to merge safety. The purpose of the collaborative control is optimal vehicle driving strategies by speed adjustment and gap alignment process for the involved vehicles (C1, A1, A2, B1, and B2) under the premise of collision avoidance.

2.2. The Control Algorithm of Single-Turning Vehicle. As shown in Figure 1, the cooperative control for the merging maneuver starts when a U-turn vehicle wants to perform turning operation and a virtual U-turn vehicle is mapped into space between vehicle A1 and A2 after passing the space between the vehicles B1 and B2 during the period of $t \in [t_0, t_{\text{end}}]$. The initial distances between vehicle A2 and the point S2 and vehicle A1 and S2 are $L_{\text{A1}}(t_0)$ and $L_{\text{A2}}(t_0)$, respectively. The initial distances between vehicle B2 and the point S2 and vehicle B1 and S2 are $L_{\text{B1}}(t_0)$ and $L_{\text{B2}}(t_0)$, respectively. The initial distance between C1 and the point S2 is $L_{\text{C1}}(t_0)$. Assume that the speeds of all vehicles are equal initially, symbolized by v_0.

2.2.1. The Driving Behavior Constraints of Vehicle B2. The desired distance between the vehicle B2 and the point S2 after t seconds can be described as follows:

$$L_{\text{B2}}(t) = L_{\text{B2}}(t_0) - \int_{t_0}^{t} v_{\text{B2}}(t)\mathrm{d}t, \quad t \in [t_0, t_{\text{end}}]. \tag{1}$$

In order to get way to C1 safely, the distance $L_{\text{B2}}(t_{\text{end}})$ between the vehicle B2 and the point S2 at the time step t_{end} should meet the requirements as follows:

$$L_{\text{B2}}(t_{\text{end}}) > l_v + G_{\min}, \tag{2}$$

where l_v and $G_{\min}$ represent the vehicle length and the minimum safe distance of vehicles, respectively.

2.2.2. The Driving Behavior Constraints of Vehicle A2. The desired distance between the vehicle A2 and the point S2 after t seconds can be described as follows:

$$L_{\text{A2}}(t) = L_{\text{A2}}(t_0) - \int_{t_0}^{t} v_{\text{A2}}(t)\mathrm{d}t, \quad t \in [t_0, t_{\text{end}}]. \tag{3}$$

When vehicle C1 is going to merge to lane 1 after completing turning operation, its speed is lower than the other vehicles on the lane 1. To avoid collision with A2 at the time step t_{end}, the distance between the vehicle A2 and the C1is $L_{\text{A2}}(t_{\text{end}})$, and it will meet the requirement as follows:

$$\begin{aligned} L_{\text{A2}}(t_{\text{end}}) > v_{\text{A2}}(t_{\text{end}}) \times \frac{[v_{\text{A2}}(t_{\text{end}}) - v_{\text{C1}}(t_{\text{end}})]}{a_{\text{A2}}(t_{\text{end}})} \\ - \frac{[v_{\text{A2}}^2(t_{\text{end}}) - v_{\text{C1}}^2(t_{\text{end}})]}{2a_{\text{A2}} + G_{\min} + l_v}, \end{aligned} \tag{4}$$

where $v_{\text{A2}}(t_{\text{end}})$, $v_{\text{C1}}(t_{\text{end}})$, and $a_{\text{A2}}(t_{\text{end}})$ are the speeds of the vehicles A2 and C1 and the acceleration of A2 at time step t_{end}, respectively.

2.2.3. The Driving Behavior Constraints of Vehicles A1, B1, and C1. To realize the zip merge one by one, vehicles A1 and B1 will adjust their speeds to keep their positions ahead of the merging vehicle C1. The distance between the vehicle A1 and the point S2 is $L_{\text{A1}}(t_{\text{end}})$. The distance between the B1 and the S2 is $L_{\text{B1}}(t_{\text{end}})$. They should meet the requirements as shown in equation (5) and (6) at time step t_{end}. The constraint of distance $L_{\text{C1}}(t_{\text{end}})$ is shown in equation (7):

$$L_{\text{A1}}(t_{\text{end}}) - \int_{t_0}^{t_{\text{end}}} v_{\text{A1}}\mathrm{d}t < 0, \tag{5}$$

$$L_{\text{B1}}(t_{\text{end}}) - \int_{t_0}^{t_{\text{end}}} v_{\text{B1}}\mathrm{d}t < 0, \tag{6}$$

$$\int_{t_0}^{t_{\text{end}}} v_{\text{C1}}\mathrm{d}t - L_{\text{C1}}(t_0) = 0. \tag{7}$$

2.3. The Control Algorithm of Multi-Turning Vehicles. There are two strategies of merging processing when two or more vehicles want to U-turn. The first one is the zip merging, that is to say, each U-turn vehicle merge to the target main lane consecutively. The other one is platoon merging, that is to say, a platoon of turning vehicles merge to the target lane at a time. In this work, the two control strategies are discussed, respectively, with their corresponding scenarios.

As shown in Figure 2, it describes the zip merging process of six vehicles. The U-turn vehicle C1 merges in between the vehicle A1 and A2 after crossing the gap between B1 and B2. The U-turn vehicle C2 merges after the vehicle A2 when passing the lane 2 after vehicle B2. As shown in Figure 3, it describes the platoon merging process. A platoon of U-turn vehicle composed of C1 and C2 merges in between the vehicles A1 and A2 after crossing the gap between B1 and B2.

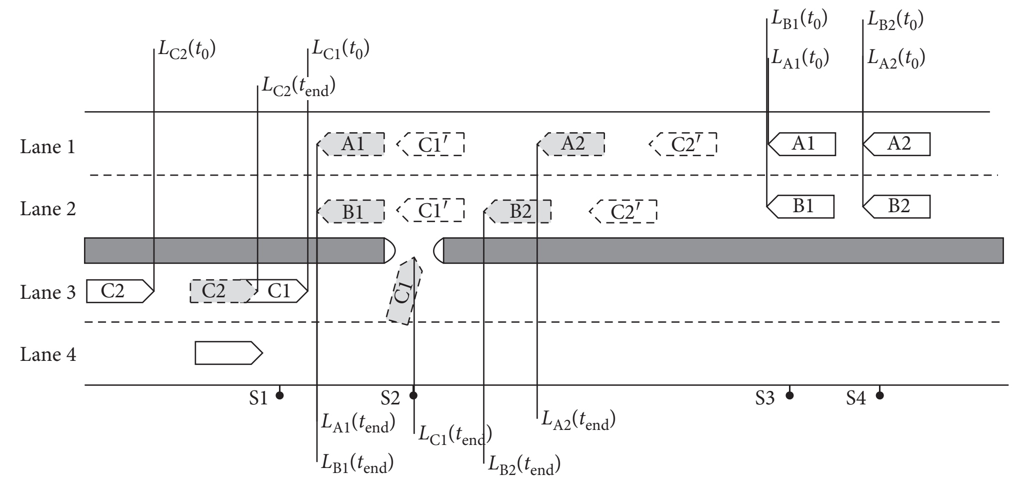

Figure 2: The framework of zip merge control.

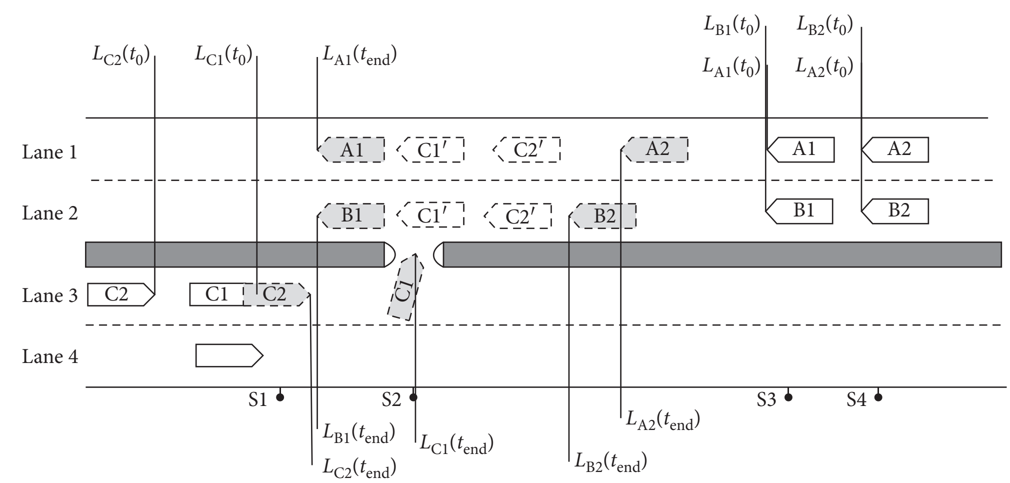

Figure 3: The framework of platoon merge control.

2.3.1. The Driving Behavior Constraints of Vehicles C1 and C2 under Zip Merge. As shown in Figure 2, the virtual vehicles C1′ and C2′ are formed beforehand. The vehicle C1 meets the constraints of (2)~(7) like the single vehicle, and vehicle C2 should merge into target lanes after A2 and B2. C2 should meet the following constraints at time step t_{end}:

$$\begin{gathered}\frac{L_{C2}\left(t_{end}\right)}{\left[v_{C2}\left(t_{end}\right) \times v_{B2}\left(t_{end}\right)\right]} - L_{B2}\left(t_{end}\right) > 0, \\ \frac{v_{A2}\left(t_{end}\right) \times L_{C2}\left(t_{end}\right)}{v_{C2}\left(t_{end}\right) - L_{A2}\left(t_{end}\right)} > 0.\end{gathered} \tag{8}$$

2.3.2. The Driving Behavior Constraints of Vehicles C1 and C2 under Platoon Merge. As shown in Figure 3, the virtual platoon of U-turn vehicles is formed beforehand. The platoon of vehicles C1 and C2 can be regarded as a single vehicle with a length of $G_{min} + 2l_v$. The constraints are shown as follows:

$$L_{B2}\left(t_{end}\right) > 2l_v + 2G_{min}, \tag{9}$$

$$\begin{aligned}L_{A2}\left(t_{end}\right) > v_{A2}\left(t_{end}\right) \times \frac{\left[v_{A2}\left(t_{end}\right) - v_{platoon}\left(t_{end}\right)\right]}{a_{A2}\left(t_{end}\right)} \\ - \frac{\left[v_{A2}^2\left(t_{end}\right) - v_{platoon}^2\left(t_{end}\right)\right]}{2a_{A2} + 2G_{min} + l_v}.\end{aligned} \tag{10}$$

Equation (9) meets the safety follow distance between B2 and U-turn platoon at time t_{end}. Equation (10) meets the safety follow distance between A2 and U-turn platoon and considers the distance needed for U-turn platoon to accelerate to form the same velocity with vehicles on target lane. $v_{platoon}(t_{end})$ is the speed of turning platoon vehicles at time step t_{end}.

2.4. The Optimization Model of Cooperative Control. Following the optimized trajectories, these vehicles can safely pass the merging point S2 without any conflicts and achieve delay minimum. The optimal control strategy is formulated as a nonlinear optimization problem as follows through (16):

$$\min\left(-\sum_{i=1}^{3}\sum_{j=1}^{n_i}\sum_{k=1}^{m} v_{i,j,t_k}\right), \tag{11}$$

s.t.

$$0 \le v_{3,j,m} \le \frac{30\,\mathrm{km}}{h}\, 0 \le v_{i,j,t_k} \le \frac{60\,\mathrm{km}}{h}, \quad i = 1,2,\ \forall j,k, \tag{12}$$

$$a_{\min} \le a_{i,j,t_k} \le a_{\max}, \quad \forall i, j, k, \tag{13}$$

$$\left|a_{i,j,t_k} - a_{i,j,t_{k+1}}\right| \le a_{\max-\mathrm{diff}}, \quad \forall i, j, k, \tag{14}$$

$$\left|x_{i,j,t_k} - x_{i,j-1,t_k}\right| \ge G_{\min} + l_v, \quad \forall i,k;\ j = 2,\ldots,n_i, \tag{15}$$

$$\begin{aligned} x_{i,\mathrm{front},t_k} - x_{i,\mathrm{lead},t_k} &\ge G_{\min} + l_v; \\ x_{i,\mathrm{fol},t_k} - x_{i,\mathrm{back},t_k} &\ge G_{\min} + l_v; \quad \forall i,k, \end{aligned} \tag{16}$$

where i is the index of the lane (i = 1, 2, 3 represent the lane 1, lane 2, and lane 3 in this work), j is the index of vehicle ($j = 1, 2, \ldots$), t_k is the k-th time step, m is the sum of time step, n_i is the sum of vehicles involved in cooperative control on lane i, a_{i,j,t_k} is the acceleration of vehicle j on lane i at time step t_k, v_{i,j,t_k} is the speed of vehicle j on lane i at time step t_k, x_{i,j,t_k} is the distance of vehicle j on lane i to merging point at time step t_k, $a_{\min}$ is the minimum acceleration, $a_{\max}$ is the maximum acceleration, $a_{\max-\mathrm{diff}}$ is the maximum acceleration change between two consecutive time steps, x_{i,lead,t_m} is the distance between the lead vehicle at time step t_k and the merging point,x_{i,fol,t_k} is the distance between the following vehicle which follows the lead vehicle at time step t_k and the merging point, x_{i,front,t_k} is the distance between the vehicles in front of the lead vehicle at the time step t_k and the merging point, and x_{i,back,t_k} is the distance between vehicle behind the following vehicle at the time step t_k and the merging point.

By optimizing the acceleration rates at each step, the optimal control model aims to minimize the total delay of all merging vehicles in each decision step subject to the following constraints:

Constraint (12) ensures that each vehicle on main lanes maintains a nonnegative speed that is no greater than the speed limit60 km/h, and each vehicle on U-turn lane (lane 3) maintains a nonnegative speed that is no greater than the speed limit 30 km/h.

Constraint (13) ensures that each vehicle maintains an acceleration rate that is no larger that $a_{\max}$ and no less that $a_{\min}$ at each time step.

Constraint (14) limits the acceleration rate changes of each vehicle between two consecutive time steps to prevent aggressive driving behaviors.

Constraint (15) requires that the distance between two consecutive vehicles in the same lane must be greater than a minimum value $G_{\min} + l_v$.

Constraint (16) makes sure that any pair of vehicles maintains a safe distance at each time step. This is achieved by projecting U-turn vehicles onto the main lane using the merging point S2 as the reference.

3. Comparison between Model Verification and Control Strategies

3.1. The Optimization Model Verification. Set $a_{\max} = 2\,\mathrm{m/s^2}$, $a_{\min} = -2\,\mathrm{m/s^2}$, $a_{\max-\mathrm{diff}} = 2\,\mathrm{m/s^2}$, and $G_{\min} = 10\,\mathrm{m}$. Since the length of the vehicle is usually 4~6 m, set $l_v = 5\,\mathrm{m}$, the initial velocity of the vehicle is $v_0 = 15\,\mathrm{m/s}$, 10 seconds time is considered as control time, and so $m = 10$ [32]. These parameters are used in each scenario.

3.1.1. Single-Turning Vehicle Scene. To verify the effectiveness of the control strategy, single U-turn vehicle and four vehicles on mainline are considered, like the scene Figure 1. Setting the initial state $x_{i,1,0} = 140\,\mathrm{m}$, $i = 1,\ 2$; $x_{i,2,0} = 155\,\mathrm{m}$, $i = 1,\ 2$; and $x_{3,1,0} = 75\,\mathrm{m}$ means that the relative distances between vehicles on lane 1 and lane 2 to S2 are same, and the U-turn vehicle is closer to S2. Setting $v_{i,j,0} = 15\,\mathrm{km/h}$, $i = 1, 2, 3$, and $j = 1, 2, 3$ means the initial speeds of all the vehicles are the same.

The simulation results are summarized in Figure 4. We project all the vehicles onto one lane, and all the values are the relative values taking the point S2 as the reference. Figure 4(a) clearly shows that the constraints on acceleration are satisfied. The changing trend of vehicle C1 is different from other vehicles because of its different limited speed constraint. Figure 4(b) shows that all the vehicles satisfy the limited speed during these 10 seconds decision intervals. The time-space trajectories of these five vehicles are shown in Figure 4(c). This is done by projecting the five vehicles onto a single lane and using S2 as the reference point for calculating the distances. By executing the optimal acceleration instructions generated by the model, it is shown that the five vehicles can merge safely with the minimum distance between each pair of vehicles, which is 10 meters. At the end of control, the distances to merging point of vehicle A1 on lane 1 and vehicle A2 on lane 2 are negative, indicating that they have passed the merging point. However, the distance of the U-turn vehicle is positive and it tends to be 0, indicating that it just completes merging.

3.1.2. Multi-Turning Vehicle Scene. The initial states of vehicles are summarized below same as single vehicle scenario. Setting $x_{i,1,0} = 140\,\mathrm{m}$, $i = 1,\ 2$; $x_{i,2,0} = 155\,\mathrm{m}$, $i = 1,\ 2$; $x_{3,1,0} = 75\,\mathrm{m}$; and $x_{3,2,0} = 90\,\mathrm{m}$ means two U-turn vehicles are coming close. Setting $v_{i,j,0} = 15\,\mathrm{km/h}$, $i = 1, 2, 3$, and $j = 1, 2, 3$ means the initial speeds of all the vehicles are the same. The modeling results for the zip merging are summarized in Figure 5, and the modeling results for the platoon merging are summarized in Figure 6.

Figures 5(a) and 6(a) show that the acceleration variations of all vehicles under the zip merging control are larger than that under the platoon merging control. Figures 5(b) and 6(b) show that the speeds of vehicles under the platoon control are slightly higher than that under the zip control. Project six vehicles onto a single lane like that in the previous

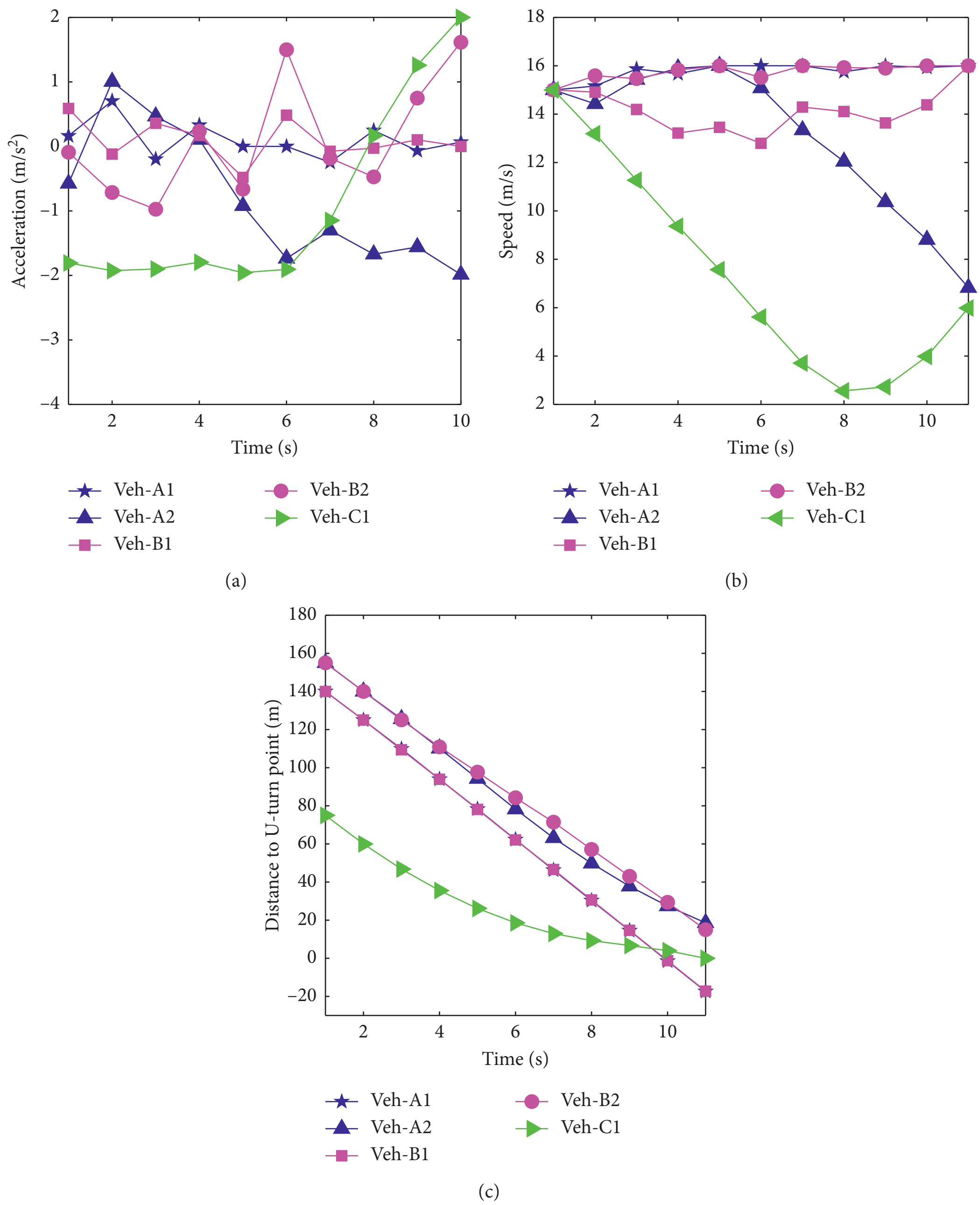

FIGURE 4: The trajectories of single vehicle merging: (a) acceleration; (b) speed; (c) displacement.

study. Figures 5(c) and 6(c) show that the all the vehicles under control merge safely at the end time step.

3.2. The Comparison between Zip Control and Platoon Control. The delay and driving comfort indexes are considered in this paper to be compared between zip merging control and platoon merging control to testify the advantage and disadvantage of each strategy. The comfort feeling of drivers is usually represented by the acceleration index based on experience. The difference of standard deviation of acceleration between these two control strategies is calculated as CT. The delay difference between these two control strategies is calculated as DT. Represent D_z and C_z as the delay and standard deviation of acceleration of the vehicle under zip merging control. Represent D_P and C_P as the delay and standard deviation of acceleration of the vehicle under platoon merging control. So, the delay and comfort differences between these two strategies can be expressed as follows:

$$\begin{aligned} \mathrm{DT} &= D_z - D_P, \\ \mathrm{CT} &= C_z - C_P. \end{aligned} \tag{17}$$

Assume that the delay and standard deviation of acceleration are influenced by the initial headways between vehicles. The variables k and l represent the headway of the front vehicle and the following vehicle in the U-turn platoon and the headway of platoon on main lane, respectively. A

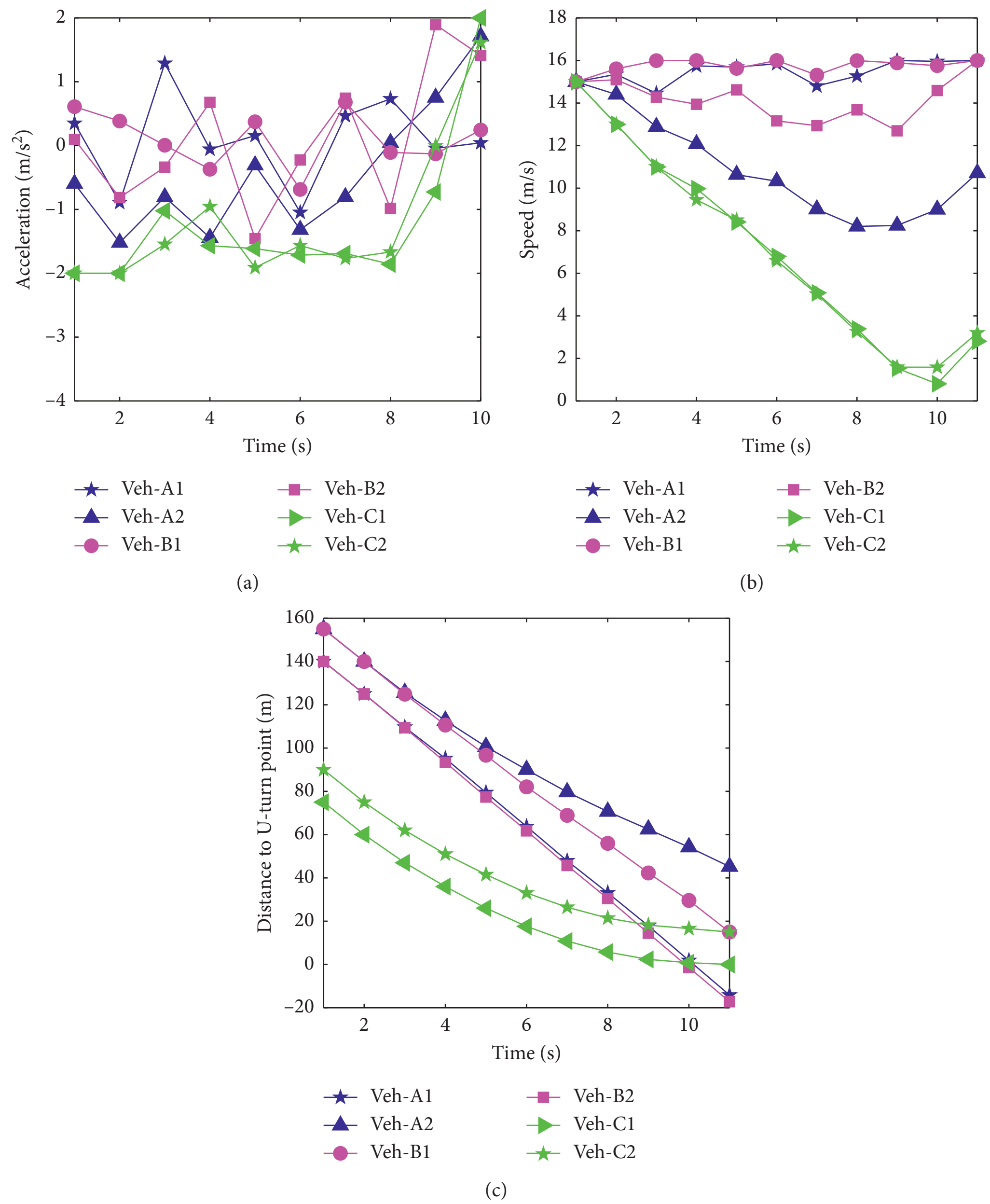

Figure 5: The trajectories of vehicles under zip merging control: (a) acceleration; (b) speed; (c) displacement.

platoon was formed when the space headway is less than 100 m according to the car-following theory, so the headway should be smaller than 100 m and larger than the minimum space headway 10 m. k and l are the headways of U-turn platoon on lane 3 and mainline platoon on lane 1, that is $10\,\text{m} \leq k$ and $l \leq 100\,\text{m}$.

In this experiment, set $x_{i,1,0} = 140\,\text{m}$, $i = 1, 2$; $x_{i,2,0} = (140 + l)\,\text{m}$, $i = 1, 2$; $x_{3,1,0} = 75\,\text{m}$; and $x_{3,2,0} = (75 + k)$ m. Set $v_{i,j,0} = 15\,\text{km/h}$, $i = 1, 2, 3$, and $j = 1, 2, 3$. The speed and acceleration of all vehicles change with the setting of k and l values of traffic flow and also change with the control strategies. And, the mechanism of headways on traffic performance is discussed as follows.

The numerical simulation results are shown in Figures 7 and 8; DT and CT change with the changing of k and l.

3.2.1. The Impacts of k and l on DT

① When $k < 50\,\text{m}$ and $\text{DT} > 0$, the delay of zip merging is larger than that of platoon merging during the distribution of l. It is advisable to adopt the platoon merging strategy under this condition.

② When $k \geq 75\,\text{m}$, the DT is gradually decreasing close to 0, ever less than 0. DT is increasing with the increase of l. When $l \geq 75\,\text{m}$, the difference is greater than 0 again. It is shown that the delay of zip merging is smaller than the platoon merging when the head way of U-turn platoon vehicles is greater than 75 m and the headways of vehicles on main lane are less than 75 m. So, when $k \geq 75\,\text{m}$ and $l \geq 75\,\text{m}$, it is advisable to adopt the zip merging strategy.

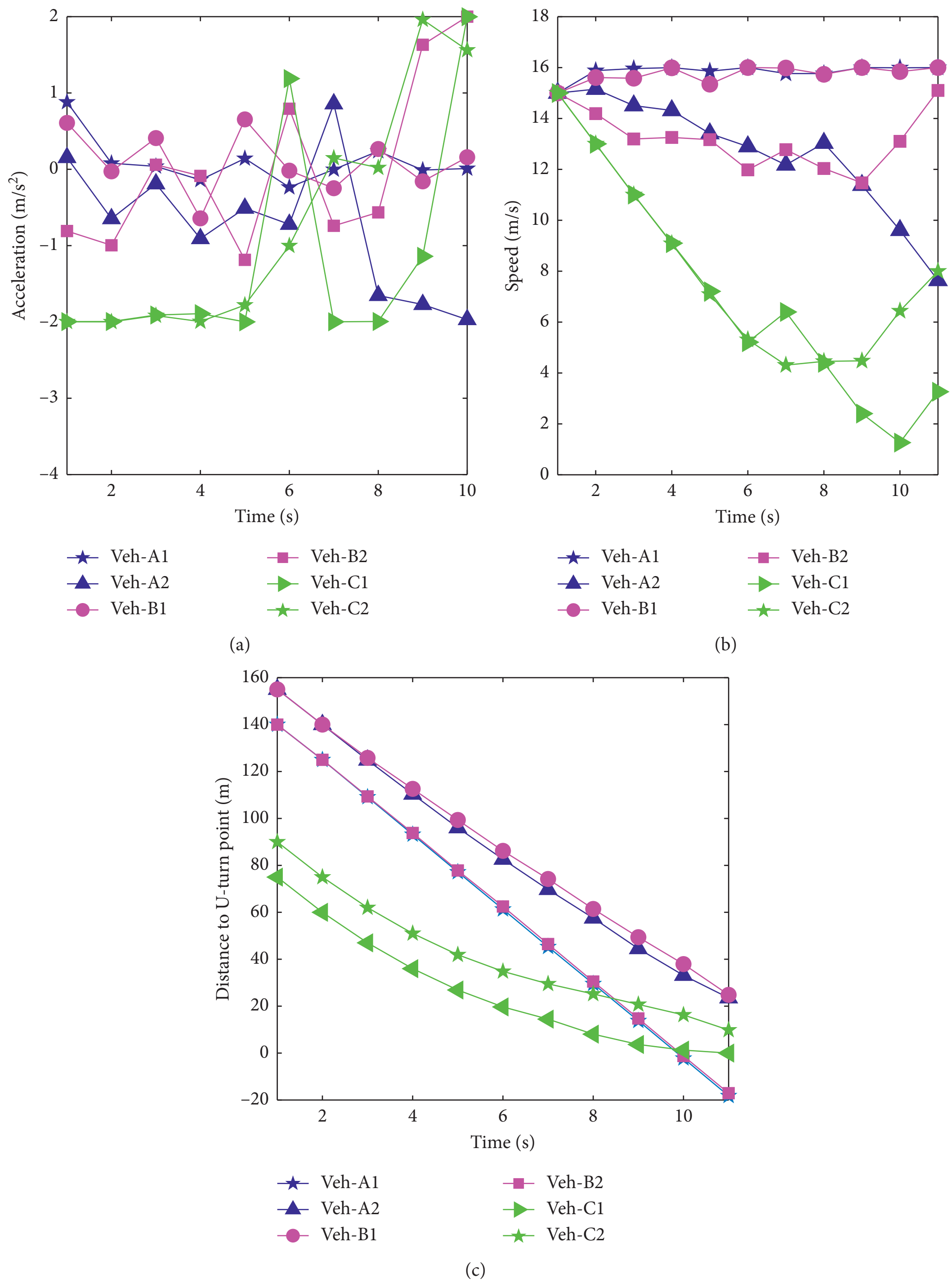

Figure 6: The trajectories of vehicles under platoon merging control: (a) acceleration; (b) speed; (c) displacement.

③ When $l \geq 75$ m and DT > 0, with the increase of l, the delay of zip control is always greater than the delay of the platoon merging. It is advisable to adopt the platoon merging strategy under this condition.

3.2.2. The Impacts of k and l on CT

① When $k < 20$ m and $l < 60$ m or $k > 90$ m and CT < 0, it indicates that the variance of acceleration under the zip merging is smaller than that under the platoon merging, so the comfort of driver under the zip merging strategy is higher under these conditions.

② In addition to the cases above, CT > 0, it indicates that the variance of acceleration under the zip merging is greater than that under the platoon merging, so the comfort of the driver under the platoon merging strategy is higher under this condition.

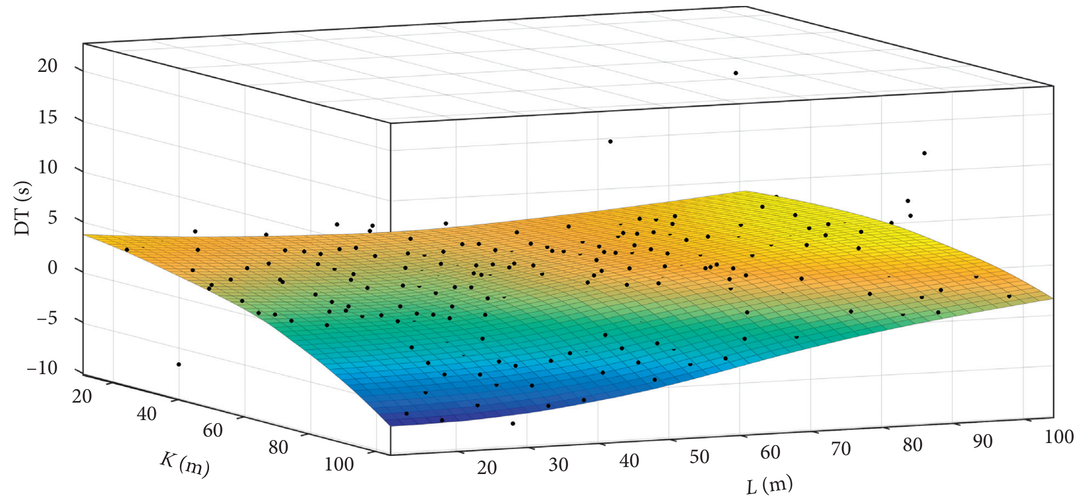

Figure 7: Delay difference between zip and platoon merging control.

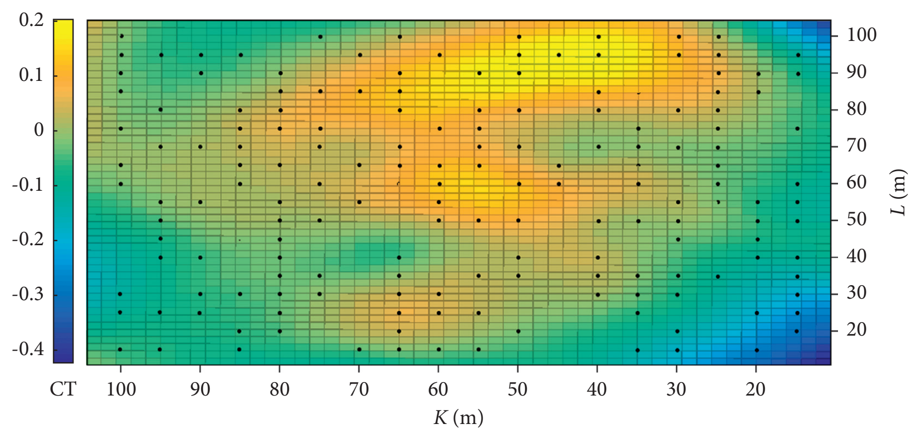

Figure 8: Comfort difference between zip and platoon merging control.

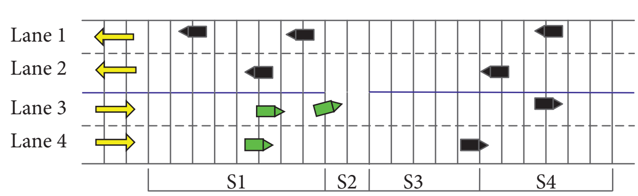

Figure 9: Simulation scene.

4. Simulation Analysis and Discussion

4.1. Assumptions and the Scenes of Simulation. A two-way four-lane cellular automata traffic flow model with a U-turn facility in the middle of road is established, as shown in Figure 9. Set the road length as 250 cells (937.5 m), and one cell represents 3. 75 m. The merging point is in 150 cells (562.5 m). The simulation time step is set to 1 s. It is assumed that all the vehicles have the same length of 2 cells (7.5 m), the max speed is 5 cells per second (67.5 km/h), and the minimum headway is 4 cells (15 m).

Using the classic lane changing rule proposed by Chowdhury et al. [33], the vehicle will change the lane with probability p_{change}. The state of vehicles is modified in each time step using the update rule of the Nash [34] model. Lane-changing probability is $p_{change} = 0.55$ (using the research by Liu and Cao [35]). Random moderation probability is $p_{slow} = 0.3$ based on experience.

Table 1: Trajectories of vehicles in cooperative control.

Time (s)	Distance to merging point S2 (m)					Headway (m)	
	A1	A2	B1	B2	C1	L1	L2
67	176.25	198.75	168.75	183.75	−153.75	22.5	15
68	153.75	180	153.75	168.75	−138.75	26.25	15
69	135	161.25	138.75	153.75	−120	26.25	15
70	120	146.25	120	172.5	−105	26.25	52.5
71	105	131.25	101.25	120	−90	26.25	18.75
72	86.25	116.25	82.5	101.25	−75	30	18.75
73	67.5	97.5	63.75	86.25	−56.25	30	22.5
74	48.75	82.5	45	67.5	−45	33.75	22.5
75	30	67.5	26.25	56.25	−33.75	37.5	30
76	15	52.5	11.25	41.25	−18.75	37.5	30
77	0	37.5	−7.5	22.5	0	37.5	30

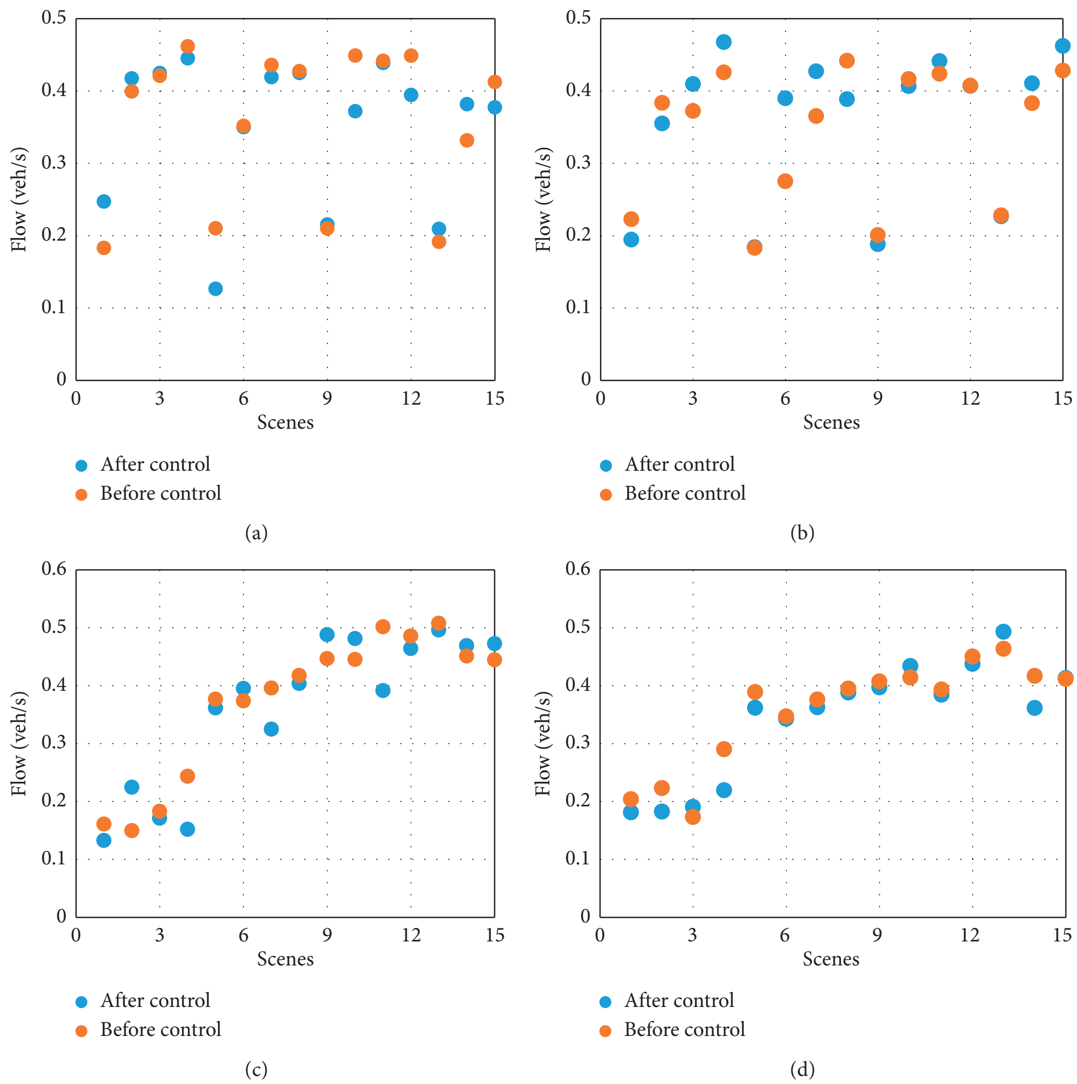

Figure 10: Traffic flow on lanes under different scenes. (a) Lane 1; (b) lane 2; (c) lane 3; (d) lane 4.

4.2. Simulation Analysis. By changing the arrival rates of vehicles of lanes 1 and 2 (marking the probability as p_{in1}), the arrival rates of vehicles of lanes 3 and 4 (marking the probability as p_{in2}) and the impact of the U-turn vehicle cooperative control on the traffic flow are simulated. The ranges of values of p_{in1} and p_{in2} are all set as {0.2, 0.4, 0.6, 0.8}, and a total of $4 \times 4 = 16$ kinds of road scenes are simulated with 500 time steps in each kind.

Take p_{in1} is 0.6 and p_{in2} is 0.8 as example to verify the effectiveness of the control strategy in simulation system, as shown in Table 1. The U-turn vehicle arrives at S1 at 67th second, and it takes 10 seconds to arrive S2. During this time period, the movement process of the vehicles A1, A2, B1, B2, and C1 is shown in the table. L1 is the headway between A1 and A2 on lane 1, and L2 is the headway between B1 and B2 on lane 2. The initial headways L1 and L2 are 6 cells (22.5 m) and 4 cells (15 m), respectively. The vehicles adjust their speeds and accelerate constantly to meet the U-turn merging requirement during these 10 seconds. The headways are 10 cells (37.5 m) in lane 1 and 8 cells (30 m) in lane 2 at the 77th time step. It is in accordance with the constraints in the algorithm. The distance of B1 is −7.5 m, which shows that it has passed S2 already. Meanwhile, the distance of A1 is zero. It means it just arrives at S2, which is consistent with the path planning in the control strategy.

4.3. Discussion

4.3.1. Delay Comparison. The setting of U-turn facility in the middle of road section will cause traffic delay for both directions of lanes. The traffic delays are compared between cooperative control environment and no-control environments. As for no-control environment, the delay is mainly caused by the lane changing behaviors in interweaving zone and the yield behaviors both for the U-turn vehicles and the incoming vehicles to collision avoidance when merging. The interaction is serious with the increase of traffic flow, which will lead to more extensive delay. As for cooperative control environment, delay is mainly caused by the adjustment of velocities of incoming vehicles for producing an available

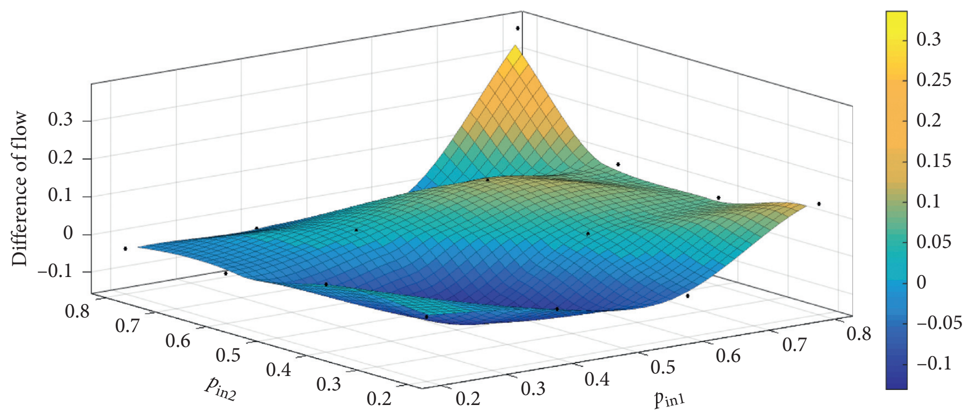

FIGURE 11: The difference of the traffic volume before and after control.

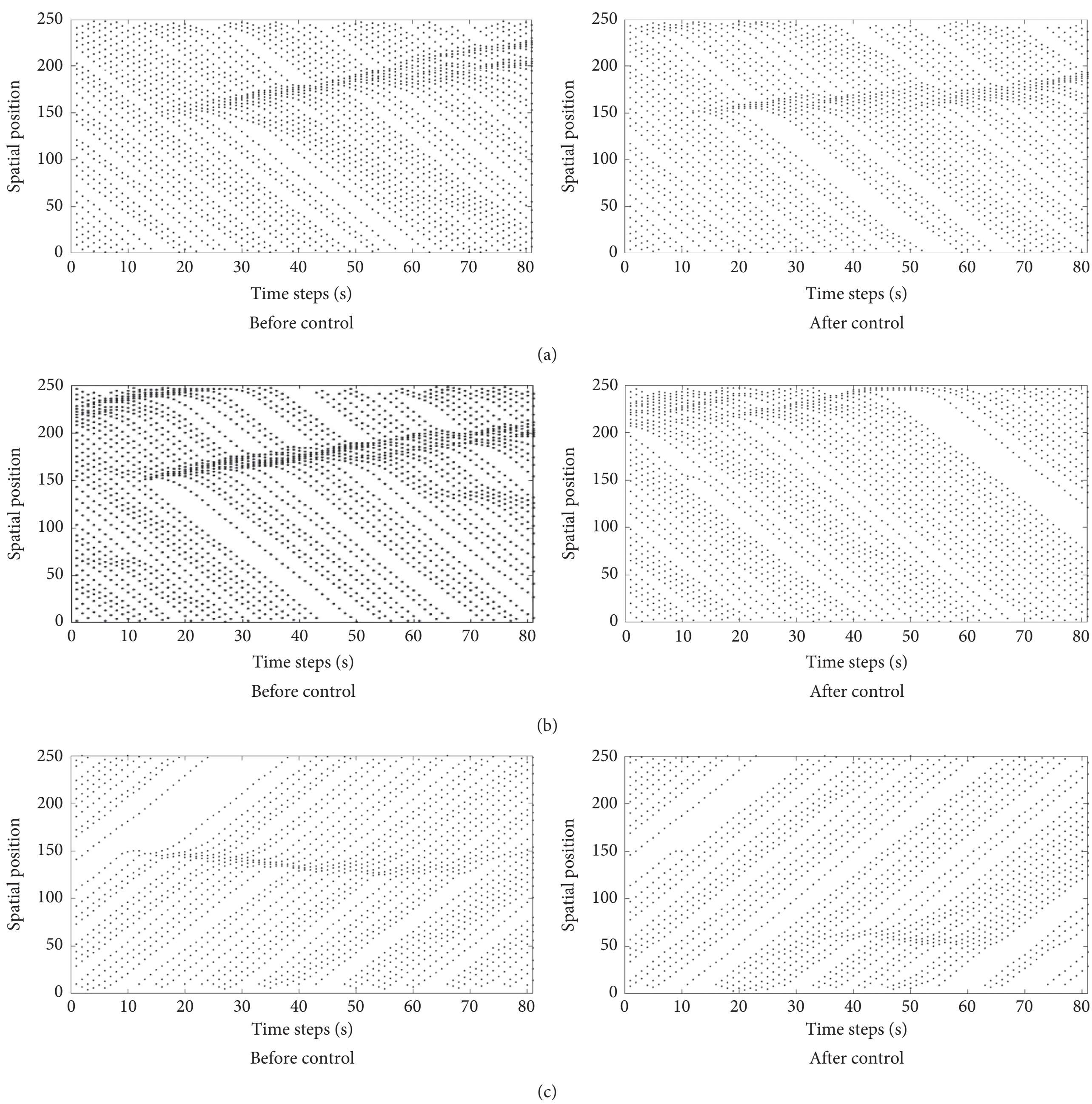

FIGURE 12: The traffic flow states before and after control at $p_{in1} = 0.4$ and $p_{in2} = 0.6$. (a) Lane 1, (b) lane 2, and (c) lane 3.

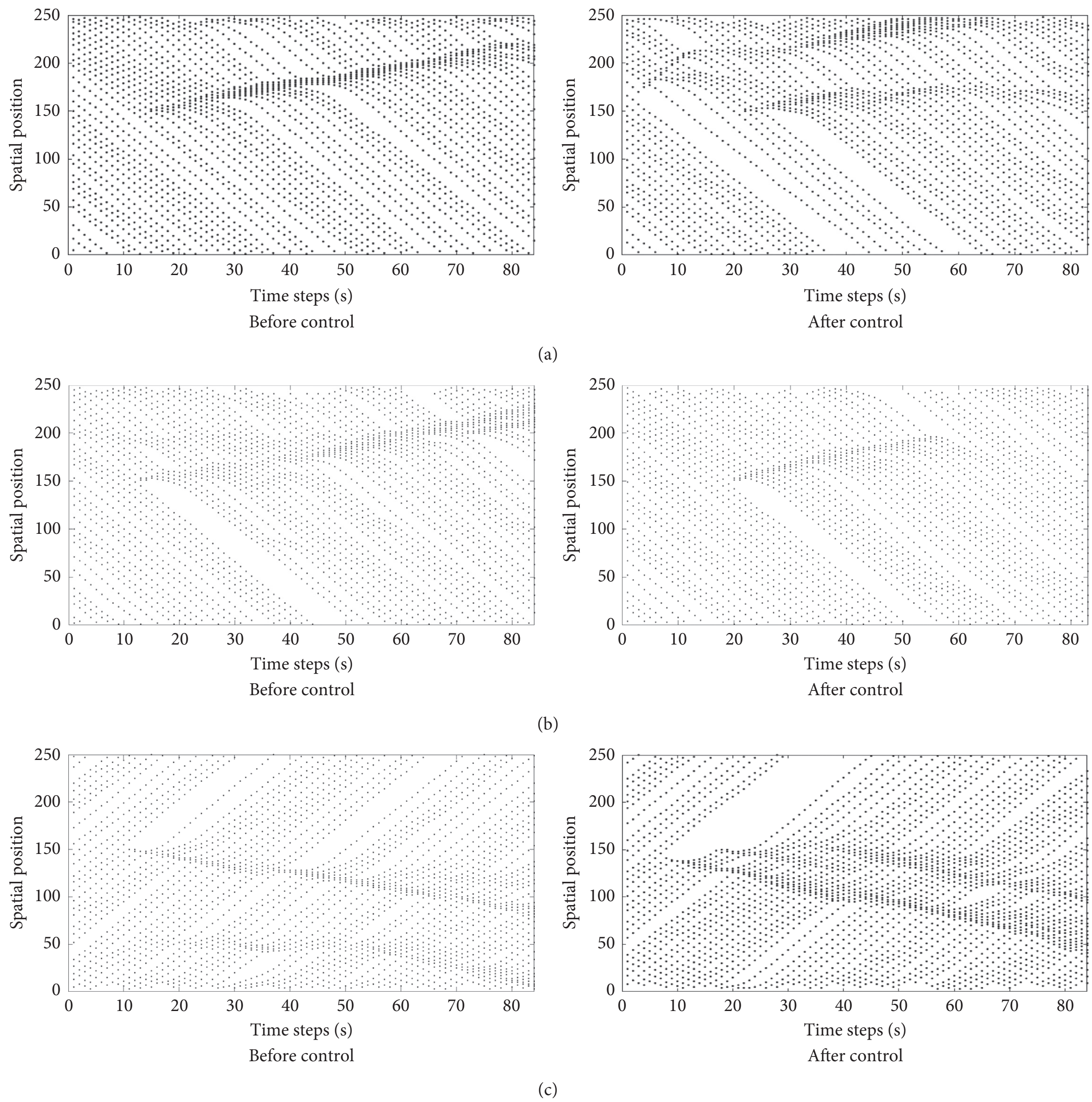

Figure 13: The traffic flow states before and after control at $p_{in1} = 0.8$ and $p_{in2} = 0.6$. (a) Lane 1, (b) lane 2, and (c) lane 3.

interval for U-turn vehicle. With the increase of traffic flow of incoming vehicles, the speeds of a wider range of vehicles will be affected to produce a suitable interval, which will cause a serious delay.

In this work, traffic delay is monitored by observing the changing of traffic flow based on the theory of traffic wave. The delays are counted by different directions of lanes. The simulation results are shown in Figure 10. The X axis represents each 16 kinds of scenes, and the Y axis is the traffic volume under each scene. The trend of delay in the same directions is similar because the vehicles are allowed to change lanes between the same lanes, which makes the traffic flow in the same lanes relatively average.

To better describe the advantageous of cooperative control, the traffic volume is compared under different situations with the change of p_{in1} and p_{in2}. The Y axis represents the flow difference before and after control, and the positive value means the larger traffic flow under no-control scenes. The result is shown in Figure 11.

① When $p_{in1} > 0.7$, the difference of traffic volume is greater than zero. It shows that no control is better in these scenes. The reason is the more time needed for the incoming vehicle to produce the intervals for U-turn vehicles when the traffic flow is high in main lane, and this delay will spread in the form of waves to the upstream resulting in continuous decrease of traffic flow, so the traffic delay is high.

② When $p_{\text{in1}} \leq 0.7$, the difference of traffic volume is less than zero. It shows that cooperative control is better in these scenes. The available intervals are easy to get on the main lane for U-turn vehicles, so the cooperative control is helpful for time saving of vehicles when merging.

③ The effects of p_{in2} are significant for no-control environment but less for control, because U-turn vehicles have no need to wait for merging in our cooperative control strategy. However, the probability of waiting of vehicles on lane 3 increases with the p_{in2} increase.

Based on the analysis of the traffic delay in the section of the U-turn zone, the following conclusions can be drawn: when the arrival rate of the vehicles on main lane is not exceeding 0.7, the cooperative control is suitable for improving the capacity of the road section. Otherwise, it is not necessary to apply control strategies. So, the threshold of cooperative control is $p_{\text{in1}} = 0.7$.

4.3.2. Space-Time Diagram Comparison. The space-time distributions of the traffic under before and after cooperative control situations are shown in Figures 12 and 13. We take p_{in1} as 0.4 and p_{in1} as 0.8, for example, p_{in2} is set as 0.6 under two scenes. The X axis represents space, and the Y axis represents time. The central is the U-turn zone. As Figure 12 shows, the simulation running 10 s later, there is a continuous congestion at the U-turn point before control, but it is significantly reduced after control. Figure 13 shows the U-turn merging control strategy has a greater impact on the traffic flow upstream of lane 1 and the traffic flow upstream of the lane 3. Consistent with the conclusion above, the effect of cooperative control is not obvious, even worse the traffic when the arrival rates of vehicles on main lane is larger than 0.7. Otherwise, because of no U-turn vehicle wait on lane 4, no significant traffic changes and compared results are shown on lane 4.

5. Conclusion

The present study proposes and evaluates an optimization-based U-turn control strategy. The optimal control algorithm is established and imbedded into the cellular automata model. The effects of control strategies on the traffic performance are quantitatively investigated by microscopic simulation. Our works are mainly summarized in three aspects:

(1) The cooperative merging control algorithm is established to plan the trajectories of the U-turn vehicle, and incoming vehicles on main lane achieve the purpose of collision avoidance and delay minimum. The constraints of behaviors of vehicles are set under the single-turning vehicle scene and multivehicle scene.

(2) Two U-turn merging strategies, zip control and platoon control, are proposed. The delay and driver comfort indexes are compared between two strategies based on changing the headway of the U-turn vehicle platoon k and the headway of main lane vehicle platoon l. The numerical simulation results show that the most appropriate control strategy will be changed with the change of headway between U-turn vehicles or vehicles on the main lane.

(3) The cellular automaton simulation system composed of a two-way four-lane traffic flow with a U-turn facility in the middle of road is established with a cooperative control algorithm imbedded. Traffic volumes on different lanes are compared before and after cooperative merging control by analyzing the arrival rates of main lane and U-turn vehicles and their relationship between one another. The results show that the cooperative control can improve the traffic flow, but when the arrival rate of main lanes is up to 0.7, the improvement will not be obvious which is even worse than that of no-control scene.

Finally, it is important to note that there are many factors to be considered in the actual U-turn behavior of the vehicle, such as the size of the opening and the form of the waiting area. And, the assumption in this paper is that all the vehicles are automatic, but soon the traffic will be composed of a mix of equipped and unequipped vehicles, and management systems usable in this transition period should be developed.

Data Availability

No data were used to support this study.

Conflicts of Interest

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

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