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A Cooperative Control Algorithm for Real-time On-ramp Merging of Connected and Automated Vehicles

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***Abstract*—Most previous studies on on-ramp merging methods for connected and automated vehicles (CAVs) focused on single-vehicle merging algorithms with instantaneous traffic flow rather than continuous traffic stream. In this study, a cooperative control algorithm for on-ramp merging under continuous traffic flow is proposed to deal with real-time on-ramp merging problems. This algorithm includes: (1) determining the number of Roadside Units (RSUs) involved in the merging process, (2) selecting a cooperative vehicle and calculating the safety distance, and (3) calculating the merging speed. Also, a cooperative control strategy is provided to complete the merging process when the cooperative vehicle and the merging speed are determined. Finally, this paper employed SUMO and the traffic control interface (Traci) to interact with Python for simulational study. The simulational results verified the effectiveness of the proposed algorithm and strategy, especially in solving the vehicle phenomenon of the stop-and-go wave under on-ramp crowded traffic flow.**

Keywords—real-time control, on-ramp merging, cooperative control, connected and automated vehicle

I. Introduction

In China's urban road networks, many traffic entities are running on the urban expressway. In Beijing [1], although expressways account for about 9.0% of the total mileage of Beijing's road network, expressways account for about 34.3% of traffic. Therefore, solving the vehicle congestion on urban expressways can effectively improve the road capacity of the entire urban road network. One of the main reasons for traffic congestion on urban expressways is merging vehicles in the on-ramp merging area, which can be alleviated by the merging control framework for ramp vehicles and the automatic cooperative merging algorithm [2]. The merging area on the urban expressway is the primary location of the traffic bottleneck. As the ramp vehicles merge into the main lane, the main lane vehicles will decelerate significantly and lead to the stop-and-go wave phenomenon. The forced lateral conflict will cause many air pollutant emissions, or even security threats.

The vehicle merging control method in the ramp merging area of the urban expressway has attracted the attention of many researchers. With the emergence of the concept of automatic highway systems and automated vehicles, vehicles can communicate with other surrounding vehicles and roadside infrastructure in real time and exchange detailed information such as speed, acceleration, and location. It enables vehicles to collaborate, thus significantly improving traffic conditions. Under the background, some scholars have begun to explore the ramp merging control method under the concept of the automatic highway system, which can be roughly divided into the centralized method and distributed method. The centralized method means that a central controller determines at least one task in the system. As for the distributed method, each vehicle determines its control strategy based on the information received by other surrounding vehicles or the coordinator. Lu et al. [3] proposed the concept of virtual formation. Before a row of main lane vehicles and an on-ramp vehicle arrived at the merging point, a centralized method was used to collect vehicle information and invoked algorithms to merge on-ramp vehicles into the main lane fleet. Its position was mapped to the front merging point so that the speed and acceleration of all vehicles in the newly formed fleet were kept consistent.

The concept of road corridor based on time and space was proposed by Morla et al. [4], also called virtual vehicle channel, a distributed method. The main idea was to uniformly spread the recommended speed of the lane and map the slot to the single lane ahead at a constant speed. Vehicles entering the slot should replicate the attribute of the slot. The on-ramp vehicle and the main lane vehicle coordinate to adjust the slot and change lanes through Vehicle to Vehicle (V2V) communication. Marinescu et al. [5] proposed the lane change model, which was also based on the slot. The detailed information of the slot was provided by the infrastructure and required Vehicle to Infrastructure (V2I) communication. They applied this idea to the high-speed merging scenario. The evaluation results showed that the slot model could guarantee arrival time for vehicles on the highway.

With the development and maturity of V2I technology, some scholars have begun to explore ramp merging methods that focus on vehicle-road coordination. Letter et al. [6] proposed the method of time series. From God's perspective, this method can control the vehicle speed in an instantaneous state or predict a training flow's speed and departure time. This method calculates all vehicles' merging time or speed and determines the sequence to pass through the ramp merging area without conflict. The advantage of this method is centralized control, but the drawback is that it only regulates the traffic flow in a transient

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state without considering the subsequent traffic flow, and it isn't the dynamic control of the traffic flow. It also needs to calculate and control the speed of all vehicles, which consumes computing resources. Zhou et al. [7, 8] put forward the concept of collaborative merging that the main lane vehicle is used as a cooperative vehicle to help the on-ramp vehicle merge. The main lane vehicle's speed, acceleration, or position are adjusted to create a gap for the on-ramp vehicles to merge. This concept of cooperative merging transforms the merging problem into the trajectory optimization problem of two vehicles.

In the existing on-ramp Connected and Automated Vehicles (CAVs) merging research, some scholars have considered the process of determining the sequence of vehicle merging. Xu et al. [9] used a genetic algorithm to solve the optimal merging sequence, which reduced the conflicts caused by multiple merging decisions.

Contrary to this paper's purpose, we want to reduce the significant deceleration behaviour and the stop-and-go wave phenomenon of vehicles in the main lane. Therefore, according to the first-in-first-out principle, this paper considers the merging operation of a single on-ramp vehicle without greatly interfering with the operation of the main lane traffic.

II. Cooperative Algorithm for Real-time On-ramp Merging

The main purpose of this paper is to control the merging process of traffic flow and reduce the disturbance of the main lane, including the sharp deceleration behaviour and stop-and-go wave. For simplicity, we assume that the merging of the vehicle is instantaneous, which means the lateral behaviour of the vehicle is ignored, and only the longitudinal behaviour is considered. Each main-lane vehicle i can be described as a second-order dynamic model:

$$\begin{aligned} \dot{x}_i &= v_i \\ \dot{v}_i &= u_i \end{aligned} \tag{1}$$

x_i, v_i, u_i is the position, speed and acceleration of the vehicle. Let a_{min}, a_{max}, v_{min}, v_{max} be the minimum acceleration, maximum acceleration, minimum speed, maximum speed. The speed limit of the main lane is denoted as v_m, which equals to the maximum speed of the vehicle. v_r represents the speed limit of the ramp lane. We can assume that n vehicles appear in the simulation within time T with the simulation time step Δt. The objective function is to minimize the sum of the rate of change of all velocities of vehicles in each time step in the whole time T. It can be shown as follows:

$$min \sum_{i}^{n} \sum_{t=\Delta t}^{T} \left| \frac{v_i(t) - v_i(t-\Delta t)}{\Delta t} \right| \tag{2}$$

The constraints are:

$$\begin{aligned} a_{min} \le a_i \le a_{max} \\ v_{min} \le v_i \le v_{max} \end{aligned} \tag{3}$$

The initial condition is

$$v_i(t=0) = v_m \tag{4}$$

which means that vehicles depart at the maximum speed.

A. *Determine the number of RSUs that need to participate in the merging process*

The algorithm needs to select cooperative vehicles on the main lane for ramp vehicles. However, it is not necessary to consider all vehicles in the main lane. Only the vehicles roughly simultaneously as the ramp vehicle arriving at the merging point need to be selected. Therefore, the number of Roadside Units (RSUs) upstream of RSU-1 needs to be determined. The speed limit of the main lane is greater than that of the ramp lane, even the last vehicle on the main lane within the coverage of RSU-1 will arrive ahead of the ramp vehicle. So RSU-1 cannot assist the on-ramp vehicles in merging without significantly affecting the traffic flow on the main lane, the vehicle data detected by RSU-2 is required, or even the RSUs further upstream of the main lane. The number of additional RSUs required is

$$N_{rsu} = \left[\frac{\frac{R_{rsu}}{v_r} \times v_m - R_{rsu}}{2R_{rsu}}\right] \tag{5}$$

[] means to round up numbers.

B. *Select the cooperative vehicle and calculate the safe distance*

It is necessary to determine whether the list "detMainVehDictList" is empty within the communication range of RSU, in other words, to determine whether M is an empty set. If it is empty, it means that there are no vehicles on the main lane, so the ramp vehicle can pass directly without assistance and directly merges at the merging point, as shown in Fig. 1 (a). Otherwise, the cooperative vehicle should be selected in M by the algorithm. The principle of selecting cooperative vehicles is that the vehicles arrive at the merging point almost simultaneously as the on-ramp vehicles. The cooperative vehicle will slow down to create a gap for the confluence of on-ramp vehicles C. The deceleration of the cooperative vehicles is small and will not cause too much interference with the follow-up vehicles. Therefore, the time for the cooperative vehicle to arrive at the merging point should meet the following formula.

$$t_{m_c} \ge \frac{R_{rsu}}{v_{r_\delta}} \tag{6}$$

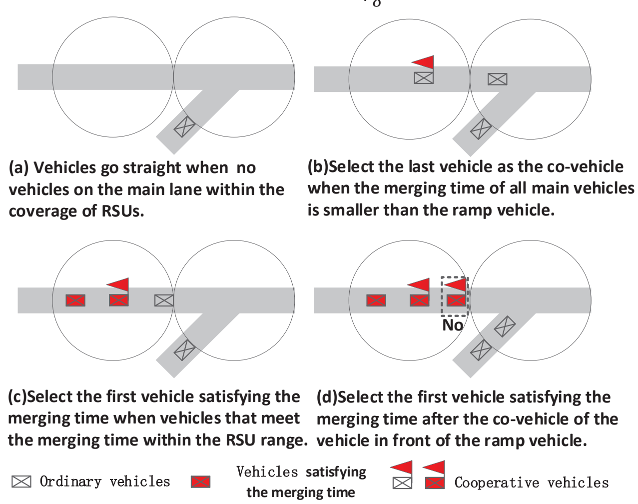

Fig. 1. Flow chart of the real-time cooperative on-ramp merging strategy

When the cooperative vehicle has the same speed as the leading vehicle, the speed of the cooperative vehicle will be made equal to the newly calculated merging speed, and the speed of the ramp vehicle will be made equal to the merging speed of the leading vehicle. When implementing the merging strategy, this paper considers the vehicles that request service first merge first, which means first in first out. The ramp vehicles that request service are put into the list to judge

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whether the first vehicle is in the accelerated lane and its speed is greater than or equal to the merging speed. Merging processing will be carried out when all these conditions are satisfied. When merging is completed, the first vehicle in the list will be deleted immediately. However, when one cooperative vehicle cooperates with multiple ramp vehicles, if the merging speed of the rear vehicle is less than the merging speed of the leading vehicle, then there may be two ramp vehicles accelerating in the acceleration lane, and the rear vehicle reaches the merging speed before the leading vehicle, but it is unable to merge because it is not the first vehicle in the list.

C. *Calculate the merging speed*

This paper proposes the following hypotheses:

(1) All vehicles run at a constant speed under the condition of not being affected.

(2) Once the ramp vehicle enters the acceleration lane, it will accelerate to the merging speed at the maximum acceleration.

(3) The cooperative vehicles on the main lane decelerate to the merging speed at the maximum deceleration.

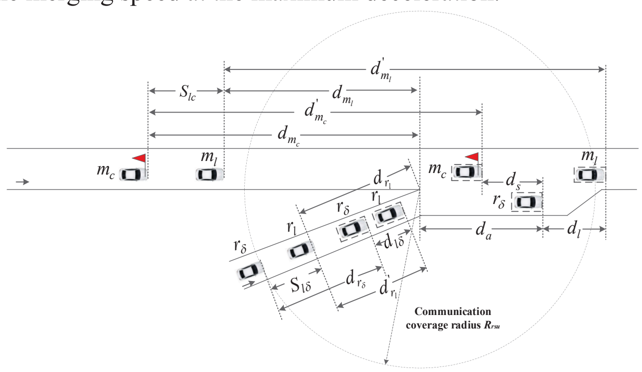

Fig. 2. Symbols of the on-ramp merging process

Some symbols of the on-ramp merging process are shown in Fig. 2. r_δ represents the ramp vehicle that makes an on-ramp merging request. m_c represents the cooperative vehicle determined by the last section. r_l and m_l are the leading vehicle of r_δ and m_c, respectively. r_δ, m_c and m_l in the dashed line frame on the acceleration lane represent the ramp vehicle, cooperative vehicle and the leading vehicle of the cooperative vehicle when the ramp vehicle is merging. d_{m_c} and d_{m_l} respectively denotes the distance from the position of m_c and m_l to the merging point. d'_{m_c} and d'_{m_l} are the distance that m_c and m_l travel when r_δ is making merging. S_{lc} denotes the distance between m_c and m_l. d_a represents the acceleration distance of the ramp vehicle on the acceleration lane. r_δ and r_l in the dashed line frame on the ramp lane represent the ramp vehicle and its leading vehicle when the speed of the ramp vehicle is greater than the leading vehicle and cannot maintain a safe distance. d_{r_δ} and d'_{r_l} respectively denotes the distance that r_δ and r_l travel when they can't maintain a safe distance. d_{r_l} is the distance from the position of r_l to the merging point. $S_{l\delta}$ denotes the distance between r_δ and r_l. $d_{l\delta}$ represents the safe distance between r_δ and r_l.

We can get the time that a ramp vehicle travels at a constant speed on the lane:

$$t_1 = \frac{R_{rsu}}{v_{r_\delta}} \tag{7}$$

The time that the ramp vehicle accelerates at the maximum acceleration on the lane is:

$$t_2 = \frac{v_h - v_{r_\delta}}{a_{max}} \tag{8}$$

Thus, the distance that the ramp vehicle travels on the acceleration lane at the maximum acceleration can be obtained:

$$d_a = \frac{(v_h)^2 - (v_{r_\delta})^2}{2a_{max}} \tag{9}$$

The calculation of the merging speed v_h is restricted by many factors, including the cooperative vehicle, the leading vehicle of the cooperative vehicle, the leading vehicle of the ramp vehicle, the length of the acceleration lane. The ramp vehicle may not merge when the safe gap is not satisfied after accelerating to the merging speed. In principle, the acceleration lane should be long enough for the ramp to slow down and stop at the end of the acceleration lane. So, the remaining length of the acceleration lane should also be considered to calculate the merging speed. The restriction of the above factors on the merging speed is calculated below.

(1) The cooperative vehicle

The safe distance should be maintained between the cooperative and ramp vehicles to determine the merging speed. We first consider the deceleration process of the cooperative vehicle, which is a positive value denoted by a_{min}. The time that the cooperative vehicle decelerates at the maximum deceleration is:

$$t_3 = \frac{v_{m_c} - v_h}{a_{min}} \tag{10}$$

So we can get the formula of d'_{m_c}:

$$d'_{m_c} = v_{m_c} \times t_3 - \frac{1}{2} \times a_{min} \times (t_3)^2 + v_h(t_1 + t_2 - t_3) \tag{11}$$

d'_{m_c} should also satisfy the following inequality:

$$d'_{m_c} \le d_{m_c} + d_a - d_s \tag{12}$$

When the time that the cooperative vehicle arrives at the merging point is much longer than that of the ramp vehicle, the cooperative vehicle may accelerate. When the acceleration is positive, the driving time of the cooperative vehicle on the main lane at the maximum acceleration is:

$$t'_3 = \frac{v_h - v_{m_c}}{a_{max}} \tag{13}$$

Currently, the formula of d'_{m_c} is:

$$d'_{m_c} = v_{m_c} \times t_3 + \frac{1}{2} \times a_{max} \times (t_3)^2 + v_h(t_1 + t_2 - t_3) \tag{14}$$

d'_{m_c} should also satisfy the following inequality:

$$d'_{m_c} \le d_{m_c} + d_a - d_s \tag{15}$$

When the calculated merging speed is less than the current speed of the cooperative vehicle, the cooperative vehicle will slow down; otherwise, the cooperative vehicle will accelerate.

(2) Leading vehicle of the cooperative vehicle

The restriction for the leading vehicle of the cooperative vehicle is that the distance between the following vehicle and the leading vehicle of the cooperative vehicle meets the safe distance, and the distance expression of the leading vehicle of the cooperative vehicle is as follows:

$$d'_{m_l} = v_{m_l} \times (t_1 + t_2) \tag{16}$$

The distance d_l can be expressed as:

$$d_l = d'_{m_l} - d_{m_l} - d_a \in \tag{17}$$

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d_l should satisfy the following inequality:

$$d_l \geq S_0 + L_{m_l} + v_h \times T_{r_\delta} + \frac{(v_h)^2}{2a_{r_\delta}} - \frac{(v_{m_l})^2}{2a_{m_l}} \qquad (18)$$

where a_{m_l} and a_{r_δ} are both represent the maximum deceleration a_{min} of the vehicle.

(3) Leading vehicle of the ramp vehicle

When the ramp vehicle arrives and initiates a service request, the ramp vehicle will drive at a uniform entry speed on the ramp. If there is a leading vehicle and its speed is lower than that of the ramp vehicle, then the ramp vehicle may not be able to drive at the uniform entry speed, and it may be restricted by the leading vehicle. Therefore, it is necessary to calculate whether the leading vehicle has an impact on the ramp vehicle. The determination condition is that when the safe distance between the ramp vehicle and the leading vehicle does not satisfy the following conditions, the ramp vehicle does not reach the merging point.

$$d'_{r_l} \geq d_{r_l} \qquad (19)$$

$$d_{r_\delta} - S_{l\delta} = d'_{r_l} - d_{l\delta} \qquad (20)$$

Suppose *t* represents the uniform driving time, then we can get:

$$v_{r_\delta} t - S_{l\delta} = v_{r_l} t - (S_0 + L_{r_l} + v_{r_\delta} \times T_{r_\delta} + \frac{(v_{r_\delta})^2}{2a_{r_\delta}} - \frac{(v_{r_l})^2}{2a_{r_l}}) \qquad (21)$$

$$\frac{S_{l\delta} - (S_0 + L_{r_l} + v_{r_\delta} \times T_{r_\delta} + \frac{(v_{r_\delta})^2}{2a_{r_\delta}} - \frac{(v_{r_l})^2}{2a_{r_l}})}{v_{r_\delta} - v_{r_l}} \times v_{r_l} \geq d_{r_l} \qquad (22)$$

If the above formula is not satisfied, the speed of the ramp vehicle is set to the speed of the leading vehicle to calculate the time to reach the rendezvous point.

III. Cooperative Strategy for Real-time On-ramp Merging

Current researches mainly focus on on-ramp merging methods in a discontinuous manner, such as [10]. These methods regulate and control the traffic at the moment without considering the subsequent traffic flow and communication details, which is not suitable for our on-ramp merging framework. Therefore, this paper considers a cooperative control strategy with the mentioned-above real-time algorithm to select the main lane vehicle to merge ramp vehicles. Regarding this strategy, Zhou et al. [7] also selected the main lane vehicle for assistance, but they didn't consider the characteristics of the on-ramp merging area and only deployed one RSU on the roadside. In most cases, the speed limit of the ramp lane is much lower than that of the main lane. Because of the limited lane speed, the cooperative vehicle in the main lane may decelerate greatly and even affect the subsequent traffic flow, contrary to this paper's purpose. Therefore, this paper considers expanding the scope and using the vehicle detected by the RSU located upstream of the main lane to assist the merge of the on-ramp vehicle.

As shown in Fig. 3, when the communication coverage radius of the RSU is equal, the RSU-1 of the ramp merging point, the RSU-2 located upstream of the main lane and even the farther RSUs transmit the basic information to the edge server by time steps. RSU-1 is also responsible for processing the service request information from the ramp vehicles. When the on-ramp vehicle reaches the RSU-1 range, the edge server starts processing the service request information, selecting a cooperative vehicle for it, and calculating a merging speed. It means when the on-ramp vehicle and cooperative vehicle are changing lanes in coordination, the speed is v_h, and the safe merging clearance d_s is satisfied.

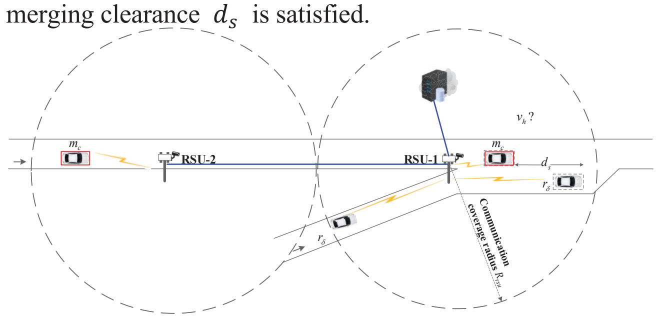

Fig. 3. cooperative merging strategy

IV. Simulation and Results

A. Settings of simulation

The network of the on-ramp merging area of the urban expressway is shown in Fig. 4. The length of the main lane L1 is 500m, the length of the main lane L3 is 500m, the length of the ramp L4 is 250m, the length of two-way road L2 in the 7merging area is 100m. The speed limit of main lane is 100km/h (about 27.78m/s), and the ramp speed limit is 40km/h (about 11.11m/s).

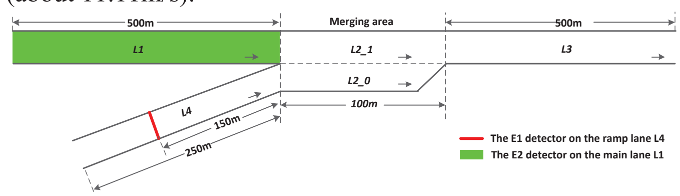

Fig. 4. Urban expressway ramp merging area road network diagram.

Simulation of Urban Mobility (SUMO) is a free, open-source transportation system simulation software. SUMO provides many supporting tools to automate the creation, execution and evaluation of traffic simulations such as road network import, route calculation, visualization and emission calculation. SUMO can be used in various scenarios, such as traffic prediction, traffic safety and risk analysis, the impact of route selection on the road network, the performance of traffic lights, the calculation of emissions (such as noise or pollutants) and so on. Three files are needed to run the SUMO simulation.

The first file is the road network file. It can be visually plotted through the executable file "netedit". The road network consists of 5 nodes and 4 edges, and its parameters are shown in TABLE I and TABLE II.

TABLE I. NODE PARAMETER OF ROAD FILE TABLE

No.	IDs of nodes	position
1	A1	(0，100)
2	A2	(500，100)
3	A3	(600，100)
4	A4	(1100，100)
5	A5	(100，50)

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TABLE II. EDGE PARAMETER OF ROAD FILE TABLE

IDs of edges	L1	L2	L3	L4
From	A1	A2	A3	A5
To	A2	A3	A4	A2
Speed	27.78	27.78	27.78	11.11
Priority	-1	-1	-1	-1
numLanes	1	2	1	1
length	500	100	500	250

The second file is the route file. It can set single-vehicle paths, multi-vehicle paths (multiple vehicles share the same path), and traffic flow. It can also set an incomplete path, that only contains departure and destination.

In this paper, the vehicle's id is set to "CAV" using <vType…/>, the maximum acceleration is 2.6 m/s^2 , the maximum deceleration is 4.5 m/s^2 , and the length of the vehicle is 5m. Two traffic flows are set up. One traffic flow id is "mainFlow", whose route of vehicles is L1-L2-L3. It is the main lane traffic flow containing 1600 vehicles per hour. The other traffic flow id is "rampFlow", and its route is L4-L2-L3. It is the ramp traffic flow containing 800 vehicles per hour.

The last file is the simulation configuration file. It is used to combine the road network and route file as well as some additional files.

B. *Results and discussions*

The simulation test environment of this paper adopts Windows operating system, and the version is Win7 64-bit flagship. The simulation was performed using an Intel (R) Core (TM) i7-4800MQ CPU @ 2.7GHz processor and 16GB RAM. The traffic simulator used SUMO1.3.1, and the online control language is python3.7. This section will analyze the strategy and algorithm of ramp merging in the following aspects: (1) selection of cooperative vehicles; (2) merging speed constraints; (3) single-vehicle merging curve; (4) merging rate.

(1) Selection of cooperative vehicles

The algorithm proposed in this paper aims to cooperate single-vehicle by single-vehicle and cooperative multi-vehicle by single-vehicle. TABLE III and TABLE IV show the data table of vehicle service requests under the condition of main lane traffic flow of 1600 vehicles/h, ramp traffic flow of 800 vehicles/h and ramp acceleration lane length of 100m within 60s. A total of eight vehicles made service requests within 60s, and all of them merged successfully. In this scenario, there was the case that single-vehicle cooperated by single-vehicle, there was also the case that multi-vehicle cooperated by single-vehicle. When single vehicle assists multiple vehicles, the cooperative vehicle will slow down several times at the calculated merging speed, while the cooperated ramp vehicle will merge at the merging speed of the leading vehicle. The above situation is consistent with the results of the algorithm proposed in this paper.

TABLE III. DATA TABLE OF VEHICLE SERVICE REQUESTS WITHIN 60S

No	IDs of ramp vehicles	Time (s)	Speed (m/s)	IDs of co-vehicles	Speed (m/s)	Distance from the merging point (m)	Merging Speed (m/s)
1	rampFlow.0	9.3	10.30	mainFlow.3	23.05	412.83	24.52
2	rampFlow.1	13	11.43	mainFlow.4	26.23	366.04	24.15
3	rampFlow.2	18.9	9.84	mainFlow.8	27.69	448.30	24.32
4	rampFlow.3	21.5	9.84	mainFlow.8	24.32	384.99	24.32
5	rampFlow.4	25.8	12.38	mainFlow.8	22.18	289.63	24.32
6	rampFlow.5	32.4	9.68	mainFlow.14	27.70	448.24	24.77
7	rampFlow.6	34.7	9.68	mainFlow.14	24.77	391.26	24.77
8	rampFlow.7	40.5	10.81	mainFlow.16	22.86	369.76	23.26

TABLE IV. DATA TABLE OF VEHICLE SERVICE REQUESTS WITHIN 60S

No	Acceleration time of the ramp vehicle (s)	LC time of the ramp vehicle (s)	Speed limit of the co-vehicle (m/s)	Speed limit of the length of acceleration lane (m/s)	Speed limit of the remaining length of acceleration lane (m/s)	Speed limit of the leading vehicle of co-vehicle (m/s)
1	23.9	29	24.52	25.02	19.92	27.78
2	26.1	30.2	24.15	25.51	20.31	26.95
3	34.1	39.2	25.23	24.84	19.77	24.32
4	35.7	39.8	22.18	24.84	19.77	27.78
5	37.9	42	21.24	25.95	20.66	27.78
6	47.9	53	24.88	24.77	19.72	False
7	49.5	54.6	22.16	24.77	19.72	27.78
8	54.3	58.4	23.26	25.24	20.09	23.87

(2) Comparative analysis of single-vehicle speed curve

Fig. 5 shows the speed-time curve of 8 ramp vehicles, cooperative vehicles and leading vehicles of the cooperative vehicles with the above algorithm applied within 60s. Fig. 6 shows the corresponding speed-time curve without control. The red lines in the above two pictures represent the speed curve of the cooperative vehicle, while the green line represents the speed curve of the leading vehicle of the cooperative vehicle, and the other lines are the speed curves of different ramp vehicles.

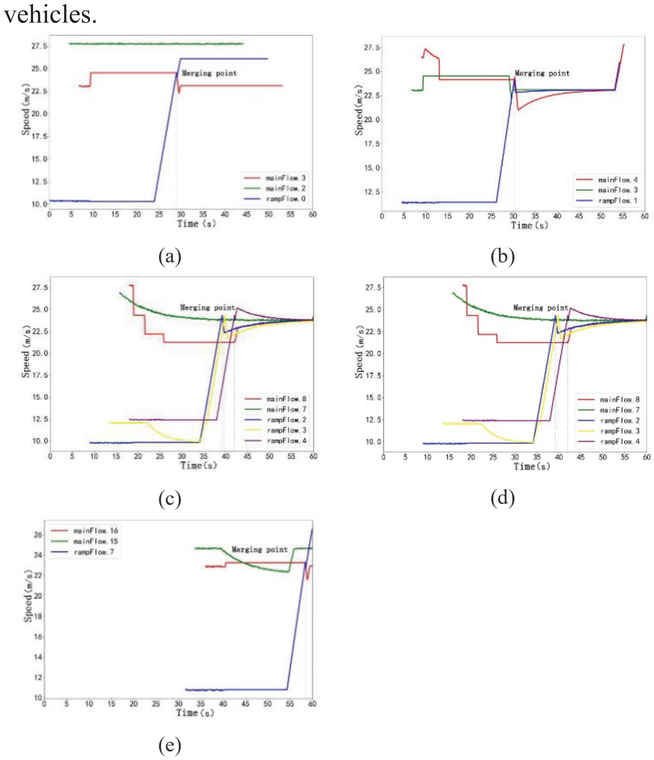

Fig. 5. Speed-time curve of 8 on-ramp vehicles within 60s (merging algorithm): (a) rampFlow.0; (b) rampFlow.1; (c) rampFlow.2, rampFlow.3, rampFlow.4; (d) rampFlow.5, rampFlow.6; (e) rampFlow.7

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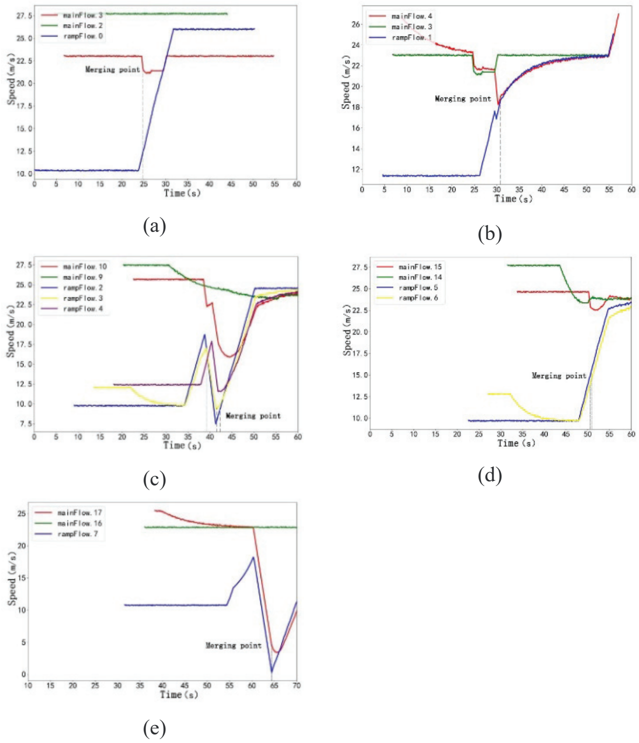

Fig. 6. Speed-time curve of on-ramp vehicles within 60s (no algorithm): (a) rampFlow.0; (b) rampFlow.1; (c) rampFlow.2, rampFlow.3, rampFlow.4; (d) rampFlow.5, rampFlow.6; (e) rampFlow.7

From comparing the speed curves of the corresponding vehicles in the above two pictures, there is no significant deceleration and braking behaviour when using the confluence strategy and algorithm, whether it is a cooperative vehicle or a ramp vehicle. According to the speed curves of Fig. 5 (c) and Fig. 6 (c), under the application of the algorithm, the cooperative vehicle of "rampFlow.2", "rampFlow.3" and "rampFlow.4" is "mainFlow.8", and the maximum deceleration of the cooperative vehicle is 3.37m / s. The three ramp vehicles merge smoothly after accelerating in the acceleration lane and then follow the leading vehicle. Without control, the above three ramp vehicles merge in front of the main vehicle, "mainFlow.10", and the maximum deceleration of the main vehicle is about 10m/s. The three ramp vehicles experience a stage of acceleration-deceleration-acceleration, resulting in substantial acceleration and deceleration behaviours. Uncontrolled vehicles even perform parking behaviour.

V. CONCLUSIONS

A real-time cooperative on-ramp merging control algorithm is proposed in this paper. The simulation that combines Python and SUMO obtains significant results that the algorithm can effectively reduce the vehicle phenomenon of the stop-and-go wave. The algorithm carefully considers the cooperative vehicle selection in the following cases: 1) whether there are main lane vehicles in the range of RSU; 2) whether there is a vehicle whose merging time is greater than or equal to the merging time of ramp vehicle in the RSU range; 3) whether the selected cooperative vehicle that satisfies the merging time is before the cooperative vehicle of the front ramp vehicle. The simulation results show that the algorithm can well implement the selection strategy of cooperative vehicle. The algorithm considers the limitations of the merging speed, including 1) the speed limit of the cooperative vehicle; 2) the speed limit of the leading vehicle of the cooperative vehicle; 3) the speed limit of the leading vehicle of the ramp vehicle; 4) the speed limit of the remaining length of the ramp. The simulation results show that the main lane vehicles' objective function value of the merging strategy and algorithm is 17.49% lower than that without control, and the ramp vehicles' objective function value is 13.76% lower than that without control.

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