Cooperative Lane Changing Strategies to Improve Traffic Operation and Safety Nearby Freeway Off-Ramps in a Connected and Automated Vehicles Environment

Yuan Zheng, Bin Ran, Xu Qu, Jian Zhang, *Member, IEEE*, and Yi Lin

***Abstract*— The study proposes a cooperative lane changing strategy to improve traffic operation and safety at a diverging area nearby a highway off-ramp in an environment with connected and automated vehicles (CAVs). The cooperative strategy was implemented by the coordination of behaviors between the diverging vehicle and its cooperative vehicle on the target lane. The Minimizing Overall Braking Induced by Lane Changes Model (MOBIL) and Intelligent Driver Model (IDM) were modified to develop a simulation platform for a CAV environment. The optimal cooperative lane changing zones were firstly calculated by a heuristic algorithm, and then were applied in the simulation platform to implement the cooperative strategy. Various metrics were considered to evaluate the proposed strategy, including: total travel time, surrogate safety measures and traffic waves in the system. The experimental results showed that the length of the optimal cooperative zones obtained in our strategy were smaller than the fixed zone required in modified MOBIL strategy. Moreover, the results indicated that the cooperative strategy with the optimal zones, could improve traffic operation, traffic safety and traffic oscillation as compared to the modified MOBIL strategy with the fixed zone. The cooperative strategy can be potentially implemented nearby highway off-ramps by vehicle-based control, with the applications of the aforementioned cooperative zones.**

***Index Terms*— Freeway off-ramps, cooperative lane changing strategy, simulation platform, connected and automated vehicles (CAVs), total travel time, collision risk.**

I. Introduction

TRAFFIC operation at a diverging bottleneck area nearby off-ramp is an important component of highway management. It involves car following (CF), mandatory lane changing (MLC) and discretionary lane changing (DLC) maneuvers [1]. MLC are forced lane changes, so as to make drivers keep following their route due to unavoidable conditions, such as the end of a merging lane and an off-ramp exit. DLC is intended to improve driving conditions. Some empirical efforts have indicated that lane change maneuver is one of the main triggers of traffic congestion nearby off-ramps [2]–[6].

With the development of the sensing and communication technology, connected and automated vehicles (CAVs) are proposed to improve operational efficiency and reliability of automated vehicles (AVs) [7], [8] or connected vehicles (CVs) [9], [10] individually. It can not only collect surrounding vehicle information relying on sensing technologies, but also exchange real-time information via Vehicle-to-Vehicle (V2V) communication or with road infrastructure via Vehicle-to-Infrastructure (V2I) communication. More CAVs will appear on roads in the future and will be helpful in alleviating traffic problems. Researchers would mitigate the CAV diverging problems by finding an efficient cooperative driving method.

Some preliminary methods have been proposed to improve traffic operations in situations similar to highway off-ramps, such as on-ramp and lane closure cases. Lane changing advisory algorithms were developed by using a variable gap based on connected vehicle technology. It provided lane changing advisories to mainline vehicles within the merging or lane closure area [11], [12]. Some strategies were proposed to assist on-ramp merging by controlling mainline vehicle deceleration to create gaps in a CAV environment [13]–[15]. Moreover, cooperative control algorithms between ramp and mainline vehicle were formulated to improve merging operations [15], [16]. The core idea of gap creation strategy by deceleration and lane changing in merging and lane closure scenarios can be also implemented nearby off-ramps. However, the cooperative strategy when used nearby an off-ramp has yet to be developed by precise controls with automation and connected technology.

To overcome the aforementioned limitations, we propose a cooperative lane changing strategy to improve traffic operations and safety at a diverging area nearby an off-ramp in a CAV environment. The contributions focus on threefold: (1) A simulation platform for a CAV environment is built to simulate dynamic traffic at a diverging area; (2) cooperative lane

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The authors are with the School of Transportation, Southeast University, Nanjing 210096, China (e-mail: seuzhengy@163.com; binran1967@hotmail.com; quxu@seu.edu.cn; jianzhang@seu.edu.cn; 260538410@qq.com).

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changing strategies are proposed and cooperative zone therein is defined and determined; and (3) The proposed strategies consider the effects from various aspects, including traffic operations and safety among diverging vehicles in the system.

Firstly, a simulation platform for a CAV environment has been built. Therein, connected and automated vehicles can consider the effect of surrounding vehicles within communication range, as well as receive and execute driving actions. It is believed that this simulation platform can better simulate the effects of connection and automation technology on car following and lane changing maneuvers of CAVs, compared to previous studies using only those new concepts of CAVs with traditional models [11], [14], [15].

Secondly, the cooperative lane changing strategy nearby off-ramps has been developed and implemented. This is due to the fact that real-time state information at microscopic vehicle level can be collected in a connected and automated environment. It should consider the relaxation characteristic during the lane changing process of diverging vehicles. It is due to the fact that the relaxation phenomenon can describe the effect of lane changing on traffic streams [17], [18]. Relaxation is the effect whereby the lane changer and new follower on the target lane temporarily accept shorter desired time gaps when a lane change is executed and gradually relax to normal values after a short period [17].

Moreover, when and where to implement the cooperative lane changing strategy have naturally been concerned by many researchers. The current off-ramp management method is usually applied in the form of a roadside warning at a fixed point [19], such as "1/2 mile for Exit 41A". However, the fixed signpost and zone were determined by experiment and experience in a traditional environment and may not be suitable for diverging CAVs. Therefore, a cooperative zone should be defined and determined to assist diverging vehicles perform mandatory lane changes.

Finally, our study is concerned with improvements of traffic system performance at a diverging area by using a cooperative strategy. That is, we can not only pursue better operational and safety performance based on the lower total travel time or collision risks, but also evaluate the effect of cooperative strategy on traffic oscillation, aiming to improve overall system performance from various respects.

The remainder of the paper is organized as follows: The following section formulates the diverging problem nearby highway off-ramps. Section III introduces the construction of a simulation platform. Section IV shows the cooperative lane changing strategy in details. Section V and VI presents the experiment design and analyzes the evaluation results of cooperative strategies. The conclusions and discussions are the last section in this paper.

II. Problem Statement

A. Design of Cooperative Lane Changing Strategy and Zone

A two-lane 2.5 km highway segment and one downstream off-ramp located on the right-hand side along the driving direction is considered in our study, as shown in Figure 1. For some diverging vehicles in the inner lane (lane 1), it is

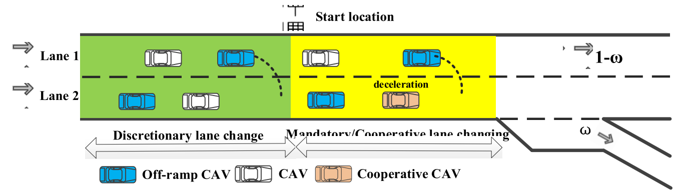


Fig. 1. Schematic diagram of a two-lane highway segment with an off-ramp.

difficult to perform a lane change when the traffic flow or diverging flow is high.

To solve the problem, we separate the diverging area into two zones by releasing the instructions in our study. The first green zone is used to conduct discretionary lane changing. It is expected that the diverging vehicles can travel on the target lane (lane 2) by performing a discretionary lane change. The second yellow zone is defined as the cooperative lane changing zone. It aims to assist diverging vehicles in the inner lane when performing a successful mandatory lane change by using a cooperative lane changing strategy. The core principle of the cooperative strategy lies in cooperation between the diverging vehicles and cooperative vehicles on the target lane. To find a safe lane changing gap, the diverging vehicles calculate their accelerations according to the motion states of the leading vehicles on the current and target lane after they arrive in the cooperative zone. Cooperative vehicles are required to decelerate to proactively and precisely create a safe lane changing gap for diverging vehicles. Note that other vehicles can still conduct a discretionary lane change in the yellow zone.

To implement the cooperative lane changing strategy among CAVs, the implemented cooperative lane changing zone must be firstly determined. The length of this zone affects the performance of the cooperative lane changing strategy. If the diverging instructions are released close to the off-ramp, the vehicle queue arising from mandatory lane changes will occur in a smaller zone. Otherwise, the mandatory lane changes can cause more traffic oscillations in the upstream of the target lane. Note that the calculation of the length of this cooperative zone can be formulated as an optimization problem according to optimization objectives.

B. Basic Rules for Experiments

To model the dynamic traffic in a diverging area nearby an off-ramp, the following rules are considered in our study.

1) There is a percentage ω vehicles in lane 1 (the current lane) needing to perform mandatory lane changes to lane 2 (the target lane), and then they can exit the highway off-ramp. The diverging vehicles can start their lane change intentions once they see the diverging instructions.

2) All vehicles are able to make discretionary lane changes before they arrive in the cooperative lane changing zone.

3) Discretionary lane changes of the diverging vehicles are not considered in the cooperative lane changing zone. In the zone, the diverging vehicles on the target lane have already prepared to exit the off-ramp after a mandatory lane change is successfully made.

4) The execution of a lane change is simplified and is regarded as an instantaneous action as suggested by studies [1], [7], [8].

5) CAVs can perceive and exchange real-time state information with surrounding vehicles, without communication time latency and packet loss rate.

6) To make the lane changing behaviours more realistic [7], we stipulate that after a lane change, vehicles maintain travelling in the current lane for a short period (2 s) before initiating a new lane change.

III. Simulation Platform

A. Development of Simulation Model

Conducting a field experiment to evaluate the cooperative strategy is very difficult as some strategies may increase crash risk to drivers. A generally acceptable surrogate method is to use traffic simulation technique. Macroscopic models such as cell transmission model focus on aggregated traffic characteristics and cannot capture individual movements. Microscopic models have been widely used in studies related to the cooperative strategy. Our study required precise vehicular control, and thus the simulation platform was built based on the microscopic model.

1) Car Following Model for CAVs: The Intelligent Driver Model (IDM) [20] was adopted and modified to simulate vehicle movements in our experiment. We selected this model because the parameters in the IDM can be easily calibrated. In addition the IDM parameters have physical meanings and are allowed to change. The IDM can also provide collision-free behaviors and smooth traffic flow. Moreover, the IDM has the advantages of more accurately describing free flow and congested traffic regimes than other models [21]. Due to these advantages, previously the IDM has been widely used in the CAV simulation studies [22], [23].

In the basic IDM, vehicle acceleration can be calculated as:

$$a_i(t) = a_{\max}\left[1 - (\frac{\upsilon_i(t)}{\upsilon_{ref,i}(t)})^{\delta} - (\frac{s_{desired,i}(t)}{s_i(t)})^2\right] \quad (1)$$

where $\upsilon_i(t)$ is the speed of the ith vehicle, $\upsilon_{ref,i}(t)$ is the desired speed of the ith vehicle, $a_{\max}$ is the maximum comfortable acceleration of the ith vehicle, δ is the exponent of free flow acceleration.

The actual gap $s_i(t)$ between the leading vehicle i-1 and the following vehicle i can be written as follows:

$$s_i(t) = x_i(t) - x_{i-1}(t) - \mathrm{L} \quad (2)$$

The minimum desired gap $s_{desired,i}(t)$ between the leading vehicle i-1 and the following vehicle i is given as follows:

$$s_{desired,i}(t) = s_0 + \max\left[T\upsilon_i(t) + \frac{\upsilon_i(t)\Delta\upsilon_i(t)}{2\sqrt{a_{\max}b_{\max}}}, 0\right] \quad (3)$$

where L is the predecessor vehicle length, s_0 is the minimum inter-vehicle distance at standstill, T is the safe time gap, $b_{\max}$ is the maximum comfortable deceleration of the ith vehicle, and $\Delta\upsilon_i(t)$ is speed difference between the leading vehicle i-1 and the following vehicle i.

Compared to the manually driven vehicles, CAVs can perceive state information (relative distance/speed) of an immediate leading vehicle and exchange traffic states with surrounding vehicles via V2V or V2I communication. Here, the modified IDM model [24] is used to simulate the communication effect by considering the weighted effects of surrounding vehicles:

$$\Delta\upsilon_i(t) = \sum\nolimits_{j=0}^{S} m_j \Delta\upsilon_{i-j} \quad (4)$$

$$s_i(t) = \sum\nolimits_{j=0}^{S} m_j s_{i-j} \quad (5)$$

where S is the set of vehicles perceived by the current vehicle, m_j is the weighted coefficient between vehicle i and perceived vehicle j. The weighted coefficient of each vehicle is computed from the proximity rule and the trust representation of the communication:

$$m_j = \rho_j \cdot T_j \quad (6)$$

where ρ_j is the proximity rule. T_j is the trust i has in j [12], [24], which is one to ensure stronger trust in our study. With respect to rule p_j, its computation is based on the collected information. The code concept is such that: for closer vehicles with a higher relative speed difference between them is, the effect on proximity is more important. Hence the proximity rule ρ_j is written as follows:

$$\rho_j = \sigma_j / \sum\nolimits_{k=0}^{S} \sigma_k \quad (7)$$

$$\sigma_j = \left|\Delta\upsilon_{i+j}\right| / \sqrt{s_{i+j}} \quad (8)$$

2) Lane Changing Model for CAVs: Several types of lane changing decision-making model were reviewed [25], including Gipps type, utility theory, cellular automata, Markov process and artificial intelligence models. The Minimizing Overall Braking Induced by Lane Changes (MOBIL) can be regarded as a variant model among the Gipps-type models, due to MOBIL can consider both safety and incentive criterion. Moreover, MOBIL has two main advantages [30]: (1) has the simplified decision making process and is convenient implementation into models; and (2) easily integrate with a car following model to describe vehicular longitudinal and lateral interactions on highways. Therefore, we select the MOBIL model to simulate a lane changing maneuver.

Along with the development of sensing and communicating technologies, a decision-making process of lane changing maneuver involves multiple vehicles, including subject vehicle, and following vehicles on the current and target lane within a communication range. The new MOBIL lane changing rule for a vehicle n in a connected and automated environment is shown as follows:

$$U(s\upsilon, c, t) = a_{ts\upsilon} - a_{cs\upsilon} + p \cdot \sum\nolimits_{i=1}^{\mathrm{S}_c} (a_{tl\upsilon_i} - a_{cl\upsilon_i}) + p \cdot \sum\nolimits_{j=1}^{\mathrm{S}_t} (a_{tl\upsilon_j} - a_{cl\upsilon_j}) \quad (9)$$

$$S_i = \left\{j \in S_{Lane}, 0 \le \left\|x_{s\upsilon} - x_j\right\| \le Lw\right\}, \ i = c, t \quad (10)$$

$$U(s\upsilon, c, t) > \Delta a_{th} \quad (11)$$

$$a_{ts\upsilon}, a_{cs\upsilon}, a_{tl\upsilon}, a_{cl\upsilon} \ge -b_{safe} \quad (12)$$

where $a_{cs\upsilon}$ *and* $a_{ts\upsilon}$ represents the acceleration of subject vehicle before and after a lane changing respectively. The coefficient c and t represents the following vehicles on the current lane and target lane respectively. $U(sv, c, t)$ represents the overall utility of subject vehicle if it makes a lane changing from the current lane to the target lane. The politeness factor p is a weighted factor of the total advantages (acceleration gain or loss) of following vehicles affected within a communication range. A switching threshold Δa_{th} denotes the permissiveness threshold of a lane changing. A safety criterion b_{safe} guarantees that the deceleration of lane changer and new follower on the target lane cannot exceed a given safe limit after a lane changing.

S_c and S_t present the set of following vehicles on the current lane and the target lane respectively within a communication range. x presents the current position of a vehicle (Euclidean norm). S_{Lane} refers to the set of vehicles in a lane at the given moment (except for subject vehicle); $||\cdot||$ presents the Euclidean norm; Lw is the wireless communication range. Note that the communication interaction range is assumed to be 300m in our study. Vehicles can mutually exchange information with other vehicles within the communication range.

B. Implementation Framework

The simulation platform was built in a MATLAB environment. The simulation platform is capable of simulating the sensing and communication characteristics of CAVs. The modified IDM and MOBIL were coded and embedded into the platform with key parameters. And they were regarded as the longitudinal and lateral models respectively. The modified IDM is used to determine the acceleration of each vehicle. The modified MOBIL can model the lateral decision-making process of discretionary and mandatory lane changes.

The overall implementation framework includes a vehicle system and a road system, as illustrated in Figure 2. Initially, we can designate the simulation environment, such as automation level and communication level etc. The elements of the road system include the origin and destination of a highway segment, lane number, off-ramp location and devices. All vehicles are regarded as CAVs, which contain the multiple functions of perception, self-driving control and communication. Each vehicle system is independent and relies on a perception-decision-control loop to ensure temporal continuity between simulation steps. In other words, a vehicle execution order cannot affect the simulation results. The vehicle and road system perceive and exchange the surrounding traffic conditions at a given time and then decide how this corresponds to perceptions. Vehicles equipped with an on-board display can receive acceleration and lane changing instructions. The vehicles can execute a precise action according to the sensed environment and decision process. Finally, the system traffic state is updated by applying the vehicles' actions.

Perception: some state data (relative speed, position etc.) can be perceived by vehicles' embedded sensors. The surrounding vehicular information is exchanged via V2V Technology. Road Side Units (RSUs) were hypothetically set to collect surrounding vehicular information for monitoring traffic. Information pertaining to vehicle and traffic conditions is exchanged via V2I Technology [12], [26].

Decision: the decision system within the vehicle system can predict traffic states based on such information. It can then provide the best driving decision for each vehicle. While a CAV generates a lane changing intention, the decision system will search for a safe gap among surrounding vehicles based on the predicted state thereof. A lane changing decision will be adjudged safe only when a suitable gap is found in the target lane.

Control: vehicles equipped with an on-board display can receive acceleration and lane changing commands from the decision system of the current vehicle. It will transform this information to the other vehicles via V2V. Vehicles perform actions to which the decision system should react. Note that our study assumes the vehicle is under full control following speed and lane changing instructions precisely, which can be achieved under a connected and automated environment.

C. Determination of Model Parameters

For the connected and automated vehicles, six parameters need to be determined in the modified IDM model, which are the time gap, desired speed, minimum distance, maximum acceleration, free flow acceleration and comfortable deceleration. In the modified MOBIL model, we require to determine three parameters, including lane changing threshold, safety criterion and politeness factor. Due to the lack of empirical data, these parameters were determined by suggestions in previous studies in our study.

Previous studies suggested that with the improvement of sensing and automated technologies, a small time gap was set to be 1.1s [22], [27], [28]. To maintain a comfortable driving, the maximum acceleration was set as 1.4 m/s2, which is adopted in our study [29]. The maximum desired speed in free-flow traffic condition is set to be 120 km/h [27]–[29]. The minimum distance was set to be 2m as suggested by the previous studies [29], [30]. The acceleration exponent was set to be 4 according to previous studies [28]–[30].

The politeness factor p in the MOBIL model is an important parameter used to determine a lane change maneuver. The parameter can vary according to traffic conditions, which results in a distinct effect on lane change maneuvers [31], [32]. In normal driving conditions, the politeness factor p and lane changing threshold are 0.5 and 1.0, which are referential to previous studies [32], [33]. Moreover, the politeness parameter is set to zero while egoistical behavior occurs [31], [33]. It means that the acceleration gains of surrounding vehicles are not considered. In our research, the diverging vehicle's mandatory lane changes are simulated by setting the parameter to zero. The safety criterion *bsafe* for a lane changing is 3.5m/s2 in our study as suggested by previous study [32]. It ensures feasibility and is considerably below the physically possible maximum deceleration.

IV. Cooperative Lane Changing Strategy

A. Overall Strategy Procedure

The logic of the cooperative lane changing strategy is to assist the diverging vehicles when exiting via the diverging area near a highway off-ramp. With such cooperative control,

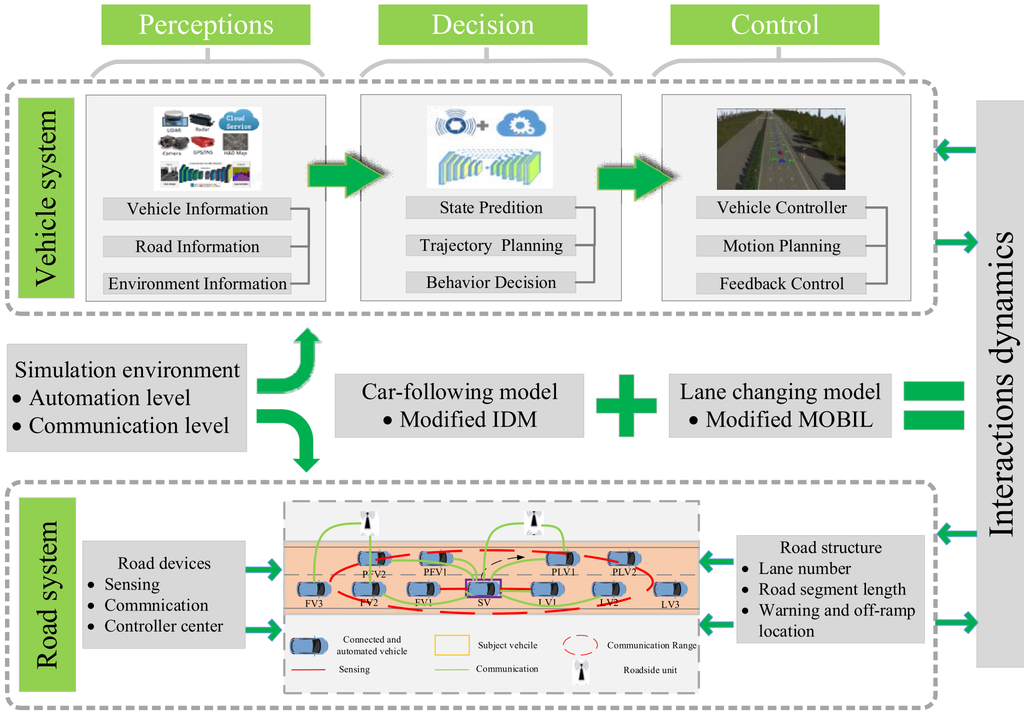


Fig. 2. Implementation framework of the simulation platform.

a mandatory lane change will be smoothly conducted by a cooperative method nearby the off-ramp. On the basis of previous strategies, we further extended the methodological framework by proposing more reasonable strategies for determining the opportunity and location of a mandatory lane change. Note that these control behaviours can be achieved and controlled more precisely with automated and connected technologies.

To this end, the cooperative strategy includes three steps, as shown in Figure 3. Firstly, a cooperative lane changing strategy is proposed considering the relaxation effect of a lane changing maneuver. Secondly, various zones are tested to find the optimal ones for different traffic conditions. Thirdly, the strategies are evaluated and compared with the applications of the optimal zones from the various aspects of traffic operation and safety.

B. Development of Cooperative Lane Changing Strategy (CLC)

The cooperative lane changing strategy is applied to assist diverging vehicles when conducting a successful mandatory lane change in the cooperative zone. The process is such that the safe lane changing gaps are proactively created to make vehicles move into the target lane by cooperative vehicle deceleration on the target lane. In our study, the time gap parameter of mandatory lane changing is modified based on the relaxation effect. We can control the diverging vehicles and cooperative vehicles so as to temporarily tolerate shorter gaps when a lane change is executed. This makes the vehicles move into the target lane more quickly even though the traffic flow is high. And time gap is relaxed to normal values after a short period.

As shown in Figure 4, when a diverging vehicle D on lane 1 cannot move into the target lane at time t, it is expected that vehicle D will move to the target lane at time $t + \Delta t$. The position of each vehicle at time $t + \Delta t$ within a given communication range will be predicted based on the its current position $x(t)$, speed $v(t)$ and acceleration $a(t)$. With regard to vehicle D travelling to the target lane at time $t+ \Delta t$, we need to search for the first following vehicle A upstream on the target lane 2. The required acceleration a_c used in the cooperative strategy is calculated using equation (17), for ensuring the predicted position of vehicle A located out of the safety zone of vehicle D. In our study, the safety zone between diverging vehicle D and vehicle A at time $t + \Delta t$ relies on the speed of vehicle A and the modified time gap considering the relaxation effect, as shown in equations (13) to (16). A shorter time gap of 0.6 s was applied during a lane change process and a lane change was just completed. Then the time gap was relaxed to normal values for a short period T_L of 20s, as suggested by study [17]. Moreover, we need to compare the required acceleration with a comfortable deceleration, maximized acceleration and the acceleration from divers' normal driving conditions. The most restricted one is selected as the acceleration used in cooperative control. Afterwards, diverging vehicle D can successfully travel on the target lane if the acceleration criteria is satisfied, based on the safe gap created by deceleration of cooperative vehicle A. Vehicle A' and D' (dotted line) in Figure 4 represent the new position of vehicle A and D, respectively. Note that the control horizon shifts to the time $t + \Delta t$, if the acceleration of both the diverging vehicle D and cooperative vehicle A used in cooperative control cannot satisfy the relevant safety criteria.

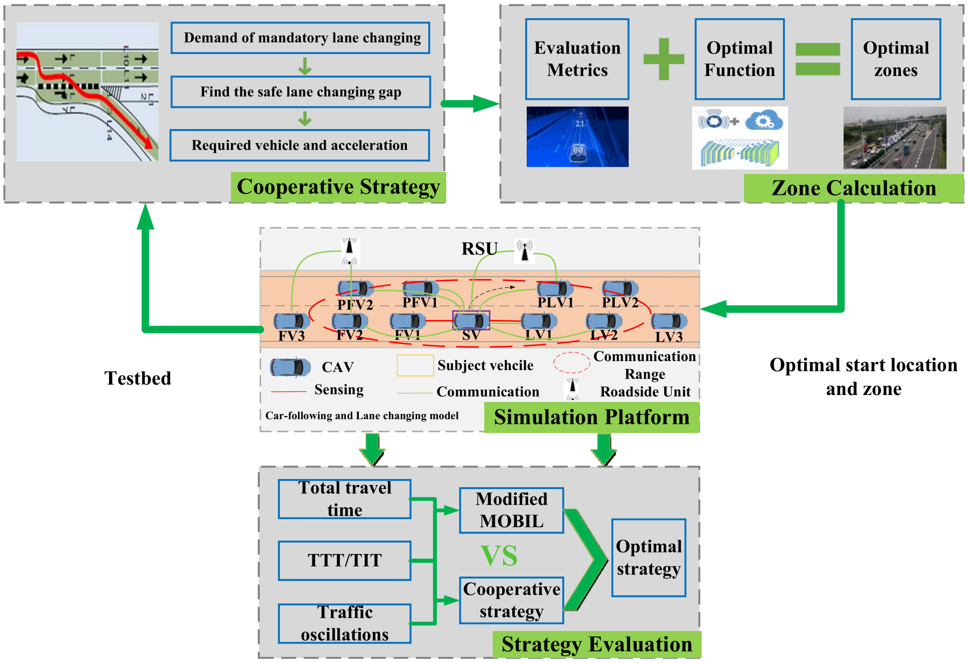


Fig. 3. Illustration of the overall strategic framework.

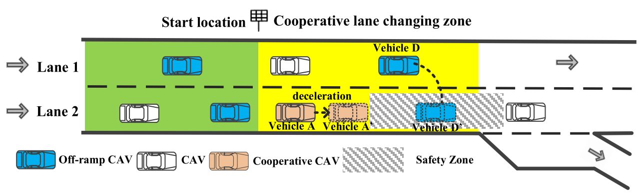


Fig. 4. Illustration of the cooperative lane changing strategy.

The acceleration will be re-calculated when the latest system state become available. The aforementioned criteria are also applicable to other diverging vehicles and potential cooperative vehicles.

$$X_A(t+\Delta t) = X_A(t)+v_A(t)\cdot \Delta t+0.5\cdot a_c\cdot \Delta t^2 \tag{13}$$

$$v_A(t+\Delta t) = v_A(t)+a_c\cdot \Delta t \tag{14}$$

$$X_A(t+\Delta t) = X_D(t+\Delta t)+v_D(t+\Delta t)\cdot T_m(t+\Delta t) \tag{15}$$

$$T_m(t+\Delta t) = T_m(t)+(T_{normal}-T_m(t))\cdot \Delta t/T_L \tag{16}$$

$$a_c = \frac{X_D(t+\Delta t)-X_A(t)-v_A(t)\cdot \Delta t-v_A(t)\cdot T}{0.5\cdot \Delta t^2+T\cdot \Delta t} \tag{17}$$

$$a_{cc} = min(min(max(a_c, b), a_{\max}), a_{normal}) \tag{18}$$

C. Metrics for Strategy Evaluation

A set of metrics were considered to evaluate the effects of cooperative strategy. An optimal strategy should consider the improvements in both traffic operation, safety and lane changing maneuvers. Thus, the total travel time and surrogate safety measurements were considered which are introduced as follows.

1) Total Travel Time: The total travel time (TTT) in a network is the main indicator to assess the operation and efficiency of transportation system [22, 33]. The total travel time is calculated by the following equation:

$$TTT = \sum_{i=1}^{N} TTT_i \tag{19}$$

where TTT_i is the time spent in the highway segment for a vehicle i and N denotes the total number of vehicles generated in the system during the simulation period.

2) Surrogate Safety Measurement: Direct safety measurements such as crash count and injury severity are not applicable in our case. Thus, the surrogate safety measures are used to evaluate the safety effects of cooperative lane changing strategies. The time-to-collision (TTC) notion was introduced by Hayward [35] and has since been applied in many studies [34]–[39]. The TTC represents the time required for two successive vehicles, occupying the same lane, to collide if they continue at their present speed when vehicle i moves faster than the preceding vehicle i-1.

Two advanced measures were developed based on the TTC [34], [40] to assess the risks associated with the vehicle movements near oscillations. It is corresponding to the Time Exposed Time-to-collision (TET) and the modified Time Integrated Time-to-collision (TIT). Both TET and TIT are aggregated indexes from TTC for safety evaluation. In particular, TET is a summation of all moments (over the simulation period T) that a driver approaches a front vehicle with a TTC value below a critical threshold (see equation (21) and (22)). A lower TET value indicates a safer situation. TIT calculates the entity of the TTC lower than the threshold, allowing to express the severity associated with safety critical situations (see equation (23) and (24)). A larger TIT indicates a more dangerous condition.

$$TTC_i(t) = \begin{cases} \dfrac{x_{i-1}(t)-x_i(t)-L}{v_i(t)-v_{i-1}(t)}, & if\, v_i(t) > v_{i-1}(t) \\ \infty, & if\, v_i(t) \le v_{i-1}(t) \end{cases} \tag{20}$$

$$TET(t) = \sum_{i=1}^{N} \gamma_t \Delta t,$$
$$\gamma_t = \begin{cases} 1, \forall 0 < TTC_i(t) \le TTC_{threshold} \\ 0, else \end{cases} \quad (21)$$
$$TET = \sum_{t=1}^{T} TET(t) \quad (22)$$
$$TIT(t) = \sum_{i=1}^{N} \left(\frac{1}{TTC_i(t)} - \frac{1}{TTC_{threshold}} \right) \Delta t,$$
$$\forall 0 < TTC_i(t) \le TTC_{threshold} \quad (23)$$
$$TIT = \sum_{t=1}^{T} TIT(t) \quad (24)$$

where L is the length of predecessor vehicle, t is time, Δt is simulation time step, i is vehicle ID, N is number of total vehicles, and $TTC_{threshold}$ is the threshold of *TTC* which is set to be 2s according to suggestions in previous studies [22].

D. Optimal Functions for Strategy Evaluation

An optimal function was proposed to compare the effects of different strategies and determine the optimal one. In our study, the metrics of traffic operation and safety are calculated to evaluate the performance of the whole system. The fitness functions of equation (25) and (26) are formulated by considering the effect of total travel time and traffic safety respectively.

$$Fitness1 = max\ (\Delta T) \quad (25)$$
$$Fitness2 = max\ (\Delta R) \quad (26)$$
$$\Delta T = (TTT_{control} - TTT_{non})/TTT_{non} \quad (27)$$
$$\Delta R = (TET_{control} - TET_{non})/TET_{non} \quad (28)$$

where ΔR is the reduction in the collision risk, $TET_{control}$ is the collision risk under cooperative control, TET_{non} is the collision risk without cooperative control, ΔT is the change in total travel time, $TTT_{control}$ is the total travel time under cooperative control, TTT_{non} is the total travel time without the cooperative control.

V. Experiment Design

Each simulation test lasts 400 s with a time step of 0.1 s. In the simulation, the vehicles have different expected speeds, which can generate distinct driving behaviours and trigger various lane changing intentions. The initial speed of all vehicles is 17 m/s, and the upper and lower expected speed is 33 m/s and 17 m/s respectively. The gap settings between each of two consecutive vehicles depend on the traffic flow conditions. To reduce the effect of simulation randomness, each test is repeated twenty times and the results are averaged.

The diverging instructions given to diverging vehicles can be transmitted at the beginning of the cooperative zone. The zone varied from 1695m to 2500m in length, due to the location is 1695m in practice. Moreover, the zone length is significantly affected by traffic flow, diverging flow and control objectives. The mainline flow was set to be 1500 veh/h/lane and 2000 veh/h/lane in order to generate different traffic states. Two scenarios with 10% and 20% lane changing rate (LCR) are analyzed for the same traffic flow, *i.e.* 10 % and 20 % of vehicles in the inner lane are required to perform mandatory lane changes.

TABLE I

Optimal CLC Zones for Various Traffic Conditions

Flow(pcu/h)	LCR (%)	SL(m)	L(m)	SD
2000	20	1910	590	255.82
2000	10	2090	410	196.92
1500	20	2090	410	193.75
1500	10	2220	280	122.92

L and SL -- length and start location of CLC zone
SD -- Standard deviation of the length of CLC zone

TABLE II

Optimal CLC Zones for Various Traffic Conditions

Flow(pcu/h)	LCR (%)	SL(m)	L(m)	SD
2000	20	1920	580	175.11
2000	10	2090	410	251.44
1500	20	1990	510	218.32
1500	10	2250	250	184.08

VI. Evaluation of Cooperative Strategy

In practice, the length of mandatory lane changing zone for diverging vehicles was usually set to be 815 m away from the off-ramp in previous study [1]. In a practical study, a fixed zone is applied to the simulation platform to make the diverging vehicles perform a mandatory lane change. The lane changes are performed based on the new MOBIL with smaller time gap, which is regarded as the modified MOBIL. The optimal zone length for such a cooperative lane changing strategy is calculated through a heuristic algorithm. Afterwards, the optimal zones are used in the simulation platform to test the cooperative strategy. The proposed cooperative lane change strategies are compared with the modified MOBIL strategy from traffic operations, traffic safety and traffic oscillation perspectives.

A. Optimal CLC Zones for Improving Traffic Operations

The experimental results in Table 1 show the optimal cooperative zones for improving the traffic operation in our strategy. The upstream start location (SL) and off-ramp exit means the start and end point of the cooperative zone along the travel direction respectively. The length (L) is defined as the distance from the start location to the off-ramp. They are smaller than the fixed zone required in modified MOBIL strategy in all four scenarios. The cooperative zones became larger for the traffic flow of 2000pcu/h and 1500pch/u, as the lane changing rate increases. This is due to the larger zone providing more room in which to dissipate the queue arising from sufficiently high diverging flow, resulting in improvements in traffic operation. As the traffic flow decreases for the same lane changing rate, the zones become smaller. This is due to the smaller flow allowing a larger gap in which to make diverging vehicles perform mandatory lane changes with less traffic delay compared to that incurred under the larger flow. Thus, a smaller cooperative zone is required when considering the positive effect of larger gaps.

B. Optimal CLC Zones for Improving Traffic Safety

Table II presents the optimal cooperative zones required for improving traffic safety. The results suggest that all

TABLE III
COMPARISONS OF OPERATIONAL EFFECT UNDER DIFFERENT STRATEGIES

Strategy	Flow(pcu/h)	LCR (%)	L(m)	ΔT (%)
Modified MOBIL	2000	20	805	--
CLC	2000	20	590	-5.6
Modified MOBIL	2000	10	805	--
CLC	2000	10	410	-1.3
Modified MOBIL	1500	20	805	--
CLC	1500	20	410	-4.8
Modified MOBIL	1500	10	805	--
CLC	1500	10	280	-0.5

TABLE IV
COMPARISONS OF SAFETY EFFECT UNDER DIFFERENT STRATEGIES

Strategy	Flow(pcu/h)	LCR (%)	L(m)	ΔR (%)
Modified MOBIL	2000	20	805	--
CLC	2000	20	580	-15.5
Modified MOBIL	2000	10	805	--
CLC	2000	10	410	-17.1
Modified MOBIL	1500	20	805	--
CLC	1500	20	510	-13.2
Modified MOBIL	1500	10	805	--
CLC	1500	10	250	-10.2

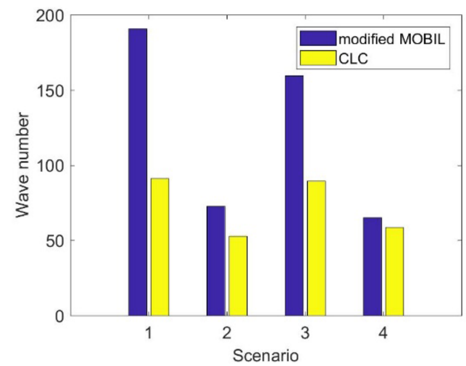
cooperative zones in our strategy are smaller than the fixed zone required in modified MOBIL strategy. The cooperative zones become larger with the increasing lane changing rate and traffic flow, as the larger zone can reduce the collision risks resulting from lane changes in high diverging flow and mainline flow conditions. Otherwise, a smaller zone can lead to traffic disturbances incurring a higher collision. These disturbances will propagate upstream and cannot be easily mitigated.

C. Impacts on Traffic Operation

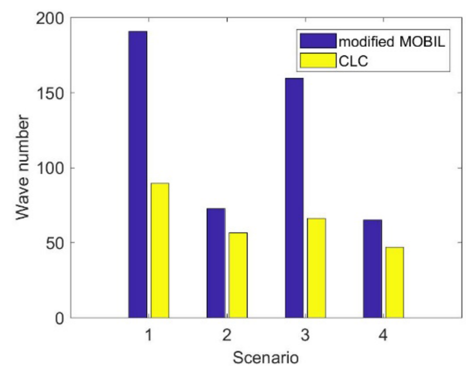
The major differences between the modified MOBIL strategy and cooperative strategy lie in the zone length of and strategy for mandatory lane changes. The impacts of the modified MOBIL and cooperative strategy on the traffic operation is illustrated in Table III. The cooperative strategies can effectively improve traffic operations compared to the modified MOBIL strategy in all scenarios with improvements ranging from 0.5 % and 5.6 %. This is because an optimal cooperative zone is adopted in the cooperative strategy, which can dynamically adjust itself given variation in traffic flow and lane changing rate. Moreover, the cooperative strategy can move more diverging vehicles into the target lane in less time. Under such control, this can reduce the traffic delay resulting from queuing nearby the off-ramp. Note that the cooperative strategy perform slightly better than the modified MOBIL strategy in a scenario involving medium traffic flow and a lower lane changing rate. It is due to an offset arising from the deceleration required to create a lane changing gap and the caused traffic delay, as compared to the lane changes that are successfully conducted based on the original larger gap for the smaller flow. In conclusion, it is particularly beneficial to implement a cooperative strategy in larger traffic flow or for higher lane changing rate.

D. Impacts on Safety Measurements

The comparisons between the modified MOBIL strategy and cooperative strategy are summarized in Table IV. The comparisons suggest that the cooperative strategy has better performance in improving traffic safety than the modified MOBIL strategy in various scenarios. One reason is that the cooperative strategy is applied in an optimal zone, which can dynamically vary with the traffic flow and lane changing rate. Moreover, the safety zone is proactively created to make diverging vehicles safely conduct mandatory lane changes



(a)



(b)

Fig. 5. Wave number between different strategies. (a) Traffic operation; (b) Traffic safety.

in our strategy, which was not considered in the modified MOBIL strategy. In particular, the cooperative strategy reduces the risk of collision by 15.5 % and 17.1 %, for the large flow with 20 % and 10 % lane changing rate, respectively. The reductions in collision risks are larger than those in medium flow respectively. This is mainly due to the fact that more diverging vehicles that do not make a successful mandatory lane change can move into the target lane with the implementation of the cooperative strategy in the scenario with a larger traffic flow.

E. Impacts on Traffic Oscillation

The comparisons of wave number between the cooperative strategy and the modified MOBIL strategy are shown in Figure 5 for various scenarios. Figures 5(a) and 5(b) show the wave number for different strategies when considering the effects of traffic operation and traffic safety, respectively.

Moreover, Scenarios 1 and 2 present the wave number for a traffic flow of 2000 pch/h with 20 % and 10 % lane changing rate respectively. Scenarios 3 and 4 correspond to a traffic flow of 1500 pcu/h. Here, we count one wave number when the speed of a vehicle is less than 1 m/sec. A new wave can be calculated only after 10 s from the last time that the speed is less than 1 m/s, as adopted in previous study [41]. Particularly, it is found that the cooperative strategy reduces the number of traffic waves by 10.2 % to 52.1 % in Figure 5(a). In addition, the wave numbers are reduced by 22.1 % to 58.4 % in cooperative strategy Figure 5(b). This suggests that the cooperative strategy can improve traffic oscillation based on the larger reductions of wave number in various scenarios. It is mainly due to the traffic oscillations (stop-and-go waves) being significantly mitigated by the cooperative procedure involved in our cooperative strategy.

VII. Conclusion

The study proposed a cooperative lane changing strategy to improve traffic operation and safety at a diverging area nearby a highway off-ramp. IDM and MOBIL were modified to develop a simulation platform for a connected and automated vehicle (CAV) environment. The optimal cooperative zones were determined by heuristic method. Then the cooperative lane changing strategy was implemented to assist diverging vehicles when performing a mandatory lane changing in the designated zone. Metrics were considered to evaluate the proposed cooperative strategy, including those related to total travel time, surrogate safety measures and wave number.

In summary, a simulation platform for a CAV environment was built. It could simulate the dynamic traffic at a diverging area on freeways. On basis of this, several important insights arose from the research. First of all, all optimal cooperative zones were smaller than the fixed zone required in modified MOBIL strategy. The vehicles can effectively perform a lane change within a smaller zone when using connected and automated technology. This was implemented by a cooperative procedure working between paired vehicles in a coordinated lane changing event. Secondly, the cooperative zones became larger with increasing traffic flow and lane changing rate. Finally, adaptation of the cooperative strategy with the optimal zones rather than the modified MOBIL strategy with a fixed zone, showed improved traffic operation, traffic safety and traffic oscillation in all scenarios. However, the cooperative strategy had slight performance improvements with regard to traffic operations under a lower lane changing rate.

In our current study, a cooperative vehicle was assumed to be controlled at exactly the required acceleration. On highways with mixed autonomous vehicles and manually-driven vehicles, the current strategy needs to be modified with regard to the selection of proper cooperative vehicle and acceleration. In addition, we could combine the simulation and mathematical optimization method to determine the cooperative zone length and test the cooperative strategy with more simulation runs. More metrics could be considered in future research, such as the comfort degree of vehicles. We could integrate jam-absorbing driving strategies into our cooperative strategy to better mitigate traffic oscillations in diverging flow areas. Furthermore, the model parameters required to simulate CAVs must be calibrated. This is not done in this study as we could not find a trajectory dataset pertinent to CAVs, but it remains a priority for future research.

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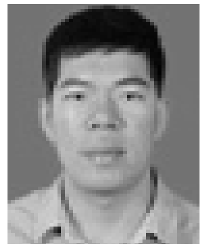

Yuan Zheng received the B.S. and M.S. degrees from the School of Transportation, Southeast University, Nanjing, China, in 2013 and 2016, respectively. He is currently pursuing the Ph.D. degree with the Joint Research Institute on Internet of Mobility, Southeast University, and the University of Wisconsin–Madison. His interest includes the modeling of microscopic traffic and connected automated vehicle highway (CAVH) systems.

Bin Ran currently serves as the Director of the Joint Research Institute on Internet of Mobility, founded by Southeast University, China, and the University of Wisconsin–Madison, Madison, WI, USA. He also holds the title of National Distinguished Expert in China and the Vilas Distinguished Achievement Professor and the Director of the Intelligent Transportation System (ITS) Program at the University of Wisconsin–Madison. He mainly engages in the researches of intelligent transportation systems and connected automated vehicle highway (CAVH) systems. He is also an Associate Editor of the *Journal of Intelligent Transportation Systems*. He is also the Founding President of the Chinese Overseas Transportation Association (COTA).

Xu Qu received the Ph.D. degree from Southeast University (SEU), Nanjing, China, in 2013. He currently serves as an Assistant to the Dean of the Joint Research Institute on Internet of Mobility, founded by Southeast University and the University of Wisconsin–Madison, Madison, WI, USA. His research interests include connected automated vehicle highway system and traffic safety. He is also a Reviewer of *IET Intelligent Transport Systems* journal.

Jian Zhang (M'13) received the Ph.D. degree from Southeast University (SEU), Nanjing, China, in 2011. He is currently an Associate Professor with the School of Transportation, SEU, the Executive Vice Director of the Research Center for Internet of Mobility, and the Assistant to the Dean of the Joint Research Institute on Internet of Mobility, founded by Southeast University and the University of Wisconsin–Madison, Madison, WI, USA. His research interests include connected automated vehicle highway systems, intelligent highway, and intelligent scheduling for public transit.

Yi Lin received the B.S. degree from the School of Transportation and Logistics, Southwest Jiaotong University, Sichuan, China, in 2017. He is currently pursuing the M.S. degree with the Research Center for Internet of Mobility, Southeast University, Nanjing, China. His interests include the modeling of CAVH, intelligent vehicles, and automated highway systems.