Hindawi
Journal of Advanced Transportation
Volume 2020, Article ID 5847814, 16 pages
https://doi.org/10.1155/2020/5847814

Research Article

Safety Evaluation for Connected and Autonomous Vehicles' Exclusive Lanes considering Penetrate Ratios and Impact of Trucks Using Surrogate Safety Measures

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Received 6 November 2019; Accepted 31 December 2019; Published 22 January 2020

Guest Editor: Feng Chen

Plenty of studies on exclusive lanes for Connected and Autonomous Vehicle (CAV) have been conducted recently about traffic efficiency and safety. However, most of the previous research studies neglected comprehensive consideration of the safety impact on different market penetration rates (MPRs) of CAVs, traffic demands, and proportion of trucks in mixture CAVs with human's driven vehicle environment. On this basis, this study is to (1) identify the safety impact on exclusive lanes for CAVs under different MPRs with different traffic demands and (2) investigate the safety impact of trucks for CAV exclusive lanes on mixture environment. Based on the Intelligent Driver Model (IDM), a CAV platooning control algorithm is proposed for modeling the driving behaviors of CAVs. A calibrated 7-kilometer freeway section microscopic simulation environment is built by VISSIM. Four surrogate safety measures, including both longitudinal and lateral safety risk indexes, are employed to evaluate the overall safety impacts of setting exclusive lanes. Main results indicate that (1) setting one exclusive lane is capable to improve overall safety environment in low demand, and two exclusive lanes are more suitable for high-demand scenario; (2) existence of trucks worsens overall longitudinal safety environment, and improper setting of exclusive lanes in high trucks, low MPR scenario has adverse effect on longitudinal safety; and (3) setting exclusive lanes have better longitudinal and lateral safety improvement in high-truck proportion scenarios. Setting one or two exclusive lanes led to [+42.4% to −52.90%] and [+45.7% to −55.2%] of longitudinal risks while [−1.8% to −87.1%] and [−2.1% to −85.3%] of lateral conflicts compared with the base scenario, respectively. Results of this study provide useful insight for the setting of exclusive lanes for CAVs in a mixture environment.

1. Introduction

Recent research studies on Connected and Autonomous Vehicle (CAV) based on the Internet of Things (IoT), artificial intelligence, sensor technology, and other emerging technologies have made it ready for real-world applications in the near future [1]. It has been well recognized that CAV has the capability of enhancing traffic safety, efficiency, and reducing emission [2–4]. Early field experiments of this technology include California PATH [5] and SARTRE [6]. It seems perfect if all vehicles on roads are connected and autonomous. However, human-driven vehicles (HDVs) and CAVs will coexist in a long period, and some researchers argued that the safety impact is mainly decided by the market penetrate rates (MPRs) of CAVs [3]. On the contrary, CAV-HDV and HDV-CAV interactions still need more experimental data [7]. Hence, the early application of CAVs is making sense to build on exclusive lanes, which is a much simpler environment. Besides, large quantities of optimization methods on autonomous driving have been conducted, such as multivehicle cooperative stability control of CAVs [8], platoon controllers for CAVs including the Proportional-Integral-Derivative controller ([9, 10]), car-following model-based controller [11] , interpolating controller [12], and so on. Cooperative vehicle and infrastructure for optimizing signal control on arterials or urban intersections and multivehicle platooning control have the possibility to be successfully applied on exclusive lanes for CAVs in the near future [13–15].

One primary consideration of this paper is to identify the safety impact on exclusive lanes for CAVs on different MPRs with different traffic demands. A considerable amount of previous studies agrees that exclusive lanes for CAVs enhance safety, capacity, and efficiency of freeway facilities compared with CAVs and HDVs sharing the same lanes (e.g., MPRs<100%) [16, 17]. However, none of them has discussed how to set one, two, or more exclusive lanes according to different traffic demands. It is irrational to place an exclusive lane with relatively low MPRs of CAVs on a congested freeway since compressing the headway to HDVs would induce higher traffic crash risk and worsen congestion. Hence, careful discussion on the impact of exclusive lanes for connected and autonomous vehicles is necessary.

Another equipollence consideration is the influence of trucks on safety impacts for CAV exclusive lanes on different traffic compositions [18]. Previous research studies often assumed that only a few trucks exist on traffic, which means that traffic mostly consists of cars. In fact, the existence of trucks is not only changing the speed distribution but also influences actual road capacity as it is longer, heavier, and clumsier than cars [19]. Traditionally, these differences between trucks and cars can be neglected in modeling the traffic system since the proportion of the truck is rare on most uncongested freeways. However, with the rapid development of China, road freight transportation, almost by trucks, takes up nearly three-quarters of the total freight volume in China [20], which produces large quantities of freight demands on the freeway. As the proportion of trucks increase, speed difference enlarged, and its safety impact is no longer negligible. Particularly in the situation that exclusive lanes have taken over one or two lanes for CAVs, the maintaining of overall safety impacts is questionable. Besides, experiments have conducted and pointed out that heavy-duty trucks' close-distance driving will result in a significant fuel reduction [21, 22]. Additional efforts need to be made to the influence of high-truck proportion toward the safety impact of freeway exclusive lanes for CAVs for the early application of CAVs.

The homogeneous CAV traffic is believed to be beneficial for the application and operation of autonomous vehicles, and the setting philosophy of CAV exclusive lanes still needs further investigation. Accordingly, in this paper, we try to make a supplement to previous research studies on investigating safety impacts of exclusive lanes for CAVs on different traffic demands and compositions to determine when it is better to set exclusive lanes.

The contribution of this paper is threefold. First, a platoon control algorithm is developed to incorporate the cooperation of autonomous vehicles in the traditional IDM model. Second, we deployed a simulation environment with surrogate safety measures technology to investigate the safety impact of the exclusive lane. Third, we conduct a comprehensive comparison analysis to analyse the safety impact on the impact of CAVs on the exclusive lane and pointed out useful perspectives for the operation of the CAV exclusive lane.

2. Literature Review

2.1. Evaluating Impacts of CAVs. Many research studies of realistically modeling CAV systems with platoon control in varied scenarios have been conducted in recent years; however, relatively few in the literature focus on exclusive lanes for CAVs. There are two major approaches for exclusive lane research studies: analytical modeling and computer simulation. One of the springboards is from the improvement of traffic flow, including increasing string stability, capacity, or preventing CAVs degraded to AVs (without cooperative) [23–26]. The above studies revealed the pros and cons of setting up exclusive lanes from the traffic flow theory perspective. On the contrary, Rahman and Abdel-Aty [27] applied surrogate safety measures to evaluate the safety impact of exclusive lanes for CAVs. Besides, other research studies on the safety impacts of CAVs applied surrogate safety measures [28, 29] presented the feasibility of this kind of evaluation. Details of aforementioned literatures are summarized in Table 1.

2.2. Simulation-Based Approaches. Simulation testbeds and approaches for research studies of CAVs or autonomous vehicles are still necessary since the proof that CAVs bring safety on roads is insufficiency. Microscopic simulation-based CAV studies have utilized different kinds of simulation platforms. Besides simulation platforms, CAV car-following algorithms are also necessary. The driving behavior for CAVs and human drivers are very different. To build car-following models for CAVs, earlier studies have applied Intelligent Driver Model (IDM) [21, 30, 31], Newell's car-following model [32, 33], full velocity difference (FVD) model [34], MICroscopic Model for Simulation of Intelligent Cruise Control (MIXIC) [35], and so on. Research [36] reviewed these car-following models and pointed out that the Intelligent Driver Model is one of the most used models, and it is considered to be more suitable to simulate behaviors of CAVs in the real world since it is able to model turbulence, oscillation, and other traffic flow characteristics.

2.3. Safety Impacts of Trucks. According to the Freeway Administration of Jiangsu Province (FAJ), China, the running speed of trucks in the Ninghu Freeway is at a range of 48 km/h to 78 km/h, far less than 65~119 km/h for human-driven cars. Such a speed difference is one of the main causes of crashes. Researchers have found the relationship between speed differences with accidents is given by the so-called Solomon curve or Crash Risk Curve [20, 37, 38]. The curve largely follows U-shape, which means that a larger

Table 1: Summary of previous research studies for connected and autonomous vehicles with mixture environment.

Study	Base model	Scenarios	Main results
[23]	A platooning model (similar with Wiedemann 99 for HDV)	1 exclusive lane	Exclusive lanes for CAV could provide up to 5.5 times the capacity of the conventional freeway when platoon size is 20, interplatoon spacing is 50 meters, and intraplatoon spacing is 1 meter
[24]	Cellular automata	1, 2 exclusive lanes and 3 exclusive rows for CAVs on 2 lanes. MPRs = 0, 10%, . . ., 90%	Exclusive lanes for CAV will greatly improve the traffic condition of the freeway on MPRs = 10%–80%
[25]	Cellular automata	0, 1, or 2 exclusive lanes. MPRs = 0, 10%, . . . , 90%	Setting CAV exclusive lanes at low MPRs deteriorates the performance of overall traffic flow throughput, particularly under a low-density level
[26]	Not available	1 exclusive lane with 3 strategies: forced-everywhere, forced-reserved, and optional-everywhere	Optional use of the exclusive lane without any limitation on the type of operation could improve congestion, increase 30% capacity for a four-lane freeway
[27]	IDM model for CAV, Wiedemann 99 for HDV	0 or 1 exclusive lane	Connected vehicles' platooning on the exclusive lane outperformed all lane scenarios
[28]	Wiedemann 99 for HDV, IDM model for CAV	MPRs = 0, 25%, 50%, 75%, and 100% on a freeway	CAVs bring about compelling benefit to road safety as traffic conflicts significantly reduce even at low penetration rates
[29]	Mixture (IDM, Wiedemann and modified Bando)	MPRs = 30%, 40%, 60%, 80%, and 100% on an arterial with 9 signalized intersections	CAVs reduce segment crash risk significantly in terms of five surrogate measures of safety

speed difference indicates more accidents. Due to the speed difference, conflicts between cars and trucks occurred. Hence, the Administration has tried to separate truck traffic by forbidding their running on the leftmost two lanes, but strong conflicts still exist on weaving areas, and safety impacts of trucks need investigation.

3. Methodologies

The evaluation of safety impacts of CAV exclusive lanes is implemented on a freeway designed in the PTV-VISSIM platform with the External Driver Model. Driving behaviors of CAVs, including car-following and lateral lane change decisions, are coded in C++ language as a Dynamic Link Library (DLL) plug-in, which allows users to override original VISSIM default driving behaviors. This section describes an overall simulation framework of evaluating safety impacts of CAV exclusive lanes, including model calibration, driving behaviors of CAVs and HDVs, and surrogate safety measure indexes. The overall architecture of this study is presented in Figure 1.

Three main assumptions of this study are as follows: (1) all CAVs would follow the proposed platooning control algorithm. (2) Communication technology of CAVs adopted Dedicated Short-Range Communications (DSRC) with a constant communication range of 300 meters. (3) The perception-reaction time for CAVs maintains a constant value.

3.1. CAVs with Platooning Control Algorithm

3.1.1. Longitudinal Car-Following Model. In this paper, the Intelligent Driver Model (IDM), proposed by [39], is chosen as a car-following model for CAVs, while human-driven vehicles (e.g., cars and trucks) follow Wiedemann 99 model, which originated from the default car-following model of VISSIM, and it has good performance on simulating human driver's driving behavior. The IDM model can be denoted as

$$a_{\mathrm{IDM}}\left(t+t_{\alpha}\right)=\max\left\{b_m, a_m\left[1-\left(\frac{v}{v_0}\right)^{\delta}-\left(\frac{s^*}{s}\right)^2\right]\right\},$$
$$s^*=s_0+\max\left[0, vT+\frac{v\Delta v}{2\sqrt{a_m b}}\right], \tag{1}$$

where t_α = the perception-reaction time, a_m = the maximum acceleration, b_m = the maximum deceleration, v = the speed of the following vehicle, v_0 = the desired speed, δ = the acceleration exponent (with a constant value of 4), s = the gap distance between the leading vehicle and the following vehicle, s_0 = the minimum gap distance at standstill, T = the safe time headway, and b = the desired deceleration.

The parameters of the IDM model for calibrating driving behaviors of CAVs should be calibrated by field-tested data which are difficult to access in current automated technology level. Thankfully, previous research studies have built and calibrated this model for Adaptive Cruise Control (ACC), and later, researches extended their study based on similar values of the parameters. In this study, the parameters of the CAV behavior model are chosen from research studies [27–29], which are shown in Table 2.

3.1.2. Vehicular Interaction between CAV-CAV, CAV-HDV, and HDV-HDV/CAV. What needs to be pointed out is that the safe time headway T varies from interact types on Table 3. If the front vehicle is a CAV, then the follower will keep driver behavior with the leader by using an aggressive headway (0.85 s), while when the leading vehicle is an HDV, the follower will keep a conservative driving strategy with a safer time headway (2.0 s). Previous research studies have

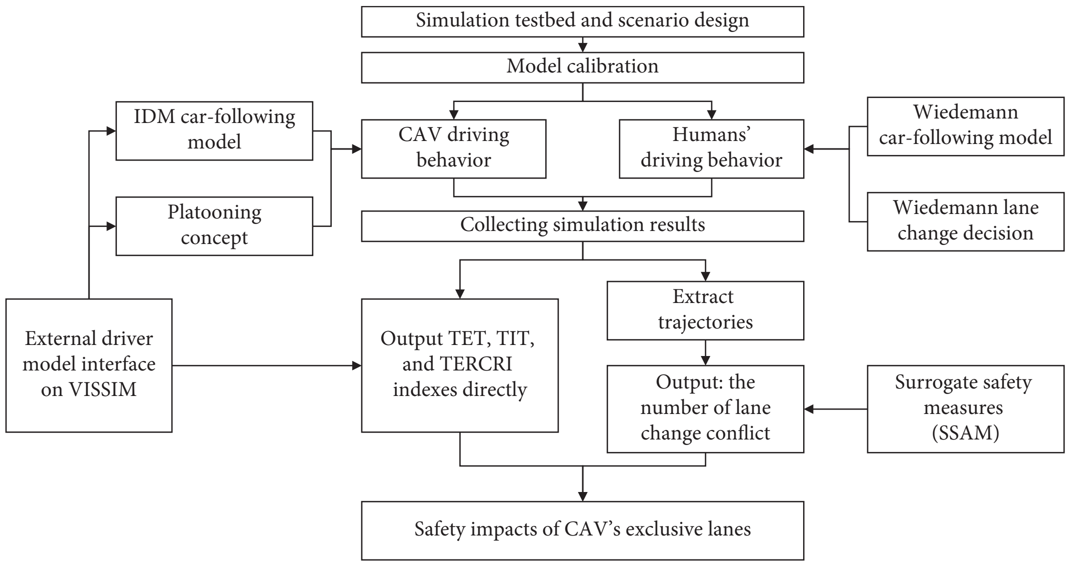

Figure 1: Architecture of the study on safety impacts of CAV's exclusive lanes.

Table 2: Parameter values of the IDM model.

Parameter	Value	Parameter	Value
a_m	1.0 m/s^2	T	0.85 s/2.0 s
b_m	−8.0 m/s^2	t_α	0.5 s
v_0	120 km/h	b	−2.8 m/s^2

Table 3: Value for the desired headway.

Interaction type (follower-leader)	Desired headway (sec)	Range (sec)	Literature
HDV-CAV HDV-HDV	1.52	1.0–1.8	[40], the value was calibrated from the FAJ
CAV-CAV	0.85	0.6–2.0	[41]
CAV-HDV	2.0	0.8–2.2	[42]

pointed out the proper range for desired headways of CAV-HDV, CAV-CAV, and HDV-HDV, which are also shown in Table 3.

Additionally, a headway examination is deployed. The reason for examination is derived from the point that the IDM model only considers the current speed difference between the leading vehicle and the following vehicle but ignores the acceleration of the leading vehicle. Since the communication delay and the perception-reaction time are unignorable, lacking of considering the acceleration of the leading vehicle might cause the following vehicle too late to act when the leading vehicle is in a sudden brake. In doing so, we propose a trimming method, which calculates the distance of the leading and the following vehicles in 2.0 seconds (Figure 2) by using the current acceleration calculated by the IDM model. If the gap between two vehicles after 2.0 s is smaller than the minimum gap at a standstill (2.0 m), the current vehicle's acceleration will decrease per 0.1 m/s^2, and repeat calculation until the gap is acceptable. The trimming method might increase safety, whereas reduce efficiency. However, how to achieve a balance between safety and efficiency still needs further investigation, which is not covered in this study. Some readers might also doubt the integrity of control logic shown in Figure 2 as it seems to be missing the logic of exiting the platoon when a CAV is ready to leave the freeway. Actually, as the CAV leaves the platoon, the CAV would try changing its lane close to the ramp under the premise of keeping safety. In this case, the CAV is no longer in the platoon control mode. The leaving freeway behavior of a single CAV makes no difference on the platoon control logic for remaining CAVs on the exclusive lane.

3.1.3. Lateral Lane Change Decision to Form or Join the Platoon. Derived from the IDM model, the platooning concept is implemented for regulating the driving behaviors from individual AVs to CAVs. To maintain the platoon, the CAVs on the searching mode will try to search the Nearest CAV (NCAV) in the DSRC communication range constantly. When an NCAV is found, the individual CAV will try to form a platoon from the rear, front, or middle cut-in by sending a join request. If the gap for lane change to form a platoon or join an existing platoon is not enough, the on platooning NCAV will slightly slow down to increase the

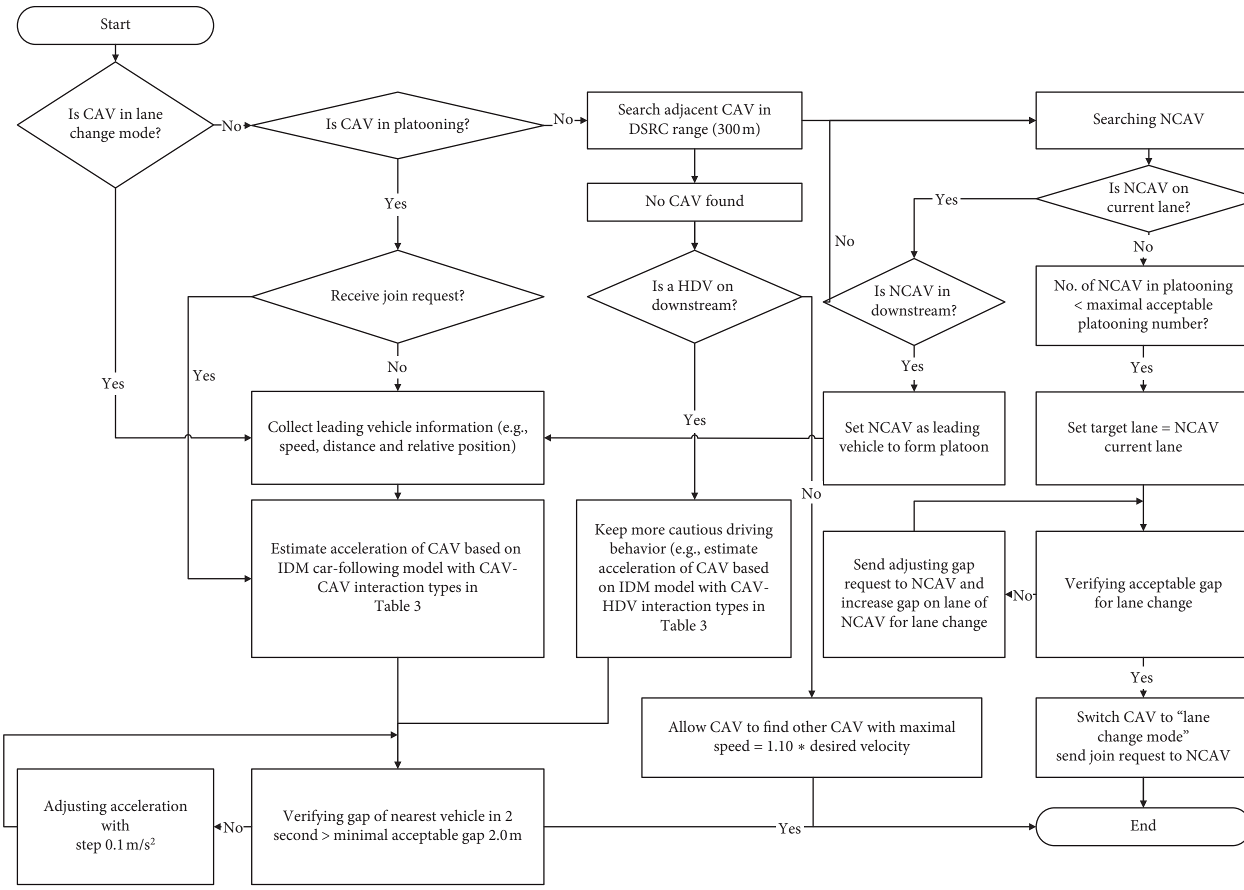

Figure 2: Platoon controlling algorithm for CAVs.

gap. If an HDV is found downstream on the current lane, the CAV will follow it with a cautious headway (e.g., change to CAV-HDV interaction types). If no vehicle is found downstream in the DSRC range, the individual CAV is allowed to cruise with an increasing 10% of the speed limit as the desired speed to search the NCAV. Note that if the current NCAV does not meet the platooning requirement, the CAV will set the second nearest CAV as NCAV.

3.2. Simulation Testbed Construction

3.2.1. Exclusive Lane Scenarios. The simulation testbed is an around 7 km segment of Ninghu Freeway, a four-lane freeway in Jiangsu province connecting Shanghai and Nanjing, China, with a speed limit of 120 km/h for cars and 80 km/h for trucks. The testbed section consists of three on-ramps and two off-ramps with approximately 30% trucks. In this study, we designed three scenarios of CAV's exclusive lanes, and Figure 3 formulates three deployment scenarios for testing. The base scenario serves as the base condition of the Ninghu segment for this study. The exclusive lane scenarios' access to one or two leftmost exclusive lanes for CAVs is studied. The left-lane deployment of exclusive lanes causes weaving activities around on-ramps and off-ramps. Therefore, the weaving length for CAVs toward or leaving the exclusive lane has to be considered. According to the experience on the existing bus managed lane, 300 meters of weaving length for the exclusive lane entry/exit is recommended by the FAJ.

3.2.2. Calibration and Validation. One of the most important parts of any simulation-based studies is calibration. In this study, humans' driving behavior data were collecting by the Administration of Ninghu Freeway from field detectors, and these data are applied for calibration and validation. Traffic volume and speed from field detectors on 16 : 30–19 : 30, September 30th, 2018, collected from 16 field detectors were aggregated into 10 minutes and used as vehicle inputs. The first 30 minutes of simulation time and the last 30 minutes cool-down time of the simulation are excluded for calibration and validation. The calibration target can be described as

$$\min \varepsilon = \sqrt{\frac{\sum_t \left(q^{\mathrm{obs}}(t) - q^{\mathrm{sim}}(t,\theta)\right)^2}{\sum_t \left(q^{\mathrm{obs}}(t)\right)^2}} + \sqrt{\frac{\sum_t \left(v^{\mathrm{obs}}(t) - v^{\mathrm{sim}}(t,\theta)\right)^2}{\sum_t \left(v^{\mathrm{obs}}(t)\right)^2}}, \tag{2}$$

where ε = calibrate error, $q^{\mathrm{obs}}(t)$ = observed traffic volume on collecting interval t, $v^{\mathrm{obs}}(t)$ = average observed travel speed on the interval t, θ = parameter vectors for simulation, $q^{\mathrm{sim}}(t,\theta)$ = traffic volume on collecting the interval t in simulation, and $v^{\mathrm{sim}}(t,\theta)$ = average travel speed on collecting interval t in simulation. Calibrate result shows that the average calibrate error is 4.66%, which meets the

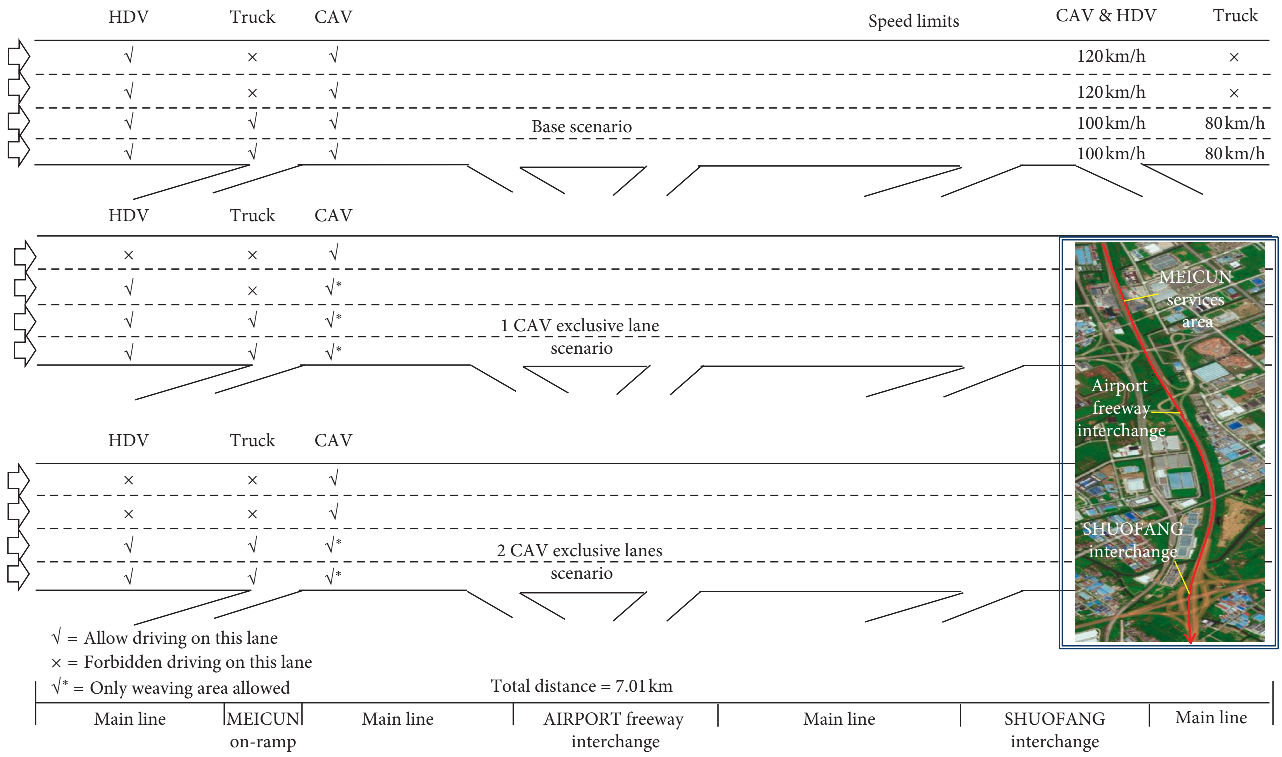

Figure 3: Description of three deployment scenarios.

requirement for further simulation. After calibration, CC0, CC1, and CC2 in Wiedemann 99 model are calibrated to 2.1 m, 1.52 s, and 0.60, respectively. Due to missing of statistic data, the lengths and weighs of cars and trucks are adopted to default normal distributions.

3.3. Surrogate Measures of Safety. Surrogate safety measures are a widely utilized technique to evaluate the risk of crashes on traffic facilities (e.g., freeway and urban road network); although crashes are rare, they may cause severe consequences. Machine learning and statistical-based approaches have been applied to analyze crashes attributes according to crash records [43], but records of crashes between CAVs and HDVs are insufficient yet. Therefore, many effective indexes have been proposed by former researchers for evaluating crash risks in mixture environment; among them, Time-to-Collision (TTC) is one of the most common indicators which can be used for calculating the safety between two individual vehicles for every simulation second or interval of subsecond. The TTC notion was firstly proposed by [44] which is referred to the time that remains until a collision between the leading and following vehicle if the speed of the following vehicle is over than the leading vehicle and the speed difference is maintained. The TTC notion can be described as

$$\mathrm{TTC}_i(k) = \begin{cases} \dfrac{x_{i-1}(k) - x_i(k) - l}{v_{i-1}(k) - v_i(k)}, & v_{i-1}(k) > v_i(k), \\ \infty, & \text{otherwise}, \end{cases} \tag{3}$$

where $\mathrm{TTC}_i(k)$ = the time-to-collision of the vehicle i at simulation instant k, x = the position of the vehicle i, v = the speed of the vehicle i, and l = the length of the preceding vehicle $i-1$.

3.3.1. Longitudinal Safety Measurement. It is intuitive that the smaller TTC value means higher crash risk. Although TTC reflects the rear-end collision risk closely, it needs to be aggregated to the more aggregated indicators for statistically compatible analysis. For this sake, two surrogate measures of safety, derived from TTC and denoted as Time Exposed Time-to-collision (TET) and Time Integrated Time-to-collision (TIT), proposed by [45], are used for building a relationship between simulation data and longitudinal safety of the CAV.

The TET represents the total time exposed in the risk of collision, characterized by TTC value lower than the threshold TTC^* value :

$$\begin{aligned} \mathrm{TET}(k) &= \sum_{i=1}^{N} \delta_t \times \Delta k, \\ \delta_t &= \begin{cases} 1, & \forall 0 < \mathrm{TTC}_i(k) \le \mathrm{TTC}^*, \\ 0, & \text{otherwise}, \end{cases} \\ \mathrm{TET} &= \sum_{k=0}^{T} \mathrm{TET}(k), \end{aligned} \tag{4}$$

where k = simulation time instant (warm-up time excluded), Δk = simulate time steps (=0.1 s), $\mathrm{TTC}_i(k)$ = the time-to-collision of the vehicle i at simulation instant k. N = the total number of vehicles, T = the simulation period, and TTC^* = the threshold of TTC. TTC^* is applied to identify from considering ones driving is safe or unsafe, and its value varies from 1 s to 3 s.

The TIT notion is also an index that measures the entity of the TTC lower than TTC^*. The reciprocal transformation is put into consideration since lower TTC means higher collision risk, and it can be described as

$$\mathrm{TIT}(k) = \sum_{i=1}^{N}\left[\frac{1}{\mathrm{TTC}_i(k)} - \frac{1}{\mathrm{TTC}^*}\right] \times \Delta k, \quad \text{when } 0 < \mathrm{TTC}_i(k) \le \mathrm{TTC}^*,$$
$$\mathrm{TIT}(k) = \sum_{k=0}^{T} \mathrm{TIT}(k). \tag{5}$$

Additionally, the Rear-End Crash Risk Index (RCRI), proposed by [46], was designed on the background of rear-end crashes which are the most common type of crashes in traffic facilities and are used for evaluating longitudinal road safety. The index illustrates a rear-end crash may appear if a leading vehicle makes a sudden brake, and the following fails to react and decelerate to safe distance in time. In this case, the stopping distance of the following vehicle should be smaller than the leading vehicle for preventing collision, and this relationship can be expressed as

$$D_{\mathrm{stop},L} = v_L(k) \times h(k) + \frac{v_L^2(k)}{2 \times a_L(k)} + l,$$
$$D_{\mathrm{stop},F} = v_F(k) \times \mathrm{PRT} + \frac{v_F^2(k)}{2 \times a_F(k)}, \tag{6}$$
$$D_{\mathrm{stop},F} < D_{\mathrm{stop},L},$$

where $D_{\mathrm{stop},L}$ and $D_{\mathrm{stop},F}$ are the stopping distance of the leading vehicle and the following vehicle, $v_L(k)$ and $v_F(k)$ are the speed of two vehicles at simulation instant k, $a_F(k)$ and $a_L(k)$ are the acceleration of two vehicles, $h(k)$ is the time headway, l is the length of the leading vehicle, and PRT is the perception-reaction time with a constant value of 1.5 s recommended by the American Association of State Highway and Transportation Officials (AASHTO). Similar to TTC, RCRI needs to be aggregate to an index for measuring surrogate safety, which is proposed by [27] and denoted as the Time Exposed Rear-End Crash Risk Index (TERCRI):

$$\mathrm{TERCRI}(k) = \sum_{i=1}^{N} \mathrm{RCRI}(k) \times \Delta k,$$
$$\mathrm{RCRI}(k) = \begin{cases} 1, & D_{\mathrm{stop},F} > D_{\mathrm{stop},L}, \\ 0, & \text{otherwise}, \end{cases} \tag{7}$$
$$\mathrm{TERCRI} = \sum_{k=0}^{T} \mathrm{TERCRI}(k).$$

3.3.2. Lateral Safety Measurement. The mentioned indexes above are all associated with longitudinal safety. However, angle and sideswipe crashes, which are highly associated with lateral safety, are also common at freeway mainline or weaving zones along with rear-end crashes. Thus, it is necessary to measure lateral safety for CAV environment. In order to evaluate the angle and sideswipe crash risk of CAVs, the Surrogate Safety Assessment Model (SSAM) is used in this study. SSAM is developed by the Federal Freeway Administration, which has several parameters to measure conflicts. SSAM utilizes trajectory files (∗.fzp) outputted from VISSIM and checks for traffic conflicts using predefined TTC and Post Encroachment Time (PET), Speed Difference (DeltaS), and some other thresholds. The default value of TTC and PET is 1.5 s and 5 s, respectively. Along with the investigation of conflicting vehicles, SSAM provides conflict results classified by the conflict type (i.e., rear-end, lane change, and crossing). In this study, the number of lane change conflicts (#LCC) of different scenarios is analyzed by SSAM.

Collection of surrogate safety measures is also implemented by the External Driver Model (EDM). The aggregated value of TET, TIT, TERCRI, and LCC is calculated directly by every simulation step for all vehicles. Note that although human-driven vehicles deployed the External Driver Model to collect SSAM data, their driving behavior maintaining is unchanged.

4. Results and Discussion

Traffic crashes are rare on freeways. Hence, surrogate safety measures are a widely used technology to evaluate the crash risk. In this paper, in order to evaluate the read-end collision risk and lane change conflict, four surrogate safety measures, including TET, TIT, TERCRI, and #LCC, are employed. The first three indexes were directly outputted by the modified External Driver Model, and the last index was transferred to SSAM to identify #LCC. It must be noted that although the threshold value of TTC was chosen as 2.0 s, a sensitivity analysis for TTC values of 1.0, 1.5, 2.0, 2.5, and 3.0 s was also conducted, and the result shows that the threshold has negligible effects on crash risks. We tested three scenarios (0, 1, or 2 exclusive lane (s)) with consideration of different traffic demands (2000, 4000, 6000, or 8000 veh/h) and compositions (truck proportion = 0, 10%, 20%, and 30%; CAV MPRs = 0, 10%, 20% and 30%). Note that the chosen ratios of truck and classifications of traffic demand were derived from the field data from the Ninghu Freeway.

4.1. Overall Analysis. Classified by traffic volume, original scatter values are converted to contour maps, and results are presented in Figures 4–7, which represent overall safety impacts of CAV exclusive lanes on different traffic demands and compositions. The input values of traffic demand cover all types of vehicles for this segment (e.g., not the single lane volume); therefore, the capacity constraint that the capacity of the freeway is around 2000 ver/h/ln can be met.

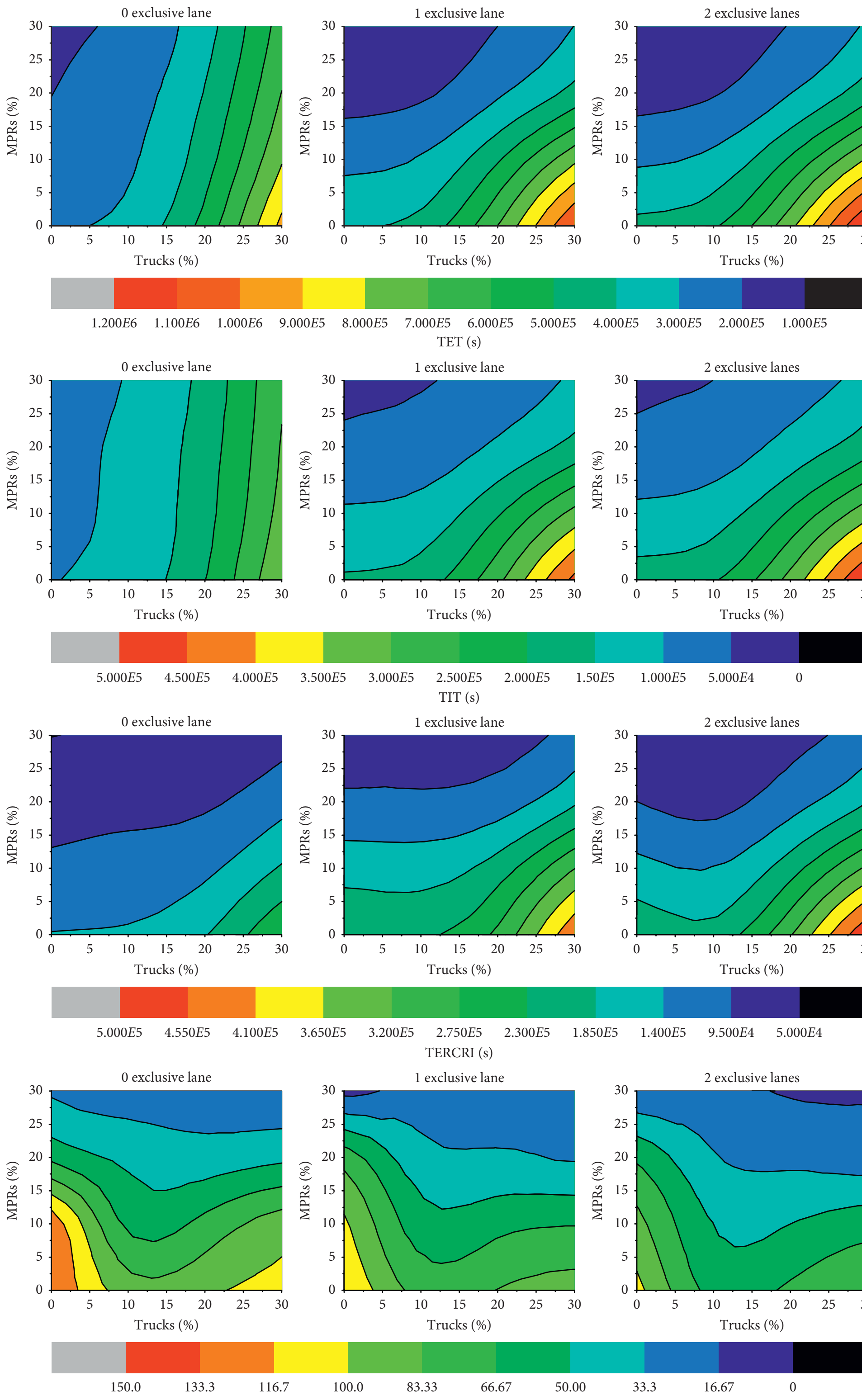

Figure 4: Safety evaluation results of CAV's exclusive lane on volume = 2000 veh/h.

Horizontal arrangement of figures has colored to the same color scales for comparison. The colors are generated by interpolation from blue to red, which stands for lower and higher values, respectively. It must be pointed out that although these figures seem to have little distinction among different colors, their absolute values are very different. Value of total TET in 2,000, 4,000, 6,000, and 8,000 veh/h with 0% truck, 0% MPRs, and 1 exclusive lane is 387553, 1131240, 1936829, and 2060508 seconds, respectively. On the contrary, for detailed analysis, a line chart analysis for

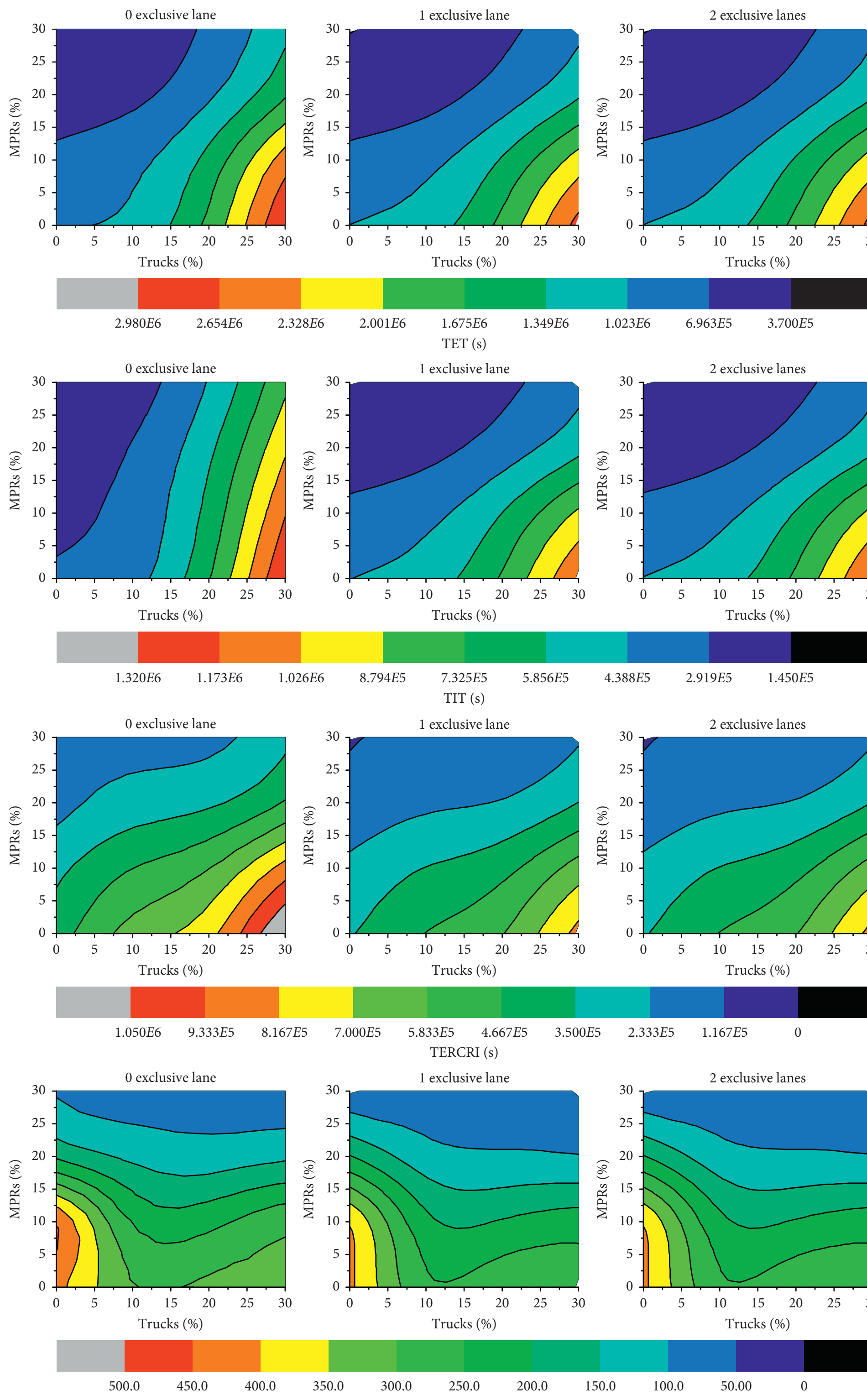

Figure 5: Safety evaluation results of CAV's exclusive lane on volume = 4000 veh/h.

TET and LCC on MPRs = 10% and 20% is presented in Figure 8. Finally, an overall longitudinal and lateral safety impact comparison of setting exclusive lane scenarios toward the base scenario is shown in Table 4.

For all situations, we found that, with the increase of truck proportion, longitudinal safety risk indexes (e.g., TET, TIT, and TERCRI) are at a rise in all scenarios, indicating that heterogeneity of traffic composition

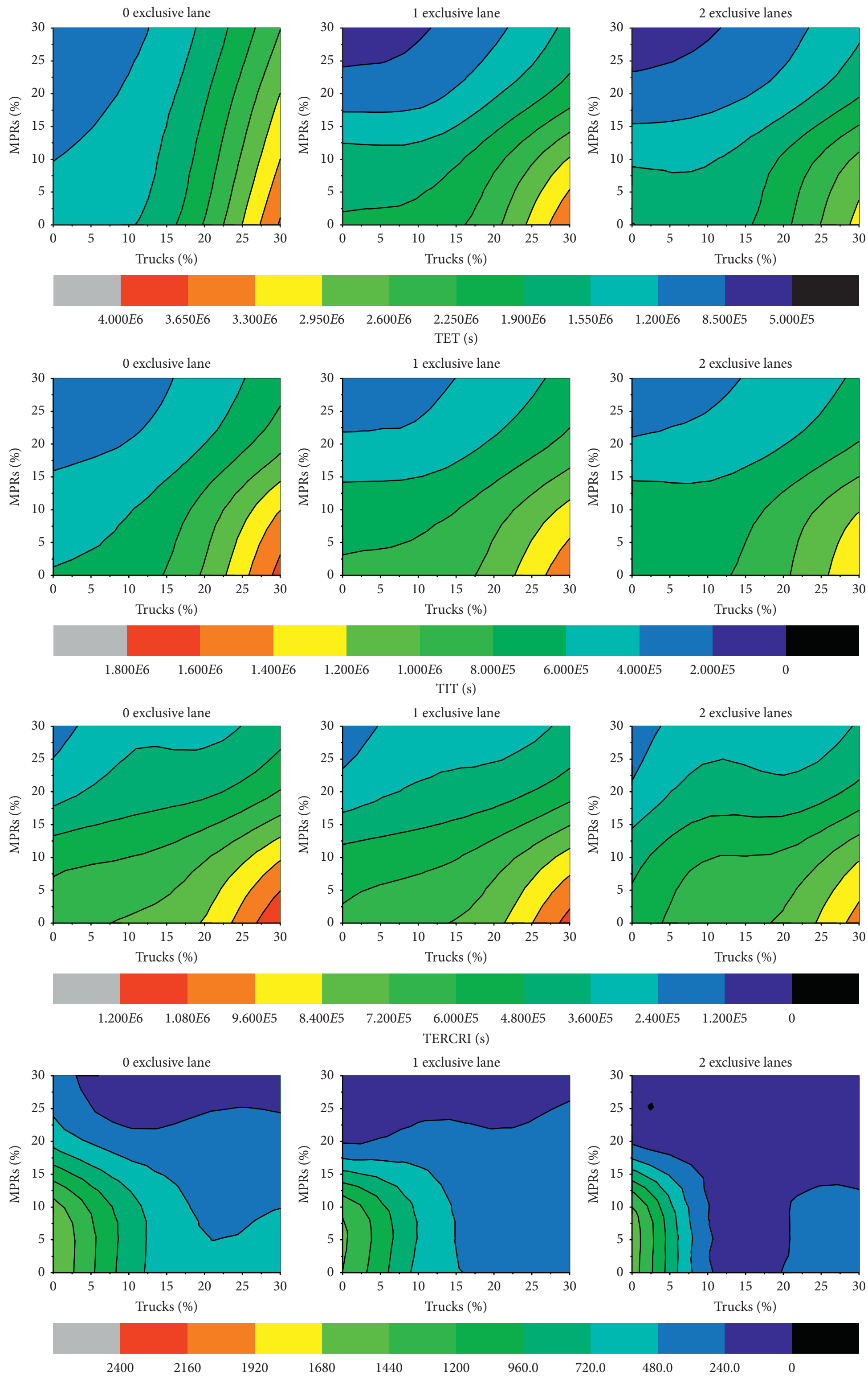

Figure 6: Safety evaluation results of CAV's exclusive lane on volume = 6000 veh/h.

contributes to rear-end crash risks. In general, the variations of three longitudinal safety risk indexes are largely similar, and since TET and TIT are different aggregate forms of TTC, their trend seem to be more similar. The similarity indicates that all three indexes are capable to be replaced by each other. In this regard, we choose TET to stand for longitudinal result in longitudinal safety impact analysis, while for #LCC, which represents lateral crash

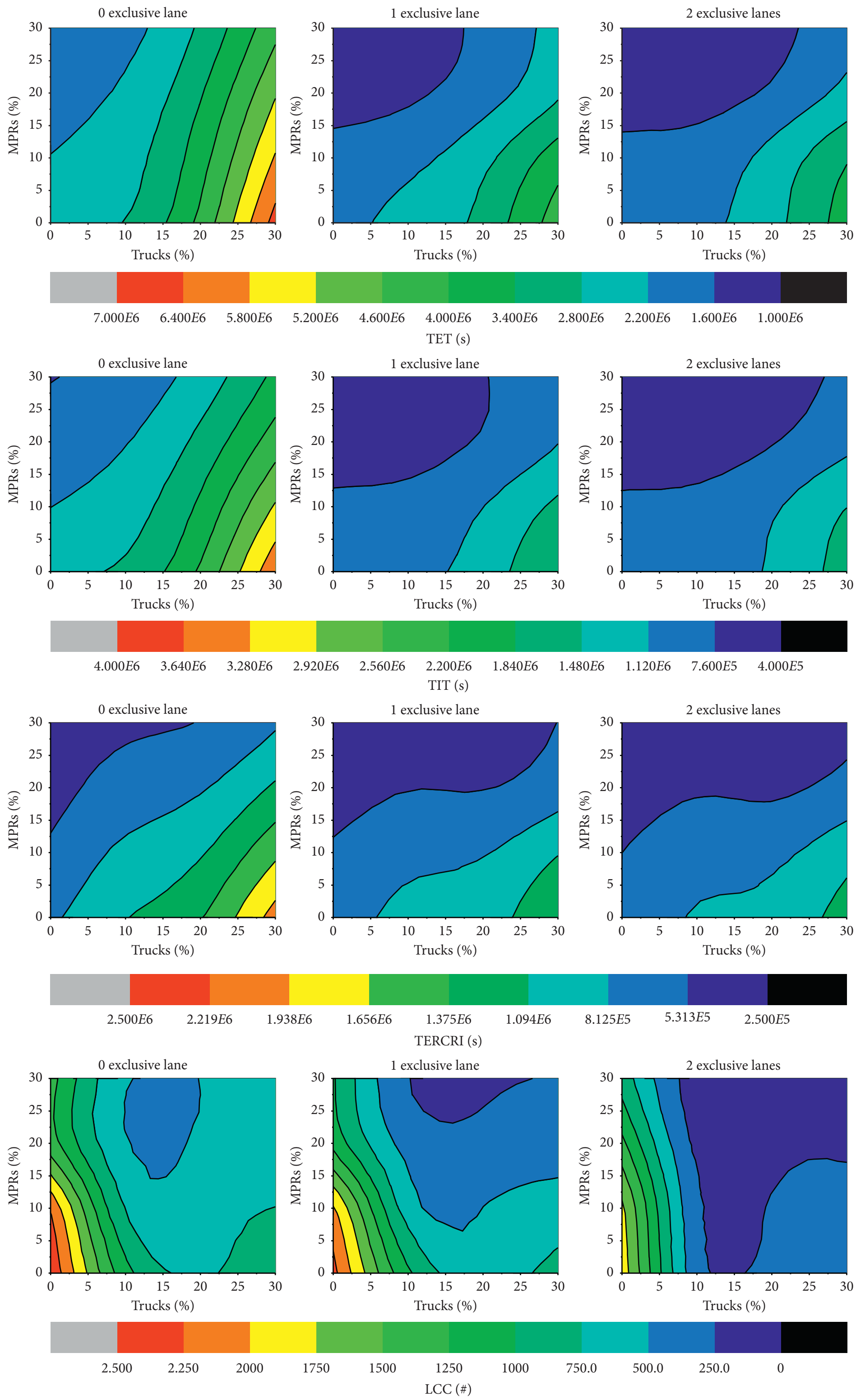

Figure 7: Safety evaluation results of CAV's exclusive lane on volume = 8000 veh/h.

risks, appeared to decrease with the increase of truck proportion firstly and then slowly rise in low MPRs of CAVs according to Figure 8 (1c-1d; 2c-2d; 3c-3d; 4c-4d). This difference reflects different driving behaviors between car and trucks. A possible explanation is that due to the limitation of available lanes, trucks' lane changes are less than cars, and with the increase of truck proportion, overall performance is deteriorating, and some radical

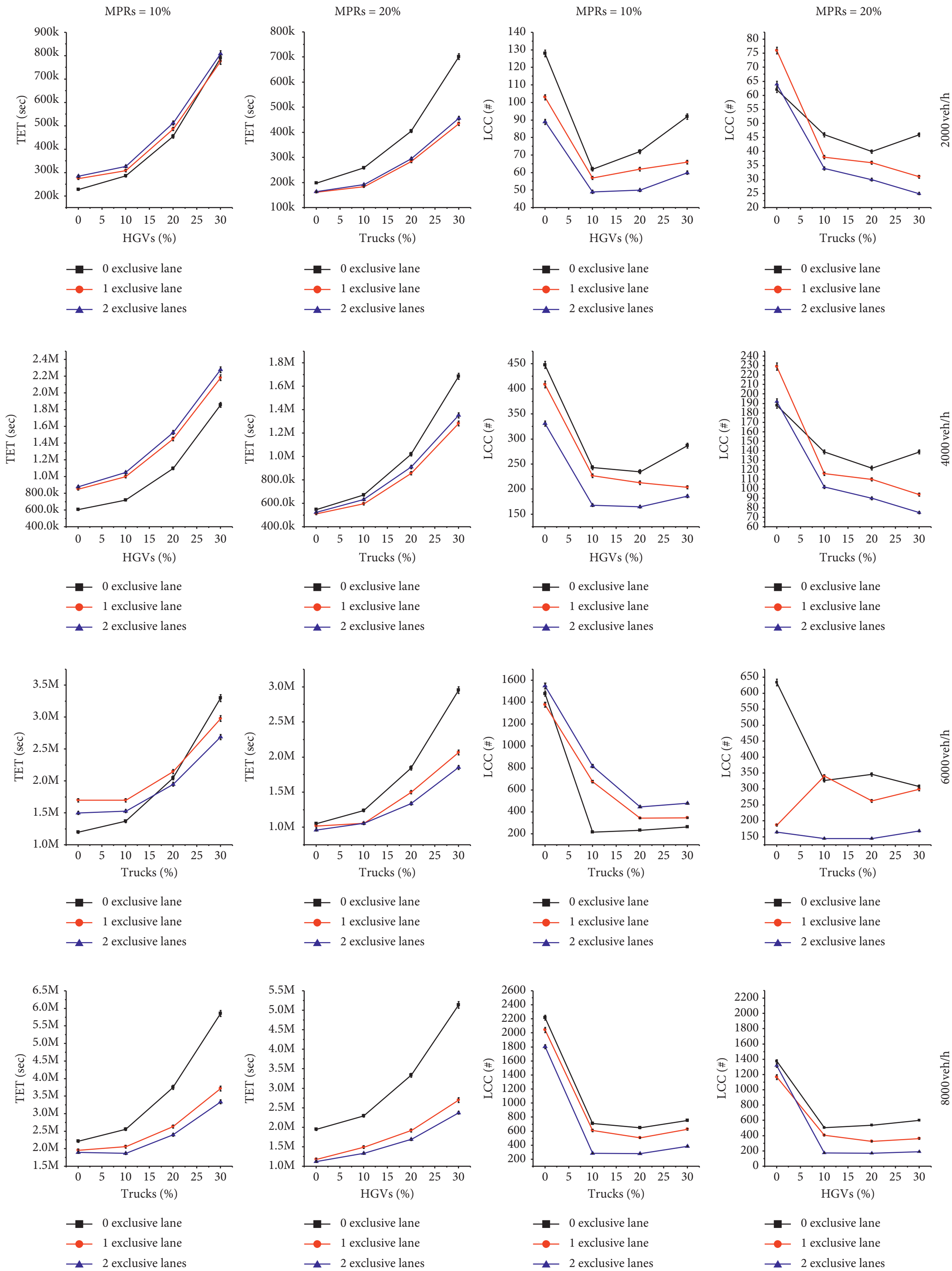

Figure 8: Comparison of safety impacts between MPRs = 10% and MPRs = 20%.

drivers would try to change the current lane for ensuring their efficiency. Since literature [47] has pointed out using simulation data for analyzing LCC has its limitation and it might not truly reflect the real-world situations, the impact of lane change still needs further examination from field test data [48].

Table 4: Safety impacts of setting exclusive lanes compared with the base scenario.

MPRs = 10%	Trucks (%)	2000 veh/h TET (%)	2000 veh/h LCC (%)	4000 veh/h TET (%)	4000 veh/h LCC (%)	6000 veh/h TET (%)	6000 veh/h LCC (%)	8000 veh/h TET (%)	8000 veh/h LCC (%)
1 exclusive lane	0	−20.5	19.5	−40.4	8.7	−42.4	11.0	11.6	7.9
	10	−7.6	8.1	−38.8	6.6	−24.4	17.1	19.7	13.8
	20	−7.0	13.9	−32.1	9.4	−5.2	23.0	29.6	21.8
	30	1.8	28.3	−17.5	28.9	9.6	27.6	36.5	16.6
2 exclusive lanes	0	−24.9	30.5	−44.7	26.1	−25.1	4.5	14.1	18.6
	10	−14.2	21.0	−45.7	30.9	−11.6	73.6	27.0	59.7
	20	−12.5	30.6	−39.0	29.8	4.9	47.8	35.9	56.9
	30	−2.3	34.8	−22.8	35.2	18.5	45.1	42.9	48.6
MPRs = 20%	Trucks (%)	2000 veh/h TET (%)	2000 veh/h LCC (%)	4000 veh/h TET (%)	4000 veh/h LCC (%)	6000 veh/h TET (%)	6000 veh/h LCC (%)	8000 veh/h TET (%)	8000 veh/h LCC (%)
1 exclusive lane	0	18.6	2.6	6.8	1.8	3.5	70.5	39.5	15.0
	10	28.9	17.4	11.2	16.5	14.8	39.8	35.0	19.7
	20	29.9	10.0	16.0	9.8	18.7	24.0	42.4	39.6
	30	38.1	32.6	23.9	32.4	30.0	2.9	47.5	39.7
2 exclusive lanes	0	17.1	3.2	4.4	2.1	8.6	74.0	42.4	4.1
	10	25.9	26.1	5.8	26.6	14.9	55.7	41.8	65.5
	20	27.1	25.0	10.8	26.2	27.4	58.1	49.3	68.3
	30	35.0	45.7	19.8	46.0	37.3	45.1	53.8	67.9
MPRs = 30%	Trucks (%)	2000 veh/h TET (%)	2000 veh/h LCC (%)	4000 veh/h TET (%)	4000 veh/h LCC (%)	6000 veh/h TET (%)	6000 veh/h LCC (%)	8000 veh/h TET (%)	8000 veh/h LCC (%)
1 exclusive lane	0	31.5	61.3	23.9	61.7	24.3	87.1	29.1	23.8
	10	40.7	4.0	27.8	3.9	25.9	60.4	32.9	52.8
	20	44.3	12.5	32.8	11.1	31.2	42.1	40.4	57.8
	30	52.9	14.3	40.1	13.8	36.5	50.8	45.1	54.3
2 exclusive lanes	0	31.7	38.7	24.4	38.3	25.6	85.3	35.2	33.1
	10	39.0	12.0	26.2	10.5	25.9	59.6	43.4	77.1
	20	43.0	37.5	30.9	36.1	33.4	47.4	50.5	77.6
	30	51.1	28.6	38.7	27.7	42.5	51.7	55.2	77.6

4.2. Safety Impacts of Exclusive Lanes. As the TIT, TET, and TERCRI indexes are shown in Figures 4–7 (1a–3c), we found that setting of exclusive lanes in MPRs < 10% led to slight increase of longitudinal safety risks on volume = 2000 veh/h (Figure 4 (1a–1c)) and continuing at a rise with the increasing of truck proportion (Figure 8 (1a–4a)). Compared with the base scenario, setting exclusive lanes in traffic demands > 4000 veh/h and MPRs < 10% inducing higher rear-end risks, which indicates only in situation that traffic demand is large enough could the CAV's exclusive lane have positive impact on safety. As the MPRs increased to 20% (Figure 8 (1b–4b)), the longitudinal and lateral safety improve proportionately compared with the base scenario.

As for the LCC index shown in Figures 4–7 (4a–4c), for all traffic demands, setting of exclusive lanes reduce overall LCCs, and the difference exists on the extent of decrease. Longitudinal comparison among demands shows that higher traffic demands have better improvement of LCC compared with low traffic demands.

Numerical comparison for exclusive lane scenarios is also conducted in Table 4 for further analyzing safety impact. As is depicted in Table 4, setting one or two exclusive lanes led to [+42.4% to −52.90%] and [+45.7% to −55.2%] for longitudinal crash risks (TET) while [−1.8% to −87.1%] and [−2.1% to −85.3%] for lateral crash risks compared with the base scenario, respectively. Only in MPRs = 10% and demands lower than 6000 veh/h scenarios, the setting of exclusive lanes has adverse effect on longitudinal, which indicates that in other scenarios, setting exclusive lanes for CAVs outweigh than the base scenario. It must be noted that the improvement of longitudinal crash risks arose with the increase of truck proportion. This is explainable as the driving behavior of trucks is largely homogenous. On the contrary, total longitudinal crash risks are at a sharp rise according to Figure 8 (1a–3b) with increasing of truck proportions, which indicates that setting exclusive lanes for CAVs have better safety improvement when truck's proportion is over 20%.

We also focused on the comparison of the number of exclusive lanes. As longitudinal indexes depicted on the low demand scenario, the distinction between one or two exclusive lanes is generally inconspicuous on low truck proportion, while in low traffic demand, high truck proportion, and low MPR condition, the setting of two exclusive lanes caused an increase of longitudinal rear-end risks compared with one exclusive lane scenario, indicating that setting two exclusive lanes for this situation is unwise. Only in demand = 8000 veh/h situation, two exclusive lane scenarios outweighs one exclusive lane scenario on both longitudinal and lateral safety improvement.

5. Conclusions and Future Study

In this work, safety evaluation of exclusive lanes for CAV on the freeway is conducted using a calibrated microscopic simulation model with surrogate safety measures. This paper firstly modelled the mixture environment [49, 50] of CAVs platooning with HDVs and then designed three exclusive lane scenarios and deployed surrogate safety measures to reveal pros and cons of exclusive lanes. In this paper, four surrogate safety measure indexes, including both longitudinal and lateral indexes, are developed. Results show that (1) setting one exclusive lane is capable of improving the overall safety in low demand, and setting two exclusive lanes is more suitable for the high-demand scenario; (2) the existence of trucks worsens the overall longitudinal safety, and improper settings of exclusive lanes in high truck's proportion and low MPRs situation could even worsen the longitudinal safety, which should be avoided; (3) setting exclusive lanes has better longitudinal and lateral safety improvement in high truck proportion scenarios; (4) when the MPRs are larger than 15%, setting exclusive lanes for CAVs can considerably reduce the overall crash risks, and the safety improves as the proportion of trucks increases; and (5) the variation among TET, TIT, and TERCRI is very similar, indicating that the three indexes can replace each other.

This paper highlights (1) the influence of trucks on the safety impact of setting exclusive lanes for CAVs on the freeway and (2) reveals the dynamic safety relationship among traffic demand, composition, MPRs, and the number of exclusive lanes. The authors hope these results can be helpful to determine when it is suitable to set the exclusive lane for CAVs. The proposed surrogated safety measures can be extended to other freeway scenarios (i.e., 2 or 3 lane freeway), and the application of exclusive lanes for CAVs has great potential in practice.

Due to inadequate data, this simulation-based research study still needs further examination and calibration with field-test data of autonomous vehicles. This paper also has some shortcomings as it only considered total safety impacts for freeway facility whereas neglecting detail investigation of its component. Merging speed and driving ability (e.g., lane change confidence, lane-keeping instability, and the merging location) on weaving areas can affect the crash risk ([51–53]), and these factors should be further analyzed. From authors view, more lateral safety risk indexes should be developed and examined to well-fit real-world situation for mixture CAV with HDV environment in future studies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

Acknowledgments

This research was supported by the National Key R&D Program in China (Grant no. 2016YFB0100906) and the Fundamental Research Funds for the Central Universities (no. 2242019R40046). The work of the first author was supported in part by the Zhishan Young Scholar Support Program of Southeast University and the Science and Technology Major Project, Transportation of Jiangsu Province.

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