Integrated Cooperative Adaptive Cruise and Variable Speed Limit Controls for Reducing Rear-End Collision Risks Near Freeway Bottlenecks Based on Micro-Simulations

Ye Li, Chengcheng Xu, Lu Xing, and Wei Wang

***Abstract*— Freeway bottlenecks lead to traffic congestion and speed reduction, resulting in increased risks of rear-end collision. This paper aimed to develop a control strategy of an integrated system of cooperative adaptive cruise control (CACC) and variable speed limit (VSL) to reduce rear-end collision risks near freeway bottlenecks. A microscopic simulation testbed was first constructed, in which the realistic PATH CACC models and surrogate safety measures of the time exposed time-to-collision (TET) and time integrated time-to-collision (TIT) were used. A feedback control algorithm was then developed for the proposed vehicle to infrastructure system of CACC and VSL. The simulation results showed that the proposed integration system with 100% CACC penetration rate can reduce the rear-end collision risks effectively, with the TIT and TET declined by 98%. The average travel time was also decreased by 33%, compared with the manual vehicles without any control. Moreover, the safety improvements of the proposed integrated system are quite stable at the various bottlenecks with different magnitudes of speed reductions. The sensitivity analyses suggested that the penetration rate of CACC has significant impact on safety performance. The VSL control plays an important role in reducing rear-end collision risks when the penetration rate of CACC is low. The combination of CACC and VSL controls mitigates the negative effects of the mixed traffic flow of the manual and CACC vehicles.**

***Index Terms*— Cooperative adaptive cruise control, variable speed limit, rear-end collision, freeway bottleneck.**

I. INTRODUCTION

FREEWAY Bottlenecks lead to traffic congestion and turbulent conditions. The subsequent speed reductions near bottlenecks have negative impacts on safety for vehicles upstream of the bottlenecks, resulting in increased risks of rear-end collisions. To prevent rear-end collisions caused by freeway bottlenecks, previous studies have proposed different dynamic traffic control systems, such as the variable speed limit (VSL) control and ramp metering. The VSL is one of the most commonly used traffic control systems for crash prevention at freeway bottlenecks [1]–[3]. The central idea of VSL control is to make an intervention proactively to adjust vehicle speed upstream of freeway bottlenecks to prevent rear-end collisions [1], [4], [5].

During the past few decades, numerous studies have been conducted to develop proactive safety control strategies on freeways by VSL [3]–[10]. Lee *et al.* [5] examined the control strategies of VSL and found that VSL controls could reduce crash potential by 5% to 17%. Lee and Abdel-Aty [6] used a driving simulator to test the effects of VSL controls and found that VSL controls can potentially reduce crash risks and improve efficiency on freeways. Abdel-Aty *et al.* [10] developed control strategies of ramp metering and VSL controls to reduce crash risks in real-time. The simulation results showed that VSL controls can effectively reduce crash potential under congested traffic conditions. Li *et al.* [3] developed a control strategy of VSL control to prevent the occurrence of rear-end collision near freeway recurrent bottlenecks. The results showed that the VSL control reduces crash potentials by 69.84% in the high demand scenario.

However, one of the limitations associated with VSL control is that manual drivers respond differently to the proposed speed of the VSL control. Some manual drivers even do not comply with the VSL control at all. The safety effects of VSL are negatively affected by the noncompliance of manual drivers. For example, Li *et al.* [11] evaluated the impacts of noncompliance on the performance of VSL control. The results indicated that the safety improvement of VSL control would be reduced by 35% if vehicle speed is merely 5 mph greater than the proposed speed of the VSL control strategy. Moreover, the issue of drivers' varying response to VSL controls may also lead to reduced vehicle efficiency. Because some sensitive drivers might respond to the VSL control by decelerating prematurely, resulting in increased travel time of passing the bottleneck.

With the rapid development of intelligent transportation systems, the advanced vehicle to infrastructure (V2I) technique is expected to overcome the varying compliance issue of VSL controls. The heterogeneity is the key reason for drivers' varying responses, such as noncompliance and prematurely decelerations. The V2I system provides a connected vehicle environment and traffic information exchange between vehicles

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and roadside infrastructures. Through precise information exchange and operational control for each individual vehicle, inter-driver heterogeneity can be avoided when responding to VSL controls.

A V2I system uses advanced connected vehicle techniques on the vehicle side and roadside intelligent infrastructure techniques on the infrastructure side. The advanced connected vehicle techniques such as the cooperative adaptive cruise control (CACC), can enable vehicles intra a platoon to receive information from their multi-leaders through the vehicle-to- vehicle (V2V) communications [12]. This advanced cooperative system has been extensively used to smooth hazardous traffic flow [13]–[17] and to improve traffic efficiency [13], [16], [18].

The fundamental advantage of CACC system is that following vehicles can obtain traffic information from leaders and proactively respond to various traffic conditions in the platoon. However, at its early stage, the CACC system cannot be employed on all vehicles on freeways. The local cooperation among vehicles in the CACC system at this stage only provides information exchange within a CACC platoon. Without traffic information downstream of the CACC platoon, the CACC system cannot respond effectively to the downstream hazardous traffic conditions. Accordingly, it is necessary to use the intelligent roadside infrastructure to enhance the CACC performances through the traffic information exchange between vehicles and roadside infrastructures (V2I) so that the CACC platoon can obtain downstream traffic information. The integration of CACC and VSL controls in the V2I system is expected to overcome the limitations of both CACC and VSL in reducing rear-end collision risks. Nevertheless, relatively few studies have considered the integration of CACC and VSL controls to prevent the occurrence of rear-end collisions [19]. Khondaker and Kattan [19] firstly established an integrated V2I system and developed corresponding VSL strategies. Due to the lack of empirical data of CACC systems, Khondaker and Kattan simulated the CACC vehicles based on theoretical intelligent driver model (IDM). Li *et al.* [37] have also developed a theoretical CACC model based on the IDM to analyze the safety performance of the CACC platoon. However, previous studies tested the IDM controller in real vehicle experiments, and found that the IDM can result in instability of vehicle platoon and cannot well model adaptive cruise control (ACC), not to mention CACC which is the advanced version of ACC [16], [17], [41]. Accordingly, additional efforts are still needed to describe CACC vehicles using more realistic models. Furthermore, our previous study [37] indicated that when the CACC penetration rates are low, the safety performances are still needed to be improved. From this perspective, the V2I system of CACC and VSL is a novel technology and worthy of being investigated.

In recent years, researchers begin to collect empirical data of real experiments using the production cars equipped with CACC system [16], [17], [20]. The PATH CACC model proposed by Milanés and Shladover [16] is one of the few models calibrated by the realistic experimental data. The study conducted by Milanés and Shladover [16] suggested that the theoretical car following model such as the IDM cannot well describe the response of following vehicles to the realistic speed changes of the preceding vehicles in CACC platoons. They also found that the realistic data based PATH CACC model can overcome this limitation and provide smooth and stable car following responses.

This study aimed to reduce the rear-end collision risks near freeway bottlenecks by integrating the PATH CACC and VSL controls. The use of PATH CACC is expected to overcome the unrealistic limitations of theoretical car following models in previous studies. The microscopic simulation testbed was constructed firstly, in which the realistic PATH CACC model and the surrogate safety measures were used. Then, the feedback control algorithm of the V2I system was developed based on the occurrence conditions of rear-end collisions. The simulation experiments were conducted to evaluate the safety effects of proposed control strategy based on various scenarios, in which the magnitude of speed reductions near bottlenecks and market penetration rates of CACC vehicles were considered. The results of the integration of PATH CACC and VSL controls were also compared with those of the conventional VSL control and only CACC control. The results of this study provide useful insights in developing advance proactive safety managements system to prevent the occurrences of rear-end collisions on freeways.

The rest of this paper is organized as follows. In Section II, the microscopic simulation testbed is introduced. Then, the feedback control algorithm of the V2I system is described in Section III. Section IV discusses the designed simulation experiments and various scenarios. The simulation results and sensitivity analyses are also discussed in Section IV. This paper ends with brief conclusions and recommendations in Section V.

II. Microscopic Simulation Testbed

The simulation testbed was developed by MATLAB. Vehicle behavior models and surrogate safety measures in the simulation testbed were introduced in this section.

A. Vehicle Behavior Model

Previous studies generally used the theoretical car following models to establish various CACCs, such as the IDM, the full velocity difference model, and the Gipps car-following model [19], [21], [22]. However, the theoretical car following models like IDM cannot fully model the production cars in the CACC systems [16]. To overcome the limitation of the theoretical CACC, the realistic PATH CACC model proposed by Milanés and Shladover [16] was employed in this study to simulate vehicles in a CACC platoon excluding the platoon leader. For the platoon leader, the realistic ACC model was employed, as illustrated in Fig. 1. Note that the interactions between different platoons were not considered in this study due to lack of realistic data and model. For comparisons, the IDM is also introduced to model the manual vehicles without any control.

1) Cooperative Adaptive Cruise Control: In the simulation testbed, the CACC vehicles are modeled based on platoons, as shown in Fig. 1(a). In each platoon, all the vehicles can receive

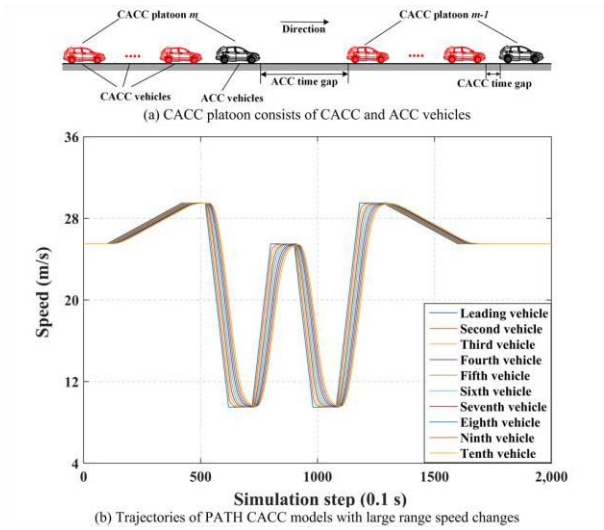

Fig. 1. Illustration of PATH CACC model.

the communicating information from the preceding and leading vehicles. Therefore, the drivability of the CACC vehicles is enhanced and the intra-platoon time gaps are shortened. The inter-platoon impacts are merely limited to that the platoon leader follows the preceding platoon using ACC technique. In that case, the leading vehicle of each CACC platoon is controlled by ACC model and the time gap is larger than that of intra-platoon.

Furthermore, the platoon length is assumed to be from 4 to 10 vehicles randomly in simulations. Actually, due to the safety and other considerations, the large scale experiment of a great number of CACC vehicles is impractical at present. The PATH CACC model proposed by Milanés and Shladoveris [16] was developed and calibrated using only four production cars. Hence, the length of a realistic CACC platoon of this study is limited to from 4 to 10 vehicles. The same assumption was also used in the simulation analyses of PATH CACC model in the study conducted by Milanés and Shladoveris [16]. Platoon length larger than 10 vehicles was not considered. This hypothesis is consistent with the previous CACC vehicle experiment and settings in related studies [12], [16], [17]. This hypothesis takes into consideration that the larger number of vehicle platoon can increase the distance between the first and the last following vehicles, resulting in the larger response delay [12], [16], [17].

The used PATH CACC vehicle model can be considered as the car following model version of an enhanced controller (CACC PATH-Nissan High-Level Controller) implemented in the production cars [17], which is one of the few realistic models based on experimental data. The CACC model is expressed as follows:

$$e_k = x_{k-1} - x_k - t_{hw} v_k \tag{1}$$

$$v_k = v_{k_{prev}} + k_p e_k + k_d \dot{e}_k \tag{2}$$

where e_k represents the gap error of the *k-th* vehicle; x_{k-1} represents the position of the preceding vehicle; x_k represents the position of the subject vehicle; v_k represents the speed of the subject vehicle; t_{hw} denotes the current time-gap setting; v_{kprev} denotes the speed of the subject vehicle in the previous iteration; k_p, k_d represent the model coefficients; and $\dot{e}_k$ represents the derivative of gap error.

When the velocity of a subject CACC vehicle is determined, the position of this vehicle x_k can be calculated by:

$$x_k = x_{k_{prev}} + v_k \Delta t \tag{3}$$

where x_{kprev} is the position of the subject vehicle in the previous iteration; and Δt is the time step.

Four parameters are included in this model, i.e. t_{hw}, k_p, k_d and Δt. The CACC time gap t_{hw} was set to be 0.6 s which is proposed by the previous studies [16], [17], [23]. The values of k_p and k_d determined by the experimental tests [17] were used ($k_p = 0.45$ and $k_d = 0.25$). The time step Δt in a microscopic simulation was set to be 0.1 s. It is worth noting that although the PATH CACC model was derived from empirical data whose speeds only change from 29.5 m/s to 25.5 m/s, the larger speed variations were also tested to prove the general applicability of this CACC model (see Fig. 1(b)).

2) Control Model of Leading Vehicles: The leading vehicle in each CACC platoon was controlled by the realistic ACC model of the production controller in commercial ACC vehicles [16]. The ACC model uses distance and speed errors as input variables:

$$a_k = k_1(x_{k-1} - x_k - t_{hw} v_k) + k_2(v_{k-1} - v_k) \tag{4}$$

where a_k represents the acceleration of the subject vehicle; x_{k-1} and v_{k-1} denote the position and speed of preceding vehicle, respectively; x_k and v_k represent the position and speed of subject vehicle, respectively; t_{hw} denotes the time gap of ACC vehicles; and k_1, k_2 represent the ACC model coefficients.

When the acceleration of each leading vehicle is determined in simulations, the velocity v_k and position x_k can be updated using the following rules:

$$v_k = v_{k_{prev}} + a_k \Delta t \tag{5}$$

$$x_k = x_{k_{prev}} + v_k \Delta t + \frac{a_k (\Delta t)^2}{2} \tag{6}$$

where x_{kprev} and v_{kprev} are the position and speed of the subject vehicle in the previous iteration; and Δt represent the time step.

There are also four parameters considered in the ACC model which are t_{hw}, k_p, k_d and Δt. The ACC time gap t_{hw} was set to be 1.1s based on commercial ACC controllers [16], [17]. The values of $k_1 = 0.23s^{-2}$ and $k_2 = 0.07s^{-1}$ were used according to the experimental tests [17]. Time step Δt was set to be 0.1 s.

3) Control Model of Manual Vehicles: In order to compare the performance of the V2I system integrating CACC and VSL controls with that of VSL control only, the manual vehicles should also be modeled. The IDM introduced by Treiber *et al.* [24] is one of the most commonly used traffic flow model to simulate manual vehicles. Accelerations of the IDM are determined by the desired speed and gap distance as

TABLE I
MODEL PARAMETERS AND VALUES OF IDM

Model parameter	Value
Desired speed v_0	120 km/h
Acceleration exponent δ	4
Maximum acceleration α	1.0 m/s^2
Desired deceleration β	2.0 m/s^2
Minimum gap distance at standstill s_0	2 m
Safe time headway T	1.5 s

follows:

$$a = \alpha_m[1 - (v/v_0)^{\delta} - (s^*/s)^2] \tag{7}$$

$$s^* = s_0 + \max[0, vT + v\Delta v/\left(2\sqrt{\alpha_m \beta}\right)] \tag{8}$$

where a represents the acceleration of subject vehicle; α_m denotes the maximum acceleration; v and v_0 are the subject vehicle speed and the desired speed, respectively; δ represents the acceleration exponent; s is the gap distance between the subject and preceding vehicles; s_0 denotes the minimum gap distance at standstill; T is the safe time headway; Δv represents the speed difference between subject and preceding vehicles; and β is the desired maximum deceleration.

Velocities and positions can be also calculated after the accelerations are determined by the IDM:

$$v = v_{prev} + a\Delta t \tag{9}$$

$$x = x_{prev} + v\Delta t + a(\Delta t)^2 \Big/ 2 \tag{10}$$

where x_{prev} and v_{prev} represent the position and speed of the subject vehicle in the previous iteration; and Δt is the time step.

Table I gives the used values of six parameters of IDM for manual drivers in this study. These values were determined according to the results of previous studies [16], [25]–[27]. Note that, the time headway T is different from time gap in that the latter does not include the vehicle length. The time step Δt in the simulations is also set to be 0.1 s.

4) Control Rule of Bottleneck: Although all the three models can be used to simulate operations of different vehicles, control rules for vehicles are also needed when they approach to the bottleneck. In this study, the operational speed of all the vehicles at freeway bottleneck is determined using the following rule:

$$v = max(0, min(v_m, v_b)) \tag{11}$$

where v_m are velocities calculated by the three models; and v_b are the bottleneck speeds or the proposed speed limits.

B. Surrogate Safety Measure

An appropriate surrogate safety measure should be applied to evaluate the rear-end collision risks. The surrogate safety measures describe the relationship between collision risk and microscopic vehicle data. Several indicators have been proposed as surrogate safety measures, such as time headway [28], deceleration rate to avoid the crash (DRAC) [29], [30] and time to collision (TTC) [30]–[33].

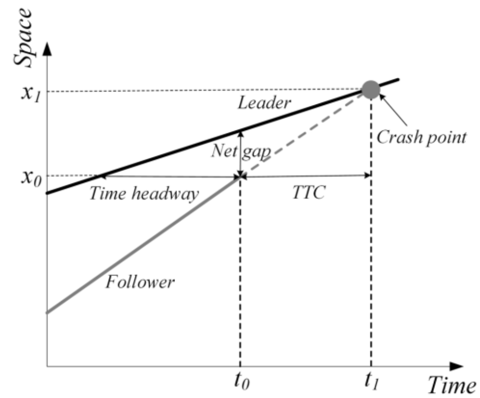

Fig. 2. Illustration of surrogate safety measures.

Among these measurements, TTC is the most commonly used indicator in rear-end crash risk assessment [11], [27], [32], [33]. TTC describes the rear-end collision conditions essentially and intuitively. Fig. 2 illustrates the occurrence of rear-end collisions. The following vehicle is approaching the leading one at the larger speed at time t_0. If the operational conditions of these two vehicles are not changed (the leading vehicle do not accelerate and the following one do not decelerate), a rear-end accident will occur at time t_1. It can be found that TTC is directly correlated with the occurrence of rear-end collision.

TTC of a following vehicle i at time step t with respect to the leading vehicle i-1 can be calculated as:

$$TTC_i(t) = \begin{cases} \dfrac{x_{i-1}(t) - x_i(t) - \bar{L}}{v_i(t) - v_{i-1}(t)}, & if\ v_i(t) > v_{i-1}(t) \\ \infty, & if\ v_i(t) \le v_{i-1}(t) \end{cases} \tag{12}$$

where x is the vehicle positions ; v represents the vehicle speeds ; and $\bar{L}$ is the average vehicle lengths, 5 m was used.

According to the definition of TTC, there are numerous TTC values at each simulation time step due to many operating vehicles. Accordingly, previous studies used the aggregated indicators of the time exposed time-to-collision (TET) and the time integrated time-to-collision (TIT) for crash risk assessments [11], [27], [34]. The TET and TIT can be calculated as:

$$\mathrm{TET}(t) = \sum_{i=1}^{N} \delta_t \cdot \Delta t, \quad \delta_t = \begin{cases} 1 & \forall\ 0 < \mathrm{TTC}_i(t) \le \mathrm{TTC}^* \\ 0 & else \end{cases} \tag{13}$$

$$\mathrm{TET} = \sum_{t=1}^{TI} \mathrm{TET}(t) \tag{14}$$

$$\mathrm{TIT}(t) = \sum_{i=1}^{N} \left[\frac{1}{TTC_i(t)} - \frac{1}{TTC^*}\right] \cdot \Delta t, \quad \forall 0 < \mathrm{TTC}_i(t) \le \mathrm{TTC}^* \tag{15}$$

$$\mathrm{TIT} = \sum_{t=1}^{TI} \mathrm{TIT}(t) \tag{16}$$

where t is the time instant; δ_t represents the switching variable at time t; Δtdenotes the time step; N is the number of vehicles; *TI* is time interval; and TTC$*$ denotes the TTC threshold which distinguishes unsafe car-following situations from safe ones.

Previously, researchers have suggested that the threshold TTC$*$ varies from 2 to 4 s [11], [28], [33]–[35]. In this study, different TTC thresholds of 2, 3 and 4 s were used and the results of different thresholds were compared in the section IV.

III. V2I Control Algorithm

A. Variable Speed Limit Control

Numerous VSL control strategies have been proposed for different objectives, such as efficiency, safety and eco-driving [1], [4], [5], [11], [19], [27]. In this study, the VSL control strategy was developed based on our previous study [11]. It was developed by the occurrence conditions of rear-end collision.

Assuming that a following vehicle $n+1$ approaches a leading vehicle n at the bottleneck, the following vehicle has to brake from a higher speed v_2 to the speed of the leading vehicle v_1, after the reaction time t_a, to avoid collision with the leading vehicle. A rear-end crash occurs if:

$$d_a(n)+d_{de}(n)+d < d_a(n+1)+d_{de}(n+1) \tag{17}$$

where $d_a(n)$ represents traveling distance of leading vehicle n in time t_a; $d_a(n+1)$ represents traveling distance of following vehicle $n+1$ in in time t_a; $d_{de}(n)$ represents traveling distance of leading vehicle n in braking timet_{de}; $d_{de}(n+1)$ represents deceleration distance of following vehicle $n+1$ in time t_{de}; d represents distance between two vehicles when the following vehicle observed the low speed of the leading vehicle, measured between the rear of the leading vehicle and the front of the following vehicle [11]. Assuming that the desired vehicle deceleration is β, eq. (17) can be written as:

$$v_1 t_a + v_1\left(\frac{v_2-v_1}{\beta}\right) + d < v_2 t_a + \frac{(v_2)^2-(v_1)^2}{2\beta} \tag{18}$$

$$v_2 > v_1 - \beta t_a + \sqrt{\beta^2 t_a^2 + 2\beta d} \tag{19}$$

Eq. (19) can be aggregated using loop detector data:

$$v_2 = \frac{1}{N}\sum_{n=1}^{N} v_2 = \bar{V}_U[t+\Delta T] \tag{20}$$

$$v_1 = \frac{1}{N}\sum_{n=1}^{N} v_1 = \bar{V}_D[t+\Delta T] \tag{21}$$

$$\begin{aligned} d &= \frac{1}{N}\sum_{n=1}^{N} d_n = \frac{1}{N}\sum_{n=1}^{N}(H_n - L_n) = \frac{1}{N}\left\{\sum_{n=1}^{N} H_n - \sum_{n=1}^{N} L_n\right\} \\ &= \frac{1}{N}\left\{\sum_{n=1}^{N}\left(\frac{1}{\bar{K}_U[t+\Delta T]}\right) - N\bar{L}\right\} \\ &= \frac{1}{N}\left\{\sum_{n=1}^{N}\left(\frac{\bar{L}}{\bar{O}_U[t+\Delta T]}\right) - N\bar{L}\right\} \\ &= \frac{\bar{L}}{\bar{O}_U[t+\Delta T]} - \bar{L} = \bar{L}\left(\frac{1-\bar{O}_U[t+\Delta T]}{\bar{O}_U[t+\Delta T]}\right) \end{aligned} \tag{22}$$

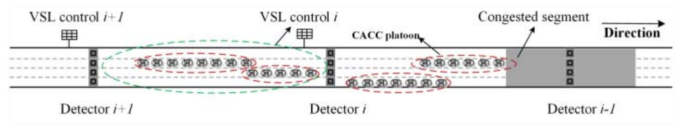

Fig. 3. Conceptual design of integration of VSL and CACC.

where ΔT denotes time interval of loop detector data, which is usually between 20 and 30 s; $\bar{V}_U$ $[t+\Delta T]$ represents average speed at upstream detector station during time $[t,\ t+\Delta T]$;$\bar{V}_D[t+\Delta T]$ represents average speed at downstream detector station during time $[t,\ t+\Delta T]$; H_n denotes distance headway between vehicle n and $n+1$; L_n denotes length of vehicle n; $\bar{K}_U[t+\Delta T]$ denotes average density at upstream detector location during time $[t,\ t+\Delta T]$; $\bar{O}_U[t+\Delta T]$ denotes average occupancy at upstream detector location during time$[t,\ t+\Delta T]$.

With Eqs. (20) to (22), the Eq. (17) can be expressed as:

$$\begin{aligned} \bar{V}_U[t+\Delta T] &> \bar{V}_D[t+\Delta T] - \beta t_a \\ &+ \sqrt{\beta^2 t_a^2 + 2\beta\bar{L}\left(\frac{1-\bar{O}_U[t+\Delta T]}{\bar{O}_U[t+\Delta T]}\right)} \end{aligned} \tag{23}$$

Accordingly, the optimal speed of avoiding the occurrence of rear-end collision is calculated by:

$$\begin{aligned} V_{SL}(x_i, t+\Delta T) &= V(x_{i-1}, t) - \beta t_a \\ &+ \sqrt{\beta^2 t_a^2 + 2\beta\bar{L}\left[\frac{1-O(x_i,t)}{O(x_i,t)}\right]} \end{aligned} \tag{24}$$

where $V_{SL}(x_i,\ t+\Delta t)$ represents the calculated speed of avoiding the occurrence of rear-end collision at location x_i at time $t+\Delta t$ (see Fig. 3); $V(x_{i-1}, t)$ represents speed reported from loop detector station at location x_{i-1} at time t; t_a is the perception reaction time, which is set to be 0.5 s for CACC [12], [16], [27]; ΔT denotes time interval of loop detector data, 30 s is used in this study; $\bar{L}$ is the average vehicle length which is 5 m in this paper; and $O(x_i, t)$ represents occupancy reported from loop detector station at location x_i at time t.

To avoid sudden changes in traffic flow operations, the calculated speed limit $V_{SL}(x_i, t+\Delta t)$ by Eq.(24) cannot be direct posted on the variable message sign (VMS). The speed change rate ΔV_{SL} is used to limit the maximum change in speed during time interval ΔT. The real speed limit $V'_{SL}(x_i, t+\Delta T)$ is determined by Eq. (25-27), and more details can be referred to [11].

$$\begin{aligned} &V'_{SL}(x_i, t+\Delta T) \\ &= V'_{SL}(x_i, t) - \Delta V_{SL}, \\ &\quad if\ V_{SL}(x_i, t+\Delta T) < V'_{SL}(x_i, t) - \Delta V_{SL} \end{aligned} \tag{25}$$

$$\begin{aligned} &V'_{SL}(x_i, t+\Delta T) \\ &= V'_{SL}(x_i, t) + \Delta V_{SL}, \\ &\quad if\ V_{SL}(x_i, t+\Delta T) > V'_{SL}(x_i, t) + \Delta V_{SL} \end{aligned} \tag{26}$$

$$\begin{aligned} &V'_{SL}(x_i, t+\Delta T) \\ &= V_{SL}(x_i, t+\Delta T), \\ &\quad if\ V'_{SL}(x_i, t) - \Delta V_{SL} \le V_{SL}(x_i, t+\Delta T) \le V'_{SL}(x_i, t) \\ &\quad + \Delta V_{SL} \end{aligned} \tag{27}$$

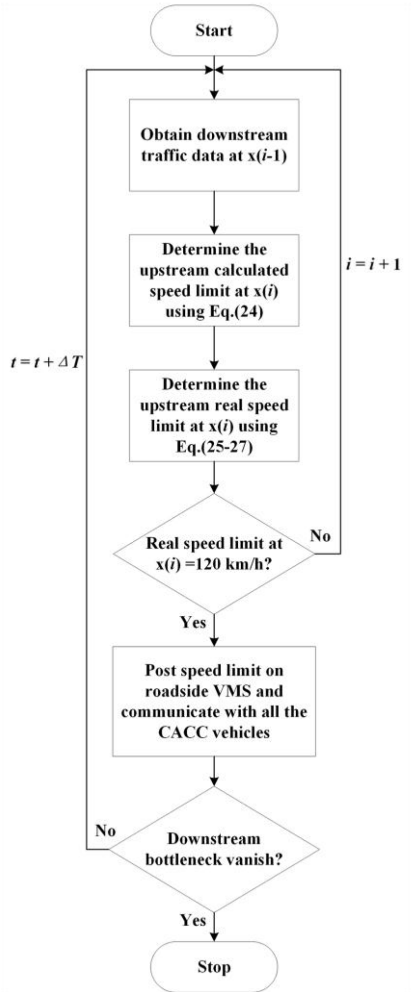

Fig. 4. Flowchart of the V2I control algorithm.

B. Feedback Control System

In order to integrate the CACC and VSL controls, a feedback control system was developed (see Fig. 3 and 4). A bottleneck occurs on the freeway due to various reasons, such as on-ramp, lane closure, or accidents. Whatever the reason is, the consequences of a bottleneck are congested traffic flow, reduced operating speeds and propagated shock wave to the upstream. Due to the sharp decline of velocities, it is dangerous for vehicles at the upstream with high speeds approaching to the congested segment, which will cause rear-end collision.

The control strategy of integrated CACC and VSL can help to reduce the risks of rear-end collision in this condition. The 30s traffic data from detector i-1 are used to calculate the safe speed for vehicles approaching congested segment using Eq. (24) to (27) (see Fig. 3 and 4). The VSL control i posts the real speed limit on the VMS at the detector i which is at the upstream of detector $i-1$. Similarly, the traffic data is also collected by detector i and used to determine the real speed limit for VSL control $i+1$ at the upstream, until the real speed limit equals to the initial speed limit of 120 km/h. All the variable speed limit values are determined spatially from the downstream to the upstream.

The CACC can help to overcome the limitations of VSL only controls that manual drivers respond differently to the proposed speed. The speed limit information is sent to all the vehicles directly through the V2I communication. Meanwhile, all the CACC vehicles including the leader follow the proposed safe speed homogeneously. The response delay is also reduced, leading to more effective reduction in rear-end collision risks.

The traffic variables of the CACC vehicles collected by the loop detectors at the current time cycle t are then used to calculate the real speed limits in the next cycle $t + \Delta T$ (see Fig. 4). Thus, the process of vehicle-to-infrastructure-to-vehicle forms an effective feedback control system.

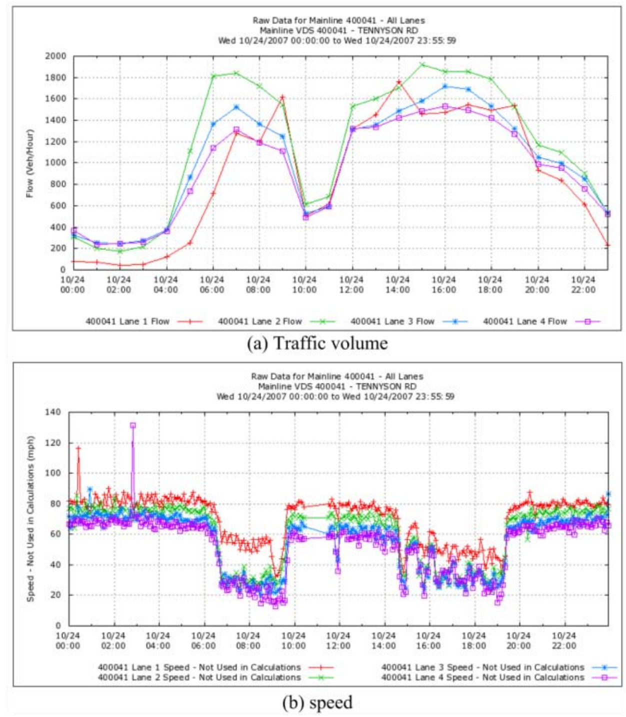

Fig. 5. Traffic flow data of the simulated bottleneck.

IV. Simulation Results

A. Simulation Experiment Design

The simulation experiments were conducted to investigate safety impacts of the integrated system. The simulation environment was based on a theoretical site with a real freeway bottleneck. The theoretical site was used as the simulation test bed of the advanced V2I system and the real bottleneck data are used for modeling congested traffic flow conditions at freeway bottleneck. A typical on-ramp freeway bottleneck was selected for simulation, located in the Interstate 880 freeway in Oakland, California. The traffic flow data of the bottleneck were collected from the Highway Performance Measurement System (PeMS) [36]. As shown in Fig. 5, two peak periods occur during one day, i.e. the morning peak from 7:00 to 9:00 and the afternoon peak from 15:00 to 17:00. The morning peak is simulated in this study, during which the average speeds reduce from 70 mph (about 112 km/h) to 20 mph (about 32 km/h) and the average flow is about 1600 veh/h/ln.

A theoretical 10-km freeway segment with four lanes in one direction was simulated, as illustrated in Fig. 6. The above on-ramp bottleneck is set at 8 km from the entrance. Ten detectors are added to collect traffic data, with the space of 1 km.

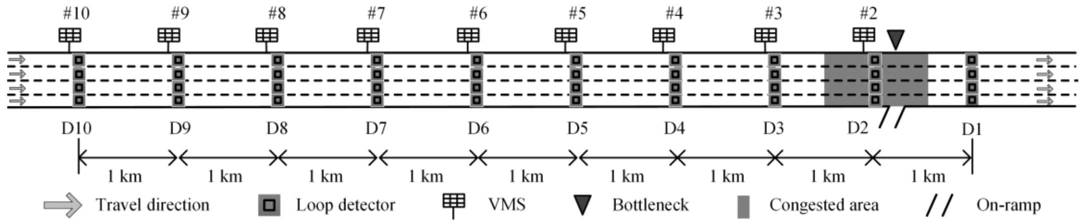

Fig. 6. The simulation roadway with the bottleneck.

And nine VMSs were used to provide variable speed limit information. The traffic flow is 1600 veh/h/ln and each vehicle initially drives at the speed of 112 km/h. All the vehicles will encounter the bottleneck and reduce their velocities to the preset speed 32 km/h. Note that, the on-ramp bottleneck is simplified using the bottleneck with speed reduction, because the lane-changing behavior is not considered in this study. Three reasons are considered for this simplification: 1) the CACC system itself is a longitudinal control system, which does not include lane change behavior. In previous studies about CACC, the lane change is generally not considered [12], [16], [17]; 2) although there are several lane change models of human drivers [38]–[40], the lane change problem of CACC vehicles is quite different from that of human drivers. It relates to the CACC vehicles' re-cooperation, i.e. clustering and dissolution strategies of CACC platoon [12]. This topic is quite complex and being under studied. And up to now there is no lane-changing model that can be used for CACC vehicles; 3) since this paper only focused on rear-end collisions, it is acceptable without including lane changing behavior.

Different bottlenecks can result in different speed reductions. Thus, the impacts of different reducing speeds were also analyzed in simulations. Furthermore, the average travel time of each vehicle was also calculated for comparing efficiency, which is the travel time from the entrance to the detector D1 (see Fig. 6).

To remove the random errors in the simulation, each simulation was repeated for 10 times. For each time, the simulation lasts for 2 hours, with the first 5 minutes as the warm-up period. At the beginning, the freeway segment is empty, and all the vehicles driving with the initial speeds before approaching the bottleneck. Then, vehicles brakes to the preset bottleneck speeds, and the reduction in speed propagates upstream so that the shock wave forms.

The scenario considering all manual vehicles without any control technique is firstly simulated as the reference. Then, the safety effects of CACC integrated with VSL and VSL control only scenarios were compared in sub-section B. Without loss of generality, the different speed change rate ΔV_{SL} were also analyzed in simulations. In addition, the sensitivity analysis of the market penetration rate of CACC vehicles and TTC threshold were given in sub-section D.

B. Comparison Analysis Between CACC+VSL and VSL Controls

The manual vehicles modeled by IDM without any control strategy was firstly simulated as the benchmark. Table II summarizes the reductions in rear-end crash risk of VSL control only and CACC+VSL relative to manual vehicles without any controls. Nine different values of ΔV_{SL} were tested in simulations, from 5km/h/30s to 10km/h/120s. The reduction in TIT and TET of VSL control only varies across the different speed change rates (see Table II). When speed change rate grows to 25km/h/30s, the VSL control achieves the largest reductions of 32.0% and 33.5% respectively in TIT and TET. The results of VSL control only are consistent with the findings of previous studies [11], [27].

The improvements of CACC+VSL control in TIT and TET are generally around 98% as the speed change rate grows, indicating the advanced characteristics of V2I and V2V systems. When a safe speed limit is determined by the VSL control algorithm, the information is sent to all the vehicles in the CACC platoon at the segment immediately. All vehicles will follow the proposed speed timely. Compared to manual drivers who respond different, the vehicles in the CACC platoon follow the proposed safe speed homogeneously.

Moreover, the average travel time illustrated in Table II also indicates the advantage of the proposed V2I system in improving traffic efficiency. The central idea of a VSL control is to make an intervention proactively and reduce vehicle speeds to avoid traffic crashes. In this case, efficiency is sacrificed to safety because of the reduction in average speed. As shown in Table II, the average travel time is increased by 7.8%, when ΔV_{SL} grows to 25km/h/30s. Accordingly, there is trade-off between safety and efficiency in the VSL only controls. However, the average travel time in the CACC+VSL can be reduced by at least 33% no what ΔV_{SL} is used, indicating that the combination of CACC and VSL can help to improve both safety and efficiency at the same time. This advantage is due to the advanced V2I communications, the rapid reactions of CACC vehicles, and the shortened intra-platoon time gaps.

Fig. 7 illustrates the changes in average speed of the three controls from detector 1 to 9 during a typical period of 25 minutes. The speed of manual vehicle without any control reduces greatly from 90 km/h to 30 km/h (see Fig. 7(a)). The excessive decline in speed is the major cause of high rear-end collision risks. The VSL control only reduces the speeds proactively and gradually. In general, the vehicles under VSL only control reduce from 90 km/h to around 45 km/h (see Fig. 7(b)). The proactive intervention of reducing speed improves traffic safety, but increases travel time. The combination of VSL and CACC, proactively and gradually reduce the vehicle speeds at upstream (see Fig. 7(c)). Compared with the VSL control only, the speed reductions in the CACC+VSL are more mitigated. The average velocities are not too low,

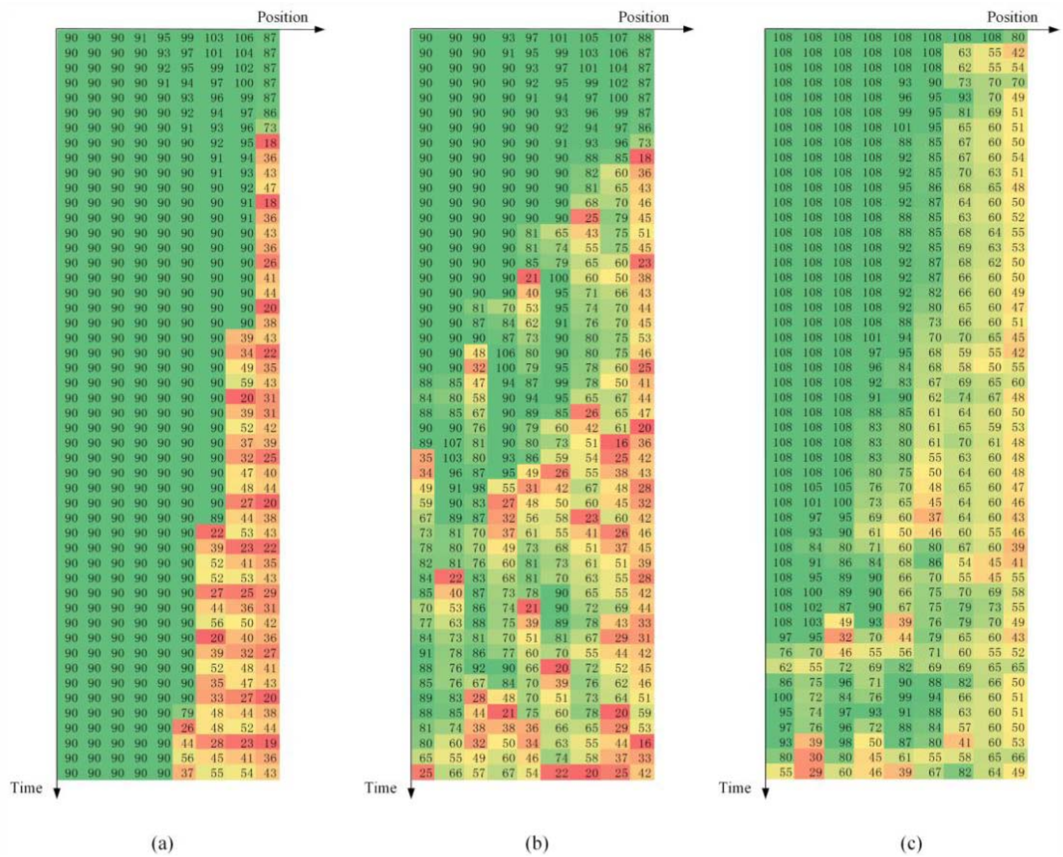

Fig. 7. The Speed changes of three scenarios: (a) Without any control, (b) VSL control only, and (c) CACC+VSL.

TABLE II

SIMULATION RESULTS OF VSL CONTROL ONLY AND CACC+VSL SCENARIOS[a]

ΔV_{SL}	VSL control only			CACC+VSL		
	TIT	TET	Average travel time	TIT	TET	Average travel time
5km/h/30s	-12.4%	-9.6%	0.5%	-98.5%	-98.6%	-35.9%
10km/h/30s	-13.2%	-14.0%	6.9%	-99.1%	-99.2%	-35.5%
15km/h/30s	-25.9%	-28.6%	6.3%	-98.8%	-98.9%	-33.5%
20km/h/30s	-21.2%	-28.7%	4.3%	-98.5%	-98.8%	-36.7%
25km/h/30s	-32.0%	-33.5%	7.8%	-98.4%	-98.5%	-33.8%
5km/h/60s	-0.1%	2.0%	1.3%	-98.8%	-99.0%	-37.5%
10km/h/60s	-15.8%	-15.8%	5.1%	-98.4%	-98.7%	-37.2%
5km/h/120s	-19.9%	-18.0%	0.0%	-98.6%	-98.7%	-35.7%
10km/h/120s	-17.1%	-17.3%	4.9%	-99.1%	-99.1%	-36.5%

[a] *Note: the simulation results of the manual vehicles without any control were used as reference.*

resulting in an increased efficiency as compared to the VSL control only.

C. Impacts of Speed Reductions Near Bottlenecks

The above analysis was based on the speed reduction from 112 km/h to 32 km/h. Considering different bottlenecks and other factors, such as various traffic and weather conditions, speed reductions can be distinct. Therefore, a variety of speed reductions were also investigated (see Table III). The simulation results of the manual vehicles without any control were also used as reference. It is obvious that the TIT and TET can be reduced by at least 95%, whatever the speed reduction is. Therefore, the integrated V2I system of CACC and VSL control can effectively reduce the rear-end collision risks under different bottleneck conditions.

The average travel time was also collected and compared among different speed reductions. As expected, the combination of CACC and VSL has better efficiency than the scenario without any control, no matter what speed reduction is (see Table III). In general, this improvement in efficiency is better in larger speed reductions. Accordingly, the combination of CACC and VSL can achieve good performance at different bottlenecks.

D. Impacts of Penetration Rates and TTC Thresholds

The market penetration rate of CACC vehicle is a critical fact that influences the performance of the integrated V2I system. With the gradual increasing proportions of CACC vehicles on freeways, different mixed traffic conditions may lead

TABLE III

SENSITIVITY ANALYSIS OF DIFFERENT SPEED REDUCTIONS NEAR BOTTLENECKS[a]

Bottleneck Speed v_b / ΔV_{SL}	TIT					TET					Average travel time				
	20 km/h	32 km/h	40 km/h	50 km/h	60 km/h	20 km/h	32 km/h	40 km/h	50 km/h	60 km/h	20 km/h	32 km/h	40 km/h	50 km/h	60 km/h
5km/h/30s	-99.6%	-98.5%	-98.5%	-97.2%	-98.7%	-99.6%	-98.6%	-98.6%	-97.5%	-98.7%	-11.6%	-35.9%	-35.8%	-24.9%	-27.9%
10km/h/30s	-99.2%	-99.1%	-97.5%	-98.1%	-98.2%	-99.4%	-99.2%	-98.0%	-98.2%	-98.4%	-11.4%	-35.5%	-34.7%	-31.4%	-27.1%
15km/h/30s	-99.2%	-98.8%	-97.5%	-98.1%	-96.5%	-99.4%	-98.9%	-98.0%	-98.3%	-97.2%	-11.6%	-33.5%	-32.6%	-30.0%	-21.6%
20km/h/30s	-99.0%	-98.5%	-97.8%	-97.1%	-96.3%	-99.2%	-98.8%	-98.0%	-97.5%	-97.1%	-11.4%	-36.7%	-32.3%	-24.5%	-20.8%
25km/h/30s	-99.1%	-98.4%	-97.9%	-96.7%	-96.3%	-99.3%	-98.5%	-98.2%	-97.3%	-96.8%	-10.2%	-33.8%	-30.6%	-28.6%	-19.6%
5km/h/60s	-99.5%	-98.8%	-98.5%	-98.0%	-98.8%	-99.6%	-99.0%	-98.9%	-98.4%	-98.9%	-12.1%	-37.5%	-37.4%	-32.5%	-28.1%
10km/h/60s	-99.6%	-98.4%	-98.3%	-98.5%	-98.8%	-99.7%	-98.7%	-98.4%	-98.7%	-98.8%	-12.1%	-37.2%	-36.1%	-31.4%	-27.9%
5km/h/120s	-99.3%	-98.6%	-98.4%	-98.3%	-98.8%	-99.5%	-98.7%	-98.6%	-98.8%	-98.8%	-11.5%	-35.7%	-37.8%	-34.1%	-28.0%
10km/h/120s	-99.5%	-99.1%	-98.8%	-98.6%	-98.3%	-99.6%	-99.1%	-99.0%	-98.7%	-98.5%	-11.5%	-36.5%	-37.6%	-32.9%	-27.6%

[a] *Note: the simulation results of the manual vehicles without any control were used as reference.*

TABLE IV

SENSITIVITY ANALYSIS OF MARKET PENETRATION RATE OF CACC VEHICLES[a]

Market penetration rates		TIT		TET		Average travel time	
CACC +VSL	CACC only	CACC +VSL	CACC only	CACC +VSL	CACC only	CACC +VSL	CACC only
10%CACC +VSL	10%CACC Only	-31.7%	-12.5%	-36.5%	-19.3%	6.2%	0.6%
20%CACC +VSL	20%CACC Only	-35.6%	-15.7%	-39.4%	-25.1%	4.2%	-2.5%
30%CACC +VSL	30%CACC Only	-40.0%	-18.7%	-46.5%	-27.2%	2.3%	-3.5%
40%CACC +VSL	40%CACC Only	-47.5%	-22.2%	-53.9%	-33.5%	1.3%	-6.9%
50%CACC +VSL	50%CACC Only	-61.4%	-39.7%	-66.5%	-52.8%	-0.9%	-11.8%
60%CACC +VSL	60%CACC Only	-75.9%	-48.2%	-78.3%	-56.6%	-6.7%	-12.1%
70%CACC +VSL	70%CACC Only	-90.5%	-74.4%	-91.8%	-77.1%	-12.3%	-14.6%
80%CACC +VSL	80%CACC Only	-95.7%	-92.3%	-96.2%	-93.4%	-17.9%	-26.9%
90%CACC +VSL	90%CACC Only	-98.3%	-96.3%	-98.4%	-97.5%	-28.3%	-38.3%
100%CACC +VSL	100%CACC Only	-98.4%	-97.3%	-98.5%	-97.5%	-33.8%	-41.6%

[a] *Note: the simulation results of the manual vehicles without any control were used as reference.*

TABLE V

SENSITIVITY ANALYSIS OF TTC THRESHOLDS[a]

Scenarios	TTC Threshold=2 s		TTC Threshold =3 s		TTC Threshold =4 s	
	TIT	TET	TIT	TET	TIT	TET
VSL control only	-32.0%	-33.5%	-31.3%	-28.8%	-30.4%	-29.0%
CACC+VSL	-98.4%	-98.5%	-98.5%	-97.9%	-97.0%	-95.1%

[a] *Note: the simulation results of the manual vehicles without any control were used as reference.*

to distinct safety impacts. Therefore, the sensitivity analysis of the penetration rate is conducted, with the fixed speed reduction from 112 km/h to 32 km/h, and speed change rate of 25 km/h/30s. Furthermore, scenarios of only CACC vehicles without VSL control were also tested at each level of penetration rate for comparisons.

As shown in Table IV, a total of 20 scenarios considering different CACC penetration rates were included, from 10% CACC vehicles to all CACC vehicles (100% CACC). As expected, the performance increases with an increase in the CACC penetration rate. The reductions of TIT and TET increase from 31.7% and 36.5% to 98.4% and 98.5%, when the penetration rate is increased from 10% to 100%. The average travel time was also given in Table IV to evaluate the efficiency impacts. Similar results were founded that the improvement in traffic efficiency increases as the penetration rate grows.

Additionally, compared with the scenarios of only CACC vehicles, the combination of CACC and VSL controls provides better safety performance (see Table IV). The improvement in safety performance of the combination of CACC and VSL controls is quite significant when the penetration rate is lower than 50%. However, such improvement decreases with an increase in the CACC penetration rate. When the penetration rate grows close to 100%, the improvement in safety performance of the combination of CACC and VSL controls is quite small. These results indicate that the VSL control plays a critical important role in the transition period from manual vehicles to CACC vehicles. The intelligent roadside infrastructures are needed to mitigate the negative effects of the mixed traffic flow conditions of the manual vehicles and CACC vehicles during the transition period.

The TTC threshold is a key factor to determine the surrogate safety measures of TIT and TET. A literature review indicated that the TTC threshold used in previous studies varies from 2 s to 4 s. The above analyses were based on the 2 s TTC threshold. Different TTC thresholds were tested to evaluate the impacts of TTC threshold on the results, with the bottleneck speed and speed change rate fixed at 32 km/h and 25km/h/30s, respectively. The sensitivity analysis results indicated that the different TTC thresholds have negligible impacts on the results (see Table V).

V. Conclusions and Discussions

This study aimed to reduce the rear-end collision risks near the freeway bottleneck by integrating CACC and VSL control techniques. The microscopic simulation testbed was firstly constructed, which included three vehicle behavior models, the realistic PATH CACC model, the ACC model and the IDM. The safety impacts were measured by the surrogate safety measures of the TIT and TET indicators. The feedback control algorithm was then developed for the proposed V2I control system of CACC and VSL controls. The simulation experiments were conducted to evaluate the safety improvements of the proposed V2I control system in different scenarios. Based on the simulation results, the following conclusions can be made:

1) Compared with the manual vehicles without any control, the combination of CACC and VSL controls can help to improve both safety and efficiency at the same time. This system with 100% CACC penetration rate reduces the rear-end collision risks by 98%, and increases the efficiency by 33%.
2) Compared with the VSL control only, the combination of CACC and VSL controls provide better performance in both safety and efficiency.
3) The integrated V2I system of CACC and VSL control can effectively reduce the rear-end collision risks and improve traffic efficiency under different bottlenecks of various speed reductions.
4) The CACC penetration rate is key factor to determine the performance of the proposed V2I system. The safety performance of the proposed V2I system increases with an increase in the CACC penetration rate. When the CACC penetration rate is low, the intelligent roadside controls are needed to mitigate the negative effects of the mixed traffic flow of manual and CACC vehicles.

The results of this study suggested that the proposed V2I system integrating CACC and VSL controls can simultaneously improve traffic safety and efficiency near freeway bottlenecks. The proposed V2I system can achieve good performance for different freeway bottlenecks. More importantly, the results suggested that the VSL control plays a critical important role in the transition period from manual vehicles to CACC vehicles. For the long time transition period, the mixed traffic flow of CACC and manual vehicles will always exist. The results of this study can help to mitigate the negative effects of the mixed traffic flow conditions of the manual vehicles and CACC vehicles during such transition period. However, before the proposed V2I system is used in practical applications, a number of issues are still needed to be resolved. Firstly, the lane changing behavior of CACC vehicle should firstly be modeled with suitable models. In our study, only the longitudinal car-following behaviors of CACC vehicles were considered. It is because that lane change behavior relates to the re-cooperation strategies of CACC, which are quite complex and still being under studied. In the future, the realistic lane change model for CACC vehicles will be developed when the re-cooperation strategies and data of CACC are available in large scale vehicle experiments. Secondly, the up to 10 vehicles of platoon length is a research limitation in this study. It may be investigated by using large scale experimental CACC data available in the future with the development of advanced vehicle communication technology. Moreover, the fuel consumption and emissions due to the frequent accelerations and decelerations at the bottleneck should also be investigated under the V2I and V2V environments. The authors recommend that future studies may focus on these issues.

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