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REALISTIC CAR-FOLLOWING MODELS FOR MICROSCOPIC SIMULATION OF ADAPTIVE AND COOPERATIVE ADAPTIVE CRUISE CONTROL VEHICLES

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ABSTRACT
Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) are important vehicle technologies toward vehicle automation and their impacts on traffic system are generally evaluated via microscopic traffic simulations. A successful simulation requires realistic vehicle behavior and a minimal number of vehicle collisions. However, most existing ACC/CACC simulation studies use simplified models that are not based on real vehicle response and rarely discuss collision avoidance in the simulation. This study aims to develop a realistic and collision-free car-following model for ACC/CACC vehicles. We propose a multi-regime model combining a realistic ACC/CACC system with driver intervention for vehicle longitudinal motions. This model assumes that human drivers resume vehicle control either according to his/her assessment or after a collision warning requests the driver to take over. The proposed model is tested in a wide range of scenarios to explore the model performance and collision-possibilities. The testing scenarios include three regular scenarios of stop and go, approaching and cut-out maneuvers, as well as two extreme safety-concerned maneuvers of hard brake and cut-in. The simulation results show that the proposed model is collision-free in the full-speed-range operation with leader accelerations within -1 to 1 m/s^2 and in approaching and cut-out scenarios, indicating that the proposed ACC/CACC car-following model is capable of producing realistic vehicle response without causing vehicle collisions in the regular scenarios for vehicle string operations.

Keywords: Adaptive cruise control, Car-following model, Collision property, Authority transition, Microscopic simulation

INTRODUCTION

Technologies of automated vehicle control have drawn great interests since the automated highway system (AHS) was introduced in the 1930s (*1*). Adaptive Cruise Control (ACC) is one of the emerging technologies for driving assistance systems and it is designed to enhance driving comfort by automatically responding to a preceding vehicle. Cooperative Adaptive Cruise Control (CACC), an extension of the ACC with Vehicle-to-Vehicle (V2V) communication, is favored by road operators since it has the possibility of vehicle coordination and cooperation, which provides a potential opportunity to enhance traffic efficiency.

Studying the potential impacts of ACC/CACC vehicles on traffic efficiency is of great importance and necessity, since the penetration rate of ACC and CACC vehicles is expected to increase in the near future. An early study showed that ACC and CACC vehicles have the potential to increase the lane capacity at 100% market penetration rates (MPR) (*2*). Unfortunately, the conclusion for ACC vehicles does not hold in a simulation if a realistic distribution of the desired time gap is considered (*3*). The impact of CACC vehicles on lane capacity is still significant in moderate and high MPR scenarios (*3*-*5*). Regarding flow stability, CACC vehicles are effective in smoothing traffic flow and damping shock waves (*4, 6*-*8*), whereas ACC vehicles may, on the contrary, deteriorate traffic stability with amplified disturbances (*9, 10*).

Existing traffic impact analyses of ACC/CACC vehicles are generally based on microscopic traffic simulations. To represent ACC/CACC vehicle behavior in traffic simulations, default human-driver car-following models need to be replaced by ACC/CACC car-following models. According to the accuracy of simulated car-following models, literature on simulating ACC/CACC vehicles can be categorized into four groups. The first group of studies (*6, 11*) used the desired speeds or accelerations from ACC/CACC controllers as the actual speeds or accelerations in the simulation. It can be easily implemented, but the predicted vehicle response may not be realistic since the model ignores driveline dynamics, rolling and aerodynamic resistance. Studies of the second group (*2, 4, 12*) applied a first-order lag between the controller command (i.e. the desired speed/acceleration) and the actual vehicle speed/acceleration to represent the driveline dynamics. The response of mechanical drivetrain is included in the simulations, whereas the effects of external factors still cannot be captured. A full vehicle dynamic model, which includes vehicle controller and both internal and external influential factors, was adopted in the third group (*13*). Although the vehicle dynamic is reasonably simulated, the detailed vehicle model consumes large computation time and it is barely feasible for the large-scale traffic simulations. The last group of studies modeled the realized speeds/accelerations of ACC/CACC vehicles as the car-following response using data collected during field tests (*9*). Empirical car-following models based on measured vehicle response are expected to outperform the aforementioned groups in the aspects of model validity as well as implementation simplicity. Empirical car-following models were, therefore, selected as our basic simulation models.

Empirical ACC and CACC models need to be developed to fulfill the requirements of large-scale traffic simulations. The first requirement is the full-speed-range operation of ACC/CACC vehicles. Empirical car-following models have been calibrated only within a speed range from 25.5 to 29.5 m/s (*9*); however, simulated ACC/CACC vehicles can easily operate at a lower speed especially when traffic congestion occurs. Secondly, vehicles collide in simulations may lead to an unexpected simulation stop or deleted vehicles. The collision-free property is often considered as an important characteristic of a car-following model to ensure proper performance of a traffic simulator. Unfortunately, the collision-free property cannot be guaranteed in simulations since the empirical car-following models are not designed to represent collision situations, which are rare events in practice. In emergency situations, drivers often override system control to avoid collisions (*14, 15*) and the car-following models need to explicitly incorporate those collision avoidance behavior (*16*). Existing studies pay insufficient attention to the integrated ACC/CACC car-following model with driver take-overs, and resulting collision properties have seldom been investigated.

This paper aims to establish ACC/CACC simulation models that originate from the empirical models, operate in full-speed range and satisfy the collision-free requirement. To achieve that, we take driver-system interaction into consideration and propose a complete model with authority transition for the full-speed range. The properties and validity of the model, especially the collision avoidance in safety-critical conditions, were tested and assessed in a wide range of simulation scenarios. This study fills, for the first time, the gap between ACC/CACC empirical car-following models in limited scenarios and its extension and applications in various traffic scenarios.

The remaining of the paper is divided into four parts. The first part introduces a conceptual car-following model for ACC/CACC simulations with model specifications. The second part builds a simulation experiment to evaluate collision avoidance in five scenarios that ACC/CACC vehicles may encounter in a simulation. The third part presents the simulation results and explores the relationship between collision and vehicle string disturbance. Conclusion and future work are discussed in the last part.

MODEL FORMULATION

This section proposes a schematic control structure of simulated ACC/CACC vehicles and formulates the models for their longitudinal behavior.

Conceptual Model and Underlying Assumptions

A multi-regime model for ACC/CACC longitudinal vehicle response is proposed with two parallel control loops: a human driver control loop and a system control loop. Each loop represents the sequential procedures for corresponding vehicle control within a simulated time step and both loops are based on a three-stage control structure from (*17*). Figure 1 illustrates the multi-regime framework of double loop control, where v_i, x_i and a_i refer to the speed, location and acceleration of vehicle *i*. At each time step, the model inputs are speed and position of preceding vehicle *i*-1 and subject vehicle *i* at a previous time step, as well as the desired time gap and the cruise speed set by human drivers. These inputs are processed either by ACC/CACC or human driver response models and eventually the actual kinematic data becomes model outputs and provides feedback information for next time step.

In the system control loop, the first perception stage obtains vehicle kinematic data through radar sensors/V2V communication and provides required inputs to the decision-making stage. In the second stage, the ACC/CACC controllers receive and process the inputs after the collision warning system does not issue a warning. A speed or acceleration command is delivered to the lower-level vehicle system in the third phase. The lower-level vehicle system, which is related to throttle and brake actuations, operates vehicles to meet commands. The final outputs are actual acceleration, speed and location. Depending on the ACC/CACC controller algorithms, relevant kinematic information is collected and used as input for decision-making of the next time step.

The human driver control loop performs similar control processes. The driver firstly perceives the leader's speed and location and determines the activation/deactivation of automation or remains the vehicle control in the last time step. If the driver take-over is initiated, the human driver response model overrules the ACC/CACC controller and generates a desired acceleration to the vehicle model in the third phase.

The proposed car-following model reflects the relations between actual vehicle speed/acceleration and vehicle's relative speed and gap error in previous time step. It can be generally formulated as equation (1) and replaces the combination of the decision-making phase and actuation phase.

$$a_{i,k} = f\left(x_{i-1,k-1}, x_{i,k-1}, v_{i-1,k-1}, v_{i,k-1}\right) \tag{1}$$

where subscript of *i* and *k* represent for vehicle sequence and time step respectively.

The driver intervention and the collision warning system determine when to switch between the two control loops. They correspond to two types of authority transition: discretionary overrides and mandatory overrides (*14, 15*). The discretionary override is initiated by drivers, for drivers actively interacting with the automation system. The mandatory override is activated as long as a collision warning is given in a safety-critical situation. Regarding automation activation, we assume the switch is only effective from the driver control loop to system control loop, and the automation system cannot switch on by itself.

ACC/CACC Car-Following Models

ACC/CACC controllers based on feedback control generally include three sub-controllers for three different motion purposes (*18*). The cruising controller is designed for maintaining a user-set desired speed if a preceding vehicle is absent. Gap regulation controller works for car-following situations and it aims to keep a constant time gap with its predecessor. When an ACC/CACC vehicle approaches its leader with a high relative speed, the gap-closing controller performs a transition from cruising controller to gap regulation controller. In the text below, models for three operation modes are formulated respectively.

Cruising Model

Cruising models for ACC and CACC vehicles are the same since additional V2V information does not play a role in vehicle cruising operation. The vehicle acceleration is modeled as a feedback control law which keeps the vehicle traveling at the desired speed. The general formula is shown as

$$a_{i,k} = k \cdot (v_{set} - v_{i,k-1}) \tag{2}$$

where the control gain *k* is a parameter to determine the rate of speed error for acceleration, and v_{set} is the desired cruising speed. This value was generally set as 0.3-0.4 s^{-1} in literature (*2-4, 7*) and 0.4 s^{-1} is selected in this study.

Car-following Models

The Milanés ACC and CACC car-following models from (*9*) are selected as the basic simulation models. The responses of ACC followers was modeled as a second-order transfer function and it is described by

$$a_{i,k} = k_1 \cdot e_{i,k} + k_2 \cdot (v_{i-1,k-1} - v_{i,k-1}) \tag{3}$$

where $e_{i,k}$ is the gap error of vehicle i at time step k. Equation (3) shows that the vehicle acceleration depends on a gap error and a speed difference with the preceding vehicle, where their feedback gain k_1 and k_2 are 0.23 s^{-2} and 0.07 s^{-1} respectively.

For CACC vehicles, the car-following behavior is represented by a first-order model. Vehicle's speed is calculated by the speed in previous time step $v_{i,k-1}$, the gap error $e_{i,k-1}$ in previous time and its derivative, according to

$$v_{i,k} = v_{i,k-1} + k_p \cdot e_{i,k-1} + k_d \cdot \dot{e}_{i,k-1} \quad (4)$$

where k_p and k_d are 0.45 s^{-2} and 0.25 s^{-1}.

Model Revision In original formulas, the gap error is determined by the inter-vehicle spacing, desired time gap and subject vehicle speed. The inter-vehicle spacing was expressed as the position difference of two consecutive vehicles, where the vehicle length was assumed as zero. A distance variable d_0 is introduced here to include the vehicle length in the gap error term, which is formulated as

$$e_{i,k} = x_{i-1,k-1} - x_{i,k-1} - d_0 - t_{des} \cdot v_{i,k-1} \quad (5)$$

where t_{des} is the desired time gap.

We re-build the original simulation scenario in (*9*) and ran the simulation by the revised models with a 5-meter vehicle length assumption. The results showed the model revision does not change the car-following response of ACC/CACC vehicles.

Dynamic Spacing Margin According to equation (5), the desired gap between vehicles at standstill is zero, if d_0 equals to the vehicle length. To prevent rear-end collisions, we formulate d_0 as a function of vehicle speed which gives additional clearance at low speeds. A preliminary full-speed-range simulation test on equation (3) and (4) suggests that ACC and CACC vehicles require different spacing margin. ACC vehicles should have a 2-meter additional clearance under the speed of 10 m/s while CACC vehicles request only one meter of spacing margin at speeds below 2 m/s. In this regard, we assume a maximum 2-meter spacing margin for ACC vehicles and the transitional speed range begins at 15 m/s where the margin gradually increase from zero. The d_0 is assumed to be inversely proportional to vehicle speed with boundaries of 5 and 7 m and is formulated as

$$d_0 = \begin{cases} 5 & v \geq 15 \text{ m/s} \\ \dfrac{75}{v} & 10.8 \leq v < 15 \text{ m/s} \\ 7 & v < 10.8 \text{ m/s} \end{cases} \quad (6)$$

For CACC vehicles, we assume a one-meter margin at speeds of 2 m/s (where the desired gap is 1.2 m) and a transitional speed range starts at 10 m/s. By a linear function, the dynamic d_0 policy for CACC vehicles is expressed as

$$d_0 = \begin{cases} 5 & v \geq 10 \text{ m/s} \\ -0.125v + 6.25 & v < 10 \text{ m/s} \end{cases} \quad (7)$$

A larger spacing margin was given to the ACC model than CACC model, for a reason that ACC vehicles need more spacing to compensate the gap variation by overshoot. The inverse proportional function and linear function of d_0 were determined through our preliminary tests to avoid rear-end collisions.

A combination of a constant time gap (CTG) policy and a dynamic spacing margin ensures a realistic ACC/CACC car-following response without collisions at low-speed operations. Maintaining a constant time gap most likely represents the driving behavior at highways. Therefore, the CTG policy is widely accepted by commercial ACC/CACC systems and becomes the dominating gap-regulation discipline in the field test (*9*) and our study for reproducing realistic vehicle response. A minimum spacing between two vehicles at standstill is often required in addition to the CTG policy to give some safety margin, which is lacking in the original model. We, therefore, proposed a dynamic spacing margin to avoid collisions only in a simulation use. The dynamic spacing margin can extend the safety margin with a smooth vehicle performance, without altering the validity of the original model in the field test speed range.

Approaching Models

The vehicle response under gap-closing controller has not been modeled previously in (*9*). We tuned the parameters of the original car-following models for approaching. The approaching model is operated once the vehicle gap is twice larger than the desired gap and it falls into the detection range of forward-looking sensors. For a smooth transition, the approaching model is switched to the car-following model when the gap and speed errors are smaller than 0.2 m and 0.1 m/s simultaneously.

Reducing the speed difference and shortening the gap are the control objectives in the approaching model. To achieve safe approaching, we increase the feedback gain on sped error and reduce the feedback gain on gap error. After tuning, k_1 and k_2 are 0.04 s^{-2} and 0.8 s^{-1} in equation (4), k_p and k_d are 0.01 s^{-2} and 1.6 s^{-1} in equation (5). This approaching model in combination with the driver intervention is able to guarantee collision-free when an ACC/CACC vehicle approaches a standstill vehicle, as we will show with simulations.

Collision Warning System and Human Take-Over

The multi-regime nature of ACC/CACC operations requires modeling transitions between different driving modes, in particular, the take-over by human drivers. We assume that the system-initiated override is performed based on a collision warning and the driver-initiated override is activated in a particular condition.

Forward Collision Warning

A safety-critical situation can be identified by either kinematic approach or perceptual approach. The kinematic approach triggers the collision warning if the spacing is equal or smaller than an estimated safety spacing; while, the perceptual approach is based on drivers' perception of critical situations and it often uses Time-to-Collision (TTC) or its variations as indicators.

The indicator and suggested criteria in the Kiefer study (1*9*) are chosen to trigger the critical situation warning. Kiefer proposed a probability indicator based on a "hardness of braking" index, which is a function of inverse TTC and subject vehicle speed. This indicator can be used for modeling and estimating the drivers' hard brake response to a variety of safety-critical conditions and here is used to evoke the collision warning. This approach is simple and computationally efficient.

Human Driver Car-following Models and Switching Assumptions

The Intelligent Driver Model from (*20*) is a collision-free car-following model for human-driven vehicles and its modified version IDM+ in (*7*) has been successfully applied in an open-source traffic simulator. Thus, IDM+ was chosen to act as the car-following model in the loop of human control.

Driver-initiated deactivation depends on the driver's subjective evaluation of the situation. Before a vehicle leaves a string, the driver may overrule the system to implement maneuvers that ACC/CACC controllers are incapable of, e.g. open a safe gap at the front or adapt the speed with the leader in an adjacent lane. Moreover, the driver may take over control when the vehicle approaches a traffic jam, which has been observed in an ACC field operational test in the Netherlands (*21*). In this case, we assume a driver-initiated overrule is performed when an ACC/CACC vehicle approaches a low-speed vehicle with a relative speed over 15 m/s, as well as the gap with the low-speed leader is less than drivers' perception range (150 m).

System-initiated overrule is evoked by the collision warning and the switch from ACC/CACC car-following model to IDM+ has a time delay considering the drivers' reaction time. Different from driver-initiated overrule, the driver is assumed not being prepared to the warning and thus the driver response is subject to a delay. The delay includes the time that drivers re-pay attention to driving tasks, the action of braking and the response of vehicle mechanism. In total, a delay of 1 s between alarm onset and vehicle actual braking is assumed.

SIMULATION EXPERIMENTAL DESIGN FOR MODEL VERIFICATION

The multi-regime model is an approximate imitation of ACC and CACC vehicles in the real world and it should be verified to the degree needed for particular applications. We designed and conducted a series of simulation experiments to scrutinize potential collision avoidance characteristics and the following response.

Experiment Design and General Simulation Setups

The experiment is to examine the impacts of several typical string disturbance on the vehicle following response and the collisions avoidance. Five representative traffic scenarios are selected: Stop and Go Scenario, Hard Brake Scenario, Cut-In Scenario, Cut-Out Scenario and Approaching Scenario.

The simulated scenarios were established and programmed in MATLAB. The vehicle speed, acceleration and location are used to represent vehicle kinematic motions and they were calculated and updated every 0.05 s. The simulation starts when a vehicle string travels at a constant speed and vehicles following their preceding vehicles in equilibrium status. The ACC vehicles maintain a 1.1 s time gap while the CACC vehicles maintain a 0.6 s time gap. Simulated disturbances are introduced at *Second Ten* and simulations end when the string return to the equilibrium status again. In each simulation, there is only one single string and the simulated vehicle string is assumed homogeneous (vehicle length 5 m). The length of ACC vehicle string is restricted to four vehicles, due to the string instability of ACC vehicles found in the field test (*9*). The length of CACC vehicle string is assumed as ten vehicles, for implementation constraints in reality and model consistency from the original model.

Scenario A: Stop and Go

Stop and Go Scenario aims to examine the full-speed-range string operation, as opposed to the limited speed range that the original car-following models were calibrated and validated. The simulated vehicle string initially travels at 32 m/s and the leader starts to decelerate at second 10 to a full stop using decelerations of 1/80 g, 1/40 g, 1/20 g and 1/10 g respectively. After a stop of

10 s, the leader accelerates to 32 m/s by a positive value of previous decelerations and remains the 32 m/s till the end.

Scenario B: Hard Brake

In Hard Brake Scenario, the string leader applies large decelerations comparing to the comfortable decelerations in the first scenario. The deceleration values and lasting time, together, define the string disturbances introduced in simulations and we tested that within different speed ranges. We select the mean value of the original speed range as the first tested initial speed and then sequentially set it towards lower values remaining a 4 m/s speed interval. The tested decelerations are from 2 m/s^2 to 6 m/s^2 and the time for decelerating is tested on a scale of 1-5 s.

Scenario C: Cut-In

Cut-In Scenario is set up for determining collision impacts of a cut-in vehicle on ACC/CACC vehicle string. The cut-in maneuver inevitably leads to a sudden drop of the gap to the direct following vehicle, which creates a critical situation. The disturbance is simulated as a vehicle cut-in at the second place of the string with a relative speed. The cut-in vehicle remains the cut-in speed and the vehicles behind respond to this new leader. We assume both ACC/CACC string vehicles maintain a 1.1 s time gap and the cut-in vehicle emerges at the place that left a 0.6 s time gap to its direct follower (*18*). If a 5-meter gap between the cut-in vehicle and its leader is taken into account, only the simulations with initial operational speeds higher than 20 m/s satisfy the aforementioned assumptions.

Scenario D: Cut-out

Cut-out Scenario simulates a potential safety-critical process of ACC/CACC vehicles leaving the string. A driver-initiated override and a comfortable deceleration to open a gap are assumed for the leaving vehicles and the remaining vehicles have to decelerate as well to respond which may raise the collision risk. A maximum number of three vehicles is designed to leave the string. The second vehicle in the string is always considered as the leaving vehicle for its extensive influence. The other leaving vehicles are chosen by a balanced-distributed sequence pattern or a concentrated distribution. All leaving vehicles are assumed to start opening gaps simultaneously at second 10 and the remaining vehicles will catch up their leader after the leaving maneuver.

Scenario E: Approaching

A vehicle string detects and approaches a leading vehicle at downstream is simulated in the Approaching Scenario. Relative speeds of the approaching is an influencing variable since it does not only determine the activation of driver-initiated overrule, but also raises high collision risks. For relative speeds below 15 m/s, the detection range was 120 m by ACC vehicle sensors and otherwise 150 m by human perception. For CACC vehicles, the detection range is assumed as the range of V2V communication, which is 300 m. At *Second Ten*, a vehicle was set up at downstream of a string and cruised at a constant speed. Tested relative speeds were set from 0 m/s up to initial vehicle speed, covering the approaching situations of standstill leaders, low-speed leaders and leaders with same speeds.

Table 1 lists the details of the tested variables in each scenario. To verify the vehicle behavior, vehicle response and string performance are evaluated by a qualitative analysis of vehicle speeds, accelerations and gaps. The collision is strictly defined as the distance gap between two vehicles equals to or is smaller than zero.

RESULTS AND DISCUSSION

Collision properties and prevented potential collision by human take-over are the results that are relevant for the verification of the conceptual model. Results of the collision avoidance are presented in the following section, followed by illustrated string performance by kinematical parameters and model capability.

Collision Property and Human Take Over

The simulation results showed that the tested disturbance does not lead to rear-end collisions in full-speed range scenario, approaching scenario and cut-out scenario. It verifies the collision-free property during normal string operation and provides strong evidence to support the model applicability in traffic simulation. Nevertheless, high collision risk still can be identified, particularly in the low-speed range operation and approaching situations. The potential collisions are eventually avoided by driver take-over on time. Table 2 lists the timing that drivers override ACC systems in the Scenario A and Scenario E.

In the stop and go scenario, collision-critical situations were found at leader decelerations of 1/20 g and 1/10 g. It is noticed that those overrides happened at speeds below 10 m/s, where we introduced a 2-meter spacing margin. The results implied that our proposed spacing margin and driver intervention work successfully in preventing collision for a full-speed-range string operation.

In approaching scenarios, collision warning is rarely triggered by the approaching vehicle when the relative speed is no larger than 10 m/s. Once the relative speed reaches beyond 10 m/s, the approaching vehicle is overruled by either system-initiated requests or driver-initiated requests at once (at 10.05 s), and resulting human hard brake may activate the warnings for the other following vehicles. High relative speed approaching is an extreme safety-critical situation. Especially for a standstill leader, 120 m detection range is insufficient for ACC vehicles to decelerate to a full stop before collisions. Override timing shows the collision warning system and driver override are effective in preventing collisions.

Interestingly, if more than one collision warning were given, ACC vehicles at the front of the string generally received the warning and switched to human driver control earlier than the vehicles at the string tail. This reflects a phenomenon that the severe disturbance propagated from downstream to upstream within an ACC string. In addition, it is worth mentioning that no critical situation was detected by CACC vehicles in both scenarios. The V2V communication reduces the speed difference within vehicle string and the disturbances do not amplify toward upstream.

No collision and warning were observed in any cut-out simulation with various operational speeds, opening gaps and leaving vehicle sequence. Particularly in CACC model tests, high collision probability was expected due to long-lasting decelerations during gap-openings. Owing to the fast and smoothing response of CACC controllers, the disturbances by gap opening were damped out and no collision occurs. In general, simulation results suggested that opening gaps by a comfortable deceleration does not cause a collision, regardless of operational speeds and settings of time gaps. The number of leaving vehicles and vehicle sequences also do not affect the collision results.

Vehicle String Performance

For illustrating the vehicle-following performance, we present nine plots of time-varied speeds, accelerations and preceding gaps for ACC and CACC models respectively. To be specific, results come from the full stop test with decelerations of -0.5 m/s^2 in the *Scenario A*, approaching a 20 m/s leader with a 10 m/s relative speed in *Scenario E* and the second vehicle cut-out at 1.8 s gap in *Scenario D* were selected.

Figure 2 shows the dynamic response plots of ACC vehicle string in those three scenarios. In (a), the string leader and the following vehicles decelerated till a full stop with a substantially amplified deceleration rate shown in (d). A deceleration of 0.5 m/s^2 leads to driver take-overs for all the following vehicles and the fourth vehicle reached a deceleration up to 1 m/s^2. This result is in accordance with (*9*) and it is explained as accumulated vehicle response delay when relying solely on on-board sensors. It is noticed that during the period of 50-75 s in subplot (d), we observed the deceleration variation by the extra spacing margin setups. ACC vehicles decelerate slightly harder than the string leader in order to create an extra spacing.

Subplot (b), (e) and (h) show a continuous deceleration and smooth approaching trajectories with the proposed model parameters for approaching. The third and fourth vehicles responded to the deceleration of the second vehicle and lead to a speed variation which may cause discomfort to drivers.

For the cut-out scenario, the second vehicle changed lane after it had opened a 1.8 s gap at second 18. The results point out that following vehicles behind the cut-out vehicle reacted properly to the comfortable deceleration during the gap-opening, and they smoothly caught up the new leader and back to car-following status soon after the cut-out vehicle left.

Compared to ACC, string operation of CACC vehicles is more smooth and efficient. Figure 3 shows the vehicle dynamic response in selected scenarios. As it is observed, CACC vehicles do not lead to amplified disturbance thanks to the V2V communication. Vehicles at the tails experienced similar accelerations to the leader even with a 10-vehicle string length. The smooth speeds and accelerations in approaching scenario suggest a reasonable vehicle trajectory toward a low-speed vehicle and the 300 m gap was effectively reduced within 100 s. These performance plots show that the conceptual CACC model functions properly in generating plausible vehicle behavior.

Model Capability in Hard Brake and Vehicle Cut-in

Table 3 summarizes the maximum deceleration time (MDT) of an ACC/CACC string leader that a collision-free string operation still can be achieved with. The number in each cell is the MDT correspond to leader's deceleration in the second row and the initial string speed in the first column. A strong correlation was found between MDT and leader decelerations. The smaller decelerations, the larger acceptable deceleration time. This suggests the proposed car-following models can accept either a long-last but soft brake or a short but strong deceleration as a disturbance that do not cause collisions. In addition, the effect of an initial ACC vehicle speed on MDT is substantial while the effect of a CACC vehicle speed is insignificant. At decelerations of -4 and -6 m/s^2, the MDTs of ACC leaders in high-speed range doubled the MDTs at low speeds.

Results of *Cut-in Scenario* showed that the maximum safety speed difference for a low-speed cut-in vehicle is 6 m/s, 6 m/s, 8 m/s and 10 m/s for string speed at 20 m/s, 24 m/s, 28 m/s and 32 m/s. The results are the same for the ACC and CACC models, suggesting that impacts of a cut-in vehicle on ACC/CACC vehicles with equal time gaps are similar. All maximum speed differences are larger than zero implies that a vehicle cut in with the same speed does not lead to collisions.

Large cut-in speed differences rarely occur in a simulation. An assumption is often made in a simulation that if the speed difference between cut-in vehicle and target leader is considerable, the corresponding lane-change gap is strongly rejected and the lane-change maneuver is canceled. For this reason, cut-in vehicles normally do not evoke extreme collision situations in a simulation.

CONCLUSION AND FUTURE WORK

The purpose of this study was to build a bridge between ACC/CACC empirical car-following models and their applications in microscopic traffic simulations. The empirical ACC/CACC car-following models presented in (*9*) are ideal for a traffic simulation owing to its well-calibrated vehicle response. Unfortunately, these models are incapable of achieving a collision-free operation in the full-speed range, which is an essential requirement for effective and efficient simulation. We propose multi-regime car-following models for ACC and CACC systems, extending the empirical ACC/CACC models with human interventions. The simulation results suggest that no collisions occur in representative traffic situations.

We conducted systematic simulation experiments to test model collision avoidance properties. Meanwhile, this paper has verified the capability of the proposed multi-regime model with human interventions to avoid collisions. We concluded that the proposed models are collision-free under the typical traffic situations and most safety-critical scenarios in simulations. It should be noted that our proposed model was only verified in simulation. An analytical proof of the collision-free property needs to be investigated further. Another research limitation comes from the same model parameter setting within a vehicle string in the simulation experiments. The impacts of different vehicle lengths, acceleration capabilities and desired time gaps within a string can be found by a sensitive analysis in subsequent simulations. Future research efforts aim to implement this model into an advanced and sophisticated traffic simulation model to discover the traffic impacts of ACC/CACC vehicles.

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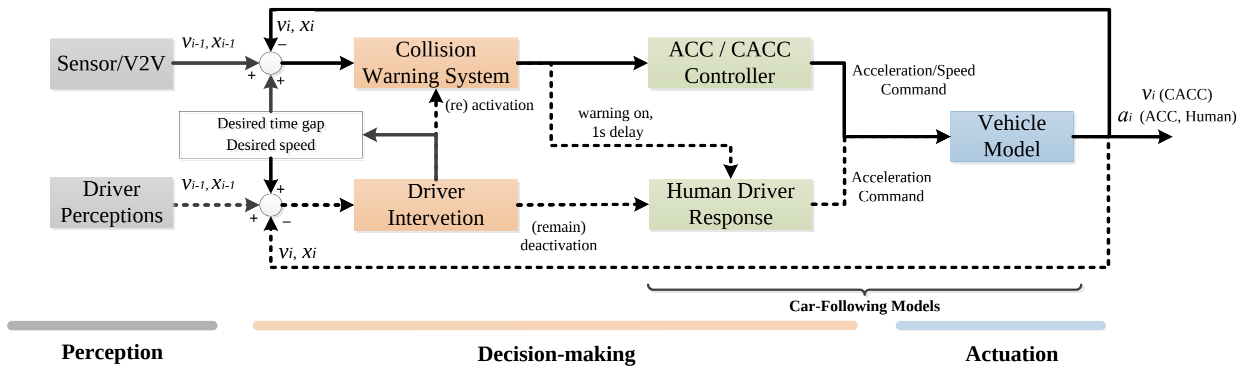

FIGURE 1 Conceptual longitudinal models for ACC/CACC vehicles in simulations.

TABLE 1 Parameter Setups for Simulated Disturbances

Reference **Milanés Models**	Scenario A **Stop and Go**	Scenario B **Hard Brake**	Scenario C **Cut-in**	Scenario D **Cut-out**	Scenario E **Approaching**
Speed Range (m/s) [25.5 29.5]	Speed Range (m/s) [0 32]	Initial Speed (m/s) 30, 25, 20, 15, 10, 5	Initial Speed (m/s) 32, 28, 24, 20	Initial Speed (m/s) 30, 25, 20, 15, 10, 5	Speed Range (m/s) 30, 25, 20, 15, 10, 5
Acceleration ±1/80g, ±1/40g, ±1/20g, ±1/10g	Acceleration ±1/80g, ±1/40g, ±1/20g, ±1/10g	Acceleration (m/s^2) -2, -4, -6	$\Delta v = v_i - v_{i-1}$ (m/s) 0, 2, 4, 6, 8, 10	Opening Gap (s) 1.2, 1.4, 1.6, 1.8	$\Delta v = v_i - v_{i-1}$ (m/s) 0, 5, 10,15, 20, 25, 30
		Deceleration Time (s) 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 5		Leaving Position **ACC** {2}, {2,3} **CACC** {2},{2,3},{2,6}, {2,5,8}, {2,3,4}	Detection Range (m) **ACC** 120 ($\Delta v < 15$ m/s) 150 ($\Delta v \geq 15$ m/s) **CACC** 300

TABLE 2 Override Timing for Each ACC Vehicle Drivers

Override timing (s) in Scenario A			
Acceleration	***2nd ACC***	***3rd ACC***	***4th ACC***
±1/80g	-	-	-
±1/40g	-	-	-
±1/20g	74.5	75	76.3
±1/10g	40.65	41.75	35.2
Override timing (s) in Scenario E			
Δv < 15 m/s, Initial Range = 120 m			
String speed (m/s) / Relative speed (m/s)	***2nd ACC***	***3rd ACC***	***4th ACC***
15 / Δv = 10	-	13.55	14.9
10 / Δv = 10	-	12.9	14.45
10 / Δv = 0	-	-	25.35
Δv ≥ 15 m/s, Initial Range = 150 m			
String speed (m/s) / Relative speed (m/s)	***2nd ACC***	***3rd ACC***	***4th ACC***
30 / Δv = 30	10.05	12.75	14.4
30 / Δv = 25	10.05	13.7	15.2
30 / Δv = 20	10.05	-	17.9
30 / Δv = 15	10.05	-	-
25 / Δv = 25	10.05	14.5	15.9
25 / Δv = 20	10.05	18.6	18.4
25 / Δv = 15	10.05	-	-
20 / Δv = 20	10.05	17	18.25
20 / Δv = 15	10.05	20.4	21.35
15 / Δv = 15	10.05	18.75	20.1

NOTE: dash line “-” means the data is not available, indicating that drivers do not override the system.

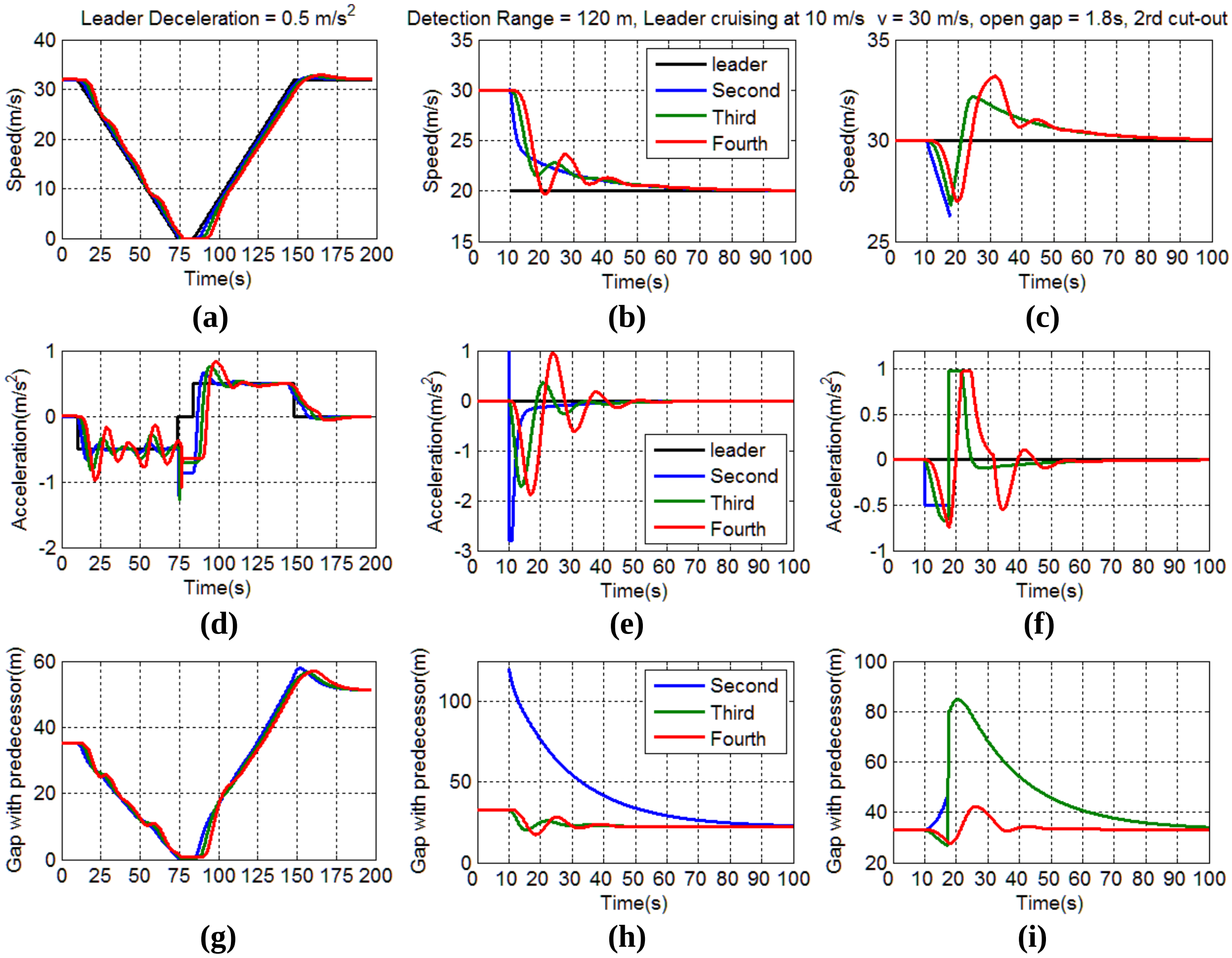

FIGURE 2 Simulated ACC vehicle speeds (a-c), accelerations (d-f) and distance gaps (g-i) in Scenario A, E and D.

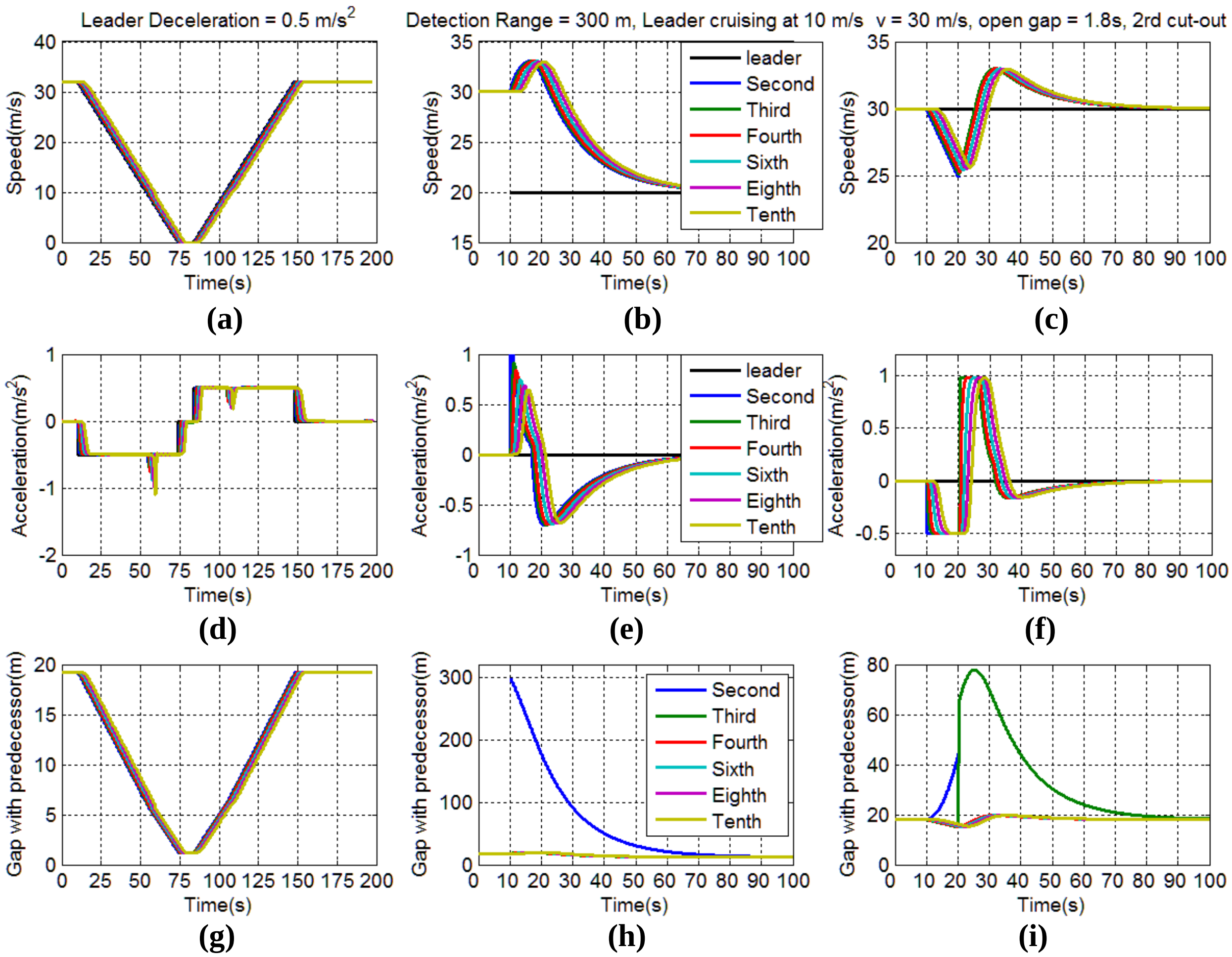

FIGURE 3 Simulated CACC vehicle speeds (a-c), accelerations (d-f) and distance gaps (g-i) in Scenario A, E and D.

TABLE 3 Maximum Deceleration Time (MDT) for Collision-Free ACC/CACC Strings in Hard Brake Scenario

Initial String Speed	**Leader Deceleration**					
	-2 m/s²		**-4 m/s²**		**-6 m/s²**	
	ACC	CACC	ACC	CACC	ACC	CACC
30 m/s	5s	5s	3.5s	2.5s	2s	1.5s
25 m/s	5s	5s	3s	2.5s	2s	1s
20 m/s	5s	5s	2.5s	2s	1.5s	1s
15 m/s	4s	5s	1.5s	2s	1s	1s
10 m/s	4s	5s	1.5s	2s	1s	1s
5 m/s	Till a full stop					