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A Multi-Vehicle Longitudinal Trajectory Collision Avoidance Strategy using AEBS with Vehicle-Infrastructure Communication

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***Abstract*—Shortening inter-vehicle distance can increase traffic throughput on roads for increasing volume of vehicles. In the process, traffic accidents occur more frequently, especially for multi-car accidents. Furthermore, it is difficult for drivers to drive safely under such complex driving conditions. This paper investigates multi-vehicle longitudinal collision avoidance issue under such traffic conditions based on the Advanced Emergency Braking System (AEBS). AEBS is used to avoid collisions or mitigate the impact during critical situations by applying brake automatically. Hierarchical multi-vehicle longitudinal collision avoidance controller is proposed to guarantee safety of multi-cars using Vehicle-to-Infrastructure (V2I) communication capability in addition to radar for longitudinal vehicle control. High-level controller is designed to ensure safety of multi-cars and optimize total energy by calculating the target braking force. Vehicle network is used to get the key vehicle-road interaction data and constrained hybrid genetic algorithm (CHGA) is adopted to decouple the vehicle-road interactive system,which can obtain the maximum ground friction through vehicle-road data, and provide key predictive parameters for multi-vehicle safety controller. Lower level non-singular Fractional Terminal Sliding Mode(NFTSM) Controller is built to achieve control goals of high-level controller. Simulations are carried out under typical driving conditions. Results verify that the proposed system in this paper can avoid or mitigate the collision risk compared to the vehicle without this system.**

***Index Terms*—Advanced emergency braking system, multi-vehicle collision avoidance, V2I communication, intelligent vehicular network, cooperative vehicle infrastructure system.**

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I. Introduction

TODAY, with the advancement of vehicle active safety and intelligent control technology, vehicles speed is getting much higher. Meanwhile, the increasing population of vehicles increases the possibility of being trapped in traffic jams. Increasing vehicle speed and shortening distance between vehicles can improve the capacity of the roads. While, as the price of bringing convenience, road traffic accidents are raised. The reduction of vehicle collision accidents is recognized as a traffic problem of the world, especially for multi-vehicle rear-end accident on a high-speed road. Therefore, vehicle longitudinal trajectory collision avoidance, especially for multi-vehicle, has the potential to avoid or reduce those traffic accidents as described above.

The on-board intelligent controller and Intelligent Transportation System (ITS) are expected to be maximally utilized. This is to solve the multi-vehicle collision avoidance problem. New control strategies should be designed to decouple and optimize the active safety of vehicle in complex traffic conditions. Our work has the following major contributions:

- This paper designs a vehicle-road Co-Interaction Controller (CIC) adopting nonlinear model-based predictive control algorithm to avoid or mitigate vehicle impact during critical traffic situations for multi-vehicle traffic system based on the vehicle-road key parameters prediction using Vehicle-to-Infrastructure (V2I) communication capability in addition to radar for longitudinal vehicle control.
- A hierarchy control strategy with twin loops is designed as a decision-making module for CIC to optimize the

multi-vehicle coordinated system and braking force allocation using the key predictive parameters of the maximum ground friction through vehicle-road data for multi-vehicle safety controller.

- In addition to speed and distance between vehicles,the vehicle-road maximum friction coefficient is an important parameter that affects the safety of vehicles.Intelligent vehicle networking with data driven function is used to collect the key vehicle-road interaction data and the CHGA is employed to estimate those parameters between road and vehicle,which can be used to assess the degree of collision risk.

In addition, low-level controller allocates realized forces with NFTSM Electronic Brake System (EBS) [1]-[3]. Moreover, an EBS is proposed to track the control target from the high-level controller of CIC quickly using the NFTSM method. Finally, simulations and analysis under different traffic conditions are proposed to verify the optimization and system characteristics of vehicle-road co-interaction system.

II. Literature Review

For traditional transportation systems, the vehicles active safety focus on the active control aiming at the vehicle itself. For example, ABS is used to provide maximum friction between tire and road and maintain braking stability of the vehicle [4]-[6]. Electronic Stability Control (ESC) is proposed based on existing ABS controlling the braking force of different wheels to improve the vehicle yaw stability [7]-[9]. In addition, the Four-wheel Steering System is established to control front and rear wheels simultaneously to improve the vehicle steering stability [10]-[11]. However, most of the mentioned active control systems mainly focus on a single or partial function, not coordinate conflicts among them. The integrated control system is considered as a promising solution to address this challenge [12]-[15].

Fig. 1. Vehicle road coordination technology with V2X [16].

In recent decades, with increasing speed and shortening inter-vehicle distance on the road, the coupled characteristics between multi-vehicles and roads are becoming hot research topics. In Fig.1, promoting intelligent vehicle technology, automatic driving technology, V2X communication technology is being accelerated into vehicle control and data exchange among driver, vehicle and surroundings [17]-[20].

We are rapidly developing advanced wireless vehicle communication technologies between vehicle and vehicle (V2V), vehicle and X device (V2X) [21]-[23](Fig.1). Based on the communication technology,cruise controller is used to improve traffic capacity using cooperative adaptive methods effectively [24]-[25]. Multiple vehicle and traffic information is fused and applied using those communication technologies for active collision avoidance technology vehicles on the road, such as warning of collisions, steering assist control, etc. [26]-[30]. From existing and rapidly evolving types of advanced driver assistance systems (ADAS) to the high-level automation intelligent unmanned driving vehicle[31]-[33], the goal of fully intelligent transportation technology is drawing research attention using multi-sensor information fusion technology [34]-[38]. This is different to Front Collision Warning which only warns the potential collision risks [39]-[42].

Furthermore, key factors affecting vehicle safety include the traffic conditions (e.g. vehicles type, road types, driver's behaviors) and vehicle-road traffic prediction [43]-[44]. The data of traffic, road and vehicles are collected and processing from vehicle-road detectors and sensors [45]-[46]. Furthermore, Dedicated Short Range Communication (DSRC) is a dedicated wireless communication protocol in the field of ITS that is specially used for vehicles with other on-board sensors, as vehicle radar system and GPS [47]-[50]. In addition, the key information of vehicles on the roads and driving traffic environment can be collected and transmitted by V2X system. Therefore, the sensors of vehicles and driving traffic environment can collect necessary driving information for ITS or Intelligent autonomous driving system using vehicular network technologies, such as V2V and V2I [51]-[54].

III. System Description

For this work, we consider a vehicle-road coupled dynamics model for vehicle collision avoidance system with key predictive parameters,such as the maximum ground friction through vehicle-road data, for multi-vehicle safety controller. This model includes the closer multi-vehicle conditions, i.e. vehicles that are longitudinally coupled and affected by each other with the smaller inter-vehicle distance and higher speed. The longitudinal maneuver of any vehicle may request other related vehicles to take corresponding active safety operation.

For the coupled multi-vehicle scenarios on the highway, its group boundaries depend on the following key factors:

1) The types of related vehicles.
2) Corresponding maximum deceleration.
3) Current speed of the related vehicles and highway conditions.
4) Corresponding friction force conditions.
5 Vehicle network communication capabilities.

In particular, the wireless network plays an important role in transmitting required information for the co-interaction controller. The information includes vehicle types, deceleration and capabilities. It is assumed that vehicle and traffic information are uploaded using the vehicular network. These key factors should be analyzed and modeled using mathematical method to meet real-time requirements. Therefore, it is possible and necessary to design coordinated control system for coupled vehicles.

The scheme of vehicle-road co-interaction system with vehicle networking communication and coordinated control system is shown in Fig.2. Vehicle-road coupled system including traffic conditions and individual vehicle states is decoupled and modeled. The different dynamic interactive characteristics of individual vehicles can be captured using intelligent computing and prediction technology based on vehicle network. Finally, Co-Interaction Controller (CIC) is designed using the proposed two-level framework. In transportation systems, vehicles and roads are normally treated as independent systems for longer inter-vehicle distance and simpler traffic environment, and vehicles are often seen as rigid body points. However, with the shortening inter-vehicle distance and increasingly complex traffic environment, investigating the coupled vehicle and road is becoming more critical. This is particularly important for intelligent automatic driving vehicles, as shown in Fig.3.

From the structure of vehicle-road co-interaction system in Fig.2 and vehicle-road coupled-interaction system in Fig.3, the steps are included in CIC of vehicle-road co-interaction system:

- Step 1: Historical data and Real-Time data of vehicle-road coupled-interaction system is collected and uploaded to the cloud, which is large, exceeding the storage capacity of the on-board equipment.And historical data and real-time data hybrid splicing method is used to improve the real-time performance of cloud computing.
- Step 2: Vehicle-road key prediction parameters are obtained using data training and mining technology based collected data. Such as, the maximum adhesion coefficient between vehicles and the changing road surface is predicted using artificial intelligence algorithm. The estimation model is difficult to design, and the amount of calculation is large, which exceeds the calculation capacity of the general on-board computing unit. This is a difficult point, and it is also the focus of this paper.
- Step 3: The maximum deceleration and minimum safety distance of vehicles on different road surface is estimated based on the obtained prediction parameters, which is important safety rule basis of vehicle-road coupled-interaction system.
- Step 4: The vehicle-road co-interaction system is optimized and controlled by CIC using predicted parameters as control constraints.
- Step 5: Rolling optimization strategy is used to avoid collisions or mitigate the impact during critical situations. The relevant data is monitored and collected, return to Step 1.

IV. Vehicle-Road System

In this section, the dynamics models of vehicle and the vehicle-road interactive system are analyzed and established with vehicle networking communication.

A. Vehicle Modeling

Vehicle model with longitudinal motion system is established. The coordinated cost function of tracking safety and comfort of the multi-vehicle interaction system including vehicle states, surroundings information, and vehicle dynamics can be analyzed in provided mathematical model. Here, vehicle states and surroundings information are linked through the relative distance and speed from the follow-up vehicle to the target vehicle. The state variables to represent vehicle dynamics are linked through speed and acceleration of the vehicle. Assuming that the influence of frictional resistance, vertical and lateral force of the vehicle is negligible and the Vehicles moves in a flat plane, the vehicle system dynamics equation including vehicle and surroundings information can be stated as follows:

$$\begin{cases} \frac{\mathrm{d}S_{Long,i}}{\mathrm{d}t} = u_i \\ \frac{\mathrm{d}u_i}{\mathrm{d}t} = \frac{1}{m_i}\sum F_{Lj,i}\left(m_i, \mu_{L,i}\right) \\ j = 1,2,3,4 \\ i = 1,2,....,N \end{cases} \tag{1}$$

where

$S_{Long,i}$ is the longitudinal distance of i-th vehicle.
u_i is the longitudinal speed.
$F_{Lj,i}$ is i-th vehicle longitudinal force of four wheels.
m_i for i-th vehicle mass.

B. Multi-Vehicle Coupled-Interaction Modeling

To consider V2I network and multi-vehicle coupled-interaction system properties, the speed and distance between front and rear vehicles is modeled between zero (stopped car) and limit (maximum and minimum safety value). To apply these equations, the longitudinal distance to the inertial coordinate system for each vehicle, the speed and distance between front and rear vehicles at each time step should be obtained. Multi-vehicle dynamic relationship on the upstream road is stated in Fig.2, which is the next to affect each other for those follow-up vehicles. Then, the following equations, which is the multi-vehicle coupled-interaction modeling based the vehicle modeling equation(1), are implemented:

$$\begin{cases} \mathrm{Spd}_{Dif,i} = u_i - u_{i-1} \\ \mathrm{Dist}_{Dif,i}=\mathrm{Sld}_{i-1} - \mathrm{Spd}_i \\ S_{Long,i} = S_{Long,0} - \sum_{1}^{i} \mathrm{Dist}_{Dif,i} \\ i = 1,2,....,N \end{cases} \tag{2}$$

where

$Spd_{Dif,i}$ is the speed difference between front and rear vehicles.
$Dist_{Dif,i}$ is the distance between front and rear vehicles.
$S_{Long,i}$ for the longitudinal distance between vehicles in inertial coordinate system.

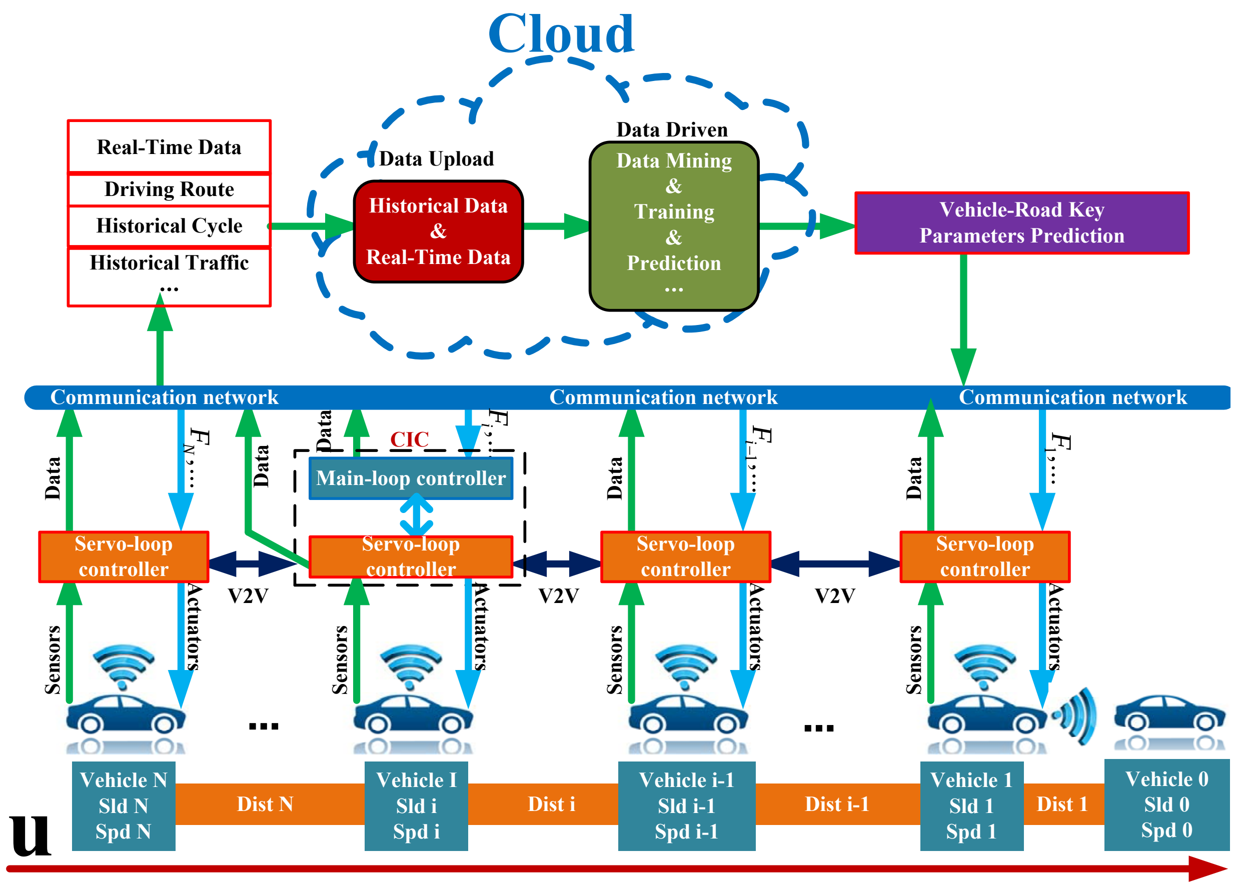
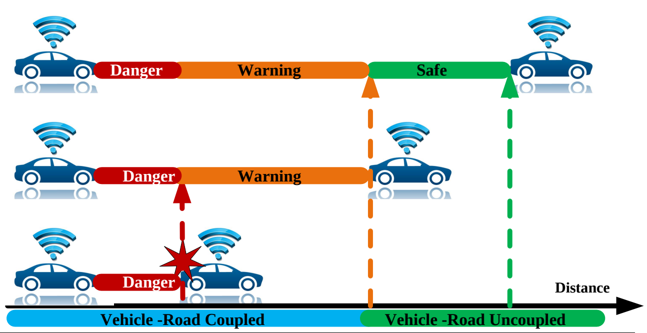


Fig. 2. Scheme of vehicle-road co-interaction system.



Partial judgment rules of vehicle-road coupled-interaction system (for example)				
Road ↓	Vehicle →	High speed & Medium distance	Medium speed & Medium distance	Low speed & Medium distance
Good road		Danger	Warning	Safe
Ordinary road		Danger	Danger	Warning
Slippery road		Danger	Danger	Danger

Fig. 3. Schematic of vehicle-road coupled-interaction system.

C. Tire-Road Friction Estimator of Infrastructure Center

Tyre-road friction force is important for the CIC,which can be estimated for the maximum ground friction through vehicle-road data, and provide key predictive parameters for multi-vehicle safety controller. However, it varies for different vehicles in different driving environments. This is a key variable which needs to be estimated. Model-based estimation method is used to estimate the friction between tire and ground using the pressure sensors mounted in EBS. Magic Formula is selected and used as an estimation tyre model [55], which is a widely recognized and applied model in the automotive field. The mathematical equation of the model is as follows:

$$\begin{aligned}\mu_L &= \mu(\lambda, B_L, C_L, D_L, E_L) \\ &= D_L \sin\left[C_L \arctan\{B_L\lambda - E_L(B_L\lambda - \arctan(B_L\lambda))\}\right]\end{aligned} \tag{3}$$

where

μ_L - friction coefficient
λ - slip
B_L - stiffness factor
C_L - shape factor
D_L - peak value
E_L - curvature factor

For B_L, C_L, D_L and E_L changing as vehicle and road conditions, they need to be estimated and updated dynamically. A performance index $\widehat{PI}_{i\_tyre}$ is mean squared index for the weighted errors of B_L, C_L, D_L and E_L.Then, taking into account the physical constraints of the variables, they are estimated based constrained optimization algorithm as:

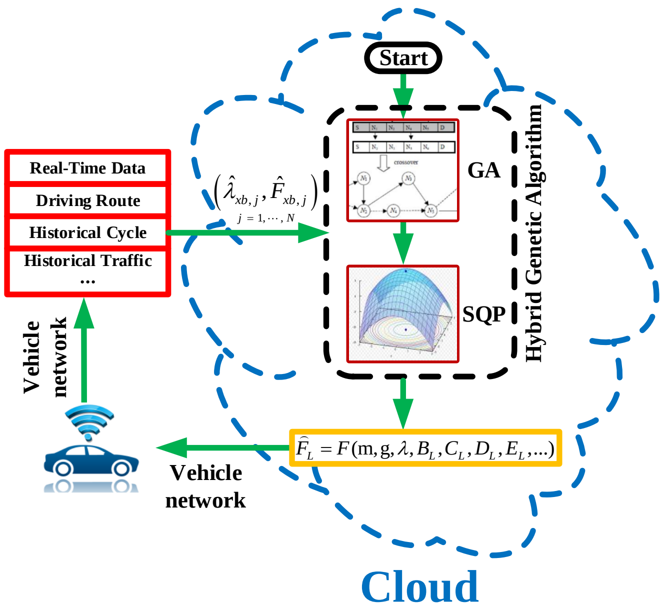


Fig. 4. Flow chart of estimation of desired longitudinal force.

$$\begin{aligned} \min_{x} \quad & \widehat{PI}_{i\_\text{tyre}} = \sum_{i=1}^{N} w_i \left[\hat{F}_{\text{xb},i} - F_z \mu \left(\hat{\lambda}_{\text{xb},i}, x^{\text{T}} \right) \right]^2 \\ & x = [B_L, C_L, D_L, E_L]^{\text{T}} \\ \text{s. t.} \quad & x_{\min} \leq x \leq x_{\max} \end{aligned} \tag{4}$$

where

w_i is the weighted index.

$x_{\max}$ and $x_{\min}$ are the maximum and minimum constrained boundary values of B_L, C_L, D_L and E_L respectively.

CHGA is used as an optimization algorithm of $\widehat{PI}_{i\_\text{tyre}}$, which can achieve complementary advantages of genetic and active-set sequential quadratic programming optimal algorithm. The combined optimization structure diagram of estimated longitudinal force is proposed in Fig.4.

For Genetic Algorithm(GA), the optimal variables of B_L, C_L, D_L and E_L can be encoded into GA binary string using fixed-length data type as:

$$\underbrace{\overbrace{B_L}^{S_1}, \overbrace{C_L}^{S_2}, \overbrace{D_L}^{S_3}, \overbrace{E_L}^{S_4}}_{string}$$

Assuming that B_L is represented by N1 bits,$C_L$is represented by N2 bits,D_L by N3 bits and E_L by N4 bits, then, the sum of bits for the chromosome in GA of B_L, C_L, D_L and E_L is N1+N2+N3+N4, get

$$\begin{aligned} & S_1 = \underbrace{10 \cdots 0100100}_{N1bits} \\ & S_2 = \underbrace{00 \cdots 010101}_{N2bits} \\ & \cdots \quad \cdots \\ & S_4 = \underbrace{10 \cdots 000101}_{N4bits} \end{aligned}$$

Convert those binary values to corresponding decimal values can be expressed as follows:

$$\begin{aligned} & B_L = B_{L,\min} + \tfrac{d_{B_L i}}{2^{N1}-1} \left(B_{L,\max} - B_{L,\min} \right) \\ & C_L = C_{L,\min} + \tfrac{d_{C_L i}}{2^{N2}-1} \left(C_{L,\max} - C_{L,\min} \right) \\ & \cdots \quad \cdots \\ & E_L = E_{L,\min} + \frac{d_{E_L i}}{2^{N4}-1} \left(E_{L,\max} - E_{L,\min} \right) \end{aligned}$$

where, $d_{B_x i}$,$d_{C_x i}$,$d_{D_x i}$, $d_{E_x i}$ one by one corresponds to the binary value of B_L, C_L, D_L and E_L.

D. Evaluation of Multi-Car Interaction System

The interaction performance of multi-car system using CIC are evaluated with two key variables. One is Time to Collision (TTC), which is interval time index between two coupled vehicles which means that the two cars will collide after this period, if the driver or active control system does not take effective operating instructions. TTC is stated as:

$$\text{TTC}_i = \frac{S_{\text{Long,Dif},i}}{u_{\text{Dif},i}}. \tag{5}$$

As above, the other is Warning Index (WI), which is interval time index between two related vehicles which means that the two cars need to take necessary avoidance actions after this warning time has elapsed. WI is described as:

$$\text{WI}_i = \frac{S_{\text{Long},i} - S_{\text{Long,Bk},i}}{S_{\text{Long,Wr},i} - S_{\text{Long,Bk},i}} \tag{6}$$

$$\begin{aligned} S_{\text{Long,Bk},i} = & u_{\text{Long},0} T_{\text{Bk,Delay}} + u_{\text{Long},0} T_{\text{Bk,Cmd}} + \frac{1}{2} \int_0^{T_{\text{Bk,Cmd}}} \dot{u}_{\text{Long}} dt \\ = & u_{\text{Long},0} T_{\text{Bk,Delay}} + \frac{u_{\text{Long},0}^2 - \left(u_{\text{Long},i} - u_{\text{Long},0} \right)^2}{2 \bar{a}_{\text{Bk,max}}} \end{aligned} \tag{7}$$

$$\begin{aligned} S_{\text{Long,Wr},i} = & u_{\text{Long},0} T_{\text{Bk,Delay}} + u_{\text{Long},0} T_{\text{Bk,Cmd}} \\ & + \frac{1}{2} \int_0^{T_{\text{Bk,Cmd}}} \dot{u}_{\text{Long}} dt + u_{\text{Long},0} T_{\text{Resp,Delay}} \\ = & \frac{u_{\text{Long},0}^2 - \left(u_{\text{Long},i} - u_{\text{Long},0} \right)^2}{2 \bar{a}_{\text{Bk,max}}} \\ & + u_{\text{Long},0} T_{\text{Bk,Delay}} + u_{\text{Long},0} T_{\text{Resp,Delay}} \end{aligned} \tag{8}$$

where

$S_{\text{Long,Bk},i}$ is the sum of braking distance of i-th vehicle caused by the factors mentioned above.

$S_{\text{Long,Wr},i}$ is the distance from i-th vehicle to target collision vehicle.

$u_{\text{Long},0}$ is longitudinal initial speed.

$u_{\text{Long},i}$ is longitudinal final speed after braking operation.

$\bar{a}_{\text{Bk,max}}$ is the equivalent value of the maximum average value of braking acceleration,which is estimated and predicted based on vehicle-road data for multi-vehicle safety controller.

$T_{\text{Bk,Delay}}$ is delay caused by operating mechanism of braking system.

$T_{\text{Bk,Cmd}}$ is the vehicle braking system delay.

$T_{\text{Resp,Delay}}$ is human physiological system delay caused by the driver's physiological structure.

From the equation (5), get:

$$\mathrm{TTC}_i^{-1} = \frac{u_i}{S_{\mathrm{Long},i}}. \tag{9}$$

To facilitate analysis, TTC is normalized as:

$$\mathrm{Idx}_{\mathrm{Norm,TTC}} = \frac{\left|\mathrm{TTC}^{-1}\right|}{\left|\mathrm{TTC}_{\mathrm{Thrd}}^{-1}\right|}. \tag{10}$$

where $\mathrm{TTC}_{\mathrm{Thrd}}^{-1}$ is threshold of TTC^{-1}. $\mathrm{Idx}_{\mathrm{Norm,TTC}}$ is normalized parameter of TTC, indicating the degree of collision risk.

Similarly, WI is normalized as:

$$\mathrm{Idx}_{\mathrm{Norm,WI}} = \frac{|\mathrm{WI}_{\max} - \mathrm{WI}|}{|\mathrm{WI}_{\max} - \mathrm{WI}_{\mathrm{Thrd}}|}. \tag{11}$$

where $\mathrm{WI}_{\mathrm{Thrd}}$ is threshold of WI. $\mathrm{Idx}_{\mathrm{Norm,WI}}$ is normalized parameter of WI, indicating the degree of warning collision.

V. Controller Design

In this section, the CIC and execution controller on the lower level is analyzed and established.

A. Upper Level Controller Design

The multi-car and road optimized interactive control system is to be established and discretized for CIC as:

$$\begin{cases} e_{S_{Long,i}}(k+1) = S_{Long,i}(k+1) - S_{des,Long,i}(k+1) \\ e_{Dist_i}(k+1) = Dist_i(k+1) - Dist_{des,i}(k+1) \\ e_{Spd_i}(k+1) = Spd_i(k+1) - Spd_{des,i}(k+1) \\ Spd_{des,i} = Spd_{i-1} \\ Dist_{des,i} = Max\left\{\psi_{i,1} \times Spd_i, \psi_{i,2} \times Spd_{i,\lim it}\right\} \\ \qquad + \psi_{i,3} \times |Spd_i - Spd_{i-1}| \\ S_{des,Long,i} = Sld_{i,0} - \sum\limits_{1}^{i} Dist_{des,i} \\ S_{Long,i}(k+1) = S_{Long,i}(k) + Spd_i(k)\Delta t + \frac{1}{2m_i}\Delta t^2 F_i(k) \\ Spd_i(k+1) = Spd_i(k) + \frac{1}{m_i}\Delta t F_i(k) \\ Dist_i(k+1) = S_{Long,i}(k+1) - S_{Long,i}(k+1) \\ i = 1, 2, ..., N \end{cases} \tag{12}$$

where

$e_{S_{Long,i}}$ is the error of $S_{Long,i}$.
e_{Dist_i} is the error of $Dist_i$.
e_{Spd_i} is the error of Spd_i.
$Dist_{des,i}$ and $Spd_{des,i}$ are the target value.
$F_i(k)$ is control force for i-th vehicle.
$\psi_{i,1}$,$\psi_{i,2}$ and $\psi_{i,3}$ are weighted factors.
Δt is discrete sampling time.

The upper level controller of CIC is designed to optimize multi-vehicle interaction system including multiple factors, such as driver factors, traffic environmental factors, driving factors and vehicle factors. The optimization performance index of the controller should be established, including these coupling interactions, such as WI and TTC. Then, taking physical constraints of these traffic factors, the multi-objective optimization problem is described as:

$$\begin{aligned} \min_{X,u_{Con}} PI = {}& \frac{1}{2}{u_{Con}}^T Q_x u_{Con} + \frac{1}{2}X^T Q_{PI} X \\ & + \sum_{i=1}^{N}\Big[w_{TTC,i}(Idx_{Norm,TTC})^2 \\ & + w_{WI,i}\delta_{WI,i}(Idx_{Norm,WI})^2\Big] \end{aligned} \tag{13}$$

$$u_{Con} = [F_1, F_2, ...F_N]^T$$

$$s.t.\ u_{ConLim,min} \le u_{Con,i} \le u_{ConLim,max} \tag{14}$$

where

$Q > 0$ is weighted matrix for input control variables.
$u_{ConLim,min}$ and $u_{ConLim,max}$ are the input estimated constraints from vehicle-road communication system using V2I,which are the key estimated and predicted parameters using Magic Formula model and vehicle-road data for multi-vehicle safety controller.
$X = \left(e_{S_{Long,1}}, e_{Dist_1}, e_{Spd_1}, ..., e_{S_{Long,N}}, e_{Dist_N}, e_{Spd_N}\right)^T$ is the penalty vector.
Q_{PI} is the dynamic state variable penalty matrix.
$w_{TTC,i}$ is the weighted factor of $Idx_{Norm,TTC}$.
$w_{WI,i}\delta_{WI,i}$ is the weighted factor of $Idx_{Norm,WI}$..
Δt is discrete sampling time.

Then,have:

$$\delta_{\mathrm{WI},i} = \begin{cases} 1, & \mathrm{WI} \le \mathrm{WI}_{\mathrm{Thrd}} \ \&\ \mathrm{T}_{\mathrm{WI}} \ge \mathrm{T}_{\mathrm{WI,Thrd}} \\ 0, & \text{otherwise} \end{cases} \tag{15}$$

$$\delta_{\mathrm{TTC},i} = \begin{cases} 1, & \begin{array}{l} \mathrm{WI} \le \mathrm{WI}_{\mathrm{Thrd}} \ \&\ \mathrm{T}_{\mathrm{WI}} \ge \mathrm{T}_{\mathrm{WI,Thrd}} \\ \ \&\ \ \mathrm{TTC}^{-1} \ge \mathrm{TTC}_{\mathrm{Thrd}}^{-1} \end{array} \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

B. Lower Level Execution Controller Design

The lower level controller of CIC is adopted to execute control instructions sent by the upper controller, which should be robust and adaptive under different vehicle-road conditions. Therefore, in this subsection, a robust lower level execution controller based on EBS is proposed to track the upper control targets.

Because of rapidity, accuracy to control error and robustness to external sensor device disturbance, sliding mode control is widely used in nonlinear control. However, it is a progressive convergence nonlinear control algorithm which maybe not meet the control requirements of high-speed multi-vehicle system in some special conditions, for extreme driving conditions. Terminal Sliding Control (TSMC), for its merit of convergence in a limited time, can be used to improve control accuracy and time effectively maintaining all the control advantages of sliding mode control. However, TSMC tends to converge slowly when the working point of the controlled system is far from the stable balance control point. To address this issue, the NFTSM is chosen to improve the tracking accuracy and reduce convergence stabilization time of the control system. Furthermore, a nonlinear terminal attractor is designed for the NFTSM, which can reduce the chattering convergent problem of the sliding mode controller. Then, a NFTSM with nonlinear terminal attractor is designed based the EBS for the lower level controller of CIC.

First of all, the sliding mode surface of the lower level controller is stated as:

$$s = \dot{e} + \alpha e + \beta e^{\frac{p}{q}} \tag{17}$$

where

$e \in R$.

α is coefficients ,and meet $\alpha > 0$.

β is coefficients.

q is a positive odd variable, and meets the ranges and relationships as $p < q < 2p$.

The tracking error of slip rate between the working value and reference value is:

$$e = \lambda - \lambda_{\text{Ref}}. \tag{18}$$

We get

$$\begin{aligned}\dot{e} =& \frac{-r_b^2 m_{ij} g \mu \left(B_{ij}, C_{ij}, D_{ij}, E_{ij}, \lambda\right) / J + (1-\lambda)\, \dot{u}}{u} \\ &+ \frac{T_b r_b}{uJ} - \dot{\lambda}_{\text{Ref}}\end{aligned} \tag{19}$$

where

$m_{ij} g$ is the vehicle weight.

$\mu \left(B_{ij}, C_{ij}, D_{ij}, E_{ij}, \lambda\right)$ is the Magic Formula(shown in Equation(3)).

Due to the non-linear switch control, the FTSM is prone to generate near-balance point chattering problems which reduces the smoothness of the control system. To solve this problem, a non-linear attractor is used for FTSM controller, which can control the system to converge towards the equilibrium point in a limited time, and improve the tracking accuracy and robust performance of the control system. Then, an attractor with a fractional order control variable of $e^{\frac{p}{q}-1}$ is designed as:

$$\dot{s} = \left(-\phi s - \gamma s^{\frac{m}{n}}\right) e^{\frac{p}{q}-1}$$

where

ϕ is coefficients with $\phi \in R^{+}$.

γ is coefficients with $\gamma \in R^{+}$.

m is a positive odd variable, n is a positive odd variable, and meet requirements of $0 < m/n < 1$.

Combine the above equation, the control rate of NFTSM is:

$$\begin{aligned}T_b =& \frac{uJ}{r_b}\left[\frac{q}{\beta p}\left(-\ddot{e} e^{1-\frac{p}{q}} - \alpha \dot{e} e^{1-\frac{p}{q}} + \phi s + \gamma s^{\frac{m}{n}}\right) - \dot{\lambda}_{\text{Ref}}\right] \\ &- \frac{uJ}{r_b} \frac{-r_b^2 m_{ij} g \mu \left(B_{ij}, C_{ij}, D_{ij}, E_{ij}, \lambda\right) / J + (1-\lambda)\, \dot{u}}{u}\end{aligned} \tag{20}$$

C. Estimator and communication of vehicle-road system

Tyre-road friction force is important for the CIC,which should be estimated for the maximum ground friction through vehicle-road data, and provide key predictive parameters for multi-vehicle safety controller.To analyze the estimation capabilities of the proposed estimator for the vehicle-road interaction key parameters using vehicle networking infrastructure, the tire-road adhesion coefficient is divided into three regions including I, Area II and Area III according to the slip rate (represented in Fig.5(a)), as:

- Area I: Low slip ratio area. This area has less braking force with more applications.
- Area II: High slip ratio area. Usually occurs in emergency braking situations, generally ABS will work.
- Area III: Sliding unstable region. Usually occurs on vehicles without ABS system, ignored in this paper.

To improve the effectiveness of designed estimator, the real-time data $\hat{F}_{xb}$ and $\hat{\lambda}_{xb}$ needs to cover all of the above areas, which is difficult during normal driving operations. However, the problem can be solved using collected real-time data and stored historical data in the data center from the vehicle-road infrastructure center.

Simulations are designed to analyze and verify the proposed identification scheme which are listed in Fig.5. In Fig.5(b) and Fig.5(e), the compare results are shown using the real-time data of Area I without the data of Area II and have the maximum error of 0.07.For containing the nonlinear characteristics of the tire model, the compare results using the real-time data of Area II is better than the first case and have the maximum error of 0.03, as listed in Fig.5(c) andFig.5(f).The optimized data comparison with both area I and II data reduced 7.42% and 2.89% separately with the V2I communication and optimization algorithm, as shown in Fig.5(d). The results prove that the identification curve matches the model value, which means that the identification accuracy of the proposed estimator can be assured by the designed CHGA algorithm using Vehicle-to-Infrastructure (V2I) communication capability in addition to radar for longitudinal vehicle control.

D. Verification of the Vehicle-Road Coupled-Interaction System

In this subsection, simulations under typical scenarios are designed to test the control capability of the CIC for the multi-vehicle system consisting of 5 vehicles. In the system, No.0 car is the target car. In those simulations, the control system is designed including the necessary vehicle factors,driver factors and traffic information. The comparisons of the vehicles with CIC and the vehicles without CIC were analyzed under different driving and traffic scenarios.

The following information of driving and traffic scenarios (represented inFig.6−Fig.8)):

The following exchange of information (represented in Fig.6, Fig.7 and Fig.8):

- Vehicle to Infrastructure (V2I). The information of the related traffic and vehicle states, such as the target vehicle, following vehicles and other vehicles in the vehicle

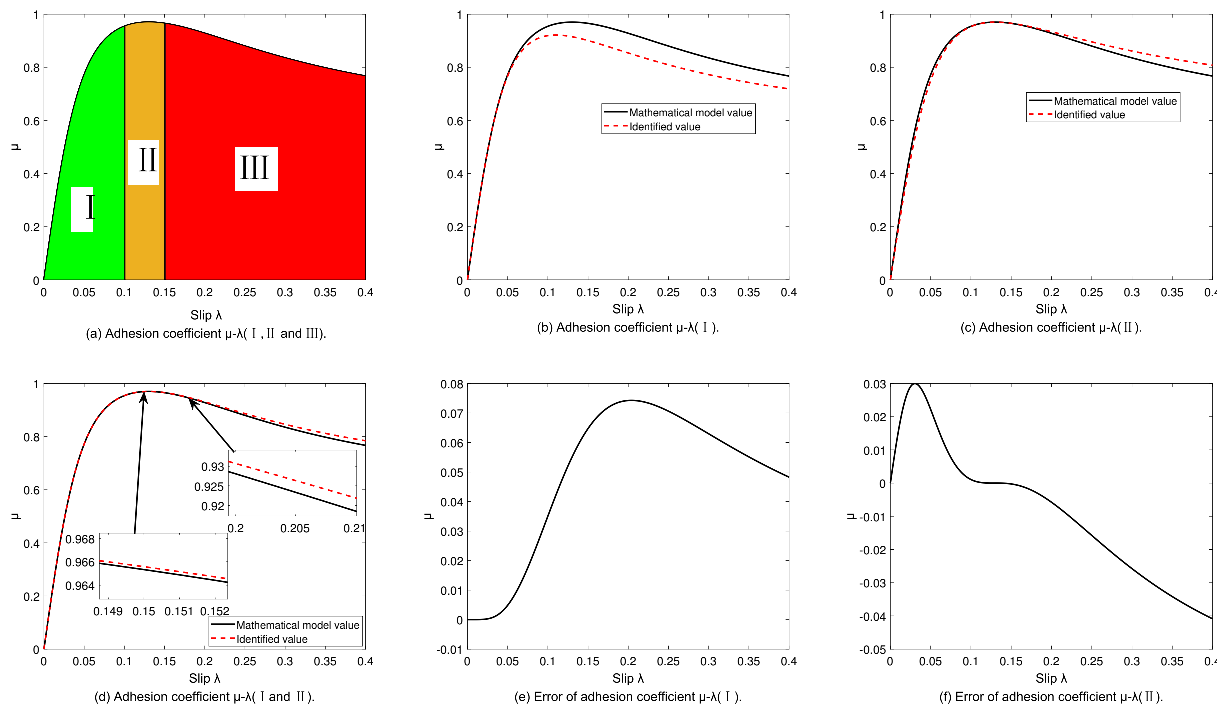


Fig. 5. Relationship between slip ratio and adhesion coefficient.

group is provided and exchanged between the vehicle and the Traffic Infrastructure Centre.

- I2V: The Traffic Infrastructure Centre provides the traffic and vehicles information mentioned above to slow down or speed up cyclically the cooperative vehicles.
- V2V: Vehicle to Vehicle communication is necessary to improve the cooperative system using more real-time information in an indirect way. So, the system can make the most of the provided information from the Transport Infrastructure Control Centre and vehicles with the proposed controller or sensors.

1) Case A: Simulation of vehicle rear-end scene in front-vehicle speed reduction using AEBS without CIC: This scenario is used to simulate traffic scenarios that may cause a collision due to vehicle congestion caused by the decelerated vehicle in front of the related vehicle group (in Fig.6).We assume that abnormal and sudden lane merging,which also a typical dangerous condition for high-speed fork driving. The information of vehicles and their driving environment are effectively transmitted and exchanged through V2I communication. equipment. Then, the cooperative vehicles controlled by only AEBS. It is described as follows:

a) Tthe target vehicle speed slows from 80 km/h to 50 km/h;
b) The vehicles No.1 to No.4 with the initial speed: 80 km/h;
c) Initial vehicle-to-vehicle clearance: 80 m;
d) Warning time before control: 1.4 s.

The analysis results are listed in Fig.7. For the preceding vehicles which is braked to start slowing down, the AEBS of the following vehicles keeps tracking and judges the safety indexes until the dangerous conditions are met and send a hazard warning signal to the related vehicles. After the warning signal, actively activate braking once the dangerous conditions are met. The comparisons of relative distance to No.0 vehicle is shown in Fig.7(a), for the relative distance always greater than zero, there is no collision. And, the changing speed of all the vehicles is shown in Fig.7(d). Evaluation indexes including Warning Index (WI) and Time to Collision (TTC) simulation analysis figures are listed in Fig.7(c) and Fig.7(f), the values are relatively small, the CIC operates autonomous system to avoid rear-end traffic accident between front and rear vehicles. The comparison of dynamic performance is listed in Fig.7(b) and Fig.7(e). It can be found that the speed of N0.4 vehicle which is ontrolled by the AEBS is much faster than other vehicles.

2) Case B: Simulation of vehicle rear-end scene in front-vehicle speed reduction using CIC.: This This scenario is similar to the Case A, however, the cooperative vehicles controlled by CIC using V2I, I2V and V2V communication information, as in Fig.8. It is stated as:

a) Target vehicle speed slows from 80 km/h to 36 km/h;
b) The vehicles No.1 to No.4 with the initial speed: 80 km/h;
c) Initial vehicle-to-vehicle clearance: 45 m.

The simulation analysis information is listed in Fig.9. It pays attention to traffic status of multiple vehicles. Similarly, for the preceding vehicle starting to decelerate causing the following vehicles deceleration. However, different from AEBS, the CIC keeps tracking and judges the safety indexes until the dangerous conditions are met and send a control information to all the related vehicles using V2I, I2V and V2V communication system. The changing speed of all the vehicles is shown in

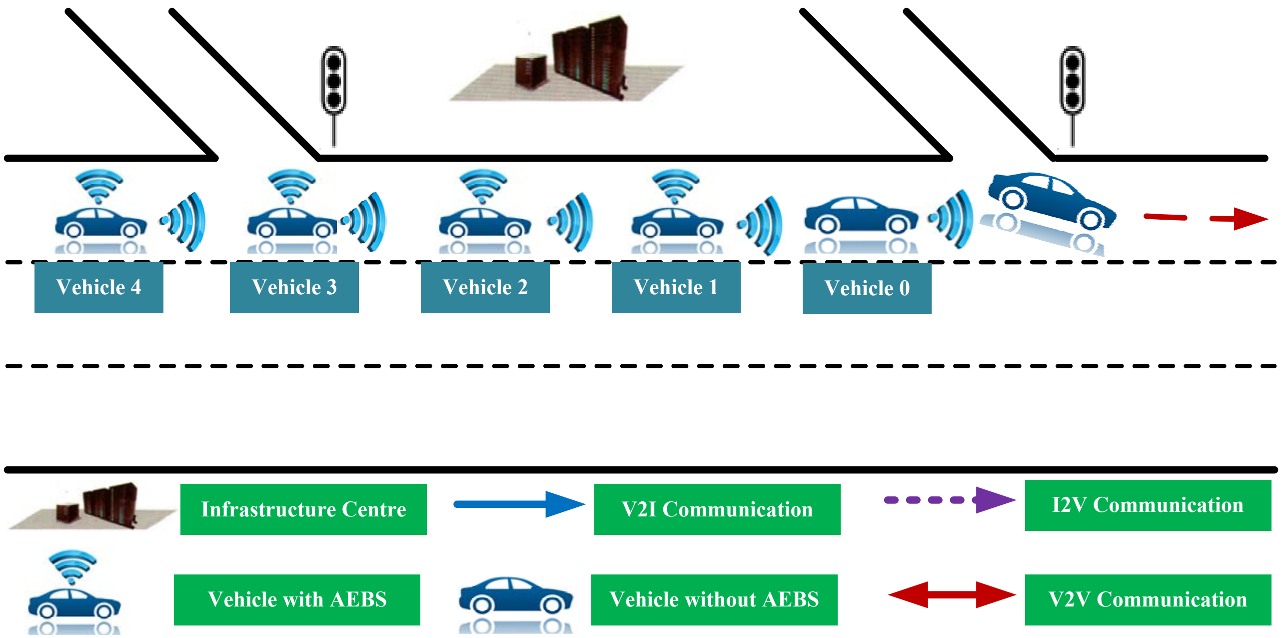


Fig. 6. Scene in front-vehicle speed reduction with AEBS.

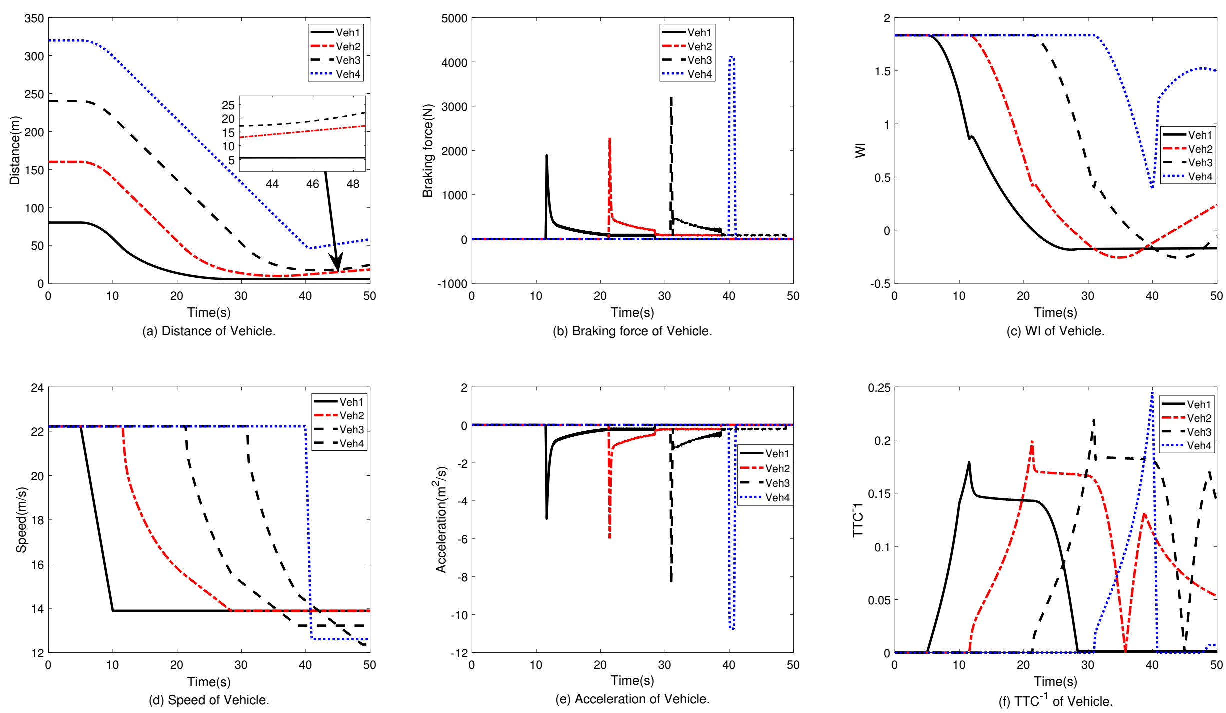


Fig. 7. Simulation results in front-vehicle speed reduction with AEBS.

Fig.9(a), while, all following vehicles can track the speed change of the target vehicle. From Fig.9(b), relative distance can be adjusted with changes in speed, reduced from the initial value of 45m to less than 20m, and always greater than zero, there is no collision. The target distance tracking results of No.1 to No.4 are provided in Fig.9(e)–Fig.9(f) respectively. And,Fig.9(g)–Fig.9(j) represent the results of distance between front and rear adjacent vehicles. From the results, the tracking error of CIC is relatively small and can meet the requirements. Fig.9(k)–Fig.9(n) shows the speed tracking results between front and rear vehicles separately, from the Figure, all vehicles can track the target speed.

3) Case C: Simulation of vehicle rear-end scene in front-vehicle emergency braking using CIC: This scenario is similar

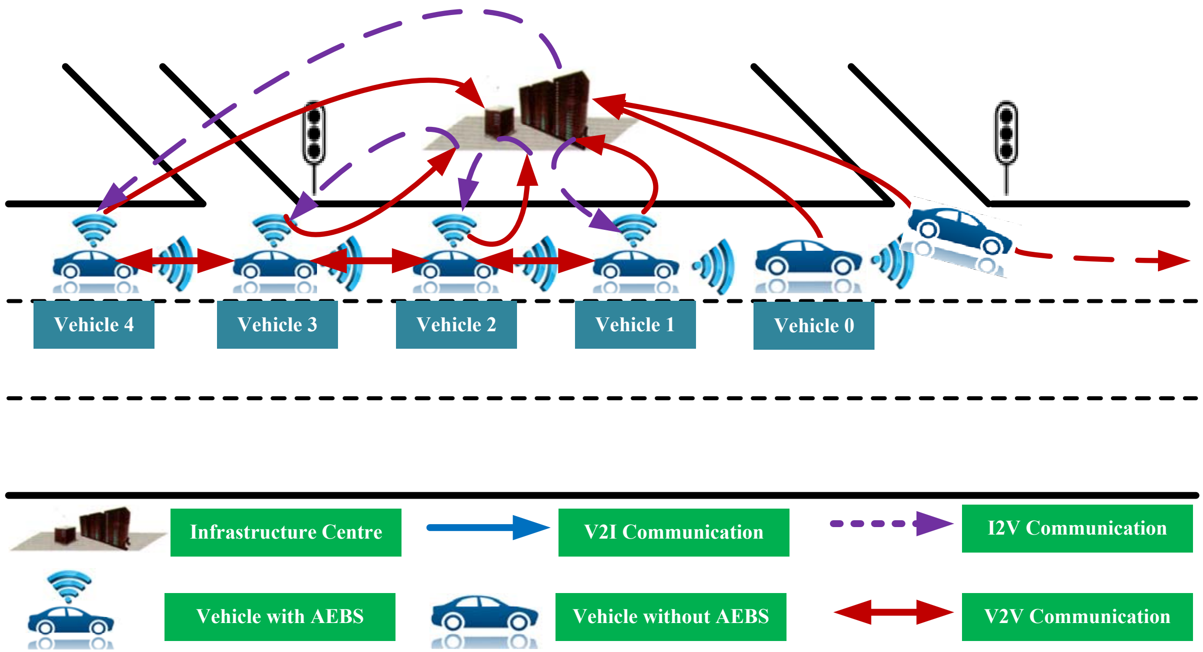


Fig. 8. Scene in front-vehicle speed reduction without CIC.

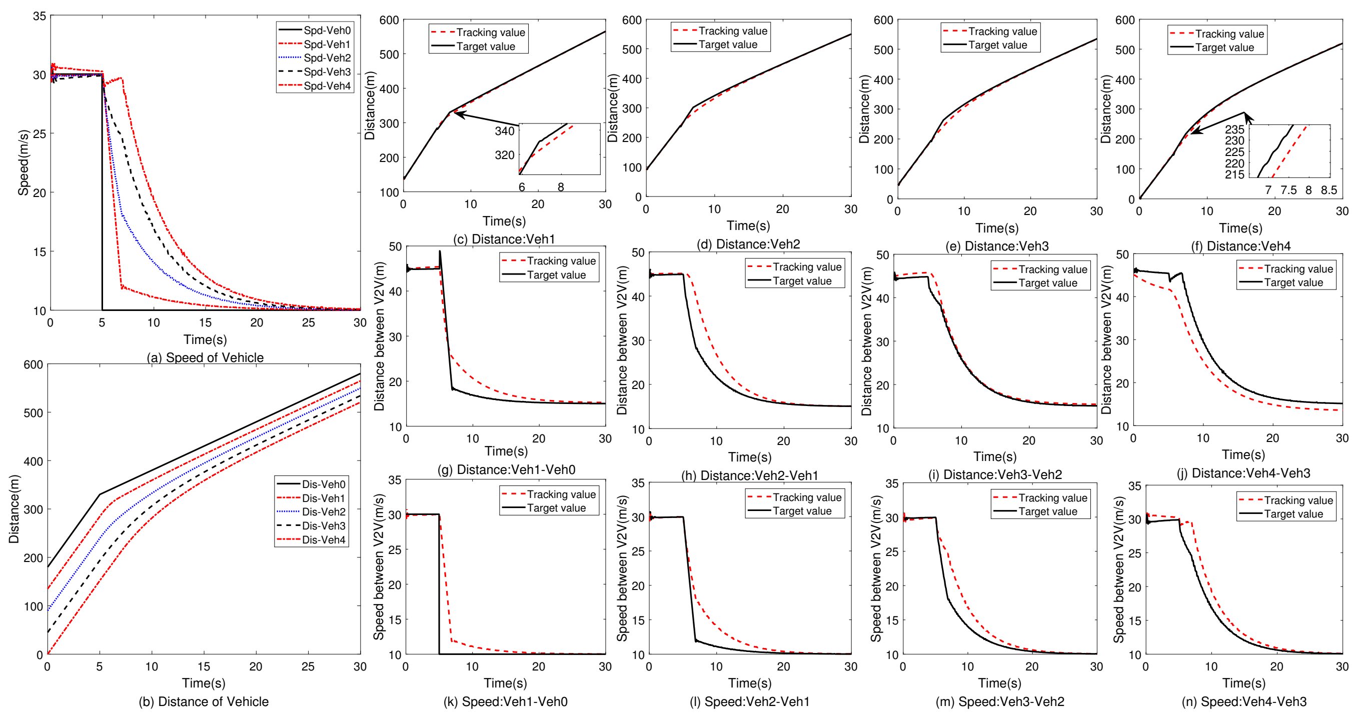


Fig. 9. Simulation results in front-vehicle speed reduction without CIC.

to Case B and is used to simulate a relatively dangerous condition for the front-vehicle emergency braking during high speed driving, as shown Fig.10.. It is described as follows:

a) The target vehicle speed slows from 80 km/h to 0 km/h;

b) The vehicles No.1 to No.4 with the initial speed: 80 km/h;

c) Smaller initial vehicle-to-vehicle clearance: 30 m.

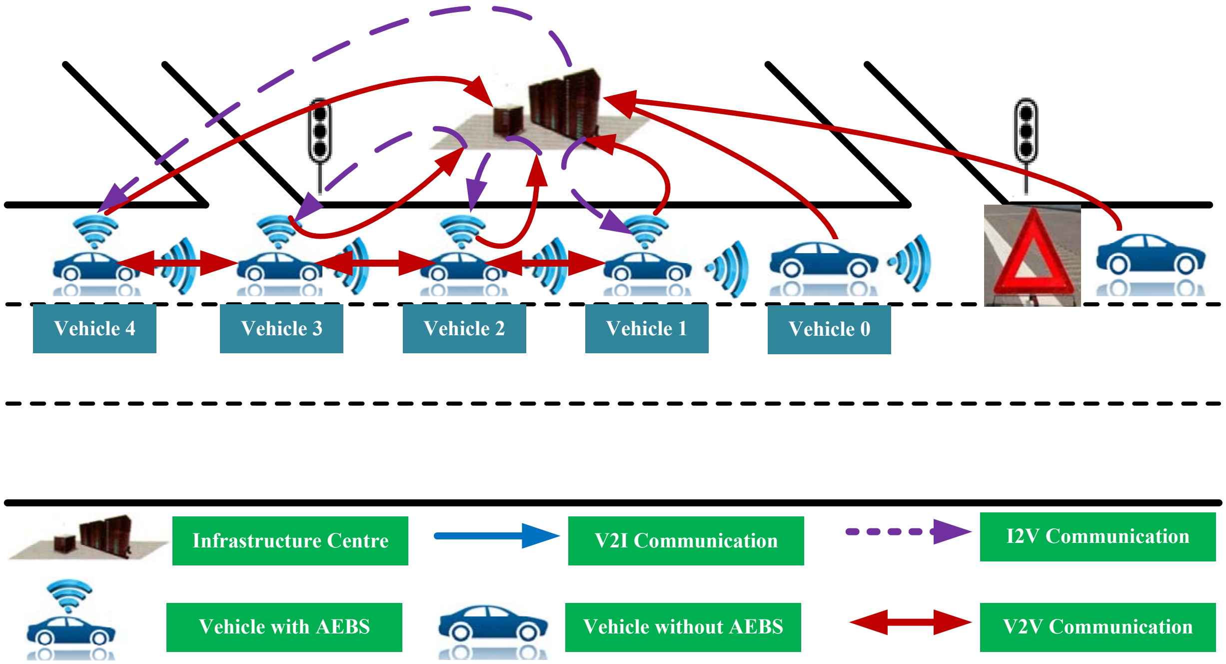


Fig. 10. Scene in front-vehicle emergency braking with CIC.

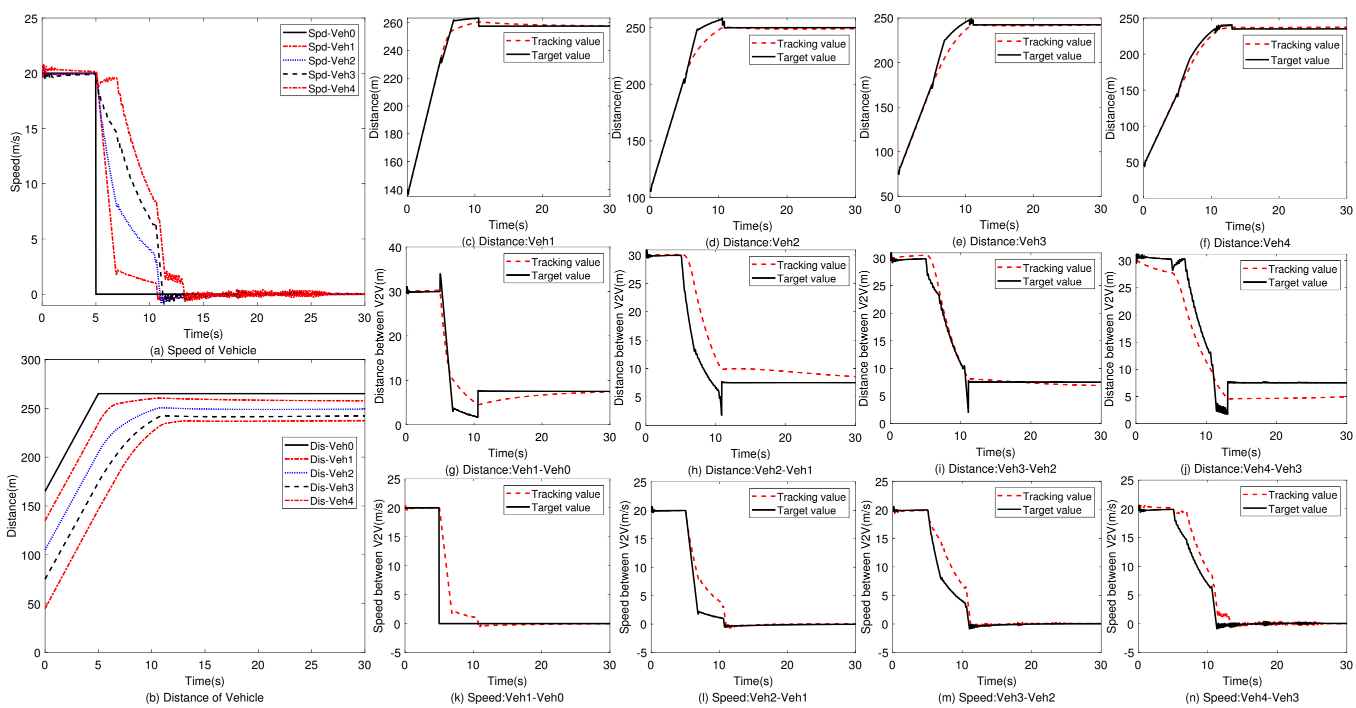


Fig. 11. Simulation results in front-vehicle emergency braking with CIC.

Simulation analysis results are listed in Fig.11. The preceding vehicle is forced to take emergency braking for the temporary faulty stopping of the front vehicle. As a consequence, the following vehicles is controlled and taken emergency braking operations by CIC. The changing speed of all the cars is listed in Fig.11(a), while, all following vehicles can take emergency braking and stopping. From the Fig.11(b), relative distance can be reduced from the initial value of 30m to less than 10m, even less than 3m around 10s. However, it is always greater than zero, which means there is no collision. The target distance tracking results of No.1 vehicle to No.4 vehicle are presented in Fig.11(c)−Fig.11(f) respectively, which show that all the controlled vehicles finally are stopped with a safe distance. Fig.11(g)−Fig.11(j) represent the results of distance between front and rear adjacent vehicles. The results show that there is no collision, which means it is can control the vehicle without collision. Fig.11(k)−Fig.11(n) show the speed tracking results between front and rear vehicles separately, where, all controlled vehicles can track the target speed and stop before a collision.

VI. Conclusion

In this paper, a two-layer hierarchical control system is analyzed and designed to solve the vehicle-road co-interaction and longitudinal collision avoidance problem of multi-vehicles in complex traffic conditions. The main characteristic of proposed system is described as follows:

1) The risk of collision varies with the coupling between the vehicle and the road. For example, the same distance between vehicles, a dry road is safe, while a slippery road may be dangerous.To solve this problem,vehicle-road coupled-interaction system is modeled and analyzed for vehicle-road CIC based on MPC method and vehicle-road key predicted parameters to avoid collisions or mitigate the impact during critical situations for multi-vehicle system.

2) The upper level model prediction controller of integrated CIC is built to decouple the vehicle-road interaction system and optimize the multi-vehicle system based on AEBS using the predicted maximum ground friction through vehicle-road data.

3) Intelligent vehicle networking with data driven function is designed to collect the key vehicle-road related data using V2I communication capability in addition to radar for longitudinal vehicle control. The CHGA is adopted to estimate the key interaction parametric variables between coupled road and the vehicle.

Then, a NFTSM controller for lower level controller of CIC is designed to track the target and converge in a limited time based on EBS. At last, simulations are executed and analyzed and for typical traffic conditions. The results can prove the effectiveness of the designed control system to avoid or mitigate rear-end collision risks, meanwhile maintaining the safety, comfortable performance of the vehicles. The future work includes:

- Expand the proposed system with tuck fleet management to solve the problem of multi-vehicle coordination and collision avoidance under mixed traffic flow conditions.
- Implement 5G vehicle network and intelligent control technology to further improve the control performances of the presented system in complex traffic conditions.
- Expand to multi-lane control system. This paper mainly focuses on the coordinated control problem for longitudinal single lane, it's interesting to apply this method to multi-lane control.
- Taking into account more testing constraints. This paper mainly focuses on vehicle dynamics limit safety control problem,it's interesting to apply with more testing constraints,such as, the maximum safe deceleration is typically below 4 m/s^2 based on CAMP testing.

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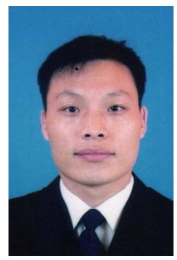

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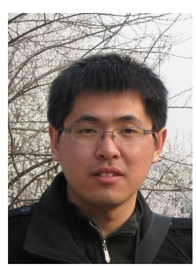

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