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COORDINATED COLLISION AVOIDANCE FOR CONNECTED VEHICLES USING RELATIVE KINETIC ENERGY DENSITY

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ABSTRACT−Vehicular collision often leads to serious casualties and traffic congestion, and the consequences are worse for multiple-vehicle collision. Many previous works on collision avoidance have only focused on the case for two consecutive vehicles using on-board sensors, which ignored the influence on upstream traffic flow. This paper proposes a novel coordinated collision avoidance (CCA) strategy for connected vehicles, which has potential to avoid collision and smooth the braking behaviors of multiple vehicles, leading to an improvement of traffic smoothness. Specifically, model predictive control (MPC) framework is used to formulate the CCA into an optimization problem, where the objective is to minimize the total relative kinetic energy density (RKED) among connected vehicles. Monte Carlo simulations are used to demonstrate the effectiveness of proposed CCA strategy by comparison with other two strategies. Among all the three control strategies, the RKED based control strategy shows the best performance of collision avoidance, including the best crash prevention rates (99.2 % on dry asphalt road and 90.5 % on wet asphalt road) and the best control of distance headways between vehicles.

KEY WORDS : Connected vehicle, Coordinated Collision Avoidance (CCA), Total relative kinetic energy density, Model Predictive Control (MPC)

1. INTRODUCTION

In the last two decades, the increasing vehicle population brings heavy burden on road traffic, and sometimes leads to heavy traffic congestion. In addition, road traffic accidents are currently recognized as a major public safety problem worldwide. Among the highway accidents in China, collision accidents hold the largest proportion (up to 66.76 %) (Transportation Bureau of the Ministry of Public Security of the PRC, 2013; Wang *et al*., 2012), resulting in serious casualties.

Collision avoidance (CA) between vehicles has the potential to avoid or mitigate a large number of collisions, making CA strategy a long-standing research topic (Horst and Hogema, 1993; Vahidi and Eskandarian, 2003). Actually, since the 1990s, various CA strategies have been proposed by considering different scenarios. Most CA systems give a warning to the driver when a risk assessment indicator is less than a predefined critical threshold. In addition, plentiful risk assessment indicators have been published. For example, in the Mazda and Honda models, a distance indicator that is often similarly defined as a function of vehicle velocity and relative velocity was used to evaluate the risk of collision (Seiler *et al*., 1998). Time-to-collision (TTC) (Horst and Hogema, 1993) and time headway (THW) (Vogel, 2003) are also widely used indicators for measuring the driving risk of car following. Miller and Huang (2002) developed a cooperative intersection collision warning system using a risk assessment indicator called time-to-intersection (TTX) (Vogel, 2003). Nowadays, more and more CA strategies have been studied based on artificial intelligence, artificial potential field theory or other advanced modern mathematical methods and analysis of the driver behavior (Yang *et al*., 2017; Jansson *et al*., 2002; Zheng *et al*., 2014; Wang *et al*., 2013; 2015a, 2015b; Gehrig and Stein, 2007; Sotelo *et al*., 2012). Wang *et al*. (2013) published an adaptive longitudinal driver assistance system considering driver characteristics. Gehrig and Stein (2007) treated the path of the leader vehicle as an elastic band that was subjected to repelling forces of obstacles in the surroundings. Wang *et al*. (2015b) proposed a novel theory called the driving safety field theory, which used field theory to represent the driving risk brought by various traffic factors. Based on this theory, a collision warning algorithm was developed, which could incorporate a greater number of traffic factors and was not limited to specific scenarios such as car following and lane changing.

However, most aforementioned CA systems mainly focus on ego and leading vehicles. This is because the collision avoidance systems are primarily based on on-board sensors to get information from the nearest vehicle.

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The problem of such systems is that they can only control ego vehicle to avoid collision with the nearest vehicle in front when emergencies occur. Nevertheless, it may lead to collision within rear vehicle platoon for the lack of braking time.

With the rapid development of communication technology, multiple vehicles in the same lane can be connected to share certain information, resulting in so-called connected vehicles (Sotelo *et al*., 2012; Milanés *et al*., 2012; Fehr *et al*., 2014; Lu *et al*., 2014). V2V and V2I are gradually fusing with telematics and in-vehicle networking to form V2X system (Sotelo *et al*., 2012; Milanés *et al*., 2012). Under connected vehicle framework, technologies on coordinated collision avoidance of multiple vehicles based on V2V and V2I communication can provide new ideas for active collision avoidance technology.

Nowadays, many researches on coordinated collision avoidance based on V2V communication technology have been carried out worldwide (Wang *et al*., 2015d; Tan and Huang, 2006; Choi and Swaroop, 2001; Sengupta *et al*., 2007; Taleb *et al*., 2010; Toledo-Moreo and Zamora-Izquierdo, 2010; Wang *et al*., 2015c; Rodriguez-Seda *et al*., 2010; Kato *et al*., 2002; Dang *et al*., 2013; Li *et al*., 2015; Zheng *et al*., 2016a, 2016b). Wang *et al*. (2015d) developed an improved cooperative collision avoidance model in which the collision can be prevented by not only decelerating the following vehicle, but also accelerating the preceding vehicle. Tan and Huang (2006) demonstrated the engineering feasibility of the cooperative collision warning system (CCWS) where vehicles are equipped with a relatively simple DGPS unit and relatively basic motion sensors. Choi and Swaroop (2001) focused on the leading vehicle's sudden braking scene and proposed a coordinated collision avoidance strategy for multiple vehicles. The rear vehicles applied different braking strategies according to the driving information of the first vehicle and the adjacent leading vehicle. By obtaining information of adjacent vehicles through V2V, Sengupta *et al*. (2007) applied TTC (Time to Collision) and DTC (Distance to Collision) as risk indexes to develop a coordinated collision of multiple vehicles. Taleb *et al*. (2010) introduced a strategy called the cluster-based risk-aware CCA (C-RACCA). Mathematical analyses and computer simulation results clearly validate its effectiveness in mitigating collision risks of the vehicles arising from accidental hazards. Toledo-Moreo and Zamora-Izquierdo (2010) designed a collision avoidance system based on fusing GPS/IMU and digital maps by predicting the position of collision between vehicles.

However, the researches on coordinated collision avoidance abovementioned just focused on the advantage of communication to make sure that the driving information of multiple vehicles are shared and transmitted accurately and promptly. However, vehicles just apply different control strategies independently according to the information received and fail to achieve real coordinated cooperation, just as the traditional algorithms and methods do. This may lead to failure on optimizing the braking strategy of rear vehicle platoon when the first vehicle conducts a sudden brake due to some emergencies.

To solve this problem, Wang *et al*. (2015d) proposed a coordinated brake control (CBC) strategy for multiple vehicles to minimize the risk of rear-end collision using MPC framework, where the objective was to minimize total relative kinetic energy (RKE) for a consecutive pair of vehicles. Nevertheless, this RKE-minimum based strategy only considers vehicle mass and relative velocity for optimization objective, and deals with the distance headways as a safety constraint deficiently. In this case, the vehicle facing a small distance headway does not make a stronger brake than the one facing a large distance headway, which can lead to underutilization of distance headways to avoid collision.

In this paper, we propose a novel indicator called the relative kinetic energy density (RKED), which makes a better consideration of distance headway. In addition, based on minimizing the RKED, we propose a multi-vehicle coordinated collision avoidance algorithm using MPC framework, which focuses on multi-vehicle collision avoidance for connected vehicles under the specific scenario in which the leading vehicle brakes suddenly. Moreover, simulation is carried out to validate the effectiveness of this algorithm. The rest of this paper is organized as follows. Firstly, Section 2 presents the system architecture and studied scenario. Then, Section 3 introduces the definition of RKED. Next, the proposed algorithm is detailed in Section 4, and simulation is conducted in Section 5. Finally, conclusion is drawn in Section 6.

2. SCENARIO DEFINITION AND VEHICLE MODEL

2.1. Scenario Definition

Figure 1 illustrates the CCA scenario definition. A vehicle platoon composes of N connected vehicles moving longitudinally in the highway. The mass and length of the i-th vehicle (i = 1, 2, ..., N) are denoted as L_i and m_i, while its displacement, velocity and acceleration at time t are denoted as $x_i(t)$, $v_i(t)$ and $a_i(t)$, respectively. In highway conditions, we assume that all vehicles' velocities range from 90 to 100 km/h and time headway (THW) between every two consecutive vehicles ranges from 0.7 to 3.8 s

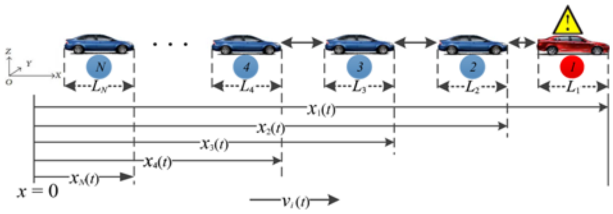

Figure 1. CCA scenario definition.

(Dang *et al*., 2013). Each vehicle is assumed to be equipped with an active braking controller and can share the information about its property (including vehicle type, mass, length and maximum deceleration capability) via V2V communication, such as DSRC (Dedicated Short Range Communication) and LTE-V (Long-Term Evolution - Vehicle) communication.

The first vehicle suddenly brakes with a hard deceleration (about 70 ~ 90 % of its maximum deceleration) due to a certain emergency at time $t = 0$. Afterwards, the following vehicles would brake to avoid collisions. In this study, we focus on the following vehicles' corresponding braking strategy by designing a control law for $a_i(t)$ ($i = 2, ..., N$) to avoid the collision (without considering lane-changing maneuver).

2.2. Vehicle Model

Considering the response delay of sensors and actuators, we assume that the acceleration response of the vehicles follows a first-order process. By denoting the control input for the i-th vehicle as the desired acceleration $a_{i,des}(t)$, the acceleration response model is given by (Li *et al*., 2015):

$$a_i(t) = \frac{1}{\tau_i s + 1} a_{i,des}(t),\ i = 2, 3, ..., N \tag{1}$$

where τ_i is the time constant of the first-order inertial delay for the i-th vehicle. Therefore, the vehicle model is as follows:

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = a_i(t) \\ \dot{a}_i(t) = \frac{1}{\tau_i}(a_{i,des}(t) - a_i(t)) \end{cases} \tag{2}$$

$i = 1, 2, ..., N$

3. RELATIVE KINETIC ENERGY DENSITY

3.1. Definition of RKED

In car following scenario of two vehicles, Wang *et al.* (2015d) defined the relative kinetic energy $E(t)$ as a function of time t to serve as the integrand of objective function:

$$E(t) = \frac{m_{sub}}{2} \cdot [v_{sub}(t) - v_{lead}(t)]^2 \tag{3}$$

where v_{lead} and v_{sub} are respectively the velocities of leading and subject vehicles, and m_{sub} is the mass of subject vehicle. As previously mentioned, the RKE indicator does not include the distance headway, which can lead to the underutilization of distance headways to avoid collision.

For improvement, we proposes a novel indicator called the relative kinetic energy density (RKED) $F(t)$, which considers the distance headway and is defined as:

$$F(t) = \frac{m_{sub}}{2S} \cdot (v_{sub} - v_{lead})^2 \cdot \Phi(v_{sub} - v_{lead}) \tag{4}$$

where S is the distance headway and $\Phi(x)$ is defined as:

$$\Phi(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases} \tag{5}$$

This indicator indicates the relative kinetic energy distribution in distance headway. Moreover, there are two situations:

1) $v_{sub} \geq v_{lead}$: the subject vehicle is approaching the leading vehicle.

Assuming a situation where the leading vehicle keeps a constant velocity and the subject vehicle keeps a constant deceleration $a_{sub}(< 0)$ after time zero to avoid a collision, the distance headway at time t is

$$\begin{aligned} S(t) &= S_0 - \frac{v_{sub}^2 - (v_{sub} + a_{sub} \cdot t)^2}{2a_{sub}} + v_{lead} \\ &= -\frac{a_{sub}}{2} t^2 - (v_{sub} - v_{lead})t + S_0 \\ &\geq -\frac{a_{sub}}{2}\left(t + \frac{v_{sub} - v_{lead}}{a_{sub}}\right)^2 + S_0 \\ &\quad + \frac{(v_{sub} - v_{lead})^2}{2a_{sub}} \end{aligned} \tag{6}$$

where S_0 is initial distance. When $t = (v_{lead} - v_{sub})/a_{sub}$, we get the minimum distance headway:

$$S_{min} = S_0 + \frac{(v_{sub} - v_{lead})^2}{2a_{sub}} \tag{7}$$

To avoid collision, S_{min} must be larger than zero. Therefore, we get the constraint for subject vehicle's deceleration:

$$|a_{sub}| \geq \frac{(v_{sub} - v_{lead})^2}{2S_0} \tag{8}$$

The critical deceleration for subject vehicle is $(v_{lead} - v_{sub})^2/2S_0$, and the corresponding critical brake force of ground is exactly as (4) shows. This means $F(t)$ represents the critical brake force of ground to avoid collision in this situation. Moreover, a large value of $F(t)$ means a large required deceleration to avoid collision, namely a high collision risk.

In this situation, considering the same v_{sub}, v_{lead} and m_{sub}, as the distance headway decreases, the collision risk increases and RKED shows the same increasing trend. However, RKE just keeps a constant value, which means RKE cannot indicate the distance headway's influence on collision risk.

2) $v_{sub} < v_{lead}$: the distance headway is increasing and no collision will happen. Therefore $F(t)$ is set to zero, which means safety.

3.2. Total RKED of Connected Vehicles

For every following vehicle shown in Figure 1, we can calculate an individual RKED between it and its front vehicle, as a possible collision might happen between them. Taking the i-th vehicle as a reference $(1 < i \le N)$, the RKED between the i-th vehicle and its front vehicle is

$$F_{\text{i,i}-1}(t) = \frac{m_\text{i}}{2[x_{\text{i}-1}(t)-x_\text{i}(t)-L_\text{i}]} \cdot [v_\text{i}(t)-v_{\text{i}-1}(t)]^2 \cdot \Phi(v_\text{i}(t)-v_{\text{i}-1}(t)) \tag{9}$$

where $x_{\text{i}-1}(t) - x_\text{i}(t) - L_\text{i}$ is the distance headway between these two vehicles at time t.

Furthermore, we calculate the total RKED of the vehicular platoon in Figure 1 as $F_\Sigma(t)$:

$$\begin{aligned} F_\Sigma(t) &= \sum_{\text{i}=2}^{\text{N}} F_{\text{i,i}-1}(t) \\ &= \sum_{\text{i}=2}^{\text{N}} \frac{m_\text{i}}{2[x_{\text{i}-1}(t)-x_\text{i}(t)-L_\text{i}]} \cdot [v_\text{i}(t)-v_{\text{i}-1}(t)]^2 \cdot \Phi(v_\text{i}(t)-v_{\text{i}-1}(t)) \end{aligned} \tag{10}$$

where $F_\Sigma(t)$ represents the possibility of the collision within vehicular platoon simultaneously.

4. CCA CONTROLLER DESIGN

4.1. Control Architecture

A centralized control architecture, shown in Figure 2, is designed for CCA. In Figure 2, the i-th vehicle will send its information, including m_i, L_i, $x_\text{i}(t)$, $v_\text{i}(t)$ and $a_\text{i}(t)$, to the DSRC communication network. Using the information, the centralized controller would calculate the desired accelerations $a_{\text{i,des}}(t)$ $(i = 2, 3, ..., N)$ for all following vehicles and send them back for control.

4.2. MPC Formulation

We apply MPC method in the centralized control. In the controller, as shown in Figure 2, the total relative kinetic energy density is used as the objective function and vehicle kinematic and deceleration capability are considered as constraints.

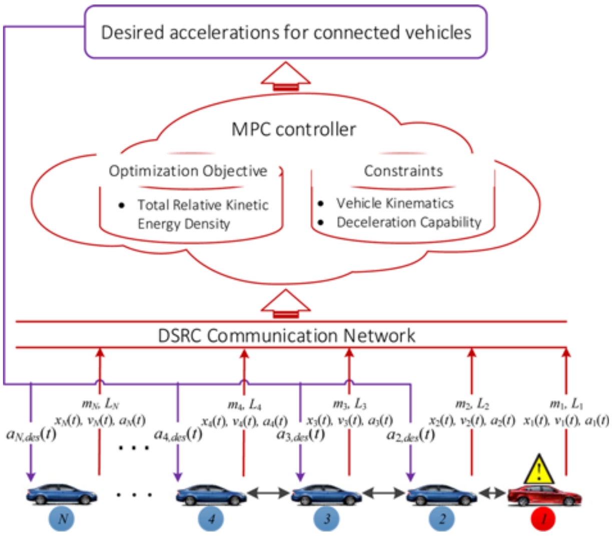

Figure 2. CCA control architecture.

4.2.1. Objective function design

As the value of the total RKED F_Σ represents the possibility of collision of the vehicular platoon, we design an integral objective function to minimize RKED:

$$\min_{a_\text{des}} J = \int_{t_0}^{t_1} F_\Sigma(\tau) d\tau \tag{11}$$

where $a_\text{des} = (a_{1,\text{des}}, a_{2,\text{des}}, .., a_{\text{N,des}})^\text{T}$ is the aggregated control input, t_0 and t_1 are the initial and end time.

4.2.2. Constraints design

The constraints include vehicle model constraint and deceleration constraint. The vehicle model constraint is given in Equation (2). The deceleration constraint shows the consideration of vehicle deceleration limits and is given as:

$$a_{\text{i,min}} \le a_{\text{i,des}}(t) \le a_{\text{i,max}},\ i = 2, 3, ..., N \tag{12}$$

where $a_{\text{i,min}}$ and $a_{\text{i,max}}$ are the minimum and maximum accelerations of the i-th vehicle, respectively.

Usually, constraints of safe distance between vehicles should also be designed to ensure safety. Nevertheless,

Table 1. Vehicle Parameter statistics.

Type	Passenger car	Medium bus	Large bus	Heavy truck	Towed tuck
Type ID	1	2	3	4	5
Length (m)	4.0 ~ 5.5	7.0 ~ 9.0	12.0	9.0 ~ 12.0	20.0
Mass (10^3 kg)	1.2 ~ 2.4	6.0 ~ 13.5	15.0 ~ 23.0	20.0 ~ 32.0	20.0 ~ 40.0
Brake model	Hydraulic	Hydraulic	Hydraulic	Pneumatic	Pneumatic
ABS equipment (Y/N)	Y	Y	Y	N	N

constraints of safe distance between vehicles may make it impossible to find proper control input, e.g. when collision between several vehicles is unavoidable. In addition, distance between vehicles has been employed in the objective function, which makes it appropriate to neglect the constraint of safe distance between vehicles here.

4.2.3. Problem discretization

The MPC problem is usually discretized for control implementation and online computation. Here $(k + l|k)$ denotes the predictive value at time $k + l$ based on the information at time k, then the discretized problem is given as:

$$\min_{a_{\text{des}}} J = \sum_{l=1}^{N_p} F_{\Sigma}(k + l|k)$$

subject to

$$\begin{cases} x_i(k + l|k) = x_i(k+l-1|k) \\ \qquad + v_i(k+l-1|k)\cdot\Delta t \\ v_i(k + l|k) = v_i(k+l-1|k) \\ \qquad + a_i(k+l-1|k)\cdot\Delta t \\ a_i(k + l|k) = \dfrac{\tau-\Delta t}{\tau} a_i(k+l-1|k) \\ \qquad + \dfrac{\Delta t}{\tau} a_{i,\text{des}}(k+l-1|k) \\ a_{i,\min} \le a_{i,\text{des}}(k+l-1|k) \le a_{i,\max} \end{cases} \tag{13}$$

$i = 1, 2, ..., N, j = 2, 3, ..., N, l = 1, 2, ..., N_p.$

where Δt is the sample time interval, N_p is the time length of the predictive horizon. By solving the open-loop nonlinear optimization problem, the first of the optimal control input, *i.e.* $a_{i,\text{des}}(k|k)$, $i = 2, 3, ..., N$, is used for actual control implement.

5. SIMULATION AND ANALYSIS

To validate the performance of the proposed RKED based strategy, three control strategies, including DRBC (Driver-reaction based Brake Control) strategy, RKE based strategy (Wang *et al.*, 2015d) and RKED based strategy, are simulated for comparison in Matlab environment. DRBC strategy means the driver would make a hard brake with the maximum deceleration after realizing the emergency brake of the front vehicle. In addition, the driver reaction time T_r (in seconds) is set to obey a Gaussian distribution $N(0.66, 0.1^2)$ (Wang *et al.*, 2015d).

As Figure 1 shows, the simulation situation includes ten connected vehicles with different types, masses, lengths and maximum deceleration capabilities running longitudinally in the highway. Each vehicle follows its front vehicle and can communicate with any other vehicles. The first vehicle suddenly brakes with a hard deceleration (about 70 ~ 90 % of its maximum deceleration) due to a certain emergency at time zero. Afterwards, the following vehicles would use three different control strategies to avoid collisions. The simulation ends when all coupled vehicles stop.

5.1. Simulation Parameters

According to the road traffic accidents statistics of China (Transportation Bureau of the Ministry of Public Security of the PRC, 2013), 89.95 % rear-end accidents in highway are caused by passenger cars, buses and commercial vehicles. The survey result of the main types of these mentioned vehicles in Chinese market is as Table 1 (Auto Home, 2016; Truck Home, 2016) shows.

According to Table 1, the simulation parameters are as follows.

1) Type: Generate the vehicle type randomly.

2) Length L: According to its type, generate the length of the vehicle randomly in the corresponding length range.

3) Mass m: Assuming a linear relationship between the mass and length for each type of vehicle, generate the mass according to the vehicle type and length.

4) Maximum deceleration - $a_{\min}$: Here we set all vehicles running on a straight asphalt highway. To explore more general situations, we consider not only the dry but also the wet roads. For dry and wet asphalt roads, the rolling adhesion coefficients are 0.85 and 0.5 respectively, and the sliding adhesion coefficients are 0.65 and 0.4 respectively (Yu, 2009). Vehicles equipped with ABS can get the theoretical maximum deceleration corresponding with the rolling adhesion coefficient, while others can only get the theoretical maximum deceleration corresponding with the sliding adhesion coefficient. Considering the comfort and general real driving situations, we set 70 ~ 90 % theoretical maximum deceleration as the maximum deceleration for each vehicle randomly.

5) Brake response time T_b: The brake response time of hydraulic brake system is 0.1 s. Nevertheless, for pneumatic brake system, the value is about 0.3 ~ 0.9 s (Yu, 2009). In the simulation, we set the brake response time value as 0.2 s for passenger cars, 0.2 ~ 0.6 s for medium and large buses, and 0.4 ~ 0.9 s for heavy and towed tucks.

6) Initial position and state: Generate the initial velocity v_0 ranging from 90 to 100 km/h randomly. The THW (s) follows a Gaussian distribution $N(1.5, 0.1^2)$ (Wang *et al.*, 2015d).

In addition, the sampling time interval Δt is 0.02 s, and the predictive time length N_p is set to be 5.

5.2. Simulation Result Analysis

5.2.1. Statistical analysis of testing conditions

To validate the performance of the RKED based strategy proposed in this paper quantitatively, we implemented 2000 simulation cases (including 1000 cases on dry asphalt road and 1000 cases on wet asphalt road) for DRBC, RKE based and RKED based strategies respectively. The statistic results are as Table 2 shows.

1) Crash prevention rate: Due to the decrease of maximum deceleration capability, the crash prevention rates of all three control strategies decrease on wet asphalt road compared with dry asphalt road. No matter what the road type is, DRBC control strategy shows the lowest crash prevention rate (23.2 % / 4.4 % on dry/wet asphalt road), while RKED based control strategy shows the highest crash prevention rate (99.2 % / 90.5 % on dry/wet asphalt road). Besides, RKE based control strategy also shows good performance (98.5 % / 86.6 % on dry/wet asphalt road). It deserves to be mentioned that compared with other two control strategies, the improvement of crash prevention rate of RKED based control strategy is more substantial on wet asphalt road.

2) Crash prevention rate in failure cases: DRBC control strategy succeeds in no failure cases of other two control strategies. While both RKE and RKED based control strategies show high crash prevention rates in the failure cases of DRBC control strategy, which implies large advantages improvements of collision avoidance in simulated cases.

On the other hand, RKE based control strategy succeeds in no failure cases of RKED based control strategy. Nevertheless, RKED based control strategy succeeds in 7 (46.7 %) and 39 (29.1 %) RKE failure cases on dry and wet asphalt roads respectively, which shows better performance of collision avoidance.

3) Stop distance: Stop distance is a kind of collision risk evaluation indicator. A smaller stop distance reflects a higher collision risk for two consecutive two vehicles. For a vehicle in the platoon, a soft brake may lead to a collision with the front vehicle. However, a hard brake may lead to a large stop distance with the front vehicle, meanwhile this can also cause a small stop distance (namely a high collision risk) with the rear vehicle. To avoid collision, all stop distances between the ten vehicles should be positive. In addition, homogeneous stop distances are appreciated. To guarantee this, proper decelerations are necessary to balance the stop distances.

For both road types, DRBC control strategy shows the

Table 2. Statistic results for three control strategies.

Road type	Strategy	Crash prevention rate	Number of failure cases	Crash prevention rate in failure cases			Stop distance[a]			
				DRBC	RKE	RKED	Max (m)	Min (m)	Mean (m)	Variance (m^2)
Dry asphalt road	DRBC	23.2 %	768	0 %	98.0 %	99.0 %	79.7	− 38.4	22.1	368.5
	RKE	98.5 %	15	0 %	0 %	46.7 %	55.6	− 8.4	36.9	51.7
	RKED	99.2 %	8	0 %	0 %	0 %	52.0	− 8.4	36.8	47.4
Wet asphalt road	DRBC	4.4 %	955	0 %	86.0 %	90.1 %	11.2	− 74.9	22.5	763.7
	RKE	86.6 %	134	0 %	0 %	29.1 %	62.7	− 30.3	35.5	92.4
	RKED	90.5 %	95	0 %	0 %	0 %	56.3	− 22.9	35.4	82.6

[a]Stop distances refer to the distances between vehicles when all vehicles have stopped.

Table 3. Vehicle simulation parameters in a specific simulation case.

ID	Type ID	L (m)	m (10^3 kg)	$-a_{min}$ (m/s^2)	T_b (s)	T_r (s)	v_0 (km/h)	THW (s)
1	1	4.27	1.46	6.76	0.20	0.73	91.29	
2	1	4.52	1.70	7.02	0.20	0.86	97.43	1.14
3	5	20.00	32.03	5.05	0.56	0.73	99.20	1.36
4	2	7.752	8.82	6.06	0.46	0.63	90.88	1.60
5	1	4.29	1.48	7.46	0.20	0.66	96.72	1.31
6	5	20.00	39.62	4.54	0.44	0.70	99.75	1.26
7	3	12.00	19.30	6.60	0.45	0.63	94.92	1.59
8	3	12.00	21.33	7.01	0.43	0.51	94.05	1.33
9	1	4.78	1.95	7.37	0.20	0.59	96.30	1.37
10	5	20.00	34.46	4.70	0.57	0.59	96.30	1.48

smallest mean stop distance and the largest variance of stop distances, which indicates the worst performance. Compared with RKE based control strategy, RKED based control strategy results in a similar mean stop distance value but a smaller variance and a much larger number of minimum variance, which indicates a better performance of balancing the distances between vehicles.

Hence, we can conclude that RKED based control strategy proposed in this paper shows the better performance of collision avoidance than the other two control strategies in successful rate and the control of stop distances.

5.2.2. Comparison and analysis of specific simulation cases

For a better comparison, a specific simulation case in which DSRC and RKE based control strategies failed to avoid collision while RKED based control strategy succeeded is studied in detail. This case is on dry asphalt road and Table 3 lists the vehicle simulation parameters in this case.

Figures 3 ~ 5 show the simulation results of DRBC, RKE based and RKED based control strategies respectively. Moreover, each figure consists of four profiles, including vehicle trajectory, stop distance, velocity and acceleration profiles.

1) For DRBC control strategy: According to the vehicle trajectory and stop distance profiles in Figure 3, three collisions happened between the 2-nd and 3-rd vehicles, the 5-th and 6-th vehicles and the 9-th and 10-th vehicles respectively in this case. It is worth mentioning that in the simulation we did not consider simulating the real situation after the collision. Each vehicle's longitudinal motion was calculated only according to its own acceleration profiles. This is because the research focus here is whether a collision would happen rather than the severity of a happened collision. Hence, take the collision between the 2-nd and 3-rd vehicles as an example, to be more accurate the 1-st vehicle might be involved in this collision.

In the case, there are three main reasons that can lead to a collision: i) a short distance headway, ii) a late brake moment and iii) a relatively poor deceleration capability. The brake moment refers to the moment when the vehicle begins to decelerate. This time is decided by three factors: the time the driver decides to brake, driver reaction time, and brake response time of the vehicle's brake system.

The initial THWs for the 3-rd, 6-th and 10-th vehicles are 1.36 s, 1.26 s and 1.48 s respectively. The initial distance headway of the 6-th vehicle is a little short while the value of the other two vehicles are proper.

The driver reaction times of the three vehicles are normal. However, according to DRBC control strategy, a vehicle would brake only after the brake of its consecutive front vehicle just as the acceleration profiles in Figure 3 shows. This would cause a delay for brake moment. Moreover, the 3-rd, 6-th and 10-th vehicles are all towed trucks. Compared with their front vehicles, they have larger brake response times and much poorer deceleration capabilities.

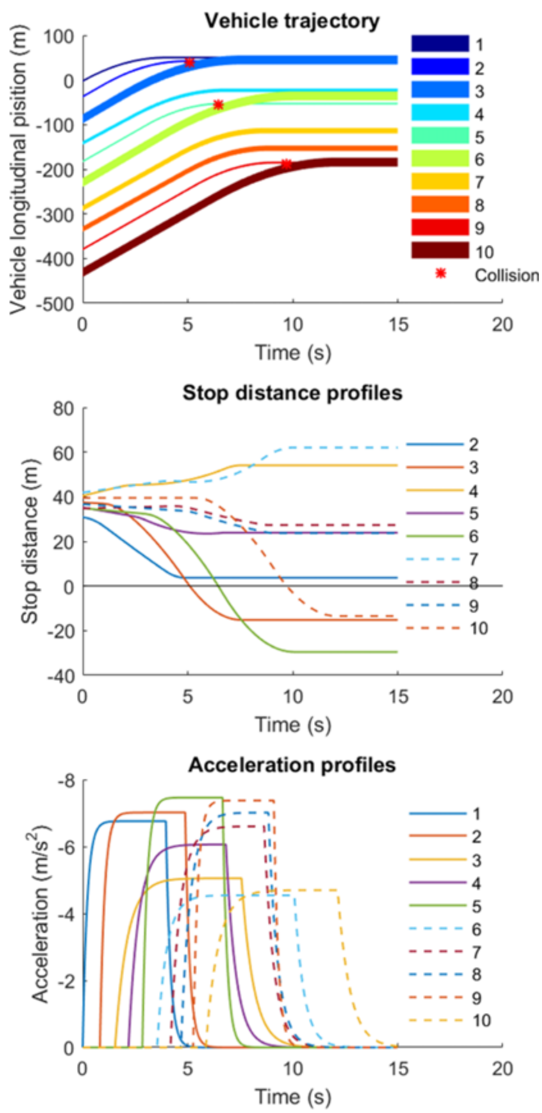

Figure 3. Simulation result of DRBC based control strategy on dry asphalt road.

Hence, even the drivers reacted in time these three vehicles collided with their front vehicles finally.

2) For RKE based control strategy: According to the vehicle trajectory and stop distance profiles in Figure 4, only one collision happened between the 1-st and 2-nd vehicles in this case. Compared with DRBC control strategy, RKE based control strategy shows a better performance in collision avoidance. The collision number decreases and most stop distances are proper. This is because all following vehicles braked beforehand as they were connected with each other and got the information of the emergency brake of the 1-st vehicle in time.

However, there is still a happened collision. As the acceleration profiles in Figue 4 shows, the 2-nd vehicle did

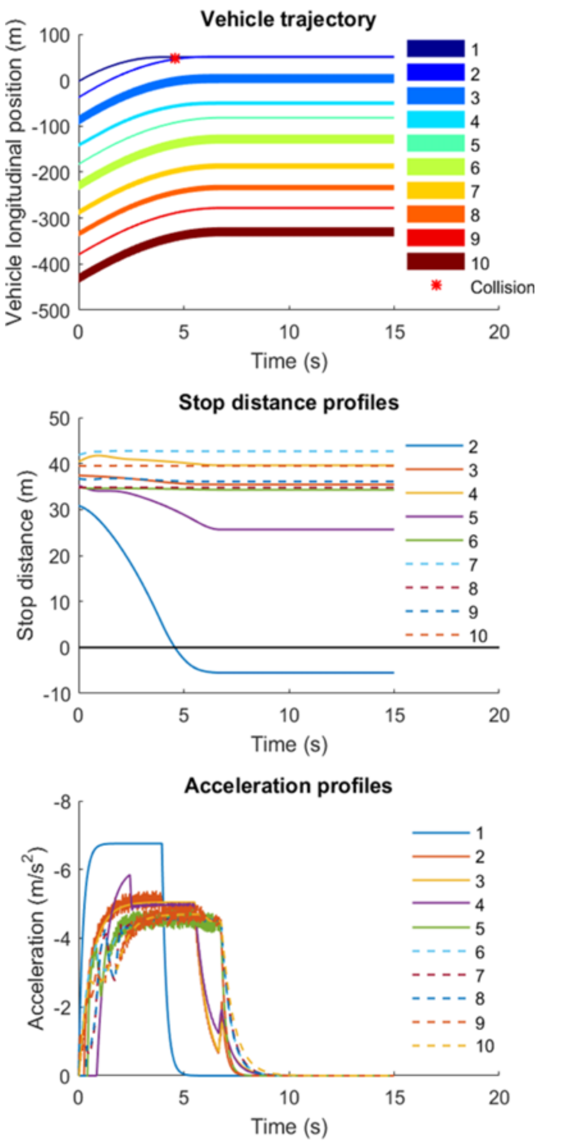

Figure 4. Simulation result of RKE based control strategy on dry asphalt road.

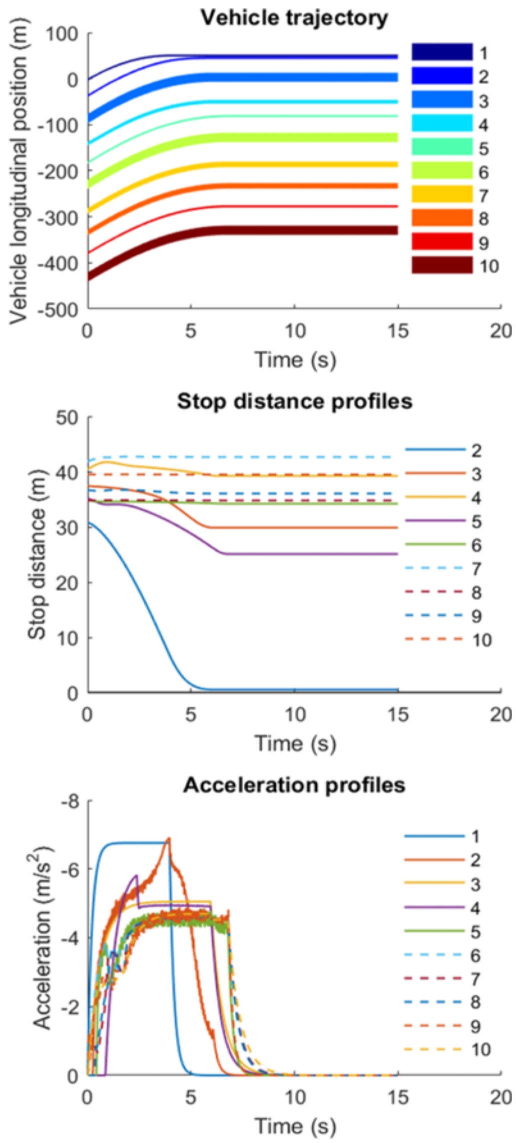

Figure 5. Simulation result of RKED based control strategy on dry asphalt road.

not make a large enough deceleration. This caused the collision finally. The maximum deceleration capability of the 2-nd vehicle is 7.02 m/s^2. While according to the acceleration profiles in Figure 3, the maximum deceleration the 2-nd vehicle actually made was 5.39 m/s^2. This is because the RKE based control strategy only optimized the relative velocities according to the masses of vehicles. The mass of the 2-nd vehicle is only 1.70×10^3 kg which is much smaller than the mass of the 3-rd vehicle 32.30×10^3 kg. Hence, the optimized relative velocity between the 2-nd and 1-st vehicles is much larger than the relative velocity between the 3-rd and 2-nd vehicles. In addition, the maximum deceleration capability of the 3-rd vehicle is relatively poor, which enhances the limitation of the deceleration of the 2-nd vehicle as a smaller relative velocity between these two vehicles was optimized.

3) For RKED based control strategy: According to the vehicle trajectory and stop distance profiles in Figure 5, no collision happened. Except for the stop distance between the 2-nd and 1-st vehicles, all stop distances are relative large. Compared with the stop distance profile of the 2-nd vehicle in Figure 4, we can find that the stop distance between the 2-nd and 1-st vehicles increased by about 6 m (from − 5.51 m to 0.54 m), which avoided the collision. This is because the RKED based control strategy optimizes the relative velocities according to not only the masses of vehicles but also the distance headways. Then a better utilization of distance headways improves the strategy's collision avoidance performance. The acceleration profile of the 2-nd vehicle in Figure 5 shows a large enough

deceleration due to the large distance between the 2-nd and 1-st vehicles even with a small mass.

6. CONCLUSION

This paper focuses on coordinated collision avoidance for multiple connected vehicles and proposes a novel indicator called relative kinetic energy density (RKED).

Based on the total RKED of multiple connected vehicles, we apply MPC control strategy for coordinated collision avoidance. Moreover, simulation is carried out to test the performance of our strategy.

The simulation results validate the good performance of the proposed coordinated collision avoidance strategy for multiple vehicles. Among all the three control strategies, the RKED based control strategy shows the best performance of collision avoidance, including the best crash prevention rates (99.2 % on dry asphalt road and 90.5 % on wet asphalt road) and the best control of distance headways between vehicles. Moreover, compared with other two control strategies, RKED based control strategy makes more substantial improvement of collision avoidance on wet asphalt road.

Although the simulation shows good performance of the proposed method, many limitations still exist in this manuscript, which bring problems for real implementation. Firstly, the adopted vehicle model is a simplified linear dynamics model, which can't precisely represent the property of the vehicles. Secondly, the impact of the communication is not considered. Actually the communication delay, package loss, communication range and other factors all have influence on the performance, among which the communication delay is of great significance for vehicle safety applications. Thirdly, the real-time implementation of the proposed method in vehicles is still a problem considering the computational cost to solve so complex an optimization problem. However, for the purpose of promoting the control strategy in vehicle collision avoidance, we neglect these relatively less important factors and just focus on the comparison of different control strategies in an ideal environment (ideal vehicle dynamics, communication and computation hardware). To further adapt the proposed method to real implementation, we will focus on solving these problems in the future research.

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