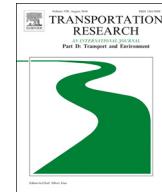




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Vehicle forward collision warning algorithm based on road friction

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ARTICLE INFO

Keywords:

Road friction
Braking deceleration
Warning distance
Vehicle forward collision warning algorithm

ABSTRACT

Forward collision warning/collision avoidance (FCW/CA) systems have been developed to reduce rear-end crashes. Deceleration of vehicle is always defined as a default value in many typical proposed FCW algorithms. Considering the braking acceleration is always changed when the vehicle is braking, this paper analyzed the five typical FCW algorithms and proposed a new FCW algorithm based on road friction. The model described vehicle deceleration variation during the braking process, which was used to set up an FCW algorithm based on road friction considering the lead vehicle in three different kinematic scenarios: stationary, constant motion, and decelerating. Finally, the five typical FCW algorithms and the proposed algorithm were compared by simulation experiments. The effectiveness of the proposed warning algorithm was verified. It was concluded that the proposed algorithm was effective and conformed to the actual situation than the five FCW algorithms. Limitations and further studying recommendations for expansion of the paper were provided at the end of the paper.

1. Introduction

Rear-end collisions have been recognized as emergent issues in road safety for the past few years and amounted to almost 30% of all crashes in the US ([Traffic Safety Facts, 2009](#)), 21.7% of all crashes in Germany ([German Federal Statistical Office, 2009](#)), and almost 35% of all crashes in Japan ([Watanabe and Ito, 2007](#)). In Shanghai, China, it was reported that rear-end collisions made up approximately 20% of all crashes. For elevated expressways and tunnels, the percentages increased to 49% and 67%, respectively ([Deng et al., 2011](#)). To reduce rear-end crashes, Forward Collision Warning/Collision Avoidance (FCW/CA) systems have been developed and become significant issues in the field of active safety research ([Taleb et al., 2010](#)).

Previous work on such algorithms can be categorized into two main types: perceptual-based algorithms and kinematic-based algorithms ([Lee and Peng, 2005](#)). The former were based on the perception of drivers, and an indicator called time-to-collision (TTC) was used to activate the warning. Yang et al. explored the possibility of using a single dashboard camera to raise the calculation accuracy of TTC ([Yang and Zheng, 2015](#)). Khan studied the effect of human factors on collision warning using the Bayesian-Monte Carlo model ([Khan, 2013](#)). Kinematic-based algorithms based on kinematic trigger warnings used the fundamental laws of motion to set up warning models ([Moona et al., 2009](#)).

Except for the five kinds of typical algorithms introduced in Section 2, many results related to kinematic-based algorithms have been proposed recently. Tang et al. developed a rear-end collision avoidance system using the monocular vision of a camera to estimate the distance between the host vehicle and the lead vehicle ([Tang et al., 2015](#)). Han et al. studied the practicability of FMCW

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(Frequency Modulated Continuous Wave) radar in the field of collision warning (Han et al., 2014). Kim et al. presented a collision warning algorithm based on neural networks to reduce the probability of collisions caused by driver inattention and error (Kim et al., 2014).

The principle of FCW algorithms is to slow down the host vehicle to keep an adequate distance from the lead vehicle. The algorithm proposed in this paper is a kind of kinematic-based algorithm, which determines a minimum distance required to stop safely. Hence, the minimum distance, named warning distance, is the kernel content of the algorithm. The warning distance can be calculated by the parameters of the vehicles and drivers. Braking deceleration caused by tire-road friction is a crucial parameter that will directly affect the accuracy of the calculation (Doi et al., 1994a).

The structure of the paper is as follows. Section 2 describes five kinds of typical forward collision warning algorithms and proposes the forward collision warning algorithm based on road friction. The simulation results of six forward collision warning algorithms are presented in Section 3. Sections 4 and 5 present discussions and conclusions drawn from the results, respectively.

2. Models and algorithms

2.1. Typical algorithms

The Stop-Distance-Algorithm (SDA) (Wilson et al., 1997) is based on “stop-distance, defined as the distance between the point at which braking begins and the point of rest of a leading vehicle and a following vehicle.” The warning distance can be calculated using Eq. (1):

$$d_w = V_1 * RT + \frac{V_1^2}{2*a_1} - \frac{V_2^2}{2*a_2} \quad (1)$$

where d_w is the warning distance (m), V_1 is the velocity of host vehicle (m/s), V_2 is the velocity of lead vehicle (m/s), RT is the driver delay. Two parameters, namely a_1 (assumed deceleration of host vehicle) and a_2 (assumed deceleration of lead vehicle), are both defined as 5.88 m/s^2 .

The Braking Algorithm based on the braking process was proposed by Wang et al. (2003). The warning distance is given by:

$$d_w = V_1 * T_h + (V_1 - V_2) * T_s + \left(\frac{V_1^2 - V_2^2}{2*a_{max}} \right) + d_0 \quad (2)$$

where d_w is the warning distance (m), V_1 is the velocity of host vehicle (m/s), V_2 is the velocity of lead vehicle (m/s), T_h is the driver delay, T_s is the system delay, d_0 is the minimum safety range. The parameter deceleration is assumed to be the maximum value. The warning distance will be higher in an actual situation because of the neglected traffic efficiency.

The Mazda Algorithm (Doi et al., 1994b) is quite similar to the SDA. The warning distance is given by:

$$d_w = V_1 * \tau_1 + (V_1 - V_2) * \tau_2 + \frac{V_1^2}{2*a_1} - \frac{V_2^2}{2*a_2} + d_0 + \varepsilon \quad (3)$$

where τ_1 is the system delay, τ_2 is the driver delay, d_0 is the minimum safety range, and ε is a system parameter. Two parameters, namely a_1 (assumed deceleration of host vehicle) and a_2 (assumed deceleration of lead vehicle), are defined as 6 m/s^2 and 8 m/s^2 .

The Honda Algorithm (Fujita et al., 1995) consists of two parts: warning distance and braking critical distance.

$$d_w = 2.2 * (V_1 - V_2) + 6.2$$

$$d_{br} = \begin{cases} \tau_2 * (V_1 - V_2) + \tau_1 * \tau_2 * a_1 - \frac{1}{2} * a_1 * \tau_1^2, & \frac{V_2}{a_2} \geq \tau_2 \\ \tau_2 * V_1 - \frac{1}{2} * a_1 * (\tau_2 - \tau_1)^2 - \frac{V_2^2}{2 * a_2}, & \frac{V_2}{a_2} < \tau_2 \end{cases} \quad (4)$$

where d_{br} is the braking critical distance (m). Two parameters, a_1 and a_2 are both defined as 7.8 m/s^2 .

According to the PATH (Berkeley) Algorithm, the warning is triggered based on a non-dimensional warning value w . When $0 < w < 1$, different modalities of warnings (visual or auditory) are triggered according to the value of w . When $w < 0$, the system should apply the brakes (Seiler et al., 1998).

$$w = \frac{d - d_w}{d_w - d_{br}}$$

$$d_w = \frac{1}{2} \times \left[\frac{V_1^2}{a} - \frac{V_2^2}{a} \right] + V_1 \times \tau + d_0$$

$$d_{br} = (V_1 - V_2) \times (\tau_1 + \tau_2) + \frac{1}{2} \times a_2 \times (\tau_1 + \tau_2)^2 \quad (5)$$

where d is the actual vehicle range, d_w is the warning critical distance, d_{br} is the braking critical distance and τ is the sum of system delay and driver delay. The parameter a is assumed to be the maximum of the deceleration and defined as 6 m/s^2 , the parameter a_2 (assumed deceleration of lead vehicle) is defined as 8 m/s^2 .

In summary, the parameter deceleration is always defined as the default value in the five types of typical algorithms. But it has been proved that the deceleration is a variable in the process of vehicle braking.

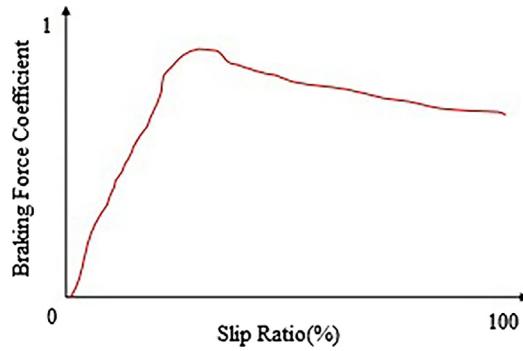


Fig. 2.1. Braking force coefficient curve.

2.2. Model of braking deceleration

Braking deceleration varies with time. To calculate warning distance, the operating principle of an ABS system was used to estimate the braking deceleration in this paper.

The slip ratio s is the relative sliding degree between a tire and pavement. It is defined as:

$$s = \frac{\omega \cdot r - v}{\max(\omega \cdot r, v)} \quad (6)$$

where ω is the wheel speed, r is radius of the wheel, and v is longitudinal velocity of the wheel, which is replaced by vehicle speed as usual.

The braking force coefficient φ_b , is the ratio between the brake force of the ground and the vertical load. It is defined as:

$$\varphi_b = \frac{F_x}{F_z} \quad (7)$$

where φ_b is the braking force coefficient, F_x is the longitudinal braking force of wheel and F_z is the vertical load on the tire.

The braking force coefficient is different from the friction coefficient and varies from the slip ratio. The relation between the braking force coefficient and the slip ratio is illustrated in Fig. 2.1. The curve shows that it was too complexity to indicate the real-time changing.

To acquire the simple analytic function, the curve was simplified, as shown in Fig. 2.2. The piecewise function was used to simplify the relationship between the braking force coefficient and the slip ratio. The function approximation was used to obtain the result.

In Fig. 2.2, point O is the origin coordinate, and point B (s_p, φ_p) is the peak coefficient of friction. The coordinate of point A is $(K_1 \cdot s_p, K_2 \cdot \varphi_p)$, and $\frac{\varphi_p - K_2 \cdot \varphi_p}{s_p - K_1 \cdot s_p} < \frac{K_2 \cdot \varphi_p}{K_1 \cdot s_p}$. Point C (s_s, φ_s) is the sliding coefficient of friction, and the slip ratio is 100%.

The slip ratio is relatively small in phase OA. The sliding between the tire and the ground did not occur; although a slip ratio existed by the changing of the rolling radius. When the braking force of the ground was generated, the contact region in front of the tire tread was extended slightly, and the growth rate of the rolling radius was proportional to that of the braking force. The curve of φ_b can be simplified approximately to a straight line.

The linear equation is assumed as:

$$\varphi_b = a_1 s \quad (8)$$

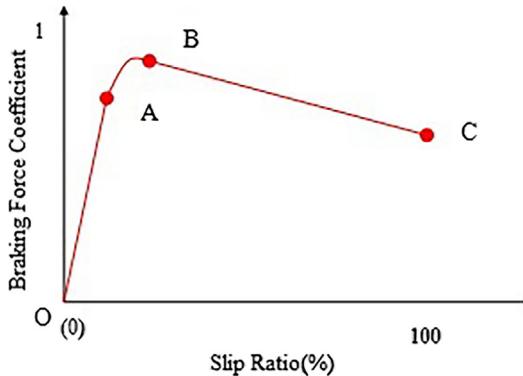


Fig. 2.2. Simplified braking force coefficient curve.

If the coordinate of point A was obtained, the result of a_1 can be calculated by Eq. (9):

$$a_1 = \frac{K_2 \cdot \varphi_p}{K_1 \cdot s_p} \quad (9)$$

In phase AB, the slip ratio is in the best stage because the road condition is good. In this phase, local slides occur between the tire and the ground, and the growth rate of φ_b slowed until the best slip rate was generated at point B. The curve of φ_b was simplified as a quadratic curve.

The curve equation is assumed as:

$$\varphi_b = a_2 s^2 + b s \quad (10)$$

If the coordinate of point A and point B are obtained, the result of a_2 and b are calculated by Eq. (11):

$$\begin{cases} a_2 = \frac{K_1^2 - K_2}{2s_p(K_1 - K_1^2)} \\ b = \frac{(K_2 - K_1^2)\varphi_p}{(K_1 - K_1^2)s_p} \end{cases} \quad (11)$$

In phase BC, the higher the slip rate, the smaller the braking force coefficient φ_b , and the slip rate would be 100% at point C, which means the wheel slips on the ground completely. The curve of φ_b can be simplified approximately to a straight line.

The linear equation was assumed as:

$$\varphi_b = a_3 s + c \quad (12)$$

If the coordinate of point B and point A are obtained, the result of a_3 and c can be calculated as:

$$\begin{cases} a_3 = \frac{\varphi_s - \varphi_p}{1 - s_p} \\ c = \frac{\varphi_p - \varphi_s \varphi_p}{1 - s_p} \end{cases}$$

According to Eq. (7), the maximum braking deceleration can be calculated as:

$$a_{bmax} = \varphi_b g \quad (13)$$

Two brake parameters, pressure regulating frequency and adjusting amplitude (Zang et al., 2011), were incorporated into the model. Hence, the braking deceleration can be given by Eq. (14):

$$a = a_{bmax} - \frac{1}{2}\delta + \frac{1}{2}\delta \cos\omega(t) \quad (14)$$

where ω is the regulating frequency that varies from 19 rad/s to 126 rad/s depending on vehicle speed and road condition, and δ is the adjusting amplitude. The adjusting amplitude can be calculated as:

$$\delta = (\varphi(0.2) - \varphi(0.15)) \cdot g \quad (15)$$

The road surface was assumed to be fine, Substituting Eq. (10) into Eq. (14), the braking deceleration can be given as:

$$a = g(a_2 s^2 + b s) - \frac{\delta}{2} + \frac{\delta}{2} \cos\omega(t) \quad (16)$$

2.3. FCW algorithm based on road friction

The relative motion between two vehicles in the braking process is presented in Fig. 2.3.

The safety distance can be calculated by Eq. (17):

$$d_w = s_r + d_0 - s_f \quad (17)$$

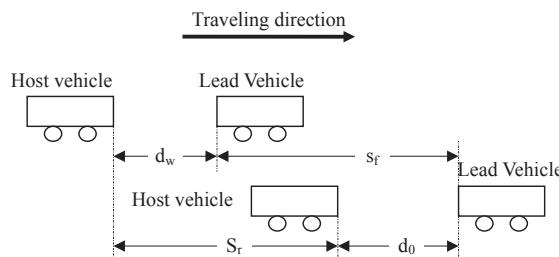


Fig. 2.3. Relative motions between two cars.

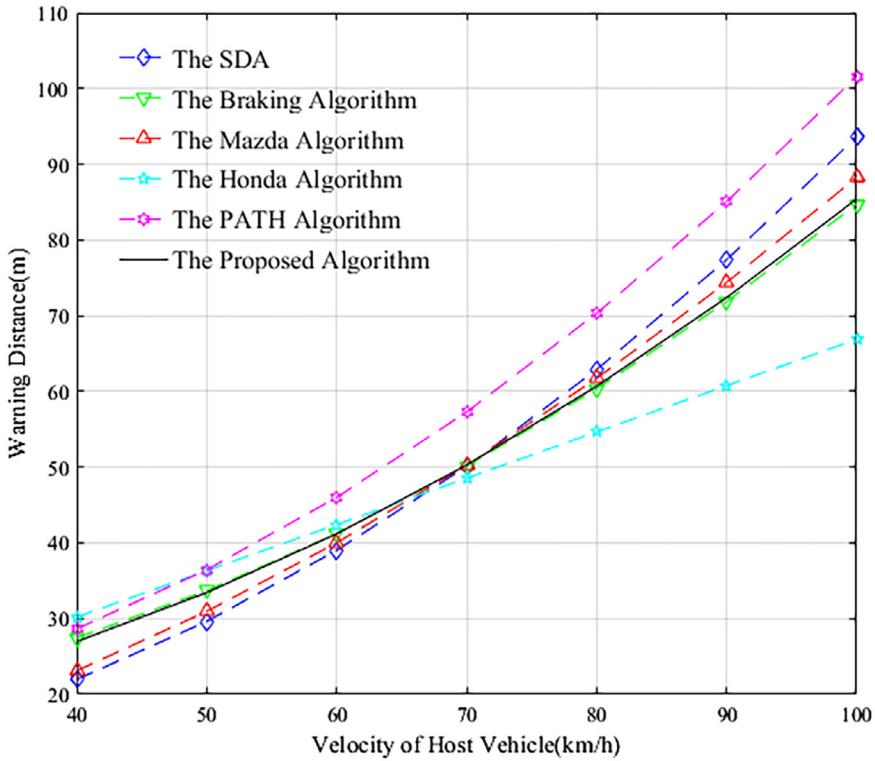


Fig. 3.1. Simulation results of static lead vehicle.

Table 3.1

Simulation velocities of constant lead vehicle.

Host vehicle velocity (km/h)	Lead vehicle velocities(km/h)						
80	25	30	35	40	45	50	55
80							

where d_w is the safety distance, d_0 is the safe stopping distance, s_f is the stop distance of lead vehicle in braking process, and s_r is the stop distance of host vehicle in braking process.

The FCW algorithm based on road friction in this paper consists of a warning distance algorithm and a braking critical distance algorithm. When the distance between two vehicles is smaller than the warning distance, the FCW system should issue warning information to the driver. When the distance between two vehicles is smaller than the braking critical distance, the system should apply the brakes.

The FCW algorithm was established according to different motion states of the lead vehicle—stationary, constant motion, and decelerating.

(1) Static

In this situation, the host vehicle gets close to the lead vehicle, and the distance between the two vehicles gets smaller. The worst situation occurs when the velocity of the host vehicle slows to 0. It must be certain that a rear-end collision does not happen at this time.

In the process of braking, the host vehicle continues traveling at its current speed in driver reaction time. In the system delay time, the deceleration of the host vehicle increases linearly to its maximum value. Then, the deceleration would change continuously.

The road surface is assumed to be good, and the stop distance of the host vehicle can be calculated as:

$$s_{r1} = v_1 \tau_1 + v_1 \tau_2 - \frac{1}{6} (a_2 s^2 + b s) g \tau_2^2 + \int_{\frac{v_1}{(a_2 s^2 + b s) g}}^0 \int_0^{\frac{v_1}{(a_2 s^2 + b s) g}} \left((a_2 s^2 + b s) g - \frac{\delta}{2} + \frac{\delta}{2} \cos \omega(t) \right) dt dt \quad (18)$$

Substituting Eq. (18) into Eq. (17), the warning distance and the braking critical distance can be expressed as:

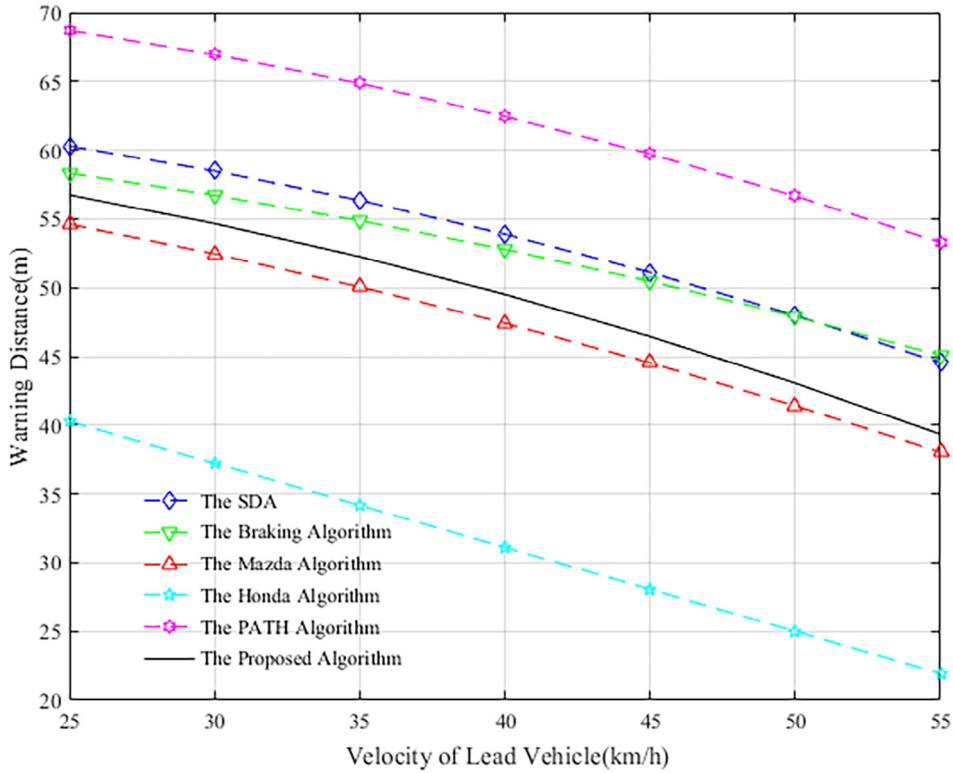


Fig. 3.2. Simulation results of constant lead vehicle.

Table 3.2

Simulation velocities of decelerating lead vehicle.

Initial velocity of lead vehicle(km/h)	Initial velocities of host vehicle(km/h)						
50	70	80	90	100	110	120	

$$d_{w1} = v_1\tau_1 + v_1\tau_2 - \frac{1}{6}(a_2s^2 + bs)gt_2^2 + \int_{\frac{v_1}{(a_2s^2+bs)g}}^0 \int_0^{\frac{v_1}{(a_2s^2+bs)g}} \left((a_2s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt + d_0 \quad (19)$$

$$d_{br1} = v_1\tau_2 - \frac{1}{6}(a_2s^2 + bs)gt_2^2 + \int_{\frac{v_1}{(a_2s^2+bs)g}}^0 \int_0^{\frac{v_1}{(a_2s^2+bs)g}} \left((a_2s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt + d_0 \quad (20)$$

(2) Constant motion

In this situation, a rear-end collision will not happen if the lead vehicle is faster than the host vehicle. The worst situation occurs when the speed of the host vehicle decreases to the same value as the lead vehicle when the lead vehicle is slower than the host vehicle. After the worst time, the distance between the two vehicles grows.

In driver time, the host vehicle continues traveling at its current speed. In system time, the deceleration of the host vehicle increases linearly to its maximum value. In the process of continuous braking, it would change continuously until the host vehicle has a same speed as the lead vehicle.

The stop distance of vehicles can be calculated as:

$$s_{f1} = v_1\tau_1 + v_1\tau_2 - \frac{1}{6}(a_2s^2 + bs)gt_2^2 + \int_{\frac{v_1}{(a_2s^2+bs)g}}^{\frac{v_2}{(a_2s^2+bs)g}} \int_0^{\frac{v_2-v_1}{(a_2s^2+bs)g}} \left((a_2s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt \quad (21)$$

$$s_{f1} = v_2 \cdot (\tau_1 + \tau_2) + \frac{v_1 - v_2}{(a_2s^2 + bs)g} \cdot v_2 \quad (22)$$

Substituting Eqs. (21) and (2) into Eq. (17), the warning distance and the braking critical distance can be expressed as:

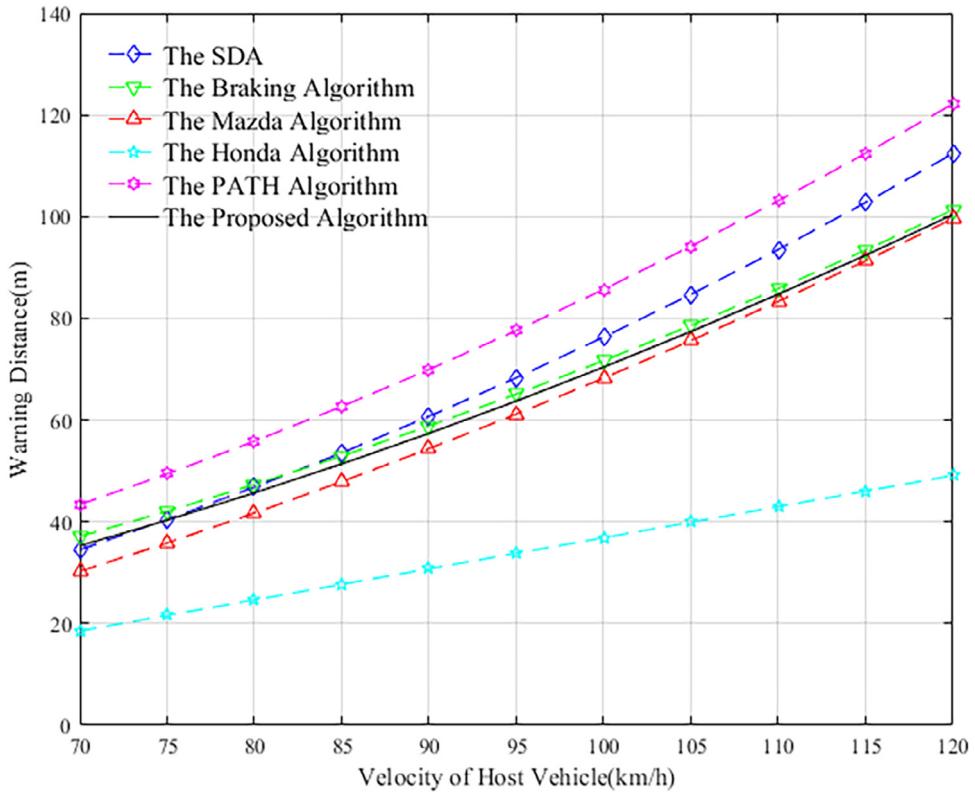


Fig. 3.3. Simulation results of decelerating lead vehicle.

$$d_{w1} = (v_1 - v_2) \cdot (\tau_1 + \tau_2) - \frac{1}{6}(a_2 s^2 + bs)g\tau_2^2 - \frac{v_1 - v_2}{(a_2 s^2 + bs)g}v_2 + \int_{\frac{(a_2 s^2 + bs)g}{(a_2 s^2 + bs)g}}^{\frac{v_2}{v_1}} \int_0^{\frac{v_2 - v_1}{(a_2 s^2 + bs)g}} \left((a_2 s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt + d_0 \quad (23)$$

$$d_{r1} = (v_1 - v_2) \cdot \tau_2 - v_2 \tau_1 - \frac{1}{6}(a_2 s^2 + bs)g\tau_2^2 - \frac{v_1 - v_2}{(a_2 s^2 + bs)g}v_2 + \int_{\frac{(a_2 s^2 + bs)g}{(a_2 s^2 + bs)g}}^{\frac{v_2}{v_1}} \int_0^{\frac{v_2 - v_1}{(a_2 s^2 + bs)g}} \left((a_2 s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt + d_0 \quad (24)$$

(3) Decelerating

In this situation, the worst situation occurs when the host vehicle stops. The deceleration of the host vehicle changes continuously until the speed slows to 0. At the same time, the lead vehicle constantly decelerates at its initial velocity.

The stop distance of two vehicles should be calculated first to derive the warning distance.

$$s_{r1} = v_1 \tau_1 + v_1 \tau_2 - \frac{1}{6}(a_2 s^2 + bs)g\tau_2^2 + \int_0^{v_1} \int_0^{\frac{v_1}{(a_2 s^2 + bs)g}} \left((a_2 s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt \quad (25)$$

$$s_{f1} = v_2 \left(\tau_1 + \tau_2 + \frac{v_1}{(a_2 s^2 + bs)g} \right) - \frac{1}{2}(a_2 s^2 + bs)g \left(\frac{v_1}{(a_2 s^2 + bs)g} \right)^2 \quad (26)$$

Substituting Eqs. (25) and (26) into Eq. (17), the warning distance and the braking critical distance can be expressed as:

$$d_{w1} = (v_1 - v_2) \cdot (\tau_1 + \tau_2) - \frac{1}{6}(a_2 s^2 + bs)g\tau_2^2 - \frac{v_1 \cdot v_2}{(a_2 s^2 + bs)g} + \int_0^{v_1} \int_0^{\frac{v_1}{(a_2 s^2 + bs)g}} \left((a_2 s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt + d_0 \quad (27)$$

$$d_{r1} = (v_1 - v_2) \cdot \tau_2 - v_2 \tau_1 - \frac{1}{6}(a_2 s^2 + bs)g\tau_2^2 - \frac{v_1 \cdot v_2}{(a_2 s^2 + bs)g} + \int_0^{v_1} \int_0^{\frac{v_1}{(a_2 s^2 + bs)g}} \left((a_2 s^2 + bs)g - \frac{\delta}{2} + \frac{\delta}{2}\cos\omega(t) \right) dt dt + d_0 \quad (28)$$

Measured by mobile units, the distance and relative velocity between the lead vehicle and the host vehicle, the velocity of the host vehicle, the parameters of ABS, and the road adhesion condition can be achieved. Then, the motion state of the lead vehicle can be

predicted as follows:

- (1) If the distance between the vehicles is constant or increasing, it can be judged that the lead vehicle is stationary or accelerating compared with the host vehicle. A rear-end crash will not occur.
- (2) If the distance between the vehicles is decreasing and the relative velocity equals the velocity of the host vehicle, it can be judged that the lead vehicle is stationary.
- (3) If the distance between the vehicles is decreasing and the relative velocity is increasing, it can be judged that the lead vehicle is decelerating.

After confirming the motion state of the lead vehicle, the warning distance and the braking critical distance can be calculated according to the FCW algorithm.

3. Simulation results

Three parameters—driver reaction time τ_1 , system delay time τ_2 , and warning stop distance—were set as 1.3 sec, 0.2 sec, and 5 m, respectively. Then, the proposed algorithm and the five typical algorithms were analyzed.

If the lead vehicle kept static, the relationship between the warning distance and the host vehicle initial velocity was as presented in Fig. 3.1. When the lead vehicle kept a constant speed, the velocities of the two vehicles are as displayed in Table 3.1. The relationship between the warning distance and the lead vehicle velocity is as presented in Fig. 3.2. The initial velocities of the two test vehicles are shown in Table 3.2 as the lead vehicle decelerated. The relationship between the warning distance and the velocity is presented in Fig. 3.3.

4. Discussions

If the lead vehicle kept static, the warning distance increased with the increase of the host vehicle velocity, which is compatible with the actual situation. Additionally, the warning distance calculated by the proposed algorithm was between the Mazda Algorithm and the PATH (Berkeley) Algorithm and close to the Braking Algorithm. Although the Braking Algorithm applied to the situation when the lead vehicle kept static, it is noted that the proposed algorithm is feasible.

In the simulation test, it was found that the warning distance decreased as the lead vehicle velocity increased when the lead vehicle was operated at a constant speed. Furthermore, the warning distance calculated by the proposed algorithm was between the results of Braking Algorithm and Mazda Algorithm. This can be expressed as:

$$D_1 < D < D_2 \quad (29)$$

where D_1 is the Mazda warning distance, D_2 is the warning distance based on Braking Algorithm, and D is the warning distance according to the proposed algorithm. The result is relatively close to the Mazda Algorithm, which was in accordance with an actual situation.

When the lead vehicle decelerated, the warning distance grew with the initial velocity of the host vehicle. The warning distance calculated by the proposed algorithm was between the results of Braking Algorithm and Mazda Algorithm. This can be expressed as:

$$D_1 < D < D_2 \quad (30)$$

where D_1 is the Mazda warning distance, D_2 is the warning distance based on the Braking Algorithm, and D is the warning distance according to the proposed algorithm. Since the result of Mazda Algorithm was relatively small and the Braking Algorithm was relatively large, the warning distance proposed in this paper was found to be an appropriate indicator.

5. Conclusions

In this paper, the relationship between the brake force and the sliding rate were analyzed. Based on the simplified thought, the mathematical model of automobile brake force coefficient and sliding rate model was established. On the basis of the working process of the application of ABS, the braking deceleration model was set up, which can reflect the road friction characteristics. By analyzing three states of deceleration process when a vehicle is braking, a forward collision warning algorithm was proposed based on the pavement frictional properties. The five typical FCW algorithms and the proposed algorithm were compared by simulation experiments. The warning distance between the host vehicle and the lead vehicle of the six algorithms at the three different stations were compared and considered as the evaluation standard. The simulation results showed the feasibility of the proposed algorithm and can describe an actual situation more appropriately compared to the previous five typical warning distance models. For vehicle collision avoidance involves many core technologies in vehicle study, there are still limitations in this paper. This paper only analyzed the longitudinal vehicle collision prevention. Some actual situations, like the complex road conditions, lane change, the influence of the radar data refresh rate, are lack of analysis. Due to the constraints, this paper only simulated the collision systems on several typical motion conditions, real vehicle experiment for the collision warning systems are needed for the verification of the effectiveness of the algorithm.

Funding

This work was supported by Science Foundation of Chinese Ministry of Transport (2015319812200); the Open Project Program of the Key Laboratory of Road Traffic Safety of Ministry of Public Security in China (2016ZDSYSKFKT05); Chinese Universities Scientific Fund (310822162018); the Natural Science Foundation of Shaanxi Province of China (2016JM5013).

References

- Deng, B., Chen, X., Wang, X., 2011. Shanghai 2020 Driving scenario models and traffic accident models development. General Motors, Shanghai, unpublished report.
- Doi, A., Butsuen, T., Niibe, T., Takeshi, T., Yamamoto, Y., Seni, H., 1994a. Development of a rear-end collision avoidance system with automatic brake control. *JSAE Rev.* 15, 335–340.
- Doi, A., Butsuen, T., Niibe, T., Yakagi, T., Yamamoto, Y., Senin, H., 1994b. Development of a rear-end collision avoidance system with automatic braking control. *JSAE Rev.* 15 (4), 335–340.
- Fujita, Y., Akuzawa, K., Sato, M., 1995. Radar brake system. *1995 Annual Meet. ITS Am.* 1, 95–101.
- German Federal Statistical Office, Verkehrsunfälle. Fachserie 8, Reihe 7, 2009.
- Han, S.K., Ra, W.S., Whang, I.H., Park, J.B., 2014. Linear recursive automotive target tracking filter for advanced collision warning systems. *Appl. Mathe. Inform. Sci.* 8 (3), 1145–1151.
- Khan, A.M., 2013. Bayesian-Monte Carlo model for collision avoidance system design of cognitive connected vehicle. *Int. J. Intell. Transp. Syst. Res.* 11 (1), 23–33.
- Kim, B., Choi, B., An, J., Hwang, J., Kim, E., 2014. Novel collision warning system using neural networks. *J. Korean Inst. Intell. Syst.* 24 (4), 392–397.
- Lee, K., Peng, H., 2005. Evaluation of automotive forward collision warning and collision avoidance algorithms. *Veh. Syst. Dyn.* 43 (10), 735–751.
- Moona, S., Moon, I., Yi, K., 2009. Design, tuning, and evaluation of a full-range adaptive cruise control system with collision avoidance. *Control Eng. Pract.* 17 (4), 442–455.
- Seiler, P., Song, B.S., Hedrick, K., 1998. Development of a collision avoidance system. *Automot. Eng.* 106 (9).
- Taleb, T., Benslimane, A., Ben Letaief, K., 2010. Toward an effective risk-conscious and collaborative vehicular collision avoidance system. *IEEE Trans. Veh. Technol.* 59, 1474–1486.
- Tang, S.J.W., Ng, K.Y., Khoo, B.H., Parkkinen, J., 2015. Real-time lane detection and rear-end collision warning system on a mobile computing platform. *IEEE Comput. Soc.* 2, 563–568.
- Traffic Safety Facts 2009, DOT HS 811 402, NHTSA, US DOT, 2009.
- Wang, W., Wang, W., Zhong, Y., 2003. Car-following safe distance control algorithm and implementation based on fuzzy inference. *J. Traffic Transport. Eng.* 3 (1), 72–75.
- Watanabe, Y., Ito, S., 2007. Influence of vehicle properties and human attributes on neck injuries in rear-end collisions. Paper No. 07-0160. 20th Int. ESV Conf., 2007.
- Wilson, T.B., Butler, W., Maghee, T.V., Dingus, T.A., 1997. Forward-looking collision warning system performance guideline. SAE Paper, 970456.
- Yang, Mau-Tsuen, Zheng, Jing-Yu, 2015. On-road collision warning based on multiple FOE segmentation using a dashboard camera. *IEEE Trans. Vehicul. Technol.* 64 (11), 4974–4984.
- Zang, M., Lu, B., Chen, X., 2011. FEM simulation on tire braking distance on dry road. *Automot. Eng.* 32 (2), 156–161.