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Research on Non-line-of-sight Collision Avoidance Warning Using the Vehicle-to-vehicle Communication System in 5G Mobile Communication Network

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In this study, the Doppler migration technology in 5G mobile communication network was investigated as a vehicle-to-vehicle communication system. The advantages of using Doppler migration technology to investigate the anti-collision warning system are that it can detect a dozen vehicles in front of the vehicle equipped with it, and it is not disturbed by environmental factors such as light, rain, smoke, and dust. This system was used in a non-line-of-sight collision avoidance warning system in an observer vehicle to effectively carry out early warning judgments on multiple vehicles ahead of the observer vehicle. Judgments on traffic collision warnings were based on Doppler migration technology that signals between different vehicles to predict whether the observer vehicle will collide with a vehicle ahead of it. MATLAB software was used, and a crossroads was selected as the scenario for the simulation. To process the simulation, the starting coordinates, starting speed, acceleration, driving direction, and simulation times of each vehicle were input as the simulation parameters. All moving conditions of each vehicle in the simulation process were generated, including the coordinates, distance, speed, and angle between the observer vehicle and other vehicles. A flowchart for the process of making a judgment on driving collision warnings was proposed to judge if a collision between two vehicles would occur.

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1. Introduction

In recent years, the vigorous development of the Internet of Things has accelerated developments of the internet of vehicles, and the investigations and research on unmanned vehicles and autonomous driving systems have changed rapidly. Among them, Google's and Tesla's self-driving vehicle systems are the leaders in the related industrial technologies. Many major traditional vehicle manufacturers have also started to develop unmanned vehicles and electric vehicles. Owing to quick developments and improvements of wireless communication networks, more and more sensors have been installed in vehicles for the purpose of auto-driving and collision warning systems. A large amount of sensing data can be integrated through the in-vehicle system and then sent through the 4G/5G wireless communication network.(1–5) Vehicle-to-everything (V2X) is a communication technology between vehicles with different objects that may affect vehicular travel or may be affected by other traveling vehicles. V2X is a vehicular communication system that incorporates other more specific types of communication, such as vehicle-to-vehicle (V2V), vehicle-to-device (V2D), vehicle-to-network (V2N), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P).(1–5)

The sensors used in the V2X technologies need to have the capabilities of sensing objects around corners and beyond any obstructions in a radius of up to several hundred meters. The main functions of V2X communication are to address the two main problems for vehicles traveling on roads: safety and mobility. Currently, owing to the demand for autonomous driving, the relevant studies on collision avoidance warning under non-line-of-sight intersections at crossroads have become very important.(6–9) Chiu and Tsai investigated the technology of path loss at crossroads using measurements from the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 link to apply in the non-line-of-sight system.(6) The results of this investigation found that higher path losses would be incurred at crossroads, but the V2V communication could still be supported by the proposed system. Schumacher *et al.* constructed a system under the IEEE 802.11p architecture; a commercial off-the-shelf network card could be used to perform V2V motion measurements of the non-line-of-sight conditions at urban crossroads.(10) This system can evaluate the results of the received signal strength indicator (RSSI) and packet delivery ratio (PDR) for different environments, like the vehicles' locations, crossroads geometries, and traffic densities. This system can also determine the reliable communication range to establish the important indicators for the application of the V2V collision avoidance warnings.

Many related studies have focused on investigations of sensors for collision avoidance warning technology,(11–13) and Zeng *et al.* proposed a vehicle collision risk detection method using a vehicle perception system.(13) In V2V and V2I scenarios, the motion states of vehicles, obstacles, and pedestrians on the roads are tracked through cameras with different sensors, such as global positioning systems (GPS) and ZigBee, and the vehicles' trajectories are predicted using Kalman filters. Many related studies have focused on collision warning algorithms.(14–16) For example, Huang *et al.* proposed a collision pre-warning algorithm (CPWA) under the wireless access in vehicular environments (WAVE) (IEEE 1609) standard. When this system is used in the vehicles, it regularly broadcasts relevant information (RI) to surrounding vehicles.(14)

The system in each vehicle can calculate a potential collision probability based on the RI values received and, if a collision might occur, the system sends a warning to the driver a few seconds before the collision. Kihei *et al.* investigated a system in which short-range communication (dedicated short-range communication, DSRC) was designated to be used for safety in the V2V system.(17) The communication using this radio frequency allows the vehicles to exchange basic safety messages (BSMs) so that a route can be used to avoid vehicles' collisions. Most vehicle collision prediction systems rely on GPS and modular sensors to obtain the vehicles' locations and dynamic information and transmit the information in the form of BSM.

Currently, all commercial products using anti-collision technologies are in the category of line-of-sight. The biggest disadvantage of line-of-sight anti-collision technologies is that their detection performance is easily affected by the weather and objects in the environment. Although millimeter-wave radar does not have this problem, this technology uses a reflective detection method, which is easily affected by obstacles and cannot detect the conditions of vehicles other than the vehicles ahead of it. However, GPS technology is a non-line-of-sight technology, the main disadvantage of which is that the update speed is too slow to be used in V2V environment. The technology proposed in this study uses the Doppler migration technology to receive the signals for the effective processing of the early warning judgments of multiple vehicles ahead in the non-line-of-sight of the observer vehicle. The anti-collision warning system can be used on the vehicle in front of the observed vehicle, or even on a dozen vehicles in front of this vehicle. Furthermore, it is not disturbed by environmental factors such as light, rain, smoke, and dust. However, the disadvantage of using Doppler migration in a collision avoidance warning method is determining whether the vehicles are from the front, rear, left, or right. This problem is a topic that we investigated and proposed to solve.

2. Simulation Process and Parameters Used

The simulation method applied uses MATLAB as software. First, the starting coordinates, starting speed, acceleration, driving direction, and simulation time of each vehicle were input as the simulation parameters. These input parameters could generate all the moving conditions of each vehicle in the simulation, including the coordinates, distance, speed, and angle between the observer vehicles and other vehicles. The TE-V2X communication protocol was used as the signal transmission technology, and the Doppler migration technique was used as the communication protocol to receive the signals for processing the effective early warning judgments of multiple vehicles in the non-line-of-sight situation.

We proposed a collision theory for different vehicles; the angles α and β were assumed to be formed by a straight line connecting the two vehicles and the direction of each vehicle. According to the simulation results obtained from the MATLAB software, if the Doppler offset value is greater than zero and the slope of the Doppler offset is equal to zero, the two vehicles collide at the crossroads. The straight line connecting the two vehicles forms a triangle, as shown in Fig. 1, the two included angles of which are α and β. According to the calculation, if the two vehicles collide, the two included angles remain unchanged until the collision occurs; in other words, the angles do not change with time.

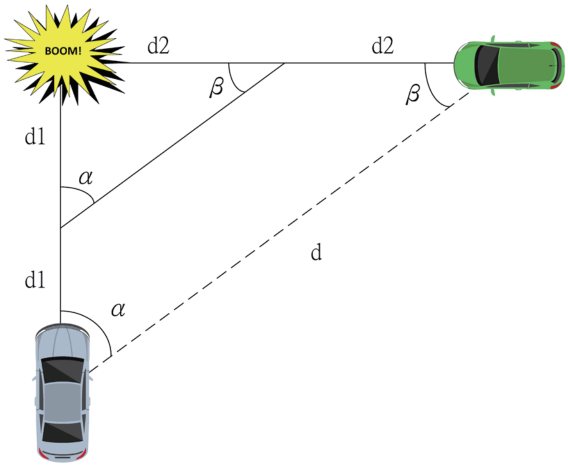

Fig. 1. (Color online) Schematic diagram of a two-vehicle collision scenario.

We proposed a judgment process to warn of traffic collisions to predict whether the observer vehicle will collide with a vehicle in front of it. First, we must judge whether the Doppler shift value is positive, zero, or negative. If the Doppler shift value is positive, there is a possibility of collision when the two vehicles approach. On the other hand, if the Doppler shift value is equal to zero or is negative, it means that the two vehicles are kept at an equal distance or become further away from each other, and there is no possibility of collision. It is necessary to determine whether the slope of the Doppler offset is equal to zero. If the value is zero, it means that the relative speeds of the two vehicles are in a constant velocity relationship, and a collision will occur at the crossroads. On the other hand, if the slope of the Doppler shift is not zero, it means that the angle formed by the driving paths of the two vehicles is not maintained, and the two vehicles will cross the crossroads without colliding, as shown in Fig. 2.

3. Theoretical Considerations

There are three different situations that result in a Doppler shift. The first is that the signal source moves and the observer does not move; the second is that the signal source does not move and the observer moves; the third is that both the source signal and the observer move. The derivations and calculations of the Doppler migration equation were carried out for each of the three conditions. As shown in Fig. 3(a), the first condition assumes that the observer is stationary in the distance, and the signal source is moving at a constant speed of v_s. The blue point is the signal source position at t_1, the red point is the signal source position at t_2, and l_1 and l_2 are the distances to the observer from the signal sources at t_1 and t_2, respectively. The distance between the two different positions is defined as Δl, which is calculated as

$$\Delta l = l_1 - l_2 = v_s \cdot \tau \cdot \cos\theta. \tag{1}$$

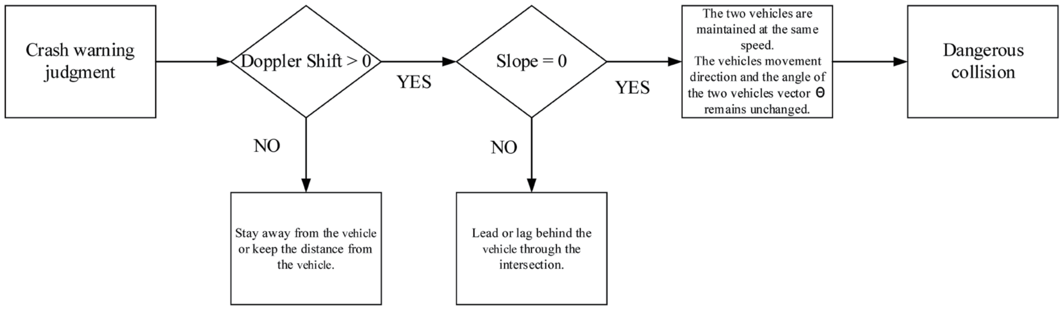

Fig. 2. Flowchart of the judgment process for collision warning.

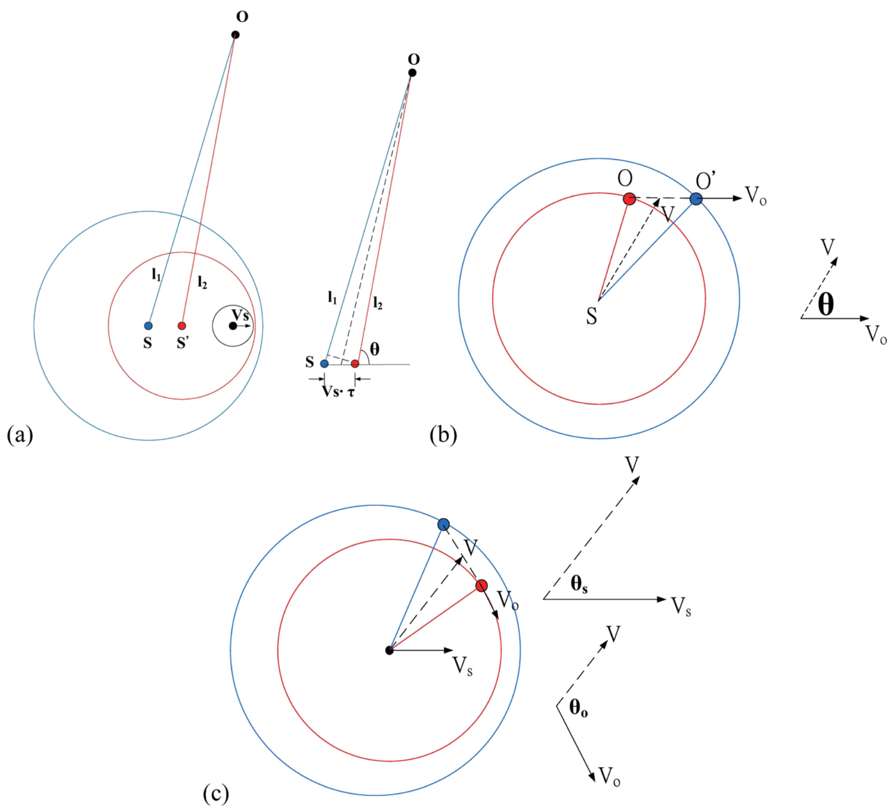

Fig. 3. (Color online) Three scenarios for the Doppler shift: (a) the source signal moves, (b) the observer moves, and (c) both the source signal and the observer move.

The term $\tau = 2\pi/\omega$ is the period of the electromagnetic wave, and τ' is the period over which the observer measures the arrival time difference between two consecutive waves:

$$T' = t_2 - t_1 = \left(\tau + \frac{l_2}{v}\right) - \frac{l_1}{v} = \tau - \frac{l_1 - l_2}{v}. \tag{2}$$

This equation can be reorganized as

$$\tau' = \tau\left(1-\frac{v_s}{v}\cos\theta\right) => \omega' = \frac{2\pi}{\tau'} = \frac{2\pi}{\tau\left(1-\frac{v_s}{v}\right)\cos\theta} = \frac{\omega}{1-\frac{v_s}{v}\cos\theta} = \omega\cdot\left(\frac{1}{1-\frac{v_s}{v}\cos\theta}\right)$$

$$= \omega\cdot\left(1+\frac{1}{1-\frac{v_s}{v}\cos\theta}-\frac{1-\frac{v_s}{v}\cos\theta}{1-\frac{v_s}{v}\cos\theta}\right) = \omega\cdot\left(1+\frac{\frac{v_s}{v}\cos\theta}{1-\frac{v_s}{v}\cos\theta}\right) = \omega\cdot\left(1+\frac{v_s\cos\theta}{v-v_s\cos\theta}\right). \tag{3}$$

Equation (3) was used to generate the Doppler offset values and to calculate the slope of the Doppler offsets between the observer vehicle and the relative vehicles for subsequent analyses. Because $\omega = 2\pi f$ and $v = c$, Eq. (3) can be rewritten as

$$f' = f\cdot\left(1+\frac{v_s\cos\theta}{v-v_s\cos\theta}\right) => f' = f\cdot\left(1+\frac{v_s\cos\theta}{c-v_s\cos\theta}\right), \tag{4}$$

$$=> \Delta f = f - f' = f\left(\frac{v_s\cos\theta}{c-v_s\cos\theta}\right). \tag{5}$$

The second condition is one in which the signal source does not move, and the observer moves at a speed of v_o. Therefore, the direction of electromagnetic wave emission and the direction of the advancing observer form an angle θ, as shown in Fig. 3(b), but only the speed parallel to v has an effect on the Doppler shift, so the relative speed v' between the signal source and observer is

$$v' = v - v_o\cos\theta. \tag{6}$$

The frequency drift equation related to the shift in the observer's velocity is

$$\omega' = \frac{2\pi v'}{\lambda} = \frac{2\pi v}{\lambda}\left(1-\frac{v_o}{v}\cos\theta\right) = \omega\left(1-\frac{v_o}{v}\cos\theta\right). \tag{7}$$

Because $v = c$ and $\omega = 2\pi f$, Eq. (7) can be rewritten as

$$=> f' = f\left(1-\frac{v_o}{v}\cos\theta\right) => f' = f\left(1-\frac{v_o}{c}\right)\cos\theta, \tag{8}$$

$$=> \Delta f = f - f' = f\left(\frac{v_o}{c}\cos\theta\right). \tag{9}$$

The third condition is one in which both the source signal and the observer move; the signal source and the observer advance at speeds of v_s and v_o, respectively. As shown in Fig. 3(c), the advancing direction of the electromagnetic wave forms included angles θ_s and θ_o between the two advancing directions. Therefore, the frequency shift equation for the movements of the signal source and the observer is

$$\omega' = \frac{\omega}{1-\frac{v_s}{v}\cos\theta_s}\left(1-\frac{v_o}{v}\cos\theta_o\right). \tag{10}$$

This equation can be simplified to

$$\omega' = \omega\left(\frac{v-v_o\cos\theta_o}{v-v_s\cos\theta_s}\right) = \omega\left(1+\frac{v-v_o\cos\theta_o}{v-v_s\cos\theta_s}-\frac{v-v_s\cos\theta_s}{v-v_s\cos\theta_s}\right) = \omega\left(1+\frac{v_s\cos\theta_s-v_o\cos\theta_o}{v-v_s\cos\theta_s}\right), \tag{11}$$

$$=> f' = f\left(1+\frac{v_s\cos\theta_s-v_o\cos\theta_o}{v-v_s\cos\theta_s}\right). \tag{12}$$

Because $v = c$, Eq. (12) can be rewritten as

$$=> \Delta f = f - f' = \left(\frac{v_s\cos\theta_s-v_o\cos\theta_o}{v-v_s\cos\theta_s}\right). \tag{13}$$

A corresponding collision warning process was proposed for the vehicles at crossroads as shown in Fig. 4. First, the Doppler shift value is used to judge the relative positions between the

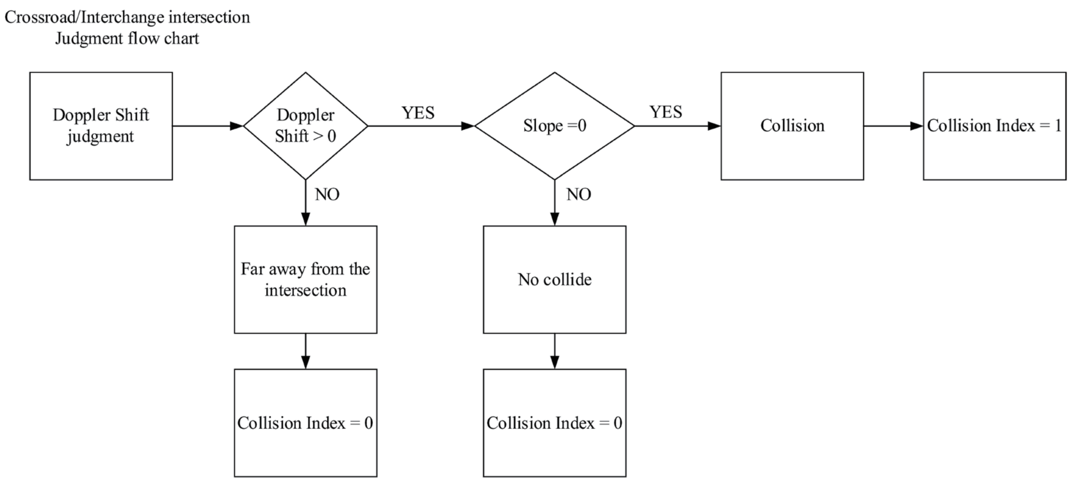

Fig. 4. Judgment flow chart for intersection at crossroads.

different vehicles. If the Doppler shift value is not greater than zero, the observer vehicle and other vehicles are far away from the crossroads, the collision index is set to zero, and the collision avoidance warning is not alarmed. If the Doppler shift value is greater than zero, the observer vehicle and other vehicles are approaching and they are heading towards the crossroads. Then it is determined whether the slope of the Doppler shift is zero or not. If the slope of the Doppler shift is not zero, the two vehicles will pass safely at the crossroads without collision. At this time, the collision parameter is set to zero, which means that the two vehicles go through the crossroads safely. If the slope of the Doppler shift is zero, it means that the two vehicles will collide at the crossroads. At this time, the collision parameter is set to one, and the collision avoidance warning is alarmed to warn the drivers that they need to react to avoid a collision.

The collision warning process proposed was simulated by a mixed scenario to verify the warning function, and the diagram of the scenario is shown in Fig. 5. In this scenario of crossroads, vehicle4 and vehicle5 are moving straight and in the same direction as the observer vehicle, and three vehicles, vehicle1, vehicle2, and vehicle3, are going straight in the lateral direction of the crossroads. In this scenario, the six vehicles are assumed to maintain constant speeds. The relevant parameters of the six vehicles, including their speeds, directions (180° is the same direction as the observer vehicle, and 90° is in the direction vertical to the crossroads), and coordinates, are all shown in Table 1.

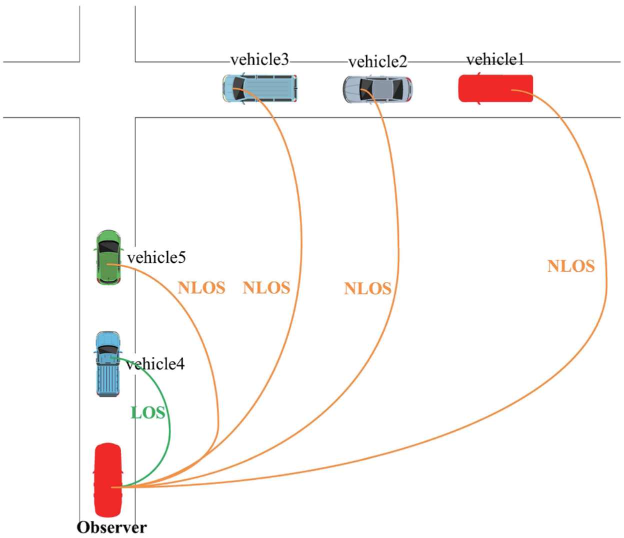

Fig. 5. (Color online) Schematic diagram of a mixed scenario.

Table 1
Simulation parameters of a hybrid scenario.

Vehicle	Speed (km/hr)	Acceleration (m/s^2)	Direction	Coordinate
Observer	60	0	90°	(0, −166.667)
Vehicle1	103.923	0	180°	(288.675, 0)
Vehicle2	100	0	180°	(250, 0)
Vehicle3	100	0	180°	(200, 0)
Vehicle4	60	0	90°	(0, −150)
Vehicle5	80	0	90°	(0, −100)

4. Results of Simulation and Discussion

The proposed judgment process for collision warning yielded the results shown in Figs. 6(a)–6(d). From the results shown in Fig. 6(a), the Doppler shift value of vehicle1 changes from positive to negative at the tenth second. This result suggests that there is the chance of a collision between the observer vehicle and vehicle1. Figure 6(a) also shows that only the value of vehicle5 is smaller than zero and that of vehicle4 is equal to zero. This means that the Doppler shift values of vehicle4 and vehicle5, moving in the same direction as the observer vehicle, are zero and negative, respectively. These results indicate that the two vehicles are moving at the same speed and away from the observer vehicle. The slopes of the Doppler shifts for all vehicles are shown in Fig. 6(b), which can be used to judge the collision time of the observer vehicle with other vehicles. The results in Fig. 6(b) indicate that vehicle2 and vehicle3 pass through the crossroads first, and that vehicle1 will collide with the observer vehicle at the tenth second

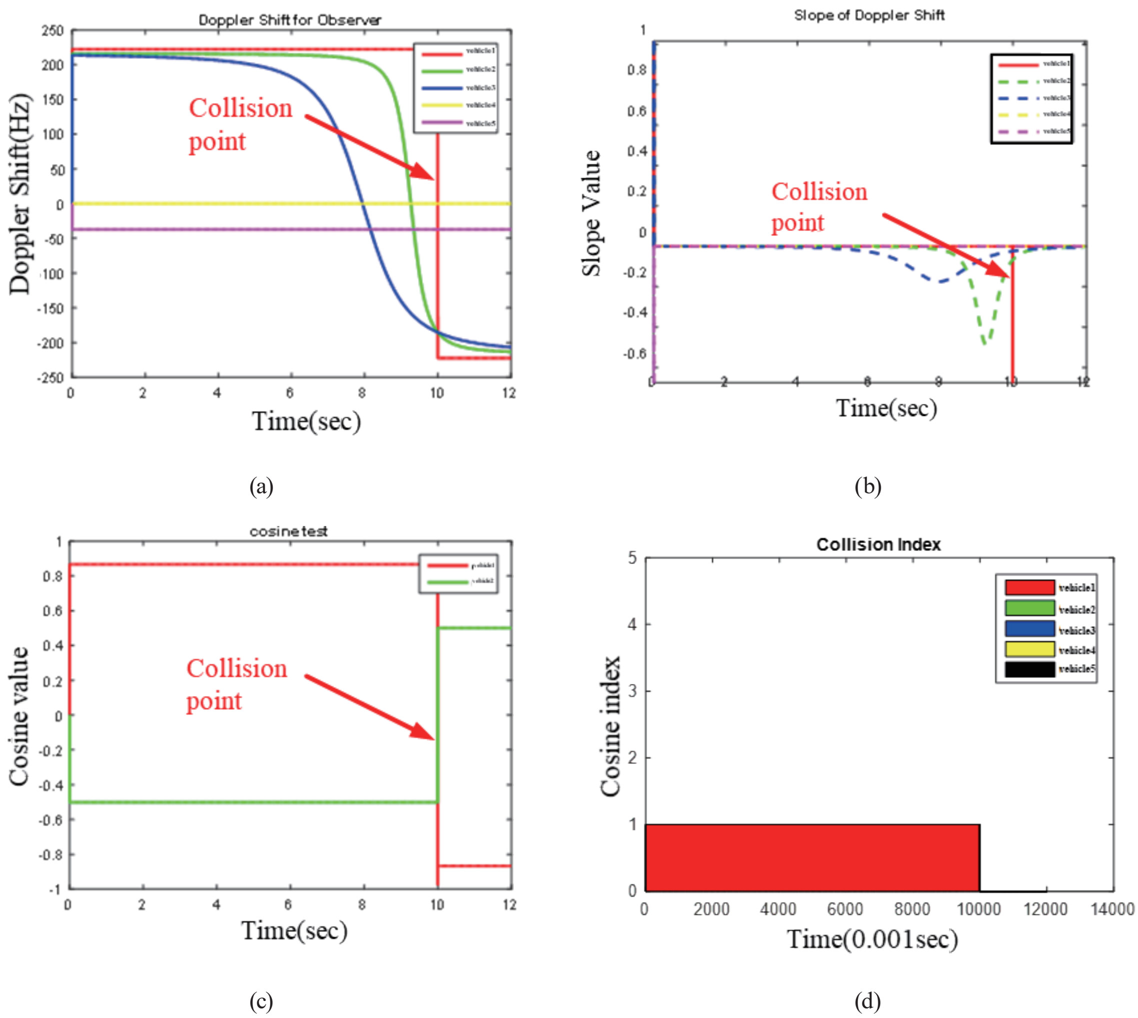

Fig. 6. (Color online) (a) Doppler shift value of each vehicle, (b) slope of Doppler shift of each vehicle, (c) vehicle1 cosine value, and (d) collision index of each vehicle.

because the slope of the Doppler shift has a pulse at the tenth second. According to Fig. 6(c), the angle of the two vehicles maintains a fixed value before the impact, and when the collision occurs at the tenth second, the angle changes instantaneously. The results in Fig. 6(c) show that the cosine value of vehicle2 changes from negative to positive, and that of vehicle1 changes from positive to negative at the tenth second. These results suggest that the collision between the observer vehicle with vehicle1 will happen. The results indicate that vehicle2 may pass through the crossroads without colliding with the observer vehicle but may also collide with the observer vehicle. Figure 6(d) shows the collision indexes of vehicle1 through vehicle5; these are the early warning results obtained from this process for the five vehicles in this scenario. Figure 6(d) indicates that only vehicle1 meets the conditions for collision and that the system will generate an early warning before that collision occurs.

According to Fig. 6(a), the Doppler shift value of vehicle4 is zero, which means that both the vehicle and the observer vehicle are moving at the same speed and maintain the same distance. The Doppler shift value of vehicle5 is less than zero, which means that the vehicle maintains a distance from the observer vehicle. Vehicle3 will pass the intersection first, followed by vehicle2, and finally, vehicle1 will collide with the observer vehicle. According to Fig. 6(b), the observer vehicle will collide with vehicle1, while vehicle3 and vehicle4 will pass through the crossroads before this time. After the collision, the angle of the two vehicles will change. The results for this scenario are shown in Fig. 7 for the five vehicles. First, both vehicle4 and vehicle5 are screened out in the first judgment, because their Doppler shift values are larger than zero and their collision indexes are set to zero. Next, vehicle2 and vehicle3 are screened in the second judgment, because the slopes of their Doppler shifts are equal to zero and their collision indexes are set to zero. Finally, vehicle1 passes all the judgments, which generates a collision warning for vehicle1, and the collision avoidance warning produces an alarm. These results indicate that the proposed system can effectively be used as a non-line-of-sight collision avoidance warning system.

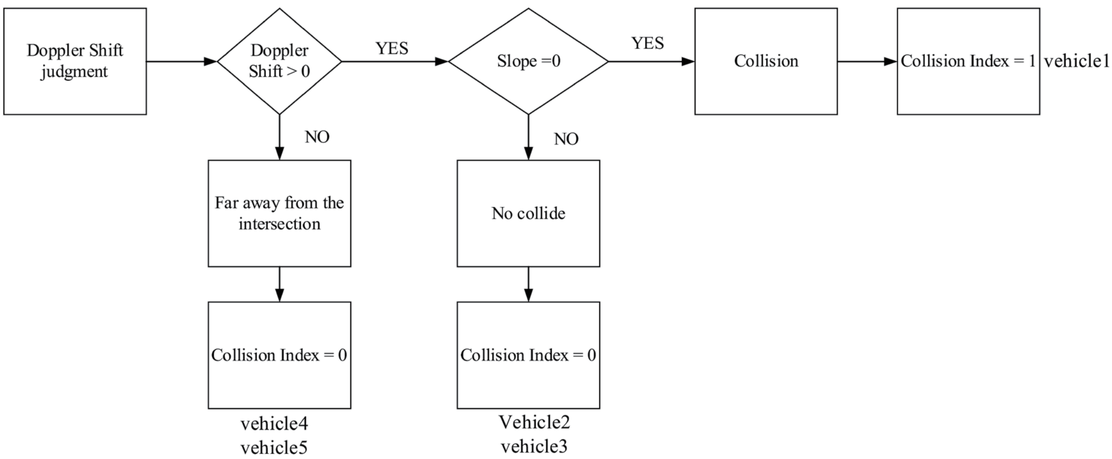

Fig. 7. (Color online) Results of the mixed scenario from the non-line-of-sight collision avoidance early warning system.

5. Conclusions

We proposed a judgment process for traffic collision warnings to predict whether an observer vehicle will collide with other vehicles at a crossroads. According to the results of a simulation obtained from MATLAB software, the equations for three different situations that cause changes in the Doppler shift were investigated, and a corresponding collision warning process between an observer vehicle and other vehicles was proposed for the scenario at the crossroads. The results indicated that, if the Doppler offset value was greater than zero and the slope of the Doppler offset was equal to zero, then, the two vehicles collide at the crossroads. The system was used to simulate the relationships between the observer vehicle and five other vehicles. Both vehicle4 and vehicle5 were screened out in the first judgment, because their Doppler shift values were larger than zero and their collision indexes were set to zero. Both vehicle2 and vehicle3 were screened out in the second judgment, because the slopes of their Doppler shifts were equal to zero and their collision indexes were set to zero. Finally, vehicle1 passed all the judgments, the simulation system generated a collision warning for vehicle1, and the collision avoidance warning issued an alarm. These results indicate that the system described herein can effectively be used as a non-line-of-sight collision avoidance warning system.

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