Sensors and Materials, Vol. 35, No. 3 (2023) 723–732
MYU Tokyo

S & M 3206

Simulation for Non-line-of-sight Collision Avoidance Warning System Based on 5G Mobile Car Communication Network

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(Received September 12, 2022; accepted October 27, 2022)

Keywords: simulation, non-line-of-sight, collision avoidance warning system, 5G mobile, Doppler shift

In this study, the 5G long-term evolution (LTE) system and the Doppler migration technique are combined to investigate a non-line-of-sight collision avoidance warning system. The 5G LTE system is used as the communication networks of mobile cars and the Doppler migration technique is used to quickly detect the relative speeds and driving directions (coordinates) of target cars. Then, MATLAB software is used as simulation software and a straight expressway is used as the simulation scenario to simulate the non-line-of-sight collision avoidance warning system. A car is used as the observer and other cars with different conditions are used as tested objects in the simulation of the non-line-of-sight collision avoidance warning system based on the investigated 5G mobile communication network. The starting coordinates, starting speeds, accelerations, driving directions, and simulation time of all the cars are input in MATLAB software as the parameters to generate the moving coordinates, distances, speeds, and angles of all the cars in the simulation process. The simulation time is 15 s under different conditions, and the changes in both the Doppler shift and its slope between the observer car and other cars are observed and analyzed to judge the collision conditions. The analysis results show that the investigated system can generate an avoidance warning before the collision occurs.

1. Introduction

Owing to the rapid improvements and development of wireless networks, an increasing number of sensors are installed in cars. A large amount of sensing data can be integrated through an in-vehicle system then sent through 4G/5G wireless communication networks. Vehicle communication transmission methods, such as vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to pedestrian (V2P), are collectively referred to as vehicle networking communication technologies (V2X).[1–4] The wireless communication systems are constructed using V2X technologies and have been investigated with the aim of enabling data exchange

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https://doi.org/10.18494/SAM4110

ISSN 0914-4935 © MYU K.K.
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between traveling cars and their surroundings. The V2X communication protocol is based on 5.9 GHz short-range communication technologies, and a Wi-Fi derivative can be specifically used for fast-moving objects and to establish reliable radio links, even under non-line-of-sight conditions. Under the definition of the 3rd Generation Partnership Project (3GPP) V2X, when V2V is used, vehicles can broadcast their own information, including the current position, speed, acceleration, and estimated trajectory. In the specification of the TR22.885 file, there are 18 implementation cases that are defined and used in V2X. Among them, the two implementation cases of forward collision warning and queue warning are similar and related to the simulation in this paper.[(5)]

Many studies previously discussed collision avoidance warning technology under the V2V architecture.[(6–8)] Among them, Zhou and He proposed a forward collision warning system and a message transmission mechanism, which defined two kinds of messages: warning and emergency messages.[(6)] When a car is equipped with the forward collision warning system and its brake light is on, it sends a warning message signal, and the cars to the rear that are also equipped with this system can assess whether they have maintained a safe distance on the basis of this signal. When the braking speed of a car is greater than 4 m/s^2, the car sends an emergency message to inform the car drivers behind, who must brake immediately to avoid a collision.

Many studies on sensors related to collision avoidance warning technology have also been reported.[(9–11)] Zeng *et al.* proposed the use of a car perception system for the detection of car collision risk detection.[(10)] In V2V and V2I scenarios, the motion statuses of vehicles, obstacles, and pedestrians on roads can be tracked through sensors such as cameras, global positioning systems, and ZigBee, and the Kalman filter is used to predict vehicle trajectories. Many studies have also investigated collision warning algorithms.[(12–14)] Huang *et al.* proposed a collision warning algorithm under the WAVE (IEEE 1609) standard.[(12)] When cars use the collision warning system, they regularly broadcast relevant information to surrounding cars. Each car calculates a potential collision probability from the received relevant information and sends a warning to the driver a few seconds before a collision could occur.

In view of the diverse applications and demands of scenarios for the internet of vehicles, many studies have considered extensions of the long-term evolution (LTE) system as new businesses in vertical industries.[(13,14)] Therefore, the simulation communication protocol of this study also uses the LTE internet of vehicle technology for intelligent transportation applications, which is based on the LTE-V2X standard of 3GPP. As a comprehensive communication approach for vehicle–road collaborations, LTE-V2X can provide low-latency, high-reliability, high-speed, and secure communication capabilities in high-speed mobile environments. Therefore, it can meet the needs of various applications of the internet of vehicles. Also, when a communication system is based on time-division duplex (TDD)-LTE communication technology, it can maximize the use of resources such as TDD-LTE deployed networks and terminal chip platforms, reduce the cost of network investments, and reduce chip costs. Therefore, the communication protocol used in this simulation technology is also based on the LTE-V2X internet of vehicles technology and in standard research on demonstration applications.

Many studies have investigated the effect of the Doppler effect/shift on collision avoidance warning.[(15–18)] A novel technique was proposed by Li *et al.* for collision avoidance radars in cars, which used a new six-port microwave/millimeter wave number unphase/frequency discriminator to measure the Doppler shift.[15] By this method, the relative speed and driving direction of the target car can be quickly obtained, and the effectiveness of this method was demonstrated by simulation. In this paper, we show that the proposed Doppler migration technique can perform effective early warning judgments of multiple cars ahead in a non-line-of-sight situation. The collision avoidance warning can be performed for one car or even a dozen cars in front, and it is not affected by environmental factors such as light, rain, and smoke. In this study, LTE-V2X technology and the Doppler effect are used as the communication and detection technologies, and MATLAB software is used to simulate the non-line-of-sight collision avoidance warning system based on the 5G mobile communication network for one observer car and other tested cars.

2. Simulation Process and Parameters

The simulation method in this study uses MATLAB software. First, the simulation parameters (starting coordinates, starting speeds, accelerations, driving directions, and simulation time) of all the cars were input in MATLAB to generate all the moving coordinates, distances, speeds, and angles between the observer car and other tested cars in the simulation process. Then, Eq. (1) was used to generate the Doppler shifts of the observer vehicle and the other vehicles and calculate the slopes of the Doppler shifts for the subsequent analysis and research.

$$\begin{aligned}
\tau' = \tau\left(1-\frac{v_s}{v}\cos\theta\right) \Rightarrow \omega' = \frac{2\pi}{\tau'} = \frac{2\pi}{\tau\left(1-\frac{v_s}{v}\right)\cos\theta} = \frac{\omega}{1-\frac{v_s}{v}\cos\theta} = \omega\cdot\left(\frac{1}{1-\frac{v_s}{v}\cos\theta}\right) \\
= \omega\cdot\left(1+\frac{1}{1-\frac{v_s}{v}\cos\theta} - \frac{1-\frac{v_s}{v}\cos\theta}{1-\frac{v_s}{v}\cos\theta}\right) = \omega\cdot\left(1+\frac{\frac{v_s}{v}\cos\theta}{1-\frac{v_s}{v}\cos\theta}\right) = \omega\cdot\left(1+\frac{v_s\cos\theta}{v-v_s\cos\theta}\right)
\end{aligned} \tag{1}$$

Here, the signal source moves at an equivalent speed of v_s, t_1 and t_2 are the signal source at different positions, $\tau = 2\pi/\omega$ is the period of the electromagnetic wave for $\tau_1, \tau_2 \gg v_s\tau$, τ' is the period in which the observer measures the time difference between the arrival of two consecutive waves, l_1 and l_2 are the distances from the signal source to the observer at τ_1 and τ_2, respectively, and τ' is given as

$$\tau' = t_2 - t_1 = \left(\tau + \frac{l_2}{v}\right) - \frac{l_1}{v} = \tau - \frac{l_1 - l_2}{v}. \tag{2}$$

In the simulation process, it is assumed that when two cars collide, their speeds and directions do not change. Therefore, in the simulation results, when two cars collide, there will be a phenomenon of crossing, because we only discuss the relationship between the Doppler offset values of the two cars before the collision. In this study, the proposed simulation scenario is a straight expressway (or highway). This scenario is simulated under different conditions, then the changes in the Doppler shifts are observed and those in the slopes of Doppler shifts are calculated. Figure 1 schematically shows the simulation scenario of a straight expressway. The observer car (observer) at the rear receives all the V2V radio signals from the cars in front. All the cars in front have different speeds, accelerations, and positions in the simulations and analyses.

In this paper, in the scenario of a straight expressway, six different driving cases are set as shown in Table 1. 1. The observer car is slower than Car 1 and the two cars have zero acceleration. 2. The observer car has the same speed as Car 1 and the two cars have zero acceleration. 3. The observer car is faster than Car 1 and the two cars have zero acceleration. 4. The observer car is faster than Car 1, and the observer car has positive acceleration and Car 1 has zero acceleration, which means that the two cars have a positive relative acceleration. 5. The observer car is faster than Car 1, and the observer car has zero acceleration and Car 1 has positive acceleration, which means that the two cars have a negative relative acceleration. 6. The observer car is faster than Car 1 but the two cars are in different lanes. The simulation time is 15 s, and both the changes in the Doppler shift and its slope between the two cars are observed and analyzed to judge whether the two cars will collide.

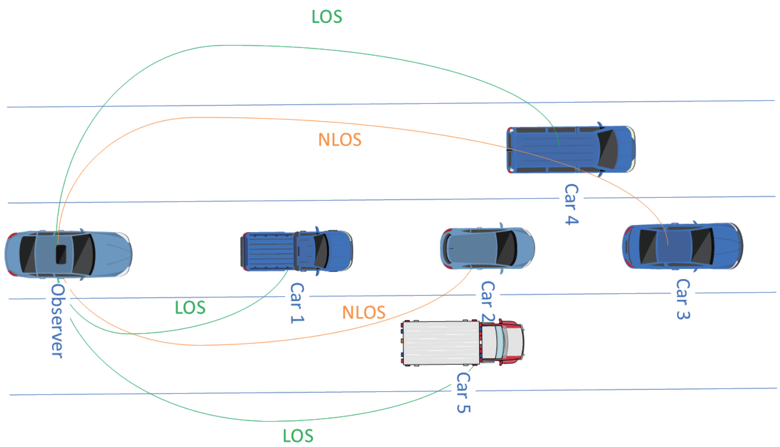


Fig. 1. (Color online) Schematic diagram of the straight expressway scenario.

Table 1
Simulation parameters on expressway.

Case	Observer car speed (km/h)	Car 1 speed (km/h)	Observer car acceleration (m/s^2)	Car 1 acceleration (m/s^2)	Observer car coordinates	Car 1 coordinates
1	100	120	0	0	(3.75, 0)	(3.75, 60)
2	100	100	0	0	(3.75, 0)	(3.75, 60)
3	100	80	0	0	(3.75, 0)	(3.75, 60)
4	100	80	5	0	(3.75, 0)	(3.75, 60)
5	100	80	0	5	(3.75, 0)	(3.75, 60)
6	100	80	0	0	(3.75, 0)	(7.5, 60)

3. Simulation Results and Discussion

In this study, we propose a driving collision warning judgment process to predict whether the observer car will collide with another car in front. First, in the simulation, it must be judged whether a Doppler shift is positive or negative. If the Doppler shift is positive, there is a possibility of collision between the two cars when they approach each other. Conversely, if the Doppler shift is zero or negative, the two cars remain equidistant from each other or move away from each other, and there is no possibility of collision. Next, it is necessary to judge whether the calculated slope of the Doppler shift is zero. If the slope of the Doppler shift is zero, the relative speed between the two cars is constant and a collision will occur. On the other hand, if the slope of the Doppler shift is not zero, the angle formed by the driving paths of the two cars is not maintained and the two cars will cross without colliding.

The Doppler shift indicates that when a car moves in a certain direction with a constant speed, the phase and frequency change due to the differences in the propagation distances. The changes in the phase and frequency are usually called the Doppler shift, and they reveal the laws by which the properties of waves change in motion. Figures 2(a) and 2(b) show the results for case 1, where the observer car (100 km/h) is slower than Car 1 (120 km/h), the accelerations for both cars are zero, and the two cars have different y coordinates. It can be seen that the Doppler shift between the two cars is less than zero, which means that the two cars are moving away from each other, and the slope of the Doppler shift is zero, which means that the relative speed between the two cars has not changed. This result suggests that there is no collision between the two cars, and the warning system will not sound an alarm when they are approaching each other.

For case 2, the speed of the observer car (100 km/h) is equal to that of Car 1, the accelerations for both cars are zero, and the two cars have different y coordinates. The simulation results of the Doppler shift and its slope for case 2 are respectively shown in Figs. 3(a) and 3(b). Both the Doppler shift between the two cars and its slope are equal to zero. These two conditions mean that the two cars maintain their equal speeds, also suggesting that no collision will occur

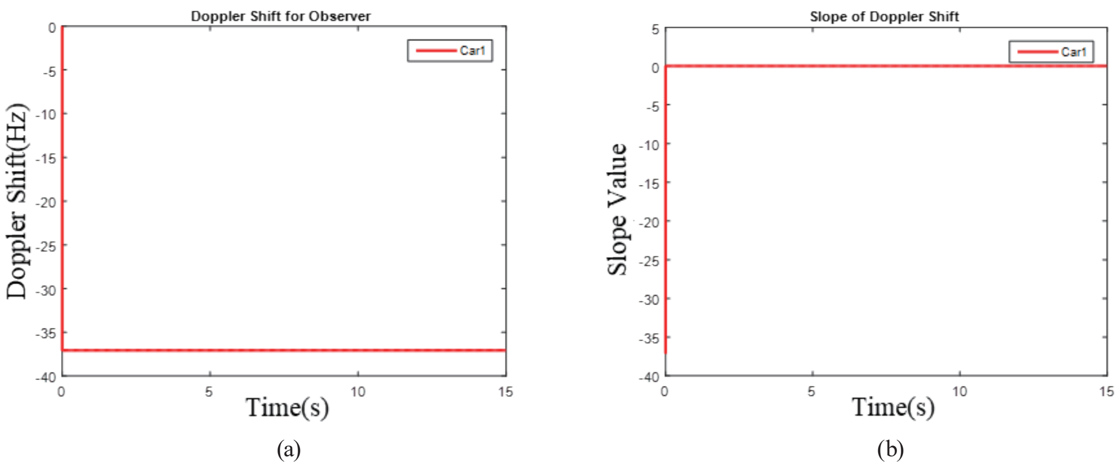
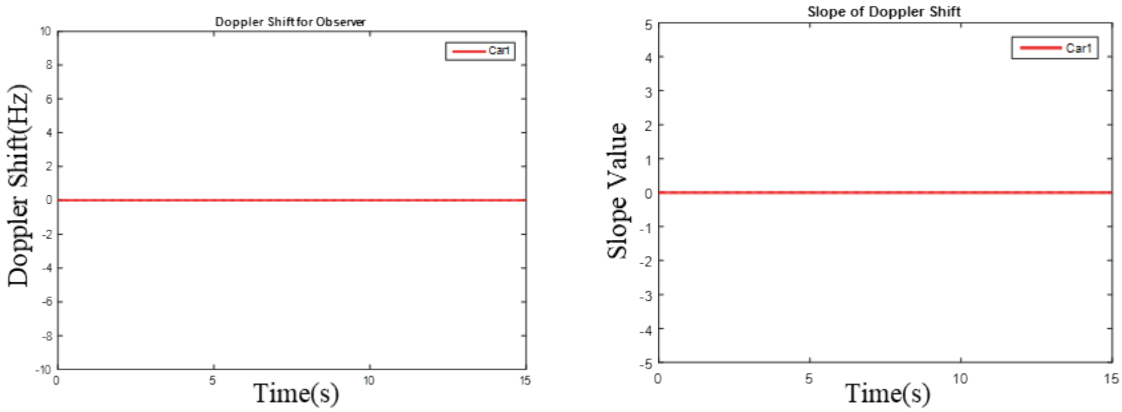


Fig. 2. (Color online) (a) Doppler shift and (b) slope of Doppler shift for case 1 on expressway.



(a) (b)

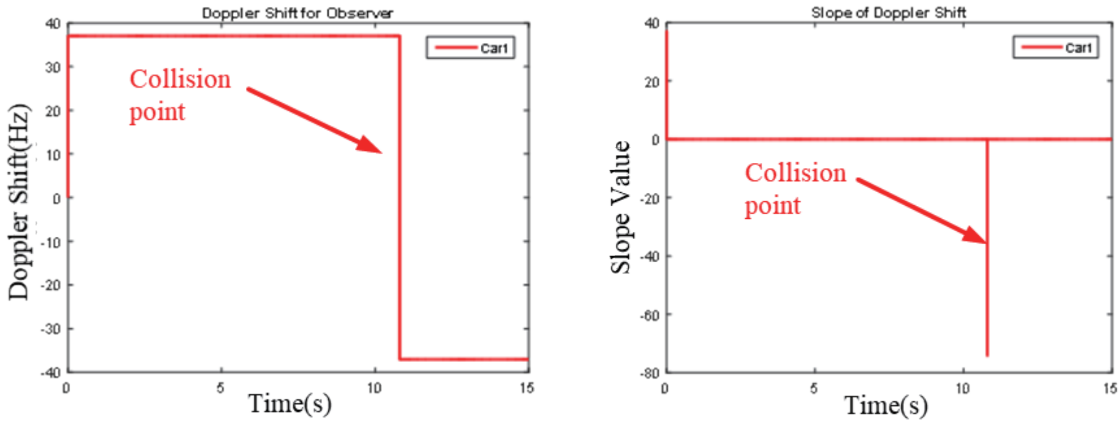
Fig. 3. (Color online) (a) Doppler shift and (b) slope of Doppler shift for case 2 on expressway.

between them, and the warning system will not sound an alarm when the two cars are approaching each other.

Figures 4(a) and 4(b) show the simulation results of case 3, in which the speed of the observer car (100 km/h) is higher than that of Car 1 (80 km/h), the accelerations for both cars are zero, and the two cars have different y coordinates. Figure 4(a) shows that the Doppler shift between the two cars first has a positive value but instantaneously becomes negative at 11 s. This result suggests that if the two cars maintain their conditions, a collision will occur at this time. Therefore, the slope of the Doppler shift between the two cars has a sudden change at 11 s (the impact point). From the slope of the Doppler shift shown in Fig. 4(b), except at the impact point, the two cars maintain a fixed speed difference, and the slope of the Doppler shift is zero. However, a collision will occur under these conditions and the warning system will sound an alarm when the two cars are approaching each other.

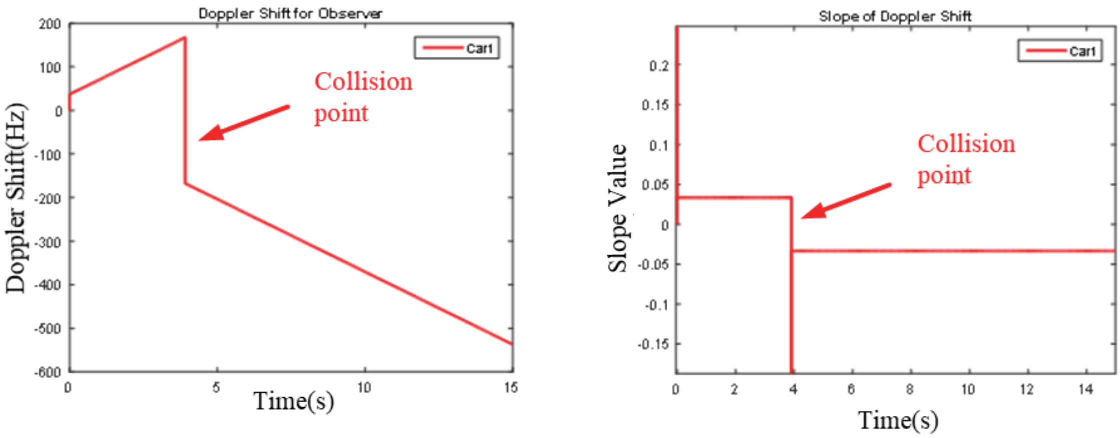
In case 4, the observer car (100 km/h) has a higher speed than Car 1 (80 km/h), the acceleration of the observer car is 5 m/s^2 and the acceleration of Car 1 is zero, and the two cars have different y coordinates. From the results in Fig. 5(a) and 5(b), the Doppler shift between the two cars is greater than zero from the beginning, and there is a positive slope of the Doppler shift, which suggests that the observer car is approaching Car 1 at an increasing rate. As shown in Fig. 5(b), there is a sudden change at 4 s, after which the Doppler shift changes from positive to negative, suggesting that a collision occurs at 4 s. After the impact, the two cars start to move away from each other with a negative acceleration (with the observer car faster than Car 1). The warning system will sound an alarm before the possible collision at 4 s.

Figures 6(a) and 6(b) show the simulation results for case 5, in which the speed of the observer car (100 km/h) is higher than that of Car 1 (80 km/h), the acceleration of the observer car is zero and that of Car 1 is 5 m/s^2, and the two cars have different y coordinates. The Doppler shift of the two cars decreases from a positive value with a fixed slope and the slope of the Doppler shift only has a negative value. In this case, because no sudden change is observed in the slope of the Doppler shift, no collision will occur and the warning system will not sound an alarm when the two cars are approaching each other.



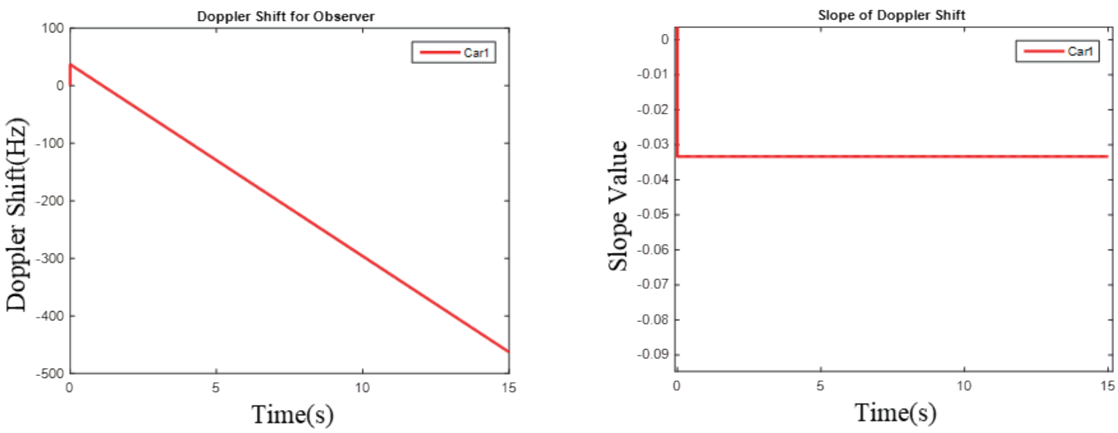
(a) (b)

Fig. 4. (Color online) (a) Doppler shift and (b) slope of Doppler shift for case 3 on expressway.



(a) (b)

Fig. 5. (Color online) (a) Doppler shift and (b) slope of Doppler shift for case 4 on expressway.



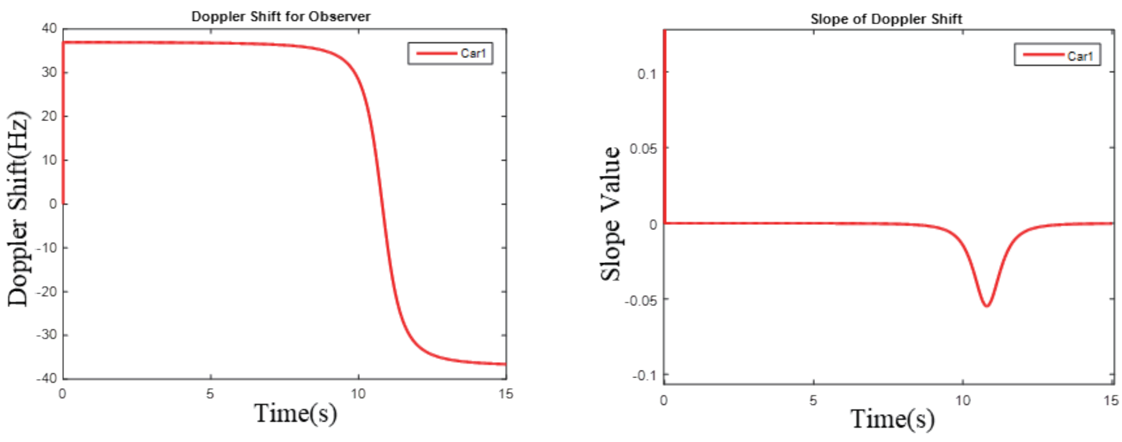
(a) (b)

Fig. 6. (Color online) (a) Doppler shift and (b) slope of Doppler shift for case 5 on expressway.

In case 6, the observer car (100 km/h) has a higher speed than Car 1 (80 km/h), the acceleration of the observer car is 5 m/s^2 and the acceleration of Car 1 is zero, and the two cars have different x and y coordinates. From Figs. 7(a) and 7(b), it can be seen for this case that the Doppler shift between the two cars initially very slowly decreases and the slope of the Doppler shift is zero. After 10 s the Doppler shift value switches from positive to negative, but not instantaneously, and the slope of the Doppler shift only has a negative peak. Because no sudden change is observed in the slope of the Doppler shift, it can be concluded that the two cars belong to different lanes and that the observer car overtakes Car 1. Therefore, no collision will occur and the warning system will not sound an alarm when the two cars are approaching each other.

The simulation results of these six cases suggest that when the Doppler shift critically changes from positive to negative, a collision between the two cars may occur. If the observer car has a positive acceleration relative to Car 1, the slope of the Doppler shift has a fixed positive value, as shown in Fig. 5(b). If the observer car has a negative acceleration relative to Car 1, the slope of the Doppler shift has a fixed negative value, as shown in Fig. 6(b). If the two cars are in different lanes and the observer car overtakes Car 1, the Doppler shift shows a change in the slope. The change in the slope of the Doppler shift is used to judge the change in the observed speed of Car 1 with time, as shown in Fig. 7(b).

From the above simulation results, a dedicated collision warning flow chart is proposed for the straight expressway scenario, as shown in Fig. 8, and three collision parameters are set to represent three different collision possibilities. First, it is determined whether the Doppler shift is greater than zero to judge whether the two cars are approaching each other, then the slope of the Doppler value is determined. If the slopes of the Doppler shifts do not change with the time, then the two cars are in the same lane. If they are not equal, then the two cars are in different lanes and there will be no collision. Finally, if the slope of the Doppler shift is greater than zero, then the two cars are close and have a positive acceleration, which suggests that their collision probability is very high. Therefore, the collision index of this situation is set to 3 and the warning system will sound an alarm. If the slope of the Doppler shift is zero, then the two cars are



(a) (b)

Fig. 7. (Color online) (a) Doppler shift and (b) slope of Doppler shift for case 6 on expressway.

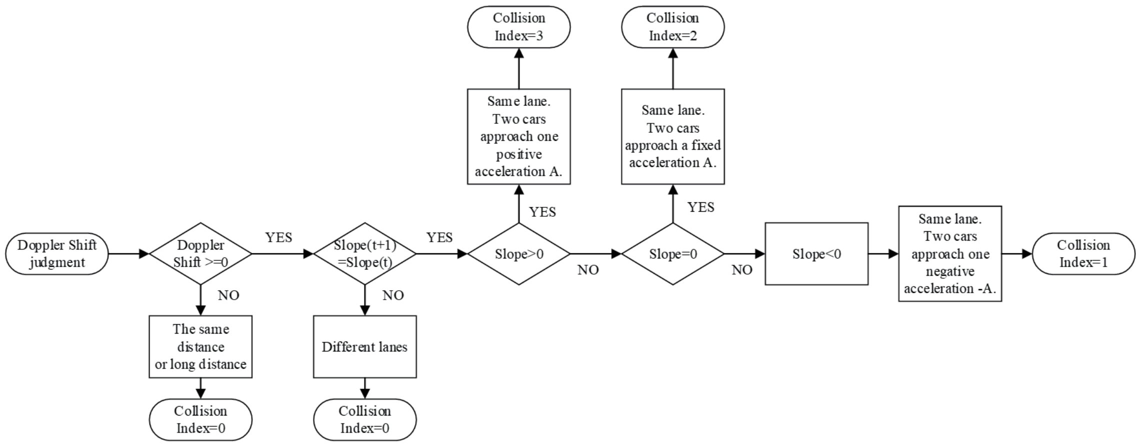


Fig. 8. Flow chart of straight-line expressway collision warning judgment.

approaching each other at a relatively equal speed. Therefore, the two cars may collide, the collision index is set to 2, and the warning system will sound an alarm. If the slope of the Doppler shift is less than zero, then the two cars have a relatively similar speed. However, they have a negative acceleration, which means that the relative approach speed of the two cars is gradually decreasing. Therefore, there may or may not be a collision, the collision index is set to one, and the warning system will sound an alarm when the two cars approach each other. Collision parameters that do not satisfy the previous conditions are set to zero, indicating that there is no danger of collision. These results suggest that the proposed system can effectively act as a non-line-of-sight collision avoidance warning system in the straight-line expressway scenario.

4. Conclusions

In this study, we used six different conditions to simulate our non-line-of-sight collision avoidance warning system based on a 5G mobile car communication network. We found that two important factors can be used to predict whether a collision will occur, the Doppler shift and its slope. When the Doppler shift changes from positive to negative, a collision between two cars may occur. If a sudden change is exhibited in the slope of the Doppler shift and the slope subsequently changes from positive to negative, the cars will collide, and the warning system will sound an alarm when the two cars are approaching each other. A dedicated collision warning flow chart is proposed, which clearly defines the judgment process for the investigated system for the straight expressway scenario. However, we only investigated the system by theoretical numerical analysis, and actual V2V channel model parameters were not used in this simulation. In the future, if the V2V 3D channel model currently defined by LTE is added as a simulation parameter for further analysis, the feasibility of implementation of the system will be greatly improved.

Acknowledgments

This work was supported by the 2020 Industry-University-Research Innovation Fund for Chinese Universities-New Generation Information Technology Innovation Project (No. 2020ITA05005), MOST 110-2622-E-390-002, MOST 110-2221-E-390-020, and MOST 110-2221-E-032-018-MY2.

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