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Simulation Method for Non-line-of-sight Collision Avoidance Warning System

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In this study, we investigated an algorithm that combines GPS and Doppler migration technologies to improve the collision prevention technology for judging vehicles' directions on a highway interchange. In this algorithm, vehicle-to-vehicle communication was accomplished using transceivers installed on the vehicles, and the investigated algorithm analyzed the characteristics of Doppler shift values of the frequency offset sent by the moving vehicles to observe the dynamic relationships between an observer vehicle and other vehicles. From the change in frequency offset (Doppler shift), the investigated system can detect the situation of multiple merging vehicles from a highway interchange and analyze whether these vehicles can safely enter the main lane. In this work, we studied and discussed the investigated collision avoidance warning system by using vehicle-to-vehicle communication in non-line-of-sight situations via the 5G mobile network. The simulations and analyses were mainly carried out under the situations described above to observe the changes in Doppler shift values. In this research, a driving collision theory is proposed for judging whether a collision will occur by the driving collision warning judgment process, and the investigated collision warning mechanism is verified.

1. Introduction

The rapid development of the Internet of Things (IoT) in recent years has accelerated the research of the Internet of Vehicles (IoV). Consequently, the developments related to unmanned and autonomous driving vehicles have rapidly advanced. Owing to the development of wireless communication networks, more and more sensors are now being equipped on vehicles. The resulting large amounts of sensor data can be integrated through the in-vehicle system and then sent through 4G/5G wireless communication networks. These are collectively referred to as

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vehicle-to-everything (V2X) communication technologies, and V2X technologies are now also being used in automotive collision avoidance systems.

Li *et al.* proposed a collision avoidance warning system for rear-end collisions.(1) Their investigated system was an integration of the global positioning system (GPS), screens, speakers, and other equipment. GPS was used in a vehicle-to-vehicle (V2V) communication environment to receive and collect the position, speed, and direction information of each moving vehicle in the context of a straight lane. This system can be used to determine whether the vehicles behind the observer are colliding and when a collision might occur; thus, this system can warn the observer via the screen and sound the horn. In other research, the relative kinetic energy was used to measure the potential for collision impacts between approaching vehicles and the observer, and a study for the problem of multivehicle collision avoidance technology was formulated and later improved.(2,3) Ashrafi *et al.* investigated a technology that was related to the use of intervehicle communication for the anticollision technology of highway serial traffic accidents.(4) They used the test bed of the Connected Vehicle Technology Project in chain collision avoidance to investigate a system for processing the large amount of intervehicle communications, which was based on the IEEE 1609/WAVE (wireless access in vehicular environments) standard. Dissanayake *et al.* proposed a novel wireless access in the vehicular environment velocity estimation technique, wherein the Doppler shifts that result in frequency shifts in the received orthogonal frequency-division multiplexing carriers were used to estimate the relative speeds of vehicles.(5) The method yields good estimations of the relative velocities even at low signal-to-noise ratios, and the simulation shows that a wide range of velocities (0 to 360 km/h) can be estimated accurately.

Woll proposed a collision warning algorithm under the IEEE 1609/WAVE standard.(6) In this algorithm, vehicles regularly broadcast relevant information (RI) to surrounding vehicles, and each vehicle calculates a potential collision probability on the basis of the received RI data and sends a warning to the driver a few seconds before a collision occurs. Alamm *et al.* investigated a dynamic estimation method of path loss indexes and distances based on the values of Doppler shift and the received signal strength.(7) In this method, the power and Doppler shift are measured over time with a preset path loss index constant, which do not have any reference point location information. In addition, for vehicles with relative mobility, when the relative speed between nodes increases, the performance of the algorithm will also be improved, and the estimation error will be lower than those of other algorithms. Kihei *et al.* investigated a safety application of V2V based on a designated short-range communication radio frequency, which can allow vehicles to exchange basic safety messages (BSMs) to avoid vehicle collisions.(8)

Tomoyama *et al.* discussed the use of the Doppler effect to estimate the speed of target vehicles at blind spots to obtain position information from GPS.(9) With the position information, the path and arrival time from the observation vehicle to the target vehicles can be calculated. In addition, the path is determined using reflected waves; therefore, the arrival angle of the observation vehicle and the speed of the target vehicles can be derived.(10) The currently used anticollision technologies are presented in Table 1. It can be found that the anticollision technologies that have been commercialized are all in the line-of-sight (LOS) category. The biggest disadvantage of LOS collision avoidance technology is that its detection performance is easily affected by weather and suspended objects in the environment.

Table 1
Current common anticollision technologies. LOS: line-of-sight, NLOS: non-line-of-sight, LiDAR: light detection and ranging, and GPS: global positioning system.

Anticollision technology	NLOS/LOS	Real time	Advantage	Disadvantage
Camera	LOS	YES	More mature technology	High computational complexity, high hardware requirements, and susceptible to environmental factors
LiDAR	LOS	YES	Higher accuracy than cameras	Susceptible to environmental disturbances
Millimeter-wave radar	LOS	YES	Penetrations of fog, smoke, and dust	Reflective detection being susceptible to obstructions
Ultrasonic radar	LOS	YES	Accurate distance resolution	Short detection distance
GPS	NLOS	NO	Long judgment distance and standard coordinate system	Low data update speed
Doppler shift	NLOS	YES	Long judgment distance, high response speed, and simultaneous detections of multiple vehicles ahead	Unable to determine vehicle direction

Although millimeter-wave radar does not have this problem since this technology uses a reflective detection method, it is easily affected by obstacles and can only detect the conditions of the vehicles in front. However, although GPS technology is a non-line-of-sight (NLOS) technology, the update speed is too low to be used in a V2V environment. The Doppler migration technology proposed in this paper can perform an effective early warning judgment of multiple vehicles ahead in the NLOS situation, and it can provide collision avoidance warning for as many as a dozen vehicles ahead. These results suggest that most safety applications rely on GPS and modular sensors to obtain the vehicles' locations and dynamic information and transmit this information in the form of BSM. The combination of Doppler and GPS technologies is not disturbed by environmental factors such as light, rain, smoke, and dust. However, the disadvantage of using Doppler shift as an anticollision warning method at present is that it cannot determine whether the vehicles are in front, behind, to the left or to the right. In this study, we used a highway interchange as a simulated scene to evaluate a NLOS collision avoidance warning system. The proposed algorithm is a combination of GPS and Doppler migration technologies to improve the collision prevention technology for judging the direction of vehicles travelling through the highway interchange.

2. Simulation Process and Parameters Used

With the advancement of technology, the related technologies required for self-driving vehicles are also becoming increasingly mature. There are two technical development priorities for autonomous vehicles on roads: active sensing technology and collaborative data computing. The latter mostly relies on the communication technologies for data exchange and collection to form the V2X service. As shown in Fig. 1, the V2X system mainly includes the V2V, vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) systems. Figure 2 is a schematic of the situation of the highway interchange. The observation vehicle is moving straight ahead in the highway

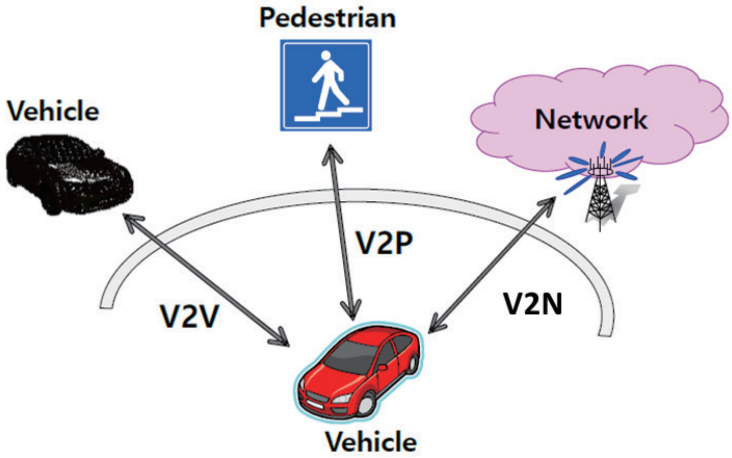


Fig. 1. (Color online) Architecture of LTE V2X system.

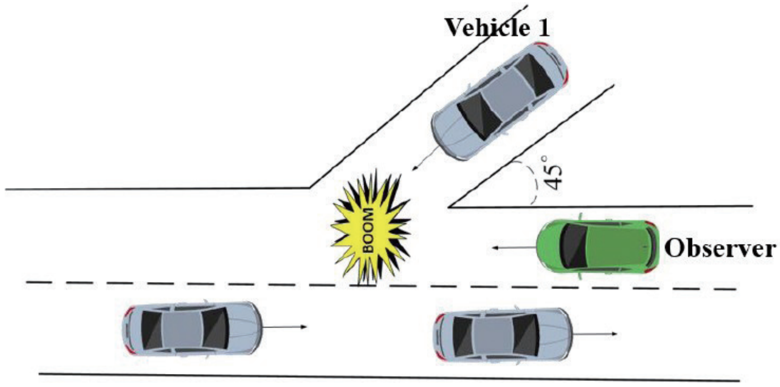


Fig. 2. (Color online) Schematic of the situation of the highway interchange.

lane, and vehicle 1 is heading from the approaching lane and preparing to enter the main lane. The two vehicles are simulated and analyzed with different speeds, accelerations, and positions.

In this study, nine different driving conditions are set in the situation of the highway interchange. As shown in Table 2, the coordinates of the observer vehicle and vehicle 1 are different. These indicate that the two vehicles meet at the highway interchange under different circumstances, and the accelerations for both vehicles are set to zero. From Table 2, there are three types of speed difference between the observer vehicle and vehicle 1: (1) observer vehicle > vehicle 1, (2) observer vehicle = vehicle 1, and (3) observer vehicle < vehicle 1. Each type of speed difference is further divided into three situations: (1) the observer vehicle passes through the highway intersection first, (2) the two vehicles collide as they pass through the highway intersection at the same time, and (3) vehicle 1 passes through the highway intersection first. The simulation time is 12 s, and variations of the Doppler shift and the slope of the Doppler shift between the two vehicles are calculated and analyzed.

Table 2
Simulation parameters of highway interchange.

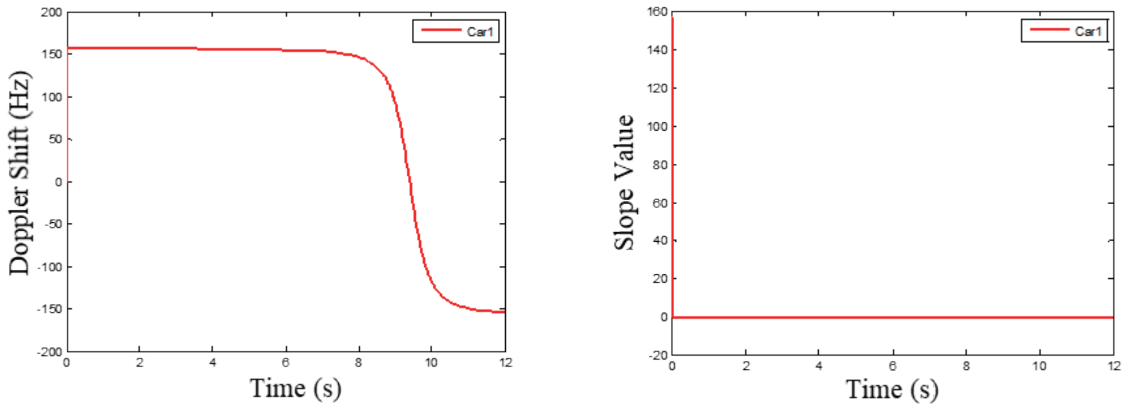
Case	Speed of observer vehicle (km/h)	Speed of vehicle 1 (km/h)	Direction of observer vehicle	Direction of vehicle 1	Coordinates of observer vehicle	Coordinates of vehicle 1
1	120	80	90°	135°	(0, −314.27)	(157.1347, −157.1347)
2	113	80	90°	135°	(0, −314.27)	(157.1347, −157.1347)
3	100	80	90°	135°	(0, −314.27)	(157.1347, −157.1347)
4	80	80	90°	135°	(0, −200)	(157.1347, −157.1347)
5	80	80	90°	135°	(0, −222.22)	(157.1347, −157.1347)
6	80	80	90°	135°	(0, −250)	(157.1347, −157.1347)
7	80	100	90°	135°	(0, −200)	(196.4187, −196.4187)
8	80	100	90°	135°	(0, −222.22)	(196.4187, −196.4187)
9	80	100	90°	135°	(0, −250)	(196.4187, −196.4187)

3. Simulation Results and Discussion

We investigated a NLOS collision system to predict whether the observer vehicle will collide with another vehicle at a highway interchange and whether the NLOS avoidance warning system will sound an alarm if the collision of the two vehicles is imminent. When a vehicle moves at a constant speed and in a certain direction, the Doppler shift value indicates both the frequency and phase changes owing to differences in propagation distances. The changes in both the frequency and phase are called the Doppler shift, and they are governed by the laws by which the properties of waves change with their motions. Because speed and position (coordinates, as shown in Table 1) are used as parameters, the accelerations for both vehicles are set to zero, and the two vehicles have different speeds and coordinates.

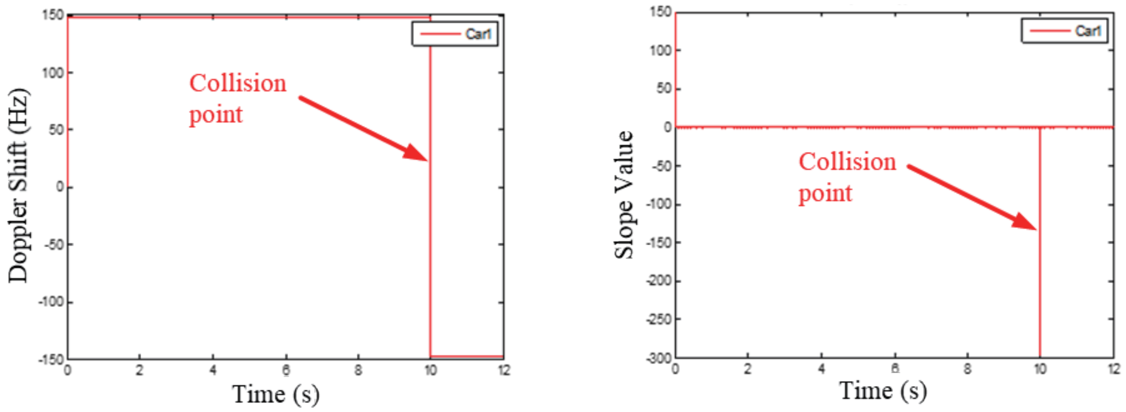
Figures 3(a) and 3(b) show the results for case 1 of highway interchange wherein the observer vehicle (120 km/h) is faster than vehicle 1 (80 km/h). It can be seen that the Doppler shift between the two vehicles is slightly changed from positive to negative as the time increases from the eighth second to the tenth second. The slope of the Doppler shift is always kept at zero when the two vehicles approach at the highway interchange and move away during the time from the eighth second to the tenth second. These results indicate that the relative speed between the two vehicles is not changed and the two vehicles are moving apart because the observer vehicle is faster than vehicle 1. These results also suggest that, in this case, the two vehicles will not collide, and the NLOS collision avoidance warning system will not sound an alarm when the two vehicles are approaching each other at the highway interchange.

Figures 4(a) and 4(b) show the simulation results for case 2. In this case, the observer vehicle (113 km/h) is faster than vehicle 1 (80 km/h) but is slower than the observer vehicle in case 1, and the two vehicles have the same coordinates as those in case 1. Figure 4(a) shows that the Doppler shift between the two vehicles is positive, and it critically changes from positive to negative at the tenth second. This result suggests that if the two vehicles maintain the given condition, the two vehicles will collide at the tenth second (collision time). As shown in Fig. 4(b), the slope of the Doppler shift for the two vehicles has an impulse signal at the tenth second, which is the collision point. Except at the collision point, the two vehicles maintain a relative relationship at



(a) (b)

Fig. 3. (Color online) (a) Doppler offset and (b) slope of Doppler offset for case 1 of highway interchange.



(a) (b)

Fig. 4. (Color online) (a) Doppler offset and (b) slope of Doppler offset for case 2 of highway interchange.

their respective speeds, and the slope of the Doppler shift is equal to zero. These results suggest that, under this condition, the two vehicles will collide at the tenth second. Therefore, the NLOS collision avoidance warning system will sound an alarm before the two vehicles approach each other at the highway interchange.

The simulation results for case 3 are shown in Figs. 5(a) and 5(b). In this case, the observer vehicle (100 km/h) is faster than vehicle 1 (80 km/h) but is slower than the observer vehicle in case 1, and the two vehicles have the same coordinates as those in case 1. It can be seen from Fig. 5(a) that the Doppler shift between the two vehicles is positive, and it changes from positive to negative at the eighth second. This result suggests that the two vehicles change from the approaching state to the away state in the range from the eighth second to the tenth second, so that no collision will occur between the two vehicles. Figure 5(b) shows that the slope of the Doppler shift is equal to zero as the two vehicles approach each other, which means that the relative distance between the two vehicles does not change as the two vehicles approach each other, and the observer vehicle will pass through the highway interchange first. These simulation

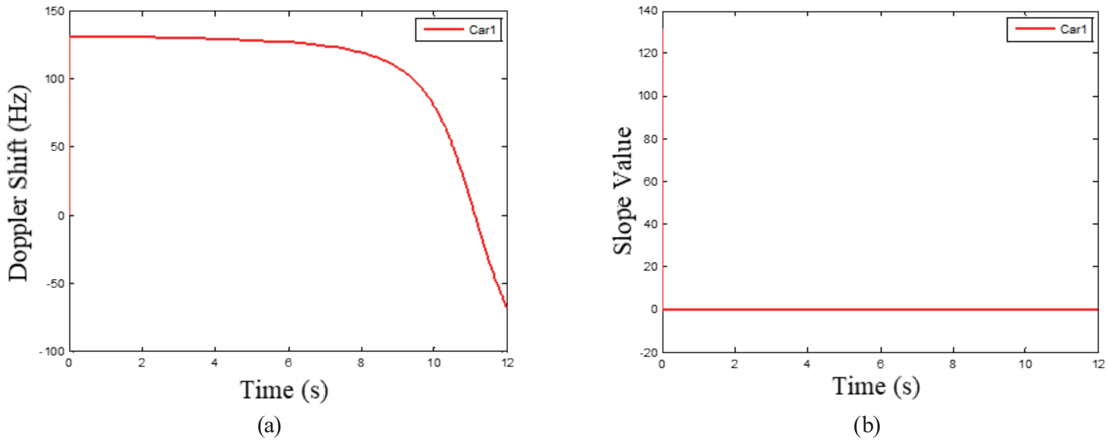


Fig. 5. (Color online) (a) Doppler offset and (b) slope of Doppler offset for case 3 of highway interchange.

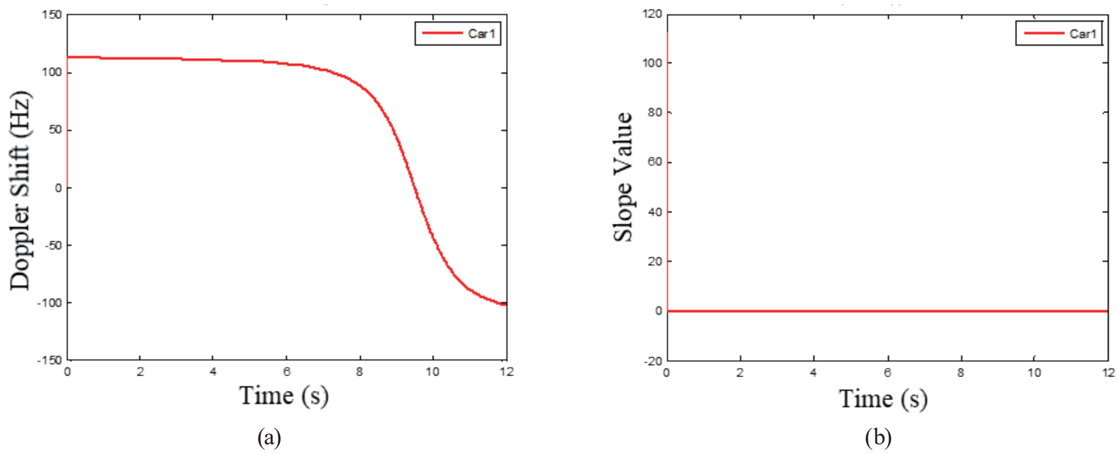


Fig. 6. (Color online) (a) Doppler offset and (b) slope of Doppler offset for case 4 of highway interchange.

results prove that the NLOS collision avoidance warning system will not sound an alarm when the two vehicles are approaching each other in this case because no collision between the two vehicles will occur.

Figures 6(a) and 6(b) show the results for case 4 of highway interchange wherein the observer vehicle (80 km/h) and vehicle 1 (80 km/h) are moving at the same speed. Vehicle 1 has the same coordinates as those in cases 1–3, but the coordinates of the observer vehicle differ from those in cases 1–3. It can be seen that the Doppler shift is positive but it also changed slightly to negative at the ninth second, which means that the two vehicles are approaching each other before the ninth second and moving away after the ninth second. The slope of the Doppler shift is equal to zero in the duration from zero to the twelfth second, which means that the relative distance does not change to zero and the two vehicles do not approach each other. These results suggest that there will be no collision between the two vehicles in this case and the NLOS collision avoidance warning system will not sound an alarm when the two vehicles are approaching each other at the highway intersection.

For case 7, the observer vehicle (80 km/h) is slower than vehicle 1 (100 km/h); the observer vehicle has the same coordinates as those in case 4, but the coordinates of vehicle 1 differ from those in case 4. It can be seen that the variation of the Doppler shift is the same as that shown in Fig. 6(a). This means that the Doppler shift is positive and changes slightly to negative at the ninth second. This result suggests that the two vehicles are approaching each other before the ninth second and moving away after the ninth second. The slope of the Doppler shift is the same as that shown in Fig. 6(b). Therefore, the relative distance between the two vehicles does not become zero. These results suggest that in case 7, there will be no collision between the two vehicles and the NLOS collision avoidance warning system will not sound an alarm.

Figures 7(a) and 7(b) show the simulation results for case 5, in which the speed of the observer vehicle (80 km/h) is the same as that of vehicle 1 (80 km/h). The coordinates of vehicle 1 are the same as those in case 4, but the coordinates of the observer vehicle differ from those in case 4. Figure 7(a) shows that the Doppler shift between the two vehicles is positive before the tenth second, and it changes critically from positive to negative instantly at the tenth second. This result suggests that if the two vehicles maintain this condition, the two vehicles will collide at the tenth second. As shown in Fig. 7(b), the slope of the Doppler shift has an impulse signal at the tenth second. Except at the collision point, the two vehicles maintain a relative speed, and the slope of the Doppler shift is equal to zero. The results in Fig. 7 suggest that under this condition, the collision will occur at the tenth second and the NLOS collision avoidance warning system will sound an alarm before the two vehicles approach each other.

Figures 8(a) and 8(b) show the simulation results for case 8, in which the observer vehicle (80 km/h) is slower than vehicle 1 (100 km/h). The coordinates of vehicle 1 differ from those in case 5 and the coordinates of the observer vehicle are the same as those in case 5. Figures 8(a) and 8(b) show that the Doppler shift and the slope of the Doppler shift between the two vehicles are similar to those in case 5 shown in Fig. 7. This means that the slope of the Doppler shift of the two vehicles has an impulse signal at the tenth second. The results in Fig. 8 suggest that in case 8, the collision will occur at the tenth second and the NLOS collision avoidance warning system will sound an alarm before the two vehicles approach each other.

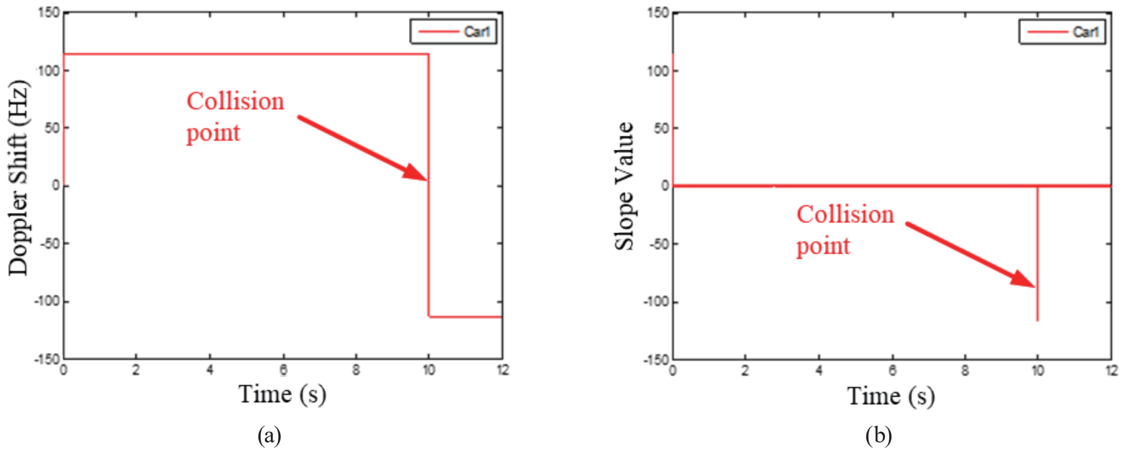
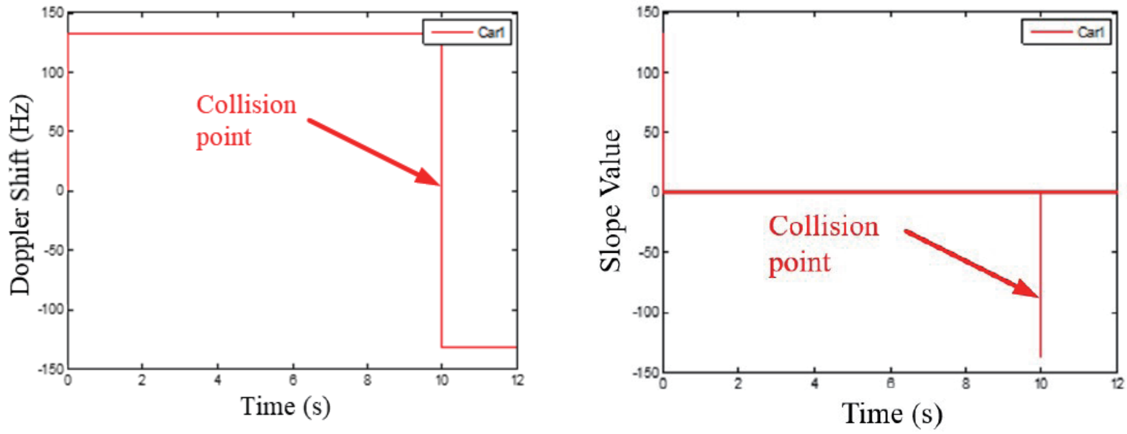


Fig. 7. (Color online) (a) Doppler offset and (b) slope of Doppler offset for case 5 of highway interchange.



(a) (b)

Fig. 8. (Color online) (a) Doppler offset and (b) slope of Doppler offset for case 8 of highway interchange.

The simulation results for case 6 are analyzed (not shown here). In this case, the speed of the observer vehicle (80 km/h) is the same as that of vehicle 1 (80 km/h). The speeds of the two vehicles and the coordinates of vehicle 1 are the same as those in cases 4 and 5, but the coordinates of the observer vehicle differ from those in cases 4 and 5. The simulation results of the Doppler offset and the slope of the Doppler offset in case 6 are similar to those in case 3. This means that the Doppler shift between the two vehicles is positive and changes slowly from positive to negative up to the eighth second, and the slope of the Doppler shift is equal to zero while the two vehicles approach each other. These results suggest that the observer vehicle will pass the highway interchange first, and the relative distance between the two vehicles does not change while the two vehicles approach each other. Therefore, the warning system will not sound an alarm and no collision between the two vehicles will occur. The simulation results for case 9 are also analyzed (not shown here), where the observer vehicle (80 km/h) is slower than vehicle 1 (100 km/h). The speeds of the two vehicles and the coordinates of vehicle 1 are the same as those in cases 7 and 8, but the coordinates of the observer vehicle differ from those in cases 7 and 8. It can be seen that the simulation trend of this situation is consistent with that of case 6; vehicle 1 passes through the highway interchange first and the relative distance between the two vehicles does not change while the two vehicles approach each other. Therefore, the warning system will not sound an alarm and no collision between the two vehicles will occur.

4. Conclusions

In this paper, we proposed the Doppler migration technology that can perform effective early warning judgment, and the NLOS collision avoidance warning system in which GPS and Doppler shift are combined was successfully demonstrated. Twelve seconds was used as the simulation time, and variations of the Doppler shift and the slope of the Doppler shift under nine different conditions between the two vehicles were well analyzed. The NLOS collision avoidance warning system successfully simulated two vehicles at a highway interchange. From the simulation results, we found that if the Doppler shift changed slightly from positive to negative and the slope of the Doppler shift was maintained zero, no collision between the two vehicles would occur and the NLOS collision avoidance warning system would not sound an alarm. If the Doppler shift changed critically from positive to negative and the slope of the Doppler shift had a pulse, the two vehicles would collide and the NLOS collision avoidance warning system would sound an alarm.

Acknowledgments

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