Hindawi
Journal of Advanced Transportation
Volume 2021, Article ID 9970978, 18 pages
https://doi.org/10.1155/2021/9970978

Research Article

Research on Performance and Function Testing of V2X in a Closed Test Field

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Received 22 March 2021; Accepted 18 August 2021; Published 26 August 2021

Academic Editor: Rakesh Mishra

The V2X and cooperative vehicle infrastructure system (CVIS), which leverage the efficient information interactions through V2V, V2I, V2P, and V2N, are known as the advanced and effective technology in reducing traffic accidents and improving traffic efficiency. The complex technical characteristics of V2X and highly reliable service demand of typical V2X applications call for the test needs before the large-scale deployment of V2X. It indicates that the performance and function of V2X devices should be systematically tested and evaluated in extreme and boundary conditions of driving and communication environments before being broadly deployed and applied in infrastructures. Motivated by the previously mentioned needs, a performance and function testing scheme of V2X in a closed test field is studied. According to the analytical viewpoint from the physical layer and MAC layer, the proposed research systematically analyses the technical differences of DSRC and LTE-V, which are two typical V2X protocols, in terms of vehicle speed, communication distance, and channel adaptability. Based on the critical practical test needs from the analytical study, a function and performance test system of V2X specifically for the closed test field is proposed. The performance and typical application effectiveness in intersection environment of DSRC and LTE-V are evaluated. The limitation and proposed improvement strategies of these V2X protocols are analytically discussed.

1. Introduction

Vehicle to everything (V2X) is a key approach to improving the performance of the current transportation system, especially when it comes to safety issues and traffic efficiency. As a typical cyber-physical system, V2X will be influenced easily by the surrounding physical and cyber factors, such as traffic and communication environment. Furthermore, in the design of applications, the requirements to the performance of V2X are heterogenous, in terms of latency, reliability, throughput, accessibility, and cybersecurity [1]. For example, automatic pilots and some safety applications for connected vehicles require extremely low latency and high reliability. Multivehicle node access within a local range should be supported under the traffic congestion environment. If the V2X performance requirements of applications are not fully satisfied, it may lead to serious traffic accidents and threaten the safety of various traffic participants. In that case, the V2X communication network should be systematically and rigorously tested and evaluated before the large-scale deployment and application of vehicles in real-life situations [2].

According to the application needs in reality, the testing methods are studied broadly. In terms of the testing objectives, it could be classified as performance and functionality testing. The performance testing is primarily used for testing the network performance such as end-to-end latency, communication range, and packet drop rate in a variety of scenarios. The functionality testing is mainly applied in evaluating the application effectiveness, including the correctness of specific scenes triggering and reacting, the capability in safeguarding, and so on.

Currently, mainstream technologies for V2X communication involve dedicated short range communication (DSRC) and cellular-vehicle to X (C-V2X) that is composed of long-term evolution-vehicle to X (LTE-V2X) and fifth new radio-vehicle to X (5G NR-V2X) [3]. DSRC, which adopts the 802.11p protocol at the physical layer and the medium access control (MAC) layer, is composed of IEEE and SAE standards. Besides, its network structure and security protocol are defined in the IEEE1609 WAVE standard. Meanwhile, the message format for communication is defined by the SAE J2735 standard, whilst various application scenes and performance requirements of V2X are defined in the J2945/X series standard at the application layer [4]. C-V2X is an automotive wireless communication technology that was evolved from cellular communication technologies, such as 4G/5G, which has been developed and continuously improved by the third generation partnership project (3GPP). C-V2X consists of two working modes, that is, Uu and PC5. In addition, LTE-V and NR-V2X are two major C-V2X communication technologies. Specifically, the 3GPP Rel-14 version standard supporting LTE-V was officially released in 2017, while the standardization of 5G NR-V2X (Rel-16+) was launched in June 2018 [5]. DSRC and C-V2X present different performances in a variety of traffic application scenes due to the use of varied technical schemes. Hence, systemic testing should be adopted to evaluate the effectiveness and performance differences between DSRC and C-V2X in the typical V2X application [6].

The modeling simulation and field test are two critical ways to figure out to what extent DSRC and C-V2X could support V2V communications. In previous studies, some researchers concentrated on modeling and simulation through various simulation platforms such as OMNeT++ and NS-3 [7–10]. However, the performance of the V2X communication cannot be fully displayed by the simulation results since the influences of related factors might be magnified by the complexity of the communication environment in the process of modeling and simulation [11]. A large number of field operational tests (FOTs) have been performed in Europe, the United States, and Japan to test the technical performance of V2X in real road environments.

DSRC is a proven communication technology. Its FOTs have been concerned by a plurality of countries and regions as well as related research institutions. Moreover, real-vehicle testing based on IEEE 802.11p has been successively analyzed in automotive testing grounds, highways, airports, urban roads, or highways by researchers from the United States, China, Germany, Spain, and Italy. Bai and Krishnan [12] performed real-vehicle field test and link layer communication performance test in the General Motors Milford Proving Ground (MPG) and US I-696 highway. During the test, the evaluation of communication reliability was executed, using packet delivery ratio (PDR), distribution of consecutive packet drops, and T-window reliability as evaluation indicators, respectively. Meanwhile, Gallagher et al. [13] performed the V2V and V2I communication tests for 5.9 GHz DSRC based on the real-vehicle field tests in a variety of scenarios. Reference [14] proved that street layout, urban environment, traffic density, existence of heavy vehicles and trees, and topographic elevation have significant impacts on the communication quality of V2I in a real-vehicle field test conducted by the iTETRIS project in Bologna, Italy. Besides, Schmidt et al. [15] built a highway-like testing scene on a 2286 $*$ 45-meter runway provided by a private airport in Munich, Germany. By using a device to simulate multiple interference nodes, they tested and evaluated the performance of IEEE 802.11p under the condition of channel interference caused by high channel load level. Performances of equipment were tested using a semiurban environment IEEE 802.11p real-vehicle testing system established at UMU in [16]. In [17], V2V communication reliability testing based on IEEE 802.11p was performed in Beijing. The results show that the communication reliability of urban environment is extremely unstable owing to the changes of communication distance. A similar research was also performed at the National Asphalt Technology Center (NCAT) of Auburn University, according to [18]. Through a set of dynamic tests and several static tests, the performance of DSRC in the driving scene of truck formation was studied. The influence of static communication distance, terrain fluctuation, curve, and other factors on the communication performance of DSRC is evaluated by delay, delivery rate, and other indicators. Besides, a V2X real-vehicle testing based on IEEE 802.11p was performed on an abandoned runway at Cambrai Airport in northern France in [19]. The influence of the communication range, high-speed vehicle movement, and data transmission rate on the performance of V2X is tested and analyzed. Reference [20], based on the road of SAIC-Tongji intelligent connected vehicles evaluation base, studied the delay and packet drop rate of DSRC under different V2X application scenarios. They mainly tested and analyzed the influence of communication distance, vehicle motion status, obstacle type, and other factors on the performance of V2V and V2I. Moreover, the internal mechanism of the testing results is explained. In [21], several typical application scenarios were constructed in the CAVTest field of Chang'an University. The influence of driving speed, communication distance, building shelter, and other factors on DSRC performance was tested using packet drop rate and transmission delay as evaluation indicators.

Affected by factors such as deployment cost, network performance, and market acceptance, IEEE 802.11p cannot be the sole V2X communication technology for market applications. Hence, many researchers have compared the performance of LTE, Wi-Fi, and LTE-V [22]. Lee and Lim [23] studied the single hop communication performance between DSRC and Wi-Fi based on real-vehicle test and explored the influence of message size, transmission rate, weather conditions, communication range, and vehicle mobility on them. By measuring changes in latency and packet drop of applications in real-vehicle field tests, the communication performance under high-speed movement in real traffic conditions was tested on the US I-85 interstate highway. Reference [24] evaluated the performance of heterogeneous V2X composed of Wi-Fi, DSRC, and LTE technologies for V2V and V2I communication under two scenarios of traffic data acquisition and forward collision warning. As the large delay of different kinds of technologies handoff, it is difficult to apply to delay sensitive traffic safety applications. Besides, a V2X testing system was constructed in the testing field in [25]. Using this testing system, communication performances of DSRC and 4G-LTE in collision avoidance, traffic information broadcasting, and multimedia files downloading were comparatively analyzed. Reference [26] constructed a plurality of typical V2X application scenes in the CAVTest field of Chang'an University to test the influences of factors such as running speed, communication distance, and building shelters in real vehicles on DSRC and LTE-V communication performance. Shi et al. [27] tested performances of 802.11p and LTE-V in real vehicles based on the established intersection scene in the National Intelligent Connected Vehicles Shanghai Demonstration Zone and evaluated the test results through establishing a probability model.

In addition, researchers focusing on the performance test of V2X applications verified the effectiveness of V2X applications via the establishment of a real-vehicle testing system. For instance, [28] constructed a cooperative communication testing platform based on IEEE 802.11p in a controlled test field. Based on the platform, the effectiveness of two cooperative active road safety applications, ICW and EEBL, were verified via testing under challenging conditions, such as communications in physical blockage, interfering communications, and various positioning accuracy levels. In [29], the influence of V2V communication message structure and communication delay on the security of a vehicle-group system is studied by establishing the dynamic model of vehicle movement. However, the author assumes a constant communication delay, which is impossible in reality. Besides, in our previous work, a CU-CVIS testbed [30, 31] was designed and implemented for the intelligent transportation system, incorporating application scenes, perception release, network links, and management services. On this basis, performance and functionality tests can be performed for the multimode and heterogeneous V2X communication system.

Based on the existing research, we find that there is a gap in the systematic field test of typical V2X protocols based on DSRC and C-V2X. It is an urgent need to know whether their performance can meet indicators such as communication distance, adaptive speed, and environmental shielding adaptability. Moreover, the evaluation of the effectiveness test of V2X applications in high-risk running environments cannot be witnessed in existing researches. For all the previously mentioned reasons, performance differences between DSRC and C-V2X in a variety of challenging scenes were systematically studied in this paper with focuses on related researches and testing practices concerning the V2X function and performance testing under various typical traffic scenes. To begin with, a modular testing platform for V2X performance and function testing was constructed at the connected and automated vehicle test (CAVTest) field of Chang'an University. Real-vehicle network performance and functionality tests were performed on the platform. Second, DSRC and LTE-V performance tests were performed in a closed testing field. Technical differences of DSRC and LTE-V communication protocols in terms of vehicle's movement speed, communication distance, and channel adaptability were comparatively analyzed from the communication network protocol physical layer and the MAC layer before the tests. Moreover, five scenes were designed to verify the influences of communication distance, shielding, and vehicle mobility on network performance, so that the performances of DSRC and LTE-V under real-life conditions can be tested. Third, an intersection collision warning application was designed in typical traffic scenes selected and evaluated via testing in a closed test field and open roads.

The rest of this paper is arranged as follows: Section 2 introduces the architecture of the CAVTest platform and equipment; Section 3 presents the experimental data and discussion of performance tests on the comparison of DSRC and LTE-V. Section 4 presents a detailed analysis of experimental data of functional tests. Section 5 finally concludes the paper.

2. Testing Platform and Equipment

2.1. Construction of Testing Platform. In order to test the performance and functionality of V2X, a modular test platform was built by the research team at the CAVTest of Chang'an University. It is used to perform all the tests in this paper (see Figure 1). CAVTest is a closed field built by Chang'an University for applied research and testing of V2X, automatic pilot, and CVIS. It can support the test of a single vehicle up to 120 km/h, with the setup of various traffic scenes and facilities, such as straights, curves, intersections, shades, and buildings. Moreover, it is deployed with differential GPS positioning base stations and multiple roadside base stations for V2X communication roadside base stations, such as LTE-V, DSRC, Wi-Fi, and 4G-LTE.

The modular testing platform constructed by CAVTest for the performance and functionality of V2X is shown in Figure 2. It consists of a scene application layer, equipment platform layer, data transmission layer, and test management layer.

In the scene application layer, various connected roadside equipment provided by CAVTest were used to simulate cities, highways, and rural roads environment, according to the test tasks. In the equipment platform layers, multiple test verification vehicles and various road infrastructures construct test scenarios that meet the test requirements. Then, according to the test tasks, the test safety personnel complete the running tasks based on the built test scenarios and test verification trolleys.

The equipment platform layer is primarily composed of a testing data acquisition system and a testing task release system. Specifically, the testing data acquisition system is to implement automatic acquisition and uploading of various testing data during the test. The testing task release system is to achieve the release of V2X functions and performance testing tasks, including the control of working statuses of various roadside devices.

The data transmission layer uploads testing data to the test management layer and distributes tasks issued by the test

Figure 1: CAVTest field of Chang'an University.

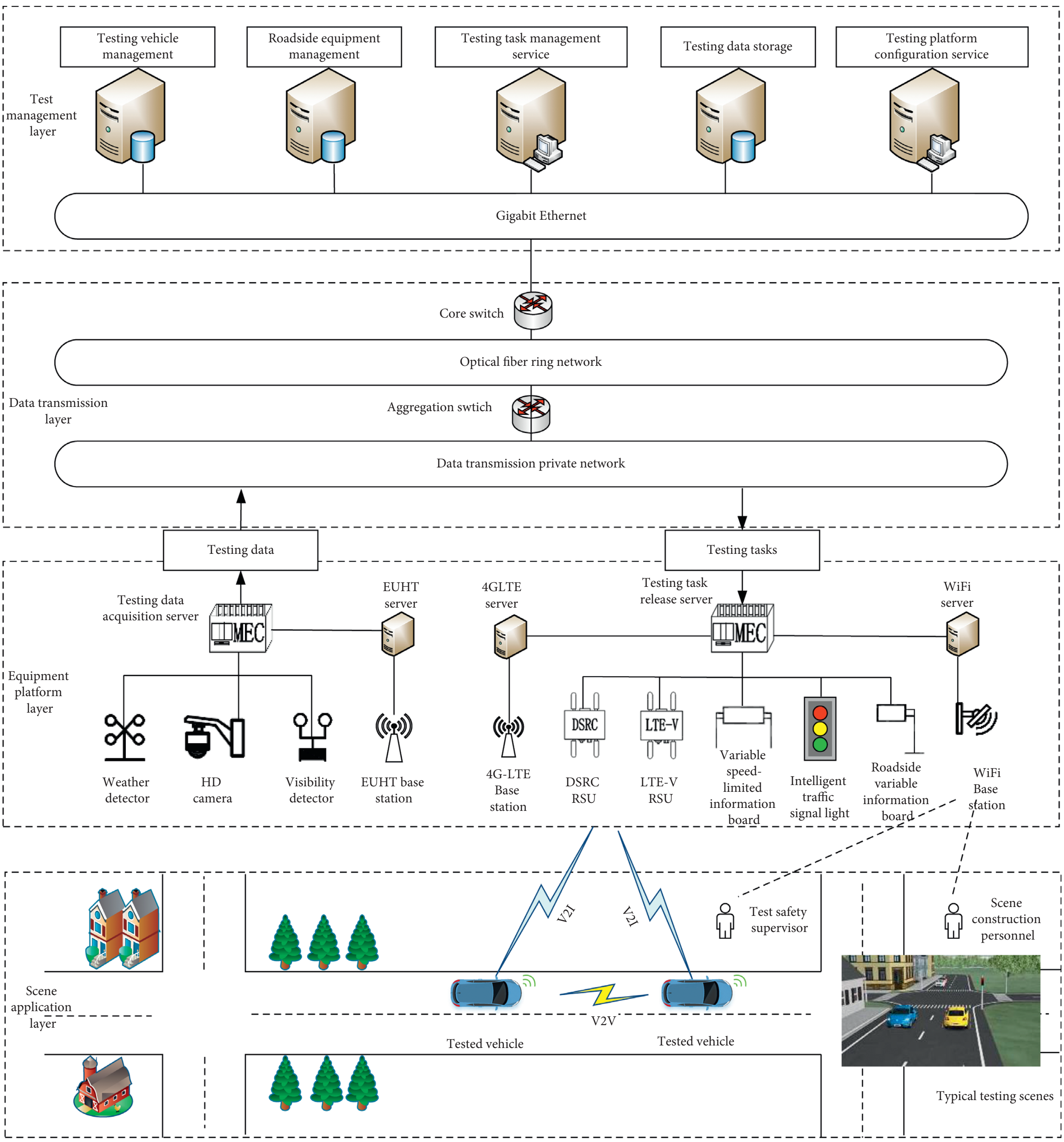


Figure 2: Modular testing platform for V2X performance and function testing.

management layer to the application test layer. It not only can provide various switches and optical fiber networks but also be responsible for the rapid transmission of log and data information of all nodes during the test.

What is more, the test management layer can perform high-speed processing, mass storage, and real-time interaction on the acquired testing data. It is responsible for processing and storing CAVTest road information and tested vehicle information as well as uniformly managing all the test devices at the testing site. It provides not only test task release and test system configuration services, but also testing data management modules for analyzing test results.

2.2. Test Equipment. Connected electric vehicles (EVs) of Chang'an University were used as the tested vehicles. As can be seen from Figure 3, the tested vehicles are equipped with DSRC and LTE-V on board units (OBU), antennas, and other related devices. The internal layout of the tested vehicle is shown in Figure 4. The technical specifications of DSRC OBU produced by Jinyi Technology are shown in Table 1. The technical specifications of LTE-V OBU produced by NEBULA-LINK are shown in Table 2.

3. DSRC and LTE-V Performance Testing Based on CAVTest Platform

3.1. Analysis on the Traffic Applicability of DSRC and LTE-V. The high-speed mobility and continuous variation of distance between vehicles are the most significant features of the V2X communication environment. It results in a frequent change of V2X network topology. Moreover, the data link is easily interrupted by the Doppler frequency shift of signal, which is generated by the high-speed mobility of vehicles. In order to adapt to the complex traffic environment, large amounts of effective design were performed on DSRC and LTE-V in the standardization process. Before the field test, it is necessary to carry out a systematic analysis, in order to design a more targeted test scheme and build a test scenario. In this section, the technical means of DSRC and LTE-V adapting to the challenges of V2X business were comparatively analyzed from the design angles of the physical layer and the MAC layer.

3.1.1. Analysis of Feasibility for High-Speed Vehicle Running. Doppler frequency shift will occur in radio wave propagation during high-speed movement, which may lead to greater frequency error as DSRC and LTE-V work in the high-frequency band of 5.9 GHz. Therefore, the applicability of high-speed running is a key consideration in the standardized V2X communication protocol.

DSRC based on IEEE 802.11p is an extension of the 802.11a standard, which adopts orthogonal frequency division multiplexing (OFDM) to achieve carrier-based modulation. 802.11p reduces the bandwidth to 10 MHz with half of the transmission rate, subcarrier interval, and other parameters of 802.11a, so as to adapt to the high-speed mobile traffic environment. Meanwhile, its guard interval length is set as twice that of 802.11a, so that greater delay extension can be tolerated in 802.11p, meeting the high-speed running vehicle environment. Furthermore, the length of 802.11p training sequence is extended to twice that of 802.11a, as the extended training sequence length contributes to the timing synchronization, carrier frequency offset estimation, and channel estimation of the receiver, playing a significant role in restoring the original signal without distortion at the receiving end. Besides, 802.11p is more sensitive to frequency offset due to the reduced subcarrier interval. To this end, four pilot subcarriers are added for conducting frequency offset correction in the receiver.

Since a high peak-to-average power ratio (PAPR) is found in OFDM, signals tend to be distorted easily under high-speed vehicle movement, leading to changes in the spectrum of superimposed signals. As a result, the orthogonality between various channel signals is destroyed, causing that the generated mutual interference could deteriorate communication performance. Nevertheless, SC-FDMA is adopted in LTE-V (Rel-14) for implementing carrier modulation, which can achieve greater transmission power under the same power amplifier due to a small PAPR impact. The LTE-V frame structure is presented in Figure 5. A subframe is comprised of four columns of demodulation reference signals (DMRS), which can effectively cope with channel detection, estimation, and compensation in high-frequency bands in typical high-speed scenes [8]. Further, channel coding adopting Turbo code is composed of two parallel subcoders and one inner interleaver. Coding can achieve random coding together with convolutional code and random interleaver, whilst long codes can be constructed by short codes via the interleaver. Meanwhile, the maximum likelihood decoding can be approached via soft output iterative decoding.

3.1.2. Analysis on the Applicability of Long-Distance Communication. One of the important V2X applications is to assist drivers or autopilot vehicles to extend their sensing range and perceive potential dangers in advance, thereby avoiding or mitigating injuries caused by accidents. There is no optimization done for DSRC to improve range. The only thing that can be of help is to increase transmit power up to the regulated limit of 33 dBm. Nevertheless, the proposed solution requires expensive radio frequency components (large power amplifier (PA)) and high quality radio frequency integrated circuits (RFIC), which is only feasible on limited trials [32].

Besides, frequency division duplex is applied in LTE-V, allowing different contents to be transmitted in different frequency bands of the channel. In this way, LTE-V can enhance its decoding capability by increasing its power spectral density. Compared with DSRC using convolutional code, LTE-V is easier to decode low SINR data under the same modulation scheme and coding rate, which makes the transmission distance longer under the same reliability.

3.1.3. Analysis of Channel Access Mechanism. V2X application cannot be implemented without the realization of effective data transmission based on wireless channel of the

(a) (b)

Figure 3: Tested vehicles equipped with test devices. (a) Tested vehicle 1. (b) Tested vehicle 2.

Figure 4: Layout of vehicle-mounted units and antenna placement.

terminal device. In particular, basic safety message (BSM) should be transmitted periodically. However, data collision might be caused by simultaneous data transmission at multiple terminals on the same channel when the density of road vehicles is large. In that case, an appropriate channel access mechanism should be established to solve potential collision problems and ensure transmission of safety-related data. Carrier sensing multiple access/collision avoidance (CSMA/CA) is utilized in DSRC to achieve resource allocation. Note that collisions on the channel cannot be detected in the course of sending data packets, which can merely be avoided as much as possible. Sensing and SPS mechanisms are regarded as the resource scheduling mechanism in LTE-V [33], which can avoid continuous resource collisions caused by the adverse effects of half-duplex using the confrontation-based reselection thanks to its comprehensive adaption of periodic characteristics of BSM. Meanwhile, resource occupancy can be estimated in the resource selection window according to the perception result. Moreover, different perception thresholds can be configured as per the priority of services to reflect the use of resources. In other words, data packets with higher priority have more opportunities to be transmitted in sidelink. Furthermore, up to eight SPS processes can be configured and activated at the same time to reduce eNB scheduling overhead. As for event-triggered messages, variable messages can be adapted using dynamic scheduling. In LTE-V, resource utilization and transmission reliability of V2X transmission can be enhanced through performing perception of resource status and collision avoidance processing operations on the receiving node.

From the previously mentioned analysis, in the vehicle environment, both DSRC and LTE-V are designed and optimized in the physical layer and the MAC layer to adapt to the high-speed mobility and continuous variation of distance. In order to test the actual performance of DSRC and LTE-V in real situations, we will design typical scenarios to verify the influences of communication distance, shielding, and running speed on network performance.

3.2. Design of Testing Scenarios and Schemes. Primarily, a performance test of V2X communication should be able to determine the maximum true range that the communication protocol can support. In this study, the control variable method was used to consider different driving speeds, communication distances, and nonline-of-sight (NLOS) communication caused by the presence of trees and buildings. The influence of these factors on the communication performance between DSRC and LTE-V was examined. Since the performance of a wireless link is usually affected by the environment, the test results may vary with

Table 1: Some OBU parameters for DSRC.

Parameter	Contents
Model	WB-L20RV mounted equipment
External dimension (mm)	$175 \times 140 \times 30$
Antenna type	Omnidirectional antenna
Maximum RF output power (dBm)	+23 (excluding antenna gain and adjustment)
Working frequency range (GHz)	5.850 to 5.925
Channel bandwidth (MHz)	10, 20

Table 2: Some OBU parameters for LTE-V.

Parameter	Contents
Model	V-Box-I
External dimension (mm)	$205 \times 127 \times 38$
Antenna type	Omnidirectional antenna
Maximum RF output power (dBm)	+23 (excluding antenna gain and adjustment)
Working frequency range (GHz)	5.905 to 5.925
Channel bandwidth (MHz)	10, 20

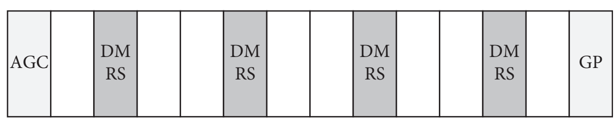


Figure 5: LTE-V frame structure.

changes in the environment. Hence, to eliminate this influence, we first measured the communication performance in the test field before each test, and we conducted the experiment only when the difference between all the measurement results was small.

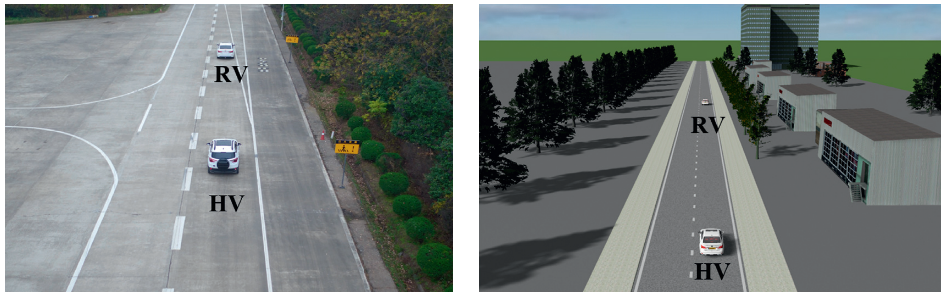
3.2.1. Valid Communication Testing. Valid communication testing was conducted on an unobstructed straight road with a total length of 1.1 km and two two-way lanes. During the test, two tested vehicles were parked at a distance of 200 m on the same lane in the same direction, as shown in Figure 6. During the test, the host vehicle (HV), which acts as the sender, sent a packet at 10 Hz. The remote vehicle (RV) received the packet and sent it back to the HV. One test is completed when a cycle of transmitting and receiving back of 200 data packets by the HV is completed. It was ensured that at least eight valid test results are obtained, and the test ends at a certain test distance. Then, the previously mentioned testing was repeated by increasing the distance between the cars to 400, 600, 700, 800, 900, and 1,000 m.

3.2.2. Communication Performance Testing for NLOS Scenario. Providing reliable V2X communication at an actual intersection is a challenge owing to the presence of shelters such as buildings or trees. Such shelters may cause complete or partial disconnection of the network between two vehicles, resulting in packet loss or delay. In the communication performance test for NLOS scenarios, we tested the scenario that the two connected vehicles traveling in different directions at an intersection may not sense each other because of shelters, such as trees and buildings. We built up scenarios to test shelters comprising buildings at an intersection and shelters comprising trees at an intersection. The center of the intersection was selected as the simulated "collision point." The communication performance of DSRC and LTE-V was evaluated by changing the distance between the test vehicle and collision point.

The scenario construction and deployment of building-shaded intersections are shown in Figure 7. The intersection was a T-junction. A metal building was present in the area between the two sections of the road, where the HV and RV are located. This building was about 8 m high, and there was also a square pile of soil about 4 m high. The building and the pile of soil block the line of sight between the HV and RV. The intersection point is the collision point.

The scenario construction and deployment of the tree-shaded intersection are depicted in Figure 8. The intersection was a T-junction. A dense forest was present in the area between the two sections of road, where the HV and RV were located. The trees acted as a shelter. The intersection point is the collision point.

After the HV and RV were driven to their test scenario sections, they were tested according to the following test scheme. First, each of the two vehicles was positioned 50 m away from the collision point. The HV, that is, the sender, sent a packet at 10 Hz; the RV received it and sent it back to the sender. One test ended after the HV transmitted 200 packets. It was ensured that at least eight valid test results are obtained, and the test ends at a certain test distance. In the case of the intersection sheltered by the building, considering the position of the building, the HV and RV were driven to distances of 100, 130, 140, 160, 180, and 200 m away from the collision point to improve the test effect. The

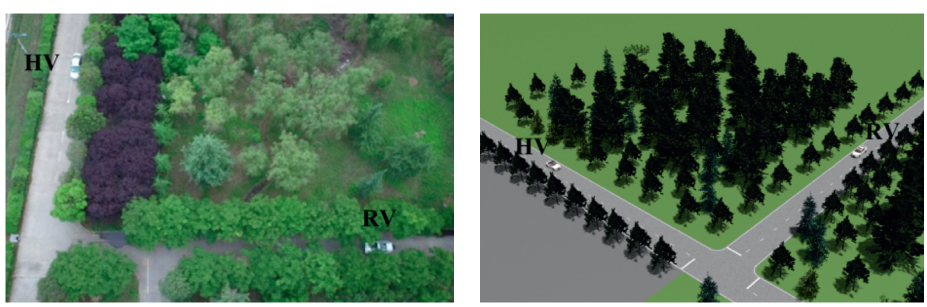


(a) (b)

Figure 6: Valid communication testing scenario. (a) Actual test scenario. (b) Virtual test scenario.

(a) (b)

Figure 7: Building-shaded intersection scenario for the communication performance test. (a) Actual test scenario. (b) Virtual test scenario.



(a) (b)

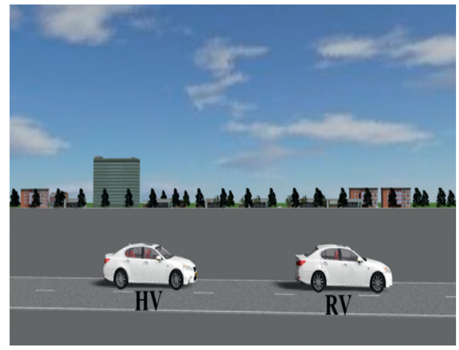
Figure 8: Tree-shaded intersection scenario for the communication performance test. (a) Actual test scenario. (b) Virtual test scenario.

testing procedure was repeated for each of these distances. In the case of the tree-sheltered intersection, the HV and RV were driven to distances of 100, 150, and 200 m away from the collision point, and the testing procedure was repeated.

3.2.3. Adaptability Testing of High-Speed Movement. In urban roads or freeways, high-speed movement usually occurs on straight roads. Considering the driving characteristics of such roads, two test scenarios were selected: the car-following scenario and two vehicles driving face-to-face scenario. The car-following scenario is depicted in Figure 9. In this scenario, the HV and RV are in the same lane and drive from west to east. Cars-approaching scenario is shown in Figure 10; the HV and RV move in two adjacent lanes and are driven in the opposite directions.

(1) Car-Following Scenario. The HV and RV move from west to east at a speed of 20 km/h while maintaining a safe distance between each other, as shown in Figure 9. Furthermore, the sender, that is, HV, sends a packet at 10 Hz; the RV receives it and sends it back to the HV. One test is completed after the vehicles reach the end of the road. Such a round of testing can be terminated after 10 valid tests. Subsequently, the traveling speeds of both vehicles were increased to 40, 60, and 80 km/h and the testing procedure was repeated for each of these speeds.

(a)



(b)

FIGURE 9: Car-following scenario. (a) Actual test scenario. (b) Simulation test scenario.

(2) Cars-Approaching Scenario. During the testing, the HV and RV were driven in two adjacent lanes in opposite directions at speeds of 20 km/h. This scenario is shown in Figure 10. To avoid exceeding the effective communication distance, the testing program was initiated once the distance between both vehicles reached 400 m. Then, the HV sent a packet at 10 Hz; the RV received it and sent it has back to the HV. One test was completed when the vehicles approached head on. It was ensured that at least eight valid test results are obtained, and the test ends at a certain test distance. In subsequent rounds of testing, the traveling speeds of both vehicles were increased to 40, 60, and 80 km/h, and the testing procedure was repeated.

3.3. Testing Results and Discussion

3.3.1. Evaluation Index Selection. Based on the communication performance testing demands of DSRC and LTE-V, the packet delivery ratio (PDR) and delay (DE) [11] were selected as the V2X performance evaluation indexes. According to the requirements of V2X application [32], an effective communication implies that the PDR is not less than 90% and that the maximum allowable delay is 100 ms.

(1) PDR. PDR (P_{dr}) can be defined as follows:

$$P_{\mathrm{dr}} = \frac{P_r}{P_s}, \quad (1)$$

where P_r refers to the data packets received by the target node, and P_s refers to those sent by the source node.

(2) DE. DE represents the time needed for transmitting data from one node to another; and the mean delay is referred to as the average delay. It is difficult to achieve full-clock synchronization at the time of testing the delay. Therefore, the problem of time synchronization is avoided by calculating the round-trip time (RTT), which is the time required for a round trip of data between a source node and a target node. First, the packet-sending time should be incorporated in the packet when a sender sends the packet. This sending time is denoted as T_1. The time when a receiver receives the packet is also recorded as T_2. Subsequently, the receiver sends the packet back to the sender, and the corresponding sending time is denoted as T_3. Finally, the sender receives the packet, and the corresponding time of receipt is denoted as T_4. The RTT is defined as follows.

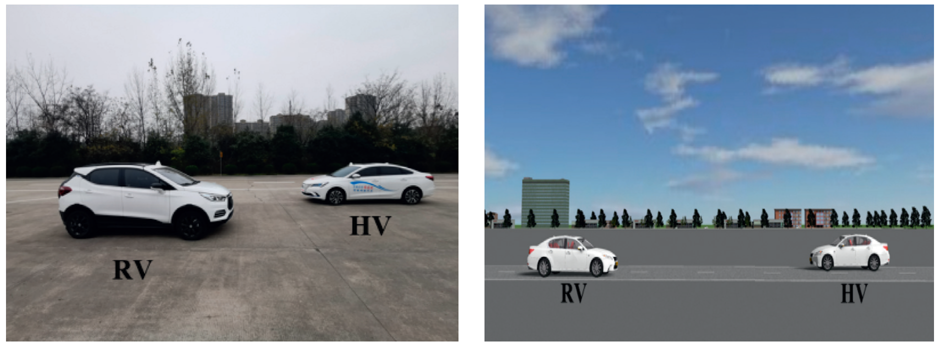
$$T_{\mathrm{RTT}} = (T_4 - T_1) - (T_3 - T_2). \quad (2)$$

The delay (T_{DE}) is obtained as follows:

$$T_{\mathrm{DE}} = \frac{T_{\mathrm{RRT}}}{2}. \quad (3)$$

3.3.2. Valid Communication Testing Results. The valid communication testing results for DSRC and LTE-V are shown in Figure 11. The PDRs of DSRC and LTE-V decline drastically with an increase in the communication range. Within a communication range of 400 m, the PDRs exhibit a slow downward trend with an increase in the communication range for both the communication technologies. Moreover, the PDR values remain above 95%. The delay of the two communication technologies increases slightly as the communication range increases. The average DSRC and LTE-V delays are about 5 ms and 16 ms, respectively, within the valid communication range. Therefore, the communication distance is regarded as an important factor that affects the communication performance between the DSRC and LTE-V. Under the static condition of the LOS scenario, the valid communication ranges for DSRC and LTE-V are defined as approximately 700 and 900 m, respectively, which is consistent with the theoretical analysis provided in 3.1.

3.3.3. Testing Results of NLOS Communication Performance. The NLOS communication performance testing results are shown in Figures 12 and 13. The results of the building-shaded intersection scenario on the communication performance are shown in Figure 12. The PDR of the two communication technologies decreases as the distances between vehicles and the collision point increase; the PDRs of the DSRC and LTE-V decreased significantly when the distances from the collision point were more than 140 m, and the PDR of DSRC decreased to 0 after 160 m. The delay of the two communication technologies increased slightly as the communication range increased. The delay of two



(a) (b)

Figure 10: Cars-approaching scenario. (a) Actual rest scenario. (b) Simulation test scenario.

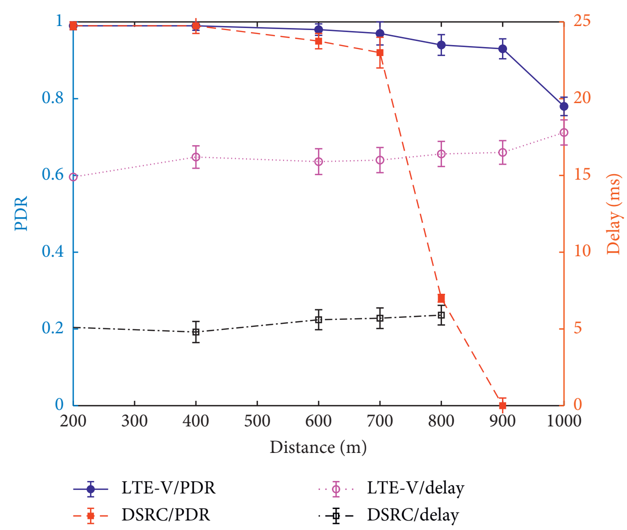


Figure 11: Valid communication testing results.

technologies increased suddenly at 140 m because of the presence of the metal building. Therefore, the building is regarded to have a great impact on the communication performance of the DSRC and LTE-V, and the valid communication range is greatly reduced by building shielding. The communication performance of the two communication technologies is seriously affected by metal buildings.

The results for the forest-shaded intersection scenario on communication performance are shown in Figure 13. The PDR of the two communication technologies decreased as the distances between the test vehicle and the collision point increased. The overall declining trend of the DSRC is more obvious, and the decline speed is greater near the metal building (about 150 m). The delay of the two communication technologies increases slightly as the communication range increases.

Based on the previously mentioned test results, it can be considered that the NLOS communication will aggravate the influence of channel fading in wireless transmission and produce path loss, which will significantly affect the communication performance of the two communication technologies, shorten the valid communication distance, and increase the packet loss rate significantly. Different shelters will have different degrees of influence. The influence of metal and earth architecture on communication performance is more severe than that of a forest. The communication performance of the LTE-V is better than that of the DSRC in the NLOS scenario, because the former adopts the cyclic prefix (CP) structure to effectively reduce the intersymbol interference (ISI) and hence has a stronger ability to resist the delay spread caused by the multipath effect.

In addition, based on the aforementioned test results, we can conclude that the LTE-V has a better PDR than the DSRC in LOS and NLOS communication scenarios under the static condition. This difference is attributed to the differences in the channel coding and resource selection mechanisms of the two communication technologies. The DSRC adopts the convolutional code, while the LTE-V adopts the turbo code, which has better coding gain. Further, in terms of resource allocation, while the DSRC adopts the CSMA/CA mechanism, the LTE-V adopts the sensing + SPS mechanism, which enables it to make full use of the

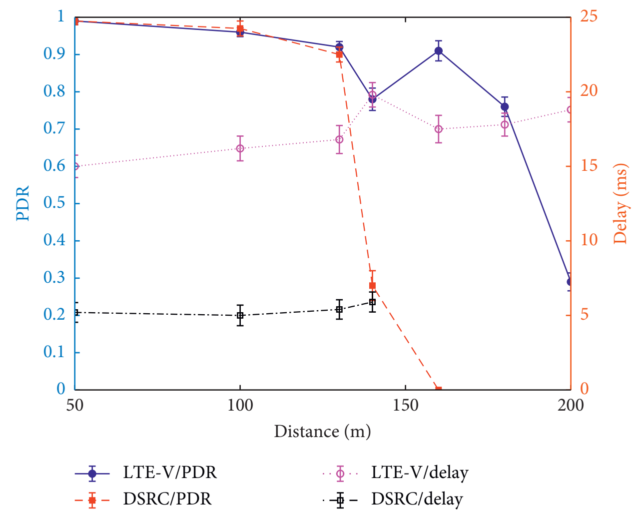


Figure 12: The results of performance in the building-shielding scenario.

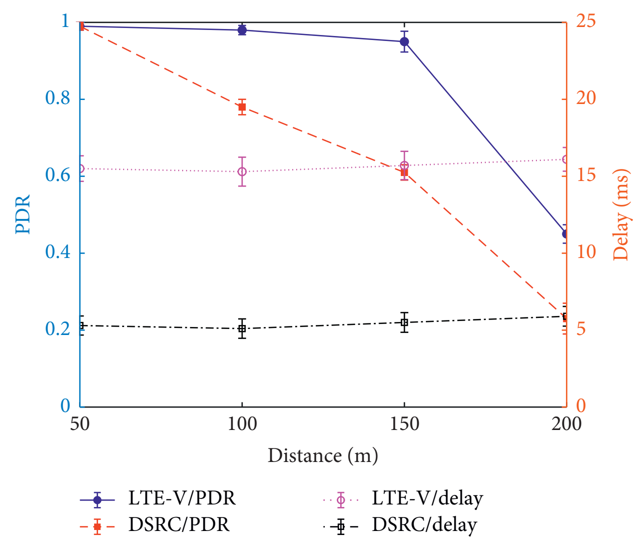


Figure 13: The results of performance in the forest-shielding scenario.

periodicity of BSM propagation and improves the utilization rate of wireless resources. However, the communication delay of the DSRC is better than that of the LTE-V because the DSRC adopts a shorter CP and symbol period structure.

3.3.4. Testing Results of Feasibility for High-Speed Vehicle Running. The high-speed motion adaptability testing results are shown in Figures 14 and 15. The effects of vehicle speed on PDR and communication delay in the car-following scenario are shown in Figure 14. The PDR value of the two communication technologies decreases slightly with the increase of vehicle speed, whereas the communication delay increases with the vehicle speed, especially in the case of the LTE-V.

The influence of vehicle speed on PDR and communication delay in the scenario of two vehicles approaching each other is shown in Figure 15. The PDR value of the two communication technologies decreases with the increase of vehicle speed, whereas the communication delay increases with the vehicle speed.

The results of feasibility for high-speed vehicle running show that the communication performances of the DSRC and LTE-V are weakly correlated with the vehicle speed, but the performance of DSRC in a high-speed motion environment is better than that of the LTE-V. These findings are consistent with the theoretical analysis provided earlier. Therefore, under the effective communication range and limited vehicle speed, the communication delay of the two communication technologies can meet the communication requirements of the V2X safety application. In addition, from the test results of the two vehicle-meeting scenarios, we find that LTE-V experiences a sudden increase in delay when the two vehicles are about to meet, and the delay value exceeds 50 ms. This delay behavior is attributed to the fact that the symbol period of the LTE-V is 10 times that of the

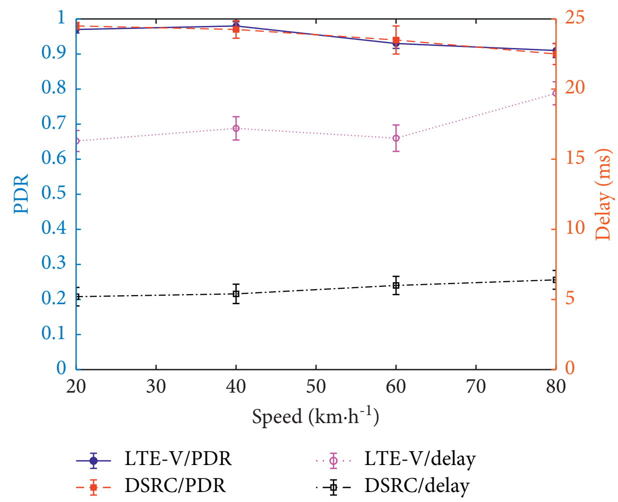


Figure 14: The results of feasibility for high-speed vehicle running in the car-following scenario.

DSRC, thereby limiting the maximum detectable Doppler frequency shift. However, the DSRC uses a short symbol period and adopts the "medium synchronous code" mode, which makes the synchronous code frequency consistent with most of the signal frequency. In a high-speed environment, the delay does not change significantly, and good performance can be maintained.

3.4. Discussion. Both communication range and shelter are essential factors that affect the communication performance of the DSRC and LTE-V. Running speed has a small influence on communication performance. Under stationary conditions, the valid communication ranges of the DSRC and LTE-V are about 700 and 900 m, respectively. When shelters are present, the PDRs may enormously reduce as the communication range increases.

The results show that the communication performances of the DSRC and LTE-V meet the requirements of the high-speed movement of vehicles and continuous variation of distance, but the communication performance of the LTE-V is better than that of the DSRC. In terms of valid communication distance, the LTE-V has a wider coverage range than the DSRC, In terms of NLOS communication, the LTE-V still provides better communication performance than the DSRC. In terms of high-speed adaptability, both the LTE-V and DSRC can meet the communication requirements under high-speed vehicle movement conditions.

4. Function Testing in Typical Traffic Scenarios

Network performance does not mean that the V2X technology can meet the requirements of practical applications. In fact, a significant percentage of road accidents occur at intersections or are intersection-related [28]. Therefore, the intersection is expected to be widely used in V2X. Based on the previously mentioned considerations, an application of intersection collision warning (ICW) is designed for unsignalized intersections, and a real-vehicle test scene is built for test evaluation.

4.1. A Strategy of Intersection Collision Warning Based on V2V. The V2V-based intersection collision scenario is shown in Figure 16. At crossroads, the HV travels from east to west, and the RV travels from north to south. The testing environment is limited to a single-lane intersection, where the collision point (C) is fixed and equal to the center of the intersection. The safety time model is used as the collision warning strategy. The time to collision is calculated to judge the collision risk:

$$\mathrm{TTC}_{\mathrm{HV}} = \frac{d(\mathrm{HV}, C)}{v_{\mathrm{HV}}}, \tag{4}$$

where $d(\mathrm{HV}, C)$ represents the distance between the HV and C. Further, v_{HV} represents the current speed of the HV. Similarly, the collision time of the RV (i.e., $\mathrm{TTC}_{\mathrm{RV}}$) can be obtained. If the unsigned difference (Δ) between $\mathrm{TTC}_{\mathrm{HV}}$ and $\mathrm{TTC}_{\mathrm{RV}}$ is below the threshold (ε), a potential hazard at the intersection is considered to be detected. Furthermore, Δ and ε can be computed as follows:

$$\Delta = \left|\mathrm{TTC}_{\mathrm{HV}} - \mathrm{TTC}_{\mathrm{RV}}\right|, \tag{5}$$

$$\varepsilon = \frac{L_{\mathrm{HV}}}{v_{\mathrm{HV}}} + \frac{L_{\mathrm{RV}}}{v_{\mathrm{RV}}}, \tag{6}$$

where L_{HV} and L_{RV} represent the length of the HV and RV.

4.2. Evaluation of Warning Accuracy. The goal of the collision warning is to make the driver respond to the warning information in time, so as to avoid collisions and consider the comfort requirements of passengers. Based on the previously mentioned considerations, this paper evaluates the warning accuracy according to the time when the test vehicle received the warning and responded.

Assuming that the speed of the vehicle approaching the intersection is v_0, when there is a potential hazard at the intersection ahead in the driving direction, the driver will apply the brake. The braking process is divided into four stages: the driver reaction stage (the driver reaction time is

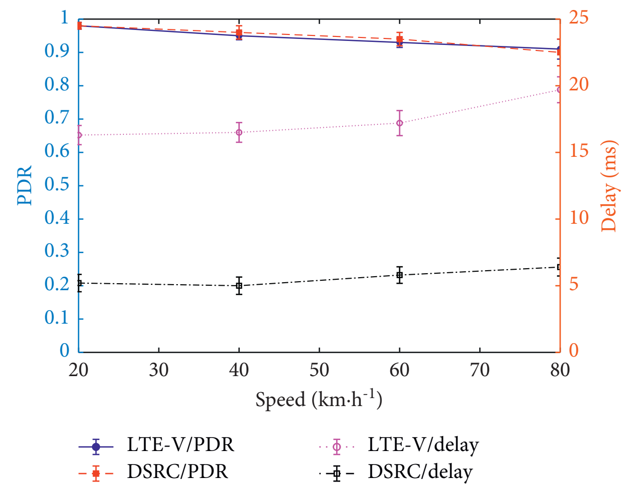


FIGURE 15: The results of feasibility for high-speed vehicle running in the cars-approaching scenario.

about 0.8–2 s), brake-coordination stage (the braking coordination time is 0.5 s), deceleration growth phase (the deceleration growth time is 0.2 s), and continuous-braking phase [34], as shown in Figure 17.

According to the different braking forces, (7) is used to calculate the duration of the braking phase, and (8) is used to calculate the total braking time:

$$t_4 = \frac{v_0}{a}, \tag{7}$$

$$T = t_1 + t_2 + t_3 + t_4. \tag{8}$$

Herein, we focus on the effectiveness of early warning applications when there is a risk of collision. As shown in Figure 18, the effectiveness of collision avoidance and driving comfort are used as evaluation indicators. According to the required braking time under different braking forces, the collision warning situation is divided into the following categories [35]:

(1) Successful warning (SW): When the driver receives a warning message, he/she responds and successfully avoids collision. SW includes precise warning and effective warning.

  (a) Precise warning (PW): A collision warning is a correct and timely zone-3 warning indication of a future collision. In this period, the driver can adopt a partial braking method, which can ensure collision avoidance while accounting for the comfort requirements.
  (b) Effective warning (EW): A collision warning is a correct and timely zone-2 warning indication of a future collision. The driver should perform full braking to avoid accidents during this period.

(2) Failed warning (FW): A failed warning includes late warnings and missed warnings in cases that there is a collision risk in the future.

  (a) Late warning (LW): A late warning is a zone-1 warning indication of a future collision; even if a collision warning is received in the area, the collision is unavoidable, but protective measures can be activated in advance.
  (b) Missed warning: This is the case that until the collision occurred, the collision warning system did not work.

4.3. Design of Testing Scenarios and Scheme. To test the effectiveness of ICW, we built three test scenarios based on the CAVTest. The scenarios included a LOS intersection, urban road intersection, and rural road intersection, as shown in Figure 19. They were used to test the effectiveness of ICW application based on the LTE-V.

For scenario one, we use software to adjust the PDR to simulate the deterioration of network communication performance. Then, we verified the impact of network communication quality on the application of ICW. The following three test conditions are designed. Condition 1 is the normal condition of communication, and PDR is not adjusted artificially. Condition 2 is set with a PDR of 75% to simulate general communication quality. Condition 3 is set with a PDR of 25% to simulate poor communication quality. For these three test conditions, we perform tests for vehicle speeds of 20, 30, and 40 km/h. The test is repeated 100 times for different vehicle speeds under each test condition.

4.4. Testing Result Analysis. The testing result of scenario 1 is shown in Table 3 and Figure 20. From the test results for scenario 1, the communication quality has a greater influence on the reliability of the ICW application. When the communication has excellent quality, the ICW application can effectively avoid a collision. However, when the communication quality is normal, with the increase in the test vehicle speed, the required safety distance increases, and the SW time exceeds the effective range of communication. This leads to a late warning (failed warning). When the communication quality is poor, the test vehicle cannot obtain status information of potential collision vehicles in time, and the warning algorithm fails, resulting in a missed warning.

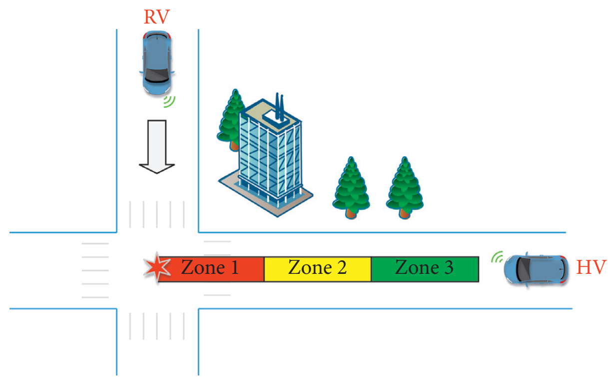


Figure 16: V2V-based intersection collision scenario.

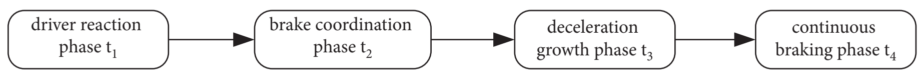


Figure 17: The process of braking.

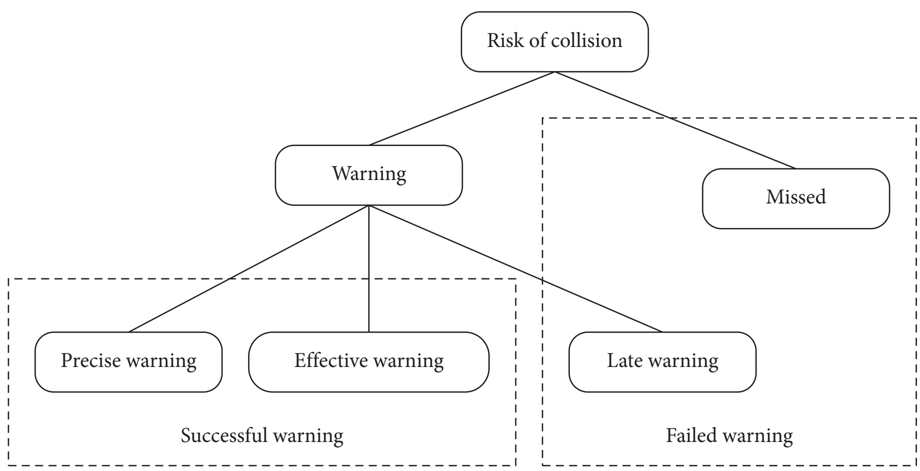
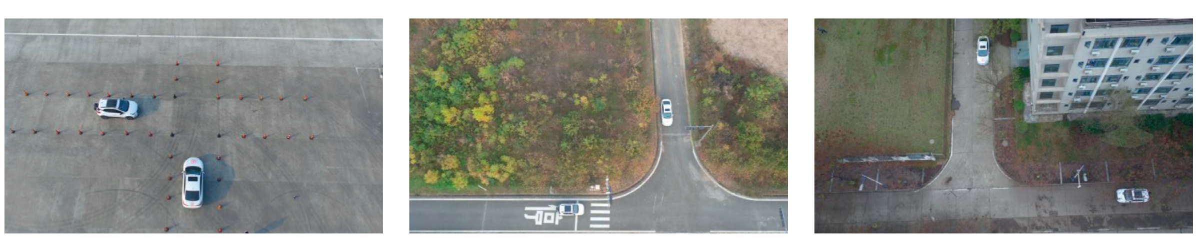


Figure 18: Types of warning.



(a) (b) (c)

Figure 19: Intersection collision warning (ICW) function test scenarios. (a) LOS intersection scenario (scenario 1). (b) Rural intersection (scenario 2). (c) Urban intersection (scenario 3).

The testing results for scenarios 2 and 3 are shown in Table 4 and Figure 21. The test results of scenarios 2 and 3 show that the warning effect of the V2X application is worse than that in scenario 1 in the approximate real intersection environment under shelters. However, the function performance is still effective. Thus, the V2X applications can still be supported. This proves that the real traffic environment will not have a significant impact on LTE-V applications. In addition, in the scenario of urban road intersections, the PW rate at a speed of 40 km/h is low. Communication distance and building shading are regarded to have a significant impact on communication quality. Meanwhile, some intermittent warnings are observed in the test results—that is, after the warning is first issued, the

Table 3: Test results for scenario 1.

Velocity ($km{\cdot}h^{-1}$)	Scenarios								
	Case 1			Case 2			Case 3		
	Probability (%)								
	PW	EW	SW	PW	EW	SW	PW	EW	SW
20	100	0	100	99	1	100	98	2	100
30	99	1	100	91	9	100	45	50	95
40	98	2	100	52	46	98	20	66	86

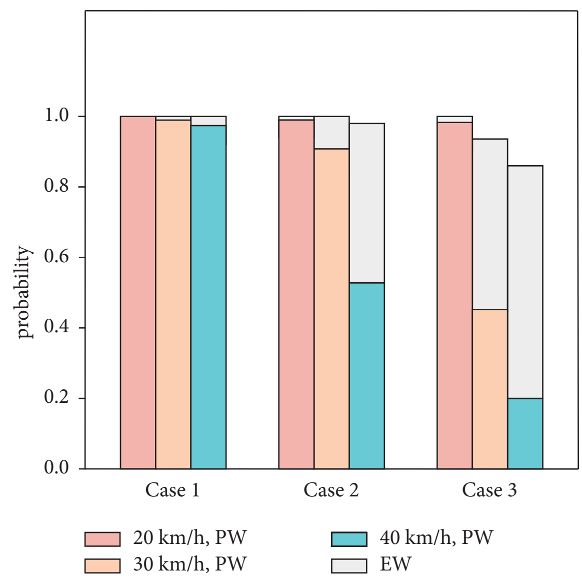


Figure 20: Test results for scenario 1.

Table 4: Test results for scenarios 2 and 3.

Velocity ($km{\cdot}h^{-1}$)	Scenarios								
	Scenario 1 case 1			Scenario 2			Scenario 3		
	Probability (%)								
	PW	EW	SW	PW	EW	SW	PW	EW	SW
20	100	0	100	100	0	100	100	0	100
30	99	1	100	99	1	100	97	3	100
40	98	2	100	95	5	100	55	42	97

situation is judged as safe and risk-free, and the situation is judged again, and a risk triggering the warning is discovered again. This may have been caused by misjudgment by the warning algorithm because of positioning deviation.

4.5. Discussion. The results indicate that the ICW application based on the LTE-V can effectively issue a warning in urban and rural environment and assist drivers to avoid collisions.

Although road shelters interfere with the communication performance of the LTE-V, they do not have a significant negative impact on the ICW application based on the LTE-V. This is mainly because the LTE-V has good communication capabilities. Road shading will not have an extremely serious impact on the LTE-V communication performance. However, poor network quality (though it may not be caused by the normal traffic environment) will cause severe delays or short-term network interruptions. Such delays may weaken the effectiveness of the Internet of vehicles function. Therefore, although the LTE-V environment has a better adaptability for LTE-V applications, due considerations should be given to the physical design of the system, routing mechanisms, congestion control mechanisms, and so on to eliminate potential causes, such as highly saturated traffic density [7], vibration, and bumps during vehicle operation. The factors that affect the quality of the network should be considered to ensure the reliability of the communication quality of the Internet of vehicles.

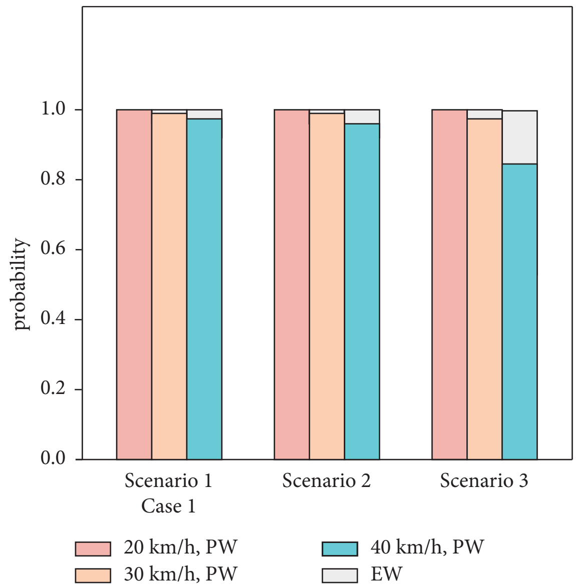


Figure 21: Test results for scenarios 2 and 3.

Although vehicle speed has a little effect on the LTE-V communication performance, it will have a significant impact on the effectiveness of ICW application. This is mainly because one of the important bases of the early warning algorithm proposed herein is the speed of the vehicle. This algorithm only considers the current position and speed of the vehicle and does not predict the future trajectory of the vehicle; this leads to the failure of the early warning. Therefore, when designing V2X applications, attention should be paid to algorithm design to eliminate the influence of vehicle speed. In addition to the vehicle speed, the positioning accuracy of the vehicle and geometric properties of the intersection (such as the intersection angle, the intersection formed by the intersection of the curving road) are expected to affect the arrival time of the vehicle at the intersection collision point. This poses great challenges to the effectiveness of V2X applications. Therefore, the previously mentioned factors should also be considered in the design of V2X applications.

In summary, the LTE-V communication performance can ensure the effectiveness of safety applications, but its reliability cannot be guaranteed in various actual traffic scenarios. The reliability is also affected by the design of physical system, actual algorithm design, vehicle speed, positioning accuracy, and other factors.

5. Conclusions

V2X is one of the key technologies in the new-generation intelligent transportation system. The performance and functionality of the V2X technology seriously restrict future traffic safety and travel efficiency. Therefore, the technology should be thoroughly tested and evaluated from all perspectives before its large-scale application. In this study, a modular test platform was constructed at the vehicle testbed of Chang'an University, in order to evaluate the performance and functionality of V2X. The platform was constructed at the vehicle testbed of Chang'an University (CAVTest). Performances of DSRC and LTE-V were evaluated under different communication distances, vehicle speeds, and traffic environments. Using this platform, a typical V2X application, namely, intersection collision warning (ICW) based on the LTE-V, was tested.

The testing results indicate that the performance of LTE-V is better than that of DSRC. The valid communication distance of DSRC is about 700 m, while the valid communication distance of the LTE-V is about 900 m. The communication distance and shelter are the main factors that affect the communication performance of V2X. Speed does not have any significant impact on the performance of V2X. The functionality testing results show that the ICW application based on LTE-V is effective, but its reliability cannot be guaranteed in all types of actual traffic scenarios. Its functional effectiveness will be affected by communication QoS, vehicle speed, the proposed algorithm, and other factors. Therefore, in the future, we will continue to explore the key factors that will affect the V2X functionality, so as to provide references for large-scale tests before the application of V2X.

Data Availability

The original codes of the numerical tests used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported in part by the National Key Research and Development Program of China (no.

2019YFB1600100), Key Research and Development Program of Shaanxi Province (no. 2021GY-290), Key Research and Development Program of Zhejiang Province (no. 2020C01057), and 111 Project of China (no. B14043).

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