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ENHANCING HIGHWAY SAFETY WITH VEHICLE-TO-INFRASTRUCTURE (V2I) RISK WARNING SYSTEMS

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Abstract: With the development of society and the improvement of transportation networks, highways have become an essential part of modern transportation systems. However, the frequent occurrence of traffic accidents poses a serious threat to life and property safety. To enhance traffic safety, it is necessary to establish an efficient and intelligent risk warning system. Vehicle-road collaboration (V2X) is an emerging technological approach that relies on vehicle-to-road communication to ensure traffic safety and improve traffic efficiency. The technological development of V2X has become a common hotspot in the transportation and information industries, both in China and globally. This paper, based on vehicle-road collaboration technology, explores the design concepts, key technologies, and promising application prospects of highway safety risk warning systems. The aim is to build a safety system capable of real-time monitoring and warning of highway risks, contributing to the development of intelligent transportation systems in China.
Keywords: Vehicle-road cooperation; Highway; Early warning system; Intelligent transportation; Driving simulation

1 INTRODUCTION

With the development of the economy and advancements in technology, Intelligent Transportation Systems (ITS) have become an integral part of modern transportation networks. In China, the government has issued documents such as the "Guiding Opinions on Promoting the Construction of New Infrastructure in the Transportation Sector" and the "13th Five-Year Plan for Road Traffic Safety," which emphasize the application of advanced technologies like 5G, Beidou Navigation System, remote sensing satellites, cybersecurity, data centers, and artificial intelligence in the transportation sector. These efforts aim to enhance the modernization and intelligence of transportation systems, develop smart transportation, and promote the digitalization and networking of transportation infrastructure[1].However, highways, as crucial transportation facilities, face significant safety challenges due to high-speed traffic, heavy flow, and harsh environmental conditions. To improve traffic safety, many countries and regions have already deployed early warning systems. Nevertheless, existing systems still face challenges in areas like the timeliness of information, diversification of communication channels, and personalized strategies. Vehicle-to-Everything (V2X) technology, as a product of the integration of the traditional automotive industry and information communication fields, has emerged as a vital means to enhance traffic safety, efficiency, and support autonomous driving. Through real-time information exchange, V2X technology enables comprehensive monitoring and early warning of highway traffic safety conditions, accurately identifying potential risks and alerting drivers to help prevent traffic accidents. A safety risk early warning system based on V2X technology has thus become an important solution for highway traffic safety issues.
In the design of highway risk warning systems, with the increasing number of vehicles and the growing prominence of traffic safety problems, technologies such as vehicle warnings and collision detection are gradually becoming central to traffic safety management. Emerging technologies, including data mining and machine learning algorithms, offer new methods to address the complexities of traffic safety. However, existing technologies still face issues such as discrepancies in the delivery of warning information, a lack of diverse warning strategies, and incomplete risk assessment methods[2]. C-V2X communication technology, as a key technology, has become a global research hotspot, especially for its potential applications in safety and efficiency improvement. Developed countries such as the United States, Japan, and European nations have made significant progress in intelligent transportation and V2X communication, particularly in the development and application of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) technologies. These efforts have contributed to the reduction of traffic accidents and the improvement of transportation safety.
This study proposes a safety risk early warning system based on V2X technology tailored for highway scenarios. By combining practical needs and current technological advancements, the system aims to provide new theoretical support and technological methods for highway traffic safety management. Through the construction of a warning system model, data analysis, and simulation experiments, this research strives to improve traffic safety, reduce accidents, and promote the application and development of V2X technology[3].

2 VEHICLE-TO-EVERYTHING (V2X) SYSTEM

The Vehicle-to-Everything (V2X) system is an intelligent transportation system that integrates next-generation communication technologies and sensor detection technologies. It leverages advanced communication and sensing technologies to obtain real-time information from both vehicles and roads. Through deep interaction among human, vehicle, and road information, V2X enables seamless connectivity between networked vehicles and infrastructure, between vehicles themselves, and between vehicles and pedestrians. This system not only optimizes traffic resource allocation and utilization to improve road safety but also effectively alleviates road traffic pressure and mitigates traffic congestion issues.

Figure 1 illustrates a typical structure of a V2X system, clearly depicting the collaborative working principles between its various modules. The V2X system primarily consists of three core components: the intelligent roadside system, the intelligent in-vehicle system, and the cloud control platform. The intelligent roadside system is responsible for collecting road information, while the intelligent in-vehicle system gathers vehicle status data. The cloud control platform, through V2X communication technology, integrates these modules into an efficient traffic management network. This collaboration not only ensures driving safety but also significantly enhances traffic efficiency.

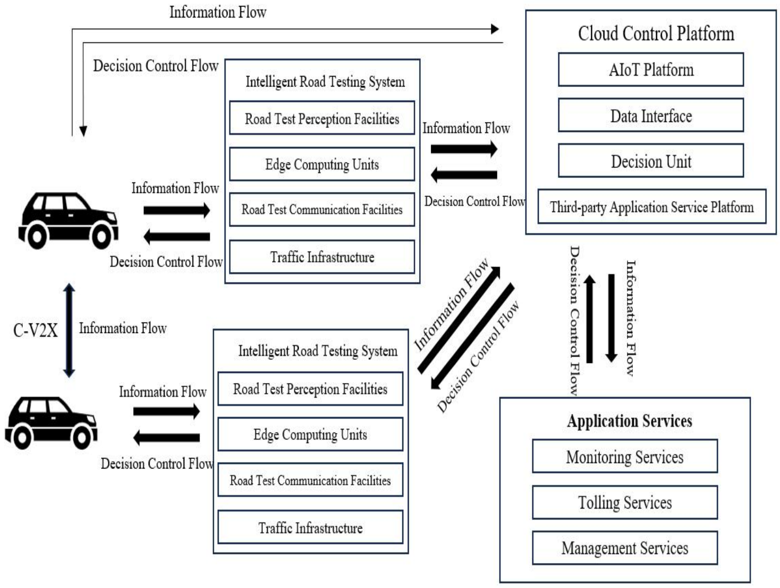

Figure 1 Vehicle-to-Everything (V2X) System

3 KEY TECHNOLOGIES OF THE HIGHWAY SAFETY RISK WARNING SYSTEM BASED ON VEHICLE-TO-EVERYTHING (V2X) COOPERATION

3.1 Chip Integration Technology

In the Highway Safety Risk Warning System based on V2X cooperation, a large amount of data and complex algorithms need to be processed. Therefore, advancements in chip integration technology are required to enhance the performance of the warning system, reduce power consumption, and minimize space occupation. Currently, artificial intelligence (AI) technologies effectively handle complex traffic environments and a large number of vehicle targets, enabling video processing and object tracking within traffic systems.

However, to maintain efficient operation across the entire system, numerous AI processor chips are involved. Thus, it is crucial to balance performance, power consumption, chip embedment, and code portability during the chip integration process. This balance ensures that the warning system's modules, such as video analysis, object detection, and behavior recognition, can operate quickly and efficiently. This allows the system to accurately identify traffic violations, abnormal driving behavior, and potential traffic hazards in the dynamic, complex, and high-target-density environment of a highway, providing reliable data support for the warning system.

3.2 On-Board Unit (OBU) Technology

The On-Board Unit (OBU) is a core component of the V2X cooperative system, responsible for collecting vehicle status, location, speed, and other information, and transmitting this data to roadside devices via wireless communication technologies. The OBU technology must fulfill the following functions:

1. **Real-time Vehicle Information Collection:** This includes vehicle location, speed, acceleration, etc.
2. **Wireless Communication:** Utilizing technologies such as Wi-Fi, 5G, and C-V2X to enable information exchange between vehicles and between vehicles and infrastructure.

3. **Data Processing:** Fusing, processing, and compressing the collected data to improve data transmission efficiency.

3.3 Traffic Risk Precise Dissemination Technology

The Highway Safety Risk Warning System under V2X cooperation also needs to ensure that the system can accurately and promptly identify and disseminate traffic risk information, avoiding overly generalized or ambiguous messages. Therefore, breakthroughs in traffic risk precise dissemination technology are essential.

Due to characteristics such as long vehicle travel distances and strong enclosure on highways, once a traffic accident occurs, the risk and impact zones are typically wide and prolonged. Implementing early warning prediction and risk notification before or at the early stages of an accident can effectively reduce the impact of traffic risks. The core of this technology is to accurately predict potential traffic hazards, locate accident sites, and precisely disseminate traffic risks for both upstream and downstream of special road segments and accident sites. This requires the integration of advanced prediction algorithms, positioning technologies, and communication systems, ensuring the timeliness, accuracy, and precision of warning information, ultimately enhancing the ability to prevent and control traffic accident risks.

4 DESIGN OF THE HIGHWAY RISK WARNING SYSTEM BASED ON VEHICLE-TO-EVERYTHING (V2X) COOPERATION

4.1 Design Principles of the Warning System

This paper adopts vehicle-to-everything (V2X) cooperation as the design concept and system functional requirements as the design basis to create the overall framework of the highway safety risk warning system, as shown in Figure 2. The framework consists of five key layers:

1.Perception Layer: Comprising on-board sensors, monitoring devices, and roadside perception equipment, this layer is primarily responsible for collecting vehicle driving data and road condition information, providing the fundamental data required for risk warning.

2.Data Storage Layer: This layer includes local and cloud-based database servers, used to store raw data and risk analysis results.

3.Data Access Layer: Responsible for transmitting instructions and data, this layer supports the warning analysis services.

4.Business Logic Layer: Integrating risk warning models and related algorithms, this layer processes raw data and generates warning results.

5.Presentation Layer: This layer displays the warning information to users and facilitates interaction with them, showing processed warning results on the system's terminal.

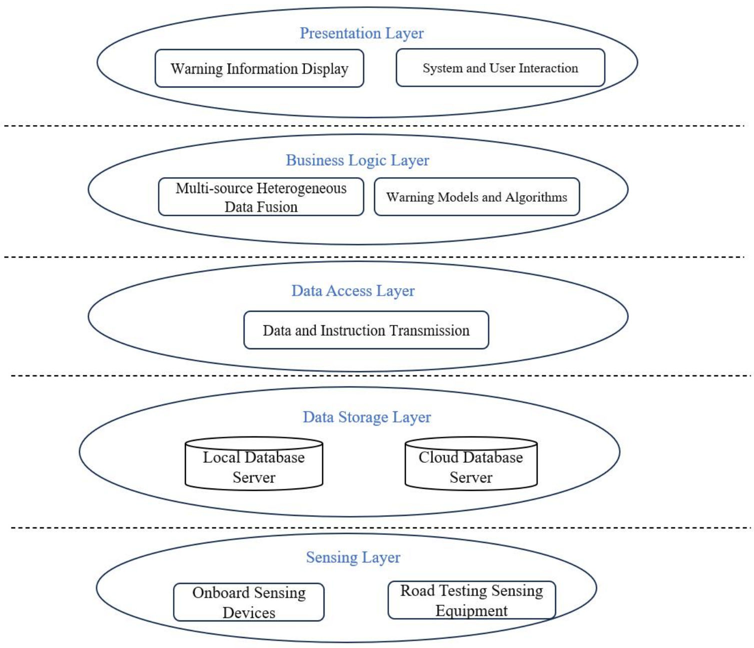

Figure 2 Overall Framework of the Highway Safety Risk Warning System Based on Vehicle-to-Everything (V2X) Cooperation

4.2 System Framework Design

This study aims to design a Vehicle-to-Everything (V2X) cooperative ecological driving warning system based on driving simulation technology, integrating ecological lanes with human-machine interaction terminals (HMI) for vehicle-road collaboration (Figure 3). The warning system consists of three parts: the driving simulator, the collaborative processing center, and the Human-Machine Interaction (HMI) terminal. The driving simulation system is responsible for road scene development, traffic element design, and experimental data collection. The collaborative processing center integrates vehicle and traffic environment data to generate driving warning information. The HMI provides real-time driving feedback and suggestions to the driver in graphical, textual, and auditory formats[4].

First, the ecological lane (Ecolane) is designed based on actual highway parameters to complete the roadside scenario development for the warning system. Then, the V2X cooperative HMI terminal (EcoHMI) is developed, using a combination of text, images, and sound to design ecological driving warning information[5]. The terminal's functions and interface layout are designed according to the importance and frequency of the information. The vehicle-side terminal development for the warning system is then completed. Finally, the collaborative processing center integrates roadside and in-vehicle data to construct a cooperative ecological driving warning system composed of the driving simulator, data processing center, and HMI terminal[6]. The UDP protocol is used to achieve data sharing and integration, enabling Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication.

More than 15 vehicle-road collaborative warning experiments, such as fog warning, collision warning, tunnel warning, and construction zone warning, have been conducted on the experimental test platform. Experimental results have validated the effectiveness of vehicle-road collaborative warning experiments based on driving simulation technology. Additionally, a subjective questionnaire was designed based on the Technology Acceptance Model (TAM) to survey participants' attitudes and experiences with EcoHMI. The survey results showed that about 60% of participants believed EcoHMI was helpful for driving operations and expressed willingness to continue using it[7-8].

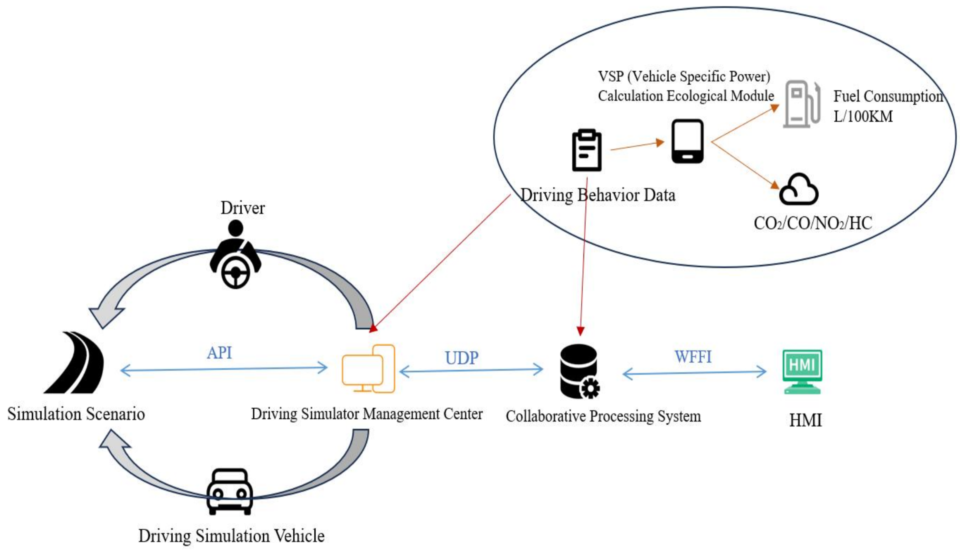

Figure 3 Schematic Diagram of the Vehicle-Road Collaborative Ecological Driving Simulation Platform

4.3 Application Scenario Design

4.3.1 Abnormal driving behavior recognition

In real road conditions, when a vehicle detects the presence of another vehicle exhibiting abnormal driving behavior, the warning system assists the vehicle in path planning. The principle of the vehicle-road collaboration system is that roadside sensing devices continuously monitor the operating conditions of surrounding vehicles, enabling real-time identification of abnormal driving behaviors such as driving in the wrong direction, slow driving, or speeding. Once the roadside sensing devices detect these abnormal behaviors, the results are immediately transmitted to the platform. The warning system analyzes and processes the data to assist the driver in making correct decisions and controlling the vehicle.

4.3.2 Road hazard warning

When a vehicle approaches a road section with potential danger (such as bridges or tunnels) and there is a risk of an accident, the warning system will alert the driver and provide risk avoidance suggestions. This function is primarily achieved through real-time monitoring of road conditions by roadside sensing devices or onboard sensors, analyzing potential hazards like sharp turns or sudden weather changes. If a potential danger is detected, the system sends warning information to the driver, urging them to take necessary safety measures.

4.3.3 Speeding warning

While driving, if the vehicle exceeds the speed limit, the warning system will issue a real-time alert to remind the driver to slow down and comply with the road's speed limit. This warning is primarily realized through real-time reporting of the vehicle's status, the business operation platform sending map and roadside information, and the warning system receiving and interpreting these messages to obtain the speed limit information. If the vehicle's actual speed exceeds the limit, the system will trigger a speeding warning, reminding the driver to reduce speed as needed.

4.3.4 Cooperative vehicle merging

When a vehicle is on an entrance ramp, information from surrounding vehicles is aggregated to generate scheduling information, coordinating the merging of ramp vehicles into the main road. The specific implementation steps involve periodic vehicle information upload, platform fusion calculation, and roadside messages sent to the vehicle. The warning system integrates vehicle status, road conditions, and traffic participant information to generate final driving behavior or path strategies.

4.3.5 Vulnerable road users collision warning

When a vehicle is at risk of colliding with vulnerable road users such as road maintenance personnel, non-motorized vehicles, or pedestrians, the system activates the vulnerable user collision warning function. This function monitors the surrounding traffic situation in real time using onboard sensors or roadside sensing devices, analyzing potential collision risks. If a collision risk with a vulnerable road user is detected, the system sends a warning message to the driver.

4.3.6 Driver emotion state recognition

Research shows that a driver's operation behavior is influenced by their current emotional state, with significant differences in reaction speed and environmental responsiveness under normal, fatigued, or intoxicated conditions. To accurately predict a driver's future actions, it is essential to capture their body movements and facial expressions to identify their emotional state.

Traffic scenarios are influenced by a combination of traffic facilities, traffic signs, road conditions, weather changes, pedestrians, and vehicles, all of which affect the driver's behavior. To study the relationship between these influences and the driver's actions, it is necessary to convert these difficult-to-formalize image data into corresponding digital codes, providing digital input parameters for subsequent driving trajectory predictions. Converting image data into digital codes, which involves understanding and analyzing images, has been a challenge in this field.

The study begins by classifying traffic scenes and manually labeling various traffic scene images. Existing methods are then used to recognize traffic objects, the distances between traffic members, climate, and road conditions. Based on these recognition results, deep convolutional neural networks are applied to establish corresponding outputs for the different inputs under various traffic scenes. In the recognition study, key indicators such as the accuracy, execution time, and adaptability of the algorithm model are used to evaluate and optimize the proposed traffic scene recognition model.

4.4 Problems to be Addressed by the System

Currently, the implementation of an active safety and early warning system based on vehicle-road collaboration on highways urgently needs to solve two major issues.

4.4.1 Real-time traffic scene understanding and classification based on video streams

Traffic scene understanding is a key technology for predicting driver behavior and ensuring driving safety. The goal of traffic scene understanding and classification is to simplify the representation of scenes and convert video or image data into digital codes that represent various traffic conditions. The key challenges in traffic scene understanding include:

1. Uncertainty in the classification system and standards for traffic scenes.
2. Identifying and extracting traffic participants in complex backgrounds.
3. Mapping models between traffic participants and scene classification results.
4. Various interference factors such as insufficient light intensity, uneven lighting, uneven scene structure, and complex and changing content.

4.4.2 Recognition, expression, and evolution of driver habits

Driver habits are intrinsic factors that determine driving behavior. The key challenges in modeling driver habits include:

1. Feature vectors for modeling user operation habits.
2. Representation formats for operation habit models.
3. Evaluation of the accuracy of operation habit models.
4. Model update strategies for changes in user behavior habits.

4.5 Warning Algorithm Design and Optimization

The warning algorithm design and optimization process for the vehicle-road collaborative ecological driving warning system based on driving simulation technology is as follows:

1. **Data Collection and Processing**: Collect various data during the vehicle's simulated driving process, and preprocess the collected data, including data cleaning, noise reduction, and feature extraction.
2. **Warning Algorithm Design**: Based on vehicle status and environmental information, design a warning algorithm to determine if there is potential danger in the current driving state.
3. **Warning Algorithm Optimization**: For machine learning methods, optimization can be done by adjusting algorithm parameters, selecting appropriate features, and increasing the number of training samples to improve the accuracy and robustness of the warning algorithm. Cross-validation and other evaluation methods can also be used to assess and compare the warning algorithms, selecting the optimal algorithm.

4. **Real-Time Warning and Feedback**: In actual driving, the warning algorithm is embedded into the vehicle's driver assistance system to monitor the driving state in real time and issue warnings. When the warning algorithm detects potential dangers, it promptly issues a warning signal to the driver, reminding them to take corresponding safety measures.

5 APPLICATION OF DRIVING SIMULATION TECHNOLOGY IN VEHICLE-ROAD COLLABORATIVE ECOLOGICAL DRIVING WARNING SYSTEM

5.1 Principles and Characteristics of Driving Simulation Technology

Driving simulation technology is a method that uses computers to simulate real driving environments and behaviors. By utilizing virtual reality technology and simulation algorithms, it places the driver in a virtual driving environment to simulate real driving operations and scenes, enabling the observation and analysis of the driver's behavior and reactions[9]. The characteristics of driving simulation technology are:
1. **Authenticity**: It can highly replicate the real driving environment, including roads, vehicles, traffic signs, and signals, allowing the driver to perform real driving operations in a virtual environment.
2. **Safety**: It provides a safe driving environment, avoiding the risks that may arise from conducting driving experiments on real roads.
3. **Controllability**: The driving environment and situations can be precisely controlled, including factors like weather, road conditions, and traffic flow, for conducting driving behavior research and testing in different scenarios.
4. **Repeatability**: Driving simulation technology allows for repeated driving experiments, enabling data comparison and analysis, which enhances the credibility and reliability of the research.

5.2 Acquisition of "Human-Vehicle-Road" Interaction Data

The raw data for the research includes vehicle driving trajectories, driver vehicle operation behaviors, vehicle operating status, and road traffic scene images. A data collection system is designed to simultaneously record driver expressions, body movements, road scene data, and vehicle operating conditions. To reflect the driving characteristics of drivers with different behavior profiles, the database should include data from multiple drivers. Once the data is acquired, it is cleaned, calibrated, and formatted. The data is then sorted and synchronized according to the needs of subsequent studies, completing the process of acquiring "human-vehicle-road" interaction data[10].

5.3 Role and Advantages of Driving Simulation Technology in Vehicle-Road Collaborative Ecological Driving Warning System

In the vehicle-road collaborative ecological driving warning system, the role and advantages of driving simulation technology are:
1. **Behavior Research and Analysis**: Driving simulation technology enables the observation and analysis of driver behavior and reactions, including assessing attention, reaction time, and decision-making ability, providing a reference for driver behavior modeling in the vehicle-road collaborative system.
2. **Driver Training and Education**: The technology provides a safe driving environment for training drivers, helping them improve driving skills and safety awareness, thus reducing traffic accidents.
3. **System Evaluation and Optimization**: Driving simulation technology allows the evaluation and optimization of the vehicle-road collaborative ecological driving warning system, testing and improving aspects like warning accuracy, response time, and user interface, ultimately enhancing system performance and user experience.
4. **Data Collection and Analysis**: Driving simulation technology generates a large amount of driving data, including driver behavior and vehicle state data, supporting the system's data analysis and algorithm optimization.
The vehicle-road collaborative ecological driving warning system based on driving simulation technology collects and records driving behavior and road condition information in real-time, providing accurate driving warnings that help drivers adopt more economical and safe driving practices. Experimental results show that this system not only reduces fuel consumption and emissions, minimizing environmental pollution, but also improves driver skills and safety awareness, reducing traffic accidents. Therefore, the system has significant application value and promotion prospects in terms of energy saving and emission reduction[11].

5.4 Optimization and Improvement of the Warning System

1. **Data Processing and Fusion Optimization**: Using big data, cloud computing, and deep learning to improve the accuracy and real-time performance of data processing and fusion.
2. **Warning Algorithm Improvement**: Developing machine learning-based collision risk assessment and vehicle behavior prediction algorithms, and introducing real-time communication mechanisms to enhance response speed.
3. **System Scalability and Compatibility**: Designing a modular architecture that supports data sharing in different vehicle-road collaborative systems and compatibility with intelligent in-vehicle devices.
By optimizing the system, the accuracy, real-time performance, and scalability of the warning system will be enhanced, ultimately reducing highway traffic accidents and ensuring traffic safety. As vehicle-road collaborative technology

progresses, the system will become more intelligent and precise, providing strong support for highway safety management.

6 CONCLUSION AND OUTLOOK

This study explores the vehicle-road collaborative highway safety risk warning system, aiming to improve traffic safety by combining traditional vehicle safety monitoring with modern information communication technology. The research indicates that vehicle-road collaborative technology can collect and transmit vehicle and road information in real-time. When combined with data analysis and warning algorithms, it significantly reduces the occurrence of traffic accidents. Furthermore, the system effectively protects vulnerable road users, such as motorcyclists and pedestrians, by providing real-time monitoring and warning drivers to be aware of their surroundings, thereby reducing accidents.

The system can also handle scenarios involving both connected and non-connected vehicles, integrating data from different vehicles to accurately predict their behavior and reduce accidents. In the application of autonomous driving, vehicle-road collaborative technology has proven its ability to improve traffic safety and prevent accidents in highway autonomous driving demonstration experiments.

The study further emphasizes that China's intelligent transportation infrastructure provides strong support for vehicle-road collaborative technology. The system can integrate with existing infrastructure to further improve warning effectiveness. However, despite the vast potential of vehicle-road collaboration, real-world applications still face challenges such as communication technology selection and standardization. To address these issues, this study proposes corresponding solutions, advancing the development of the technology.

Overall, the vehicle-road collaborative highway safety risk warning system can significantly enhance traffic safety, reduce accident rates, provide technical support for the development of intelligent highways, and has strong social application potential. Nevertheless, continuous optimization of the technology remains essential to address future changes and challenges.

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CONFLICT OF INTEREST

The authors have no relevant financial or non-financial interests to disclose.

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