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Smart V2I Alert System for Hairpin Bends

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***Abstract*—**Roadaccidentsonmountainroadswithsteepslopes and sharp hairpin bends are a serious safety concern, mainlydue to poor visibility and difficult driving conditions. Drivers approachingsuchbendsoftenhavenoinformationaboutoncom-ing vehicles until it is too late to react. To address this problem, this paper proposes a Vehicle-to-Infrastructure (V2I) based alert system that improves driver awareness and reduces the risk of collisions at blind hairpin turns.

The proposed system uses a roadside unit (RSU) equippedwith a camera and edge computing hardware to continuously monitortrafficnearthebend.Vehiclesaredetectedandclassified in real time as light or heavy vehicles using on-device processing, avoidingdelayscausedbyclouddependency.Onceavehicle is detected, the RSU generates a compact warning message containing key information such as vehicle type, speed, and estimated time of arrival. This alert is transmitted to vehicles approaching from the opposite direction, where visibility is limited.

For reliable and low-latency communication, the system em-ploys Cellular Vehicle-to-Everything (C-V2X) technology over 4G/5G or private 5G networks, achieving end-to-end latency of approximately 50–100 ms. Lane-specific alert delivery is ensured through camera-based lane detection, geographic filtering, and directional broadcasting. Receiving vehicles validate the alert using GPS position and heading before presenting visual or audible warnings to the driver.

The proposed solution is cost-effective, scalable, and suitable for real-world deployment on hazardous mountain roads. Fu-ture enhancements include AI-based collision risk prediction, improved GPS accuracy, and roadside display units for vehicles withoutonboardcommunicationsystems.Overall,thesystem demonstrates a practical approach to enhancing road safety at dangerous hairpin bends through the integration of perception, edge computing, and low-latency V2I communication.

***Index Terms*—**V2I communication, Hairpin bends, Edge com-puting, YOLO vehicle detection, C-V2X, Collision avoidance, Intelligent transportation systems

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I. INTRODUCTION

Hairpin bends on mountainous roads pose significant safety risks due to sharp curvature, narrow carriageways, and com-pleteobstructionofthelineofsightbetweenvehiclestraveling in opposite directions. Traditional safety measures such as convex mirrors and static warning signboards are largely pas-sive and unable to adapt to real-time traffic conditions, often resulting in delayed driver reactions and a high probability of severe collisions.

Recent developments in Intelligent Transportation Systems (ITS)haveenabledreal-timesensing,processing,andcommu-nication between vehicles and roadside infrastructure [7], [9]. Vehicle-to-Infrastructure(V2I)communicationfacilitatescon-tinuous monitoring of hazardous road segments by roadside unitsandallowstimelydisseminationofwarningmessages to approaching vehicles. When integrated with edge comput-ing and artificial intelligence, such systems are capable of delivering rapid, low-latency responses essential for accident prevention in visually constrained environments [2], [10].

This paper presents a Smart V2I Alert System that com-binescamera-basedvehicledetection,edge-levelAIinference, and ultra-low-latency communication to provide early hazard warnings at blind hairpin bends. The proposed decentralized architecture eliminates reliance on cloud processing, thereby ensuring consistent real-time performance, enhanced relia-bility, and scalability for deployment across accident-prone mountainous regions [8], [9].

II. LITERATUREREVIEW

Several studies have explored collision avoidance and in-telligent road safety systems using sensing, artificial intelli-gence, and vehicular communication technologies [3]. Early approaches largely relied on low-cost sensors such as ultra-sonicandinfraredmodulesforobstacledetection.While these systems offer ease of deployment, they suffer from limited detection range, poor environmental robustness, and the in-ability to classify vehicle types, reducing their effectivenessin complex traffic scenarios.

Recentresearchhasshiftedtowardcamera-basedperception combined with deep learning techniques for accurate vehicle detection and classification [4], [14]. Convolutional neural network models such as YOLO have demonstrated high real-time performance across varying environmental conditions, enabling reliable identification of vehicles on curved and visually obstructed road segments. However, many vision-based systems depend on cloud computing for processing, introducing network latency that is unsuitable for safety-critical applications.

Edge computing integrated with next-generation cellular networks has emerged as a promising solution to overcome latency limitations [2], [10]. Studies on 5G-enabled edge architectures highlight their capability to perform localizedAI inference with ultra-low response times, significantly im-proving real-time vehicular safety operations. These systems reduce bandwidth consumption while enhancing privacy and reliability by processing data closer to the sensing source.

In parallel, Vehicle-to-Infrastructure (V2I) communication frameworks have been proposed to extend driver awareness beyond onboard sensors [7], [8]. Roadside units equippedwith sensing and communication modules can detect ap-proaching vehicles and broadcast hazard alerts, particularly in regions with limited visibility such as tunnels, sharp curves, and mountainous terrain. Empirical evaluations indicate that infrastructure-assistedalertssubstantiallyreducecollisionrisk by enabling early driver response [3].

Despitetheseadvancements,existingsolutionsoftenaddress perception, computation, or communication in isolation. Few systems offer an integrated edge-based AI perception frame-work combined with low-latency V2I communication specifi-cally designed for blind hairpin bends. This gap motivates the development of a decentralized Smart V2I Alert System that unifies real-time vehicle detection, edge processing, and rapid hazarddisseminationtoenhancesafetyinvisuallyconstrained road environments [9].

III. METHODOLOGY

A. Proposed System Architecture

The proposed Smart V2I Alert System follows a decen-tralized edge-enabled architecture designed to provide real-timehazardawarenessatblindhairpinbends.Theframe-work integrates localized perception, on-device intelligence, and low-latency communication to enable proactive collision prevention.

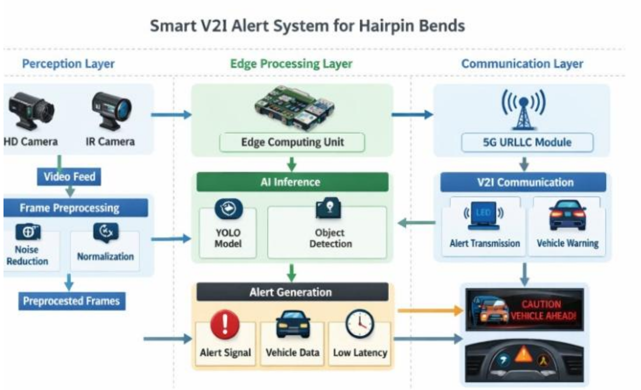

Fig. 1.Layered architecture of the proposed Smart V2I alert system showingthe perception, processing, and communication layers.

Thearchitectureisorganizedintothreefunctionallay-ers: Perception Layer, Processing Layer, and Communication Layer.

1) Perception Layer: The Perception Layer serves as the sensing interface of the system and is responsible for con-tinuous traffic monitoring at the hairpin bend. A camera unitis positioned to capture both ascending and descending lanes with wide-angle coverage.

Captured video frames undergo basic preprocessing includ-ing noise reduction, illumination normalization, and motion segmentation to enhance detection robustness. These pro-cessed frames are forwarded to the edge processing unit for real-time analysis.

*2) Processing Layer:*The Processing Layer performs real-time vehicle detection, classification, and tracking. An edge processing unit executes a YOLOv8 deep learning model optimized for fast inference [14].

Detectedvehiclesareclassifiedintolightandheavyvehicle categories. Bounding box coordinates and confidence values are generated for each detected object. Temporal filtering techniques are applied to maintain detection continuity and estimate vehicle movement.

Essential vehicle parameters including vehicle type, direc-tion, and timestamp are converted into compact metadata packets to minimize communication overhead.

3) Communication Layer: The Communication Layer en-ables low-latency V2I message exchange between roadside infrastructureandapproachingvehicles[7],[15].Vehicle metadata is transmitted wirelessly to opposite-lane vehicles through ESP32 microcontroller-based communication.

Received alerts are validated based on vehicle directionand lane relevance before triggering visual or audio warnings. Lane-specificfilteringreducesfalsealertsandensurescontex-tual accuracy.

*4) SystemWorkflow:*Theoperationalflowofthesystem follows four sequential stages:

- Continuousvideoacquisitionatthehairpinbend
- Edge-basedvehicledetectionandclassification
- Metadatagenerationandhazardevaluation
- Real-timealerttransmissionthroughV2Icommunication

Thisclosed-loopframeworkenablesearlyhazardawareness before direct visual contact between vehicles.

B. SystemImplementation

The system was implemented using a combination of com-putervision-basedvehicledetectionandESP32-basedwireless communication.

Fig.2.Experimentalprototypesetupshowingthehairpinbendmodel.

A mobile phone camera mounted on a tripod was used to simulate a roadside surveillance unit. The main processing application was executed on a laptop acting as the edge computing platform, where real-time vehicle detection was performed using the YOLOv8 model.

ESP32 microcontrollers were deployed for wireless alert transmission between infrastructure and vehicle nodes. Sup-porting components including power modules and connecting circuits ensured stable system operation.

The complete workflow involved image capture, lane iden-tification, lead vehicle detection, and alert message delivery through ESP32 communication.

C. Data Collection

Fig.3.Samplevehicleimagesusedfordatasetcreation,includingcarandtruck classes captured from different angles.

A controlled prototype environment was created using a scaled hairpin bend road model constructed from cardboard. Toycarsandtoytruckswereusedtorepresentlightandheavy vehicles.

Images were captured using the mobile camera under vary-ing orientations and lighting conditions to improve dataset di-versity.Thedatasetwasself-collectedtomaintainconsistency in environmental conditions.

Twovehicleclasseswereformed:

- Car
- Truck

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D. PreprocessingandModelTraining

More than 300 images were manually annotated using boundingboxesthroughtheRoboflowplatform.Theannotated dataset was exported in YOLO format.

Training was performed on Google Colab using the YOLOv8 training pipeline, which automatically handled im-age resizing and normalization. The trained model was saved in `.pt`format for real-time inference.

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E. SystemTesting

Testingwasconductedontheprototypehairpinbendmodel by positioning vehicles alternately across both lanes.

Initial tests revealed classification and lane overlap issues, which were resolved through algorithm refinement. A virtual lane separation mechanism was introduced to distinguish ve-hicle direction.

Lead vehicle prioritization logic was implemented to deter-mine alert triggering.

ESP32communicationwasoptimizedthroughrepeated test-ing, resulting in stable low-latency message transmission.

IV. RESULTS AND DISCUSSION

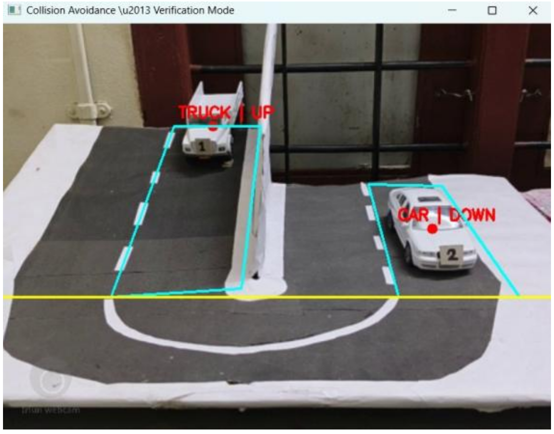

Fig.4.Output

The proposed Smart V2I Alert System was evaluated using thescaledhairpinbendprototypeenvironmenttoassess detec-tion performance, system responsiveness, and communication reliability. The layered architecture integrating perception, edge processing, and wireless communication demonstrated effective real-time operation [9].

The YOLOv8-based vehicle detection model consistently identified car and truck classes across multiple test scenarios. Vehicles approaching from both lanes were accurately local-ized using bounding box detection, enabling effective lane-wise separation and lead vehicle identification. The prepro-cessing techniques improved detection stability under varying illumination conditions.

Edge-basedinferenceensuredminimalprocessingdelay[2],[10],allowinghazardassessmentandalertgenerationto occur in near real time. The conversion of detection outputs into compact metadata packets significantly reduced communica-tion overhead while preserving essential safety information.

ESP32-based V2I communication achieved stable wireless transmission of alert messages after iterative optimization. Message delivery exhibited negligible latency and high re-liability, ensuring timely warning dissemination to receiving nodes.

The combined system performance validates the feasibility of decentralized edge-enabled safety frameworks for blind curve accident prevention. The prototype demonstrated proac-tivehazardawarenessbeforedirectvisualcontactbetween vehicles, highlighting its effectiveness for real-world moun-tainous road scenarios.

However, the current experimental setup was limited to a scaled physical model. Environmental factors such as heavy fog, rain, and long-range detection were not fully represented. These aspects will require enhanced sensing hardware in real-world deployments.

Overall, the results confirm that integrating computer vi-sion with low-latency V2I communication offers a practical and scalable solution for improving road safety at hazardous hairpin bends.

V. CONCLUSION AND FUTUR EWORK

This paper presented a decentralized, edge-enabled Smart V2I Alert System designed to enhance road safety at blind hairpin bends through real-time perception and low-latency communication. The proposed layered architecture effectively combined camera-based sensing, edge AI processing, and ESP32-enabledwirelessalerttransmissiontoprovideproactive hazard awareness.

The implemented prototype successfully demonstrated ac-curate vehicle detection, lane-wise separation, lead vehicle prioritization, and reliable alert delivery within a controlled environment. Edge-based processing minimized latency while maintaining high detection performance, validating the prac-ticality of localized intelligence for real-time traffic safety applications.

Although the system was tested on a scaled model, the obtained results indicate strong potential for real-world de-ployment. Future work will focus on integrating higher-resolution cameras, weather-resilient sensors, and long-range communication modules to enhance robustness under diverse environmental conditions.

Furtherenhancementswillincludemulti-sensorfusioncom-bining radar, GPS, and vision data to improve detection reliability and enable predictive collision risk assessment. The addition of roadside visual display units may also support vehicles lacking onboard communication systems.

The proposed framework contributes toward intelligent transportation safety solutions and offers a scalable approach foraccidentpreventioninchallengingroadwayenvironments.

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