iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: V Month of publication: May 2026

DOI: https://doi.org/10.22214/ijraset.2026.82743

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue V May 2026- Available at www.ijraset.com

Adaptive Deep Learning Framework for Harsh Weather Traffic Sign Recognition

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Abstract: Traffic sign recognition in adverse weather conditions poses a significant challenge to autonomous driving systems and demands robust and adaptive solutions. This project introduces a real-time traffic sign recognition framework designed to operate reliably under harsh weather scenarios by leveraging the adaptability and efficiency of deep learning techniques. optimized for embedded systems, for spatial feature extraction, and integrates a weather-adaptive preprocessing module to enhance image quality and maintain detection accuracy across varying environmental conditions. In advanced configurations, the framework incorporates attention mechanisms and domain adaptation strategies to dynamically adjust to visual distortions caused by rain, fog, snow, and low light settings. Upon successful recognition, the system updates contextual driving data including sign type, timestamp, and GPS coordinates, which are transmitted to the vehicle control unit and optionally to cloud services for analysis. All processed data are securely stored in cloud databases such as Firebase Fire store, enabling real-time monitoring and continuous model refinement.
Keywords: adaptive deep learning framework for harsh weather traffic sign recognition.

I. INTRODUCTION

Traffic signs are essential for safe and efficient road navigation, especially for Advanced Driver-Assistance Systems (ADAS) and autonomous vehicles (AVs). While deep learning (DL)-based Traffic Sign Recognition (TSR) systems perform well in clear weather, their accuracy drops significantly under harsh conditions such as rain, fog, snow, hail, and low light due to noise, occlusions, and reduced visibility. This limitation arises because most existing models are trained mainly on clear-weather datasets, reducing their ability to generalize to adverse environments and creating potential safety risks. To address this issue, this project proposes an Adaptive Deep Learning Framework for Harsh Weather Traffic Sign Recognition that improves recognition accuracy by using adaptive techniques such as domain adaptation, weather-specific data augmentation, and robust feature learning.

II. LITERATURE REVIEW

Traffic sign recognition evolved from traditional ML methods to CNN-based models like AlexNet and VGG-16, improving accuracy but facing real-time challenges. Lightweight text-to-speech (TTS) systems are also used for real-time driver voice alerts.

A. Real-Time Detection of images from camera

The framework performs real-time traffic sign detection using camera input under harsh weather conditions. It enables fast and accurate recognition to improve road safety.

B. Deep Learning for image captureing

Deep learning is used for image capturing and processing to detect traffic signs accurately in harsh weather conditions. It improves recognition performance through automatic feature extraction and real-time analysis.

C. Detection of blurred images in the traffic

The system detects blurred traffic images caused by harsh weather and enhances recognition accuracy using adaptive deep learning techniques. It helps maintain reliable traffic sign detection in low-visibility conditions.

D. Traffic Sign Recognition under Foggy Conditions Using Cycle AN by Zhang [2]

Zhang [2] proposed a traffic sign recognition method under foggy conditions using CycleGAN to enhance image clarity and improve detection accuracy. The approach helps deep learning models recognize traffic signs more effectively in low-visibility environments.

E. Squeeze-and-Excitation Networks" by Huetal

which improve deep learning performance by enhancing important feature channels in images. This method helps achieve better traffic sign recognition accuracy under challenging conditions.

III. METHODOLOGY

The project uses an adaptive deep learning framework to detect and recognize traffic signs from real-time camera images under harsh weather conditions. Weather-specific preprocessing and data augmentation techniques are applied to handle fog, rain, blur, and low visibility. The trained CNN-based model performs accurate traffic sign classification and provides real-time detection results for improved road safety.

A. Input Data Collection

Real-time video input is captured using an onboard camera mounted on the vehicle. These video streams are continuously processed to extract image frames that form the primary dataset for the system.

B. Data Pre -processing

The extracted images undergo initial pre-processing operations such as resizing, normalization, and noise reduction. This prepares the data for consistent and efficient input into the neural network pipeline.

C. Weather Condition Classification

A lightweight classifier or heuristic logic is used to identify the current environmental condition—fog, rain, snow, or clear. This classification informs the type of pre processing to be applied.

D. Feature Enhancement

Based on the identified weather condition, adaptive filters (e.g., CLAHE, dehazing, brightness correction) are applied to improve visibility and feature sharpness within the image.

E. Adaptive Deep Learning Model

Enhanced frames are passed into a deep learning architecture, primarily MobileNetV2, for spatial feature extraction. BiLSTM is optionally used to capture temporal coherence when working with sequential frame data.

F. Traffic Sign Detection & Recognition

The extracted features are analyzed by a classification layer (Softmax) to detect and recognize traffic signs. Detected signs are assigned a label and confidence score.

G. Post-Processing

The recognition output is filtered through post-processing logic to handle overlapping predictions, suppress noise, and prepare the final results for output modules.

H. Output: Recognized Traffic Sign

Recognized traffic signs are delivered through two output channels: on-screen display and auditory alert using a Text-to-Speech (TTS) engine. Additionally, detection data is logged to a cloud database (Firebase) for storage and analysis..

I. Implementation Phases

1) Real-time traffic sign detection using live camera input
2) Deep learning-based image processing and classification
3) Detection under harsh weather conditions such as fog, rain, and blur
4) Image preprocessing for noise reduction and visibility enhancement
5) CNN-based adaptive model for accurate traffic sign recognition

J. System Significance

The proposed system enables automated, real-time detection of violent activities, reducing dependency on manual surveillance. Its scalable design makes it suitable for deployment in smart cities, transportation systems, educational institutions, and public safety environments, ensuring faster response and enhanced security monitoring.

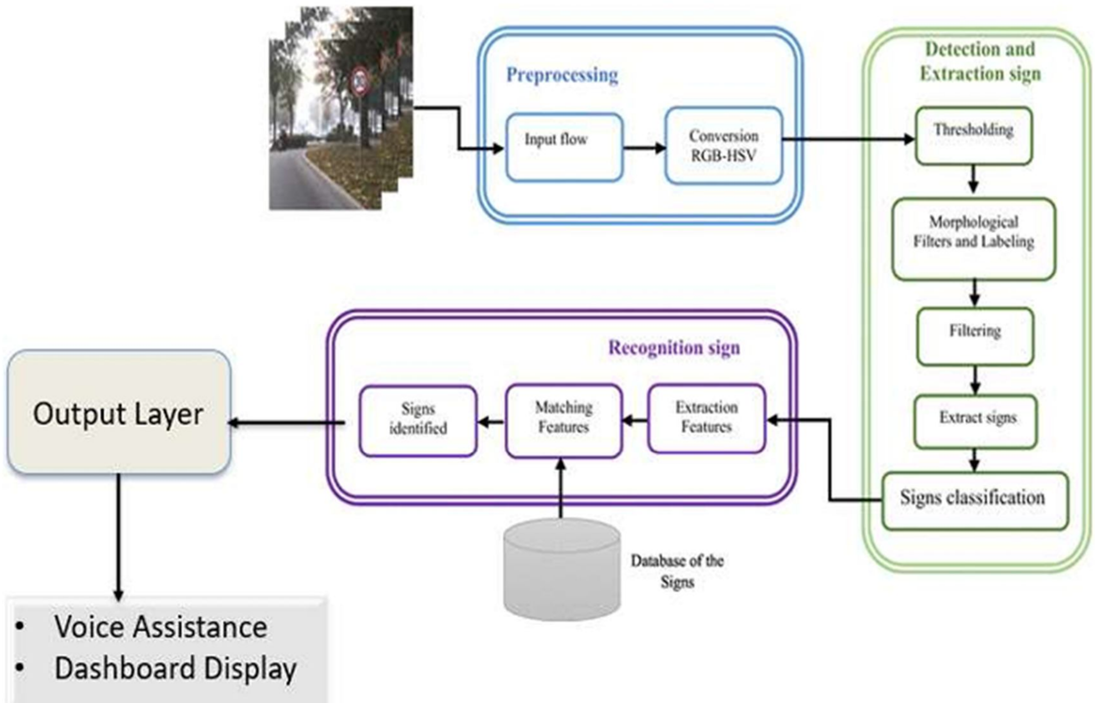

Fig. 1. Methodology of the Proposed System

IV. RESULT AND DISCUSSION

1) Experimental Results: The experimental results show that the proposed adaptive deep learning framework improves traffic sign detection accuracy under fog, rain, blur, and low-light conditions. The system achieved better real-time performance and robustness compared to traditional CNN models.
2) Dataset: The dataset used in this project consists of traffic sign images collected under both normal and harsh weather conditions such as fog, rain, blur, and low light. Data augmentation techniques were applied to create weather-affected variations, helping the deep learning model improve robustness and recognition accuracy.
3) Evaluation Metrics: The performance of the proposed model is evaluated using metrics such as accuracy, precision, recall, and F1-score. These metrics help measure the effectiveness and reliability of traffic sign detection under harsh weather conditions.\
4) Comparative Analysis: The comparative analysis shows that the proposed adaptive deep learning framework outperforms traditional CNN models in detecting traffic signs under harsh weather conditions. It achieves higher accuracy, better robustness, and improved real-time performance in fog, rain, blur, and low-light environments.
5) Quantitative Results: The quantitative results indicate that the proposed model achieved higher accuracy, precision, recall, and F1-score compared to existing traffic sign recognition methods. The framework also showed improved detection performance and reduced error rates under adverse weather conditions..
6) Qualitative Analysis: The qualitative analysis shows that the proposed framework can effectively detect and recognize traffic signs even in foggy, rainy, blurred, and low-light conditions. Visual results demonstrate improved clarity, robustness, and reliable real-time performance compared to traditional methods.
7) Confusion Matrix Analysis: The confusion matrix analysis shows that the proposed model correctly classified most traffic sign categories with fewer misclassifications under harsh weather conditions. The results indicate improved recognition accuracy and better class-wise performance compared to traditional models.

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8) Processing Performance: The processing performance results show that the proposed framework achieves fast and efficient real-time traffic sign detection with low processing delay. The system maintains stable performance and accuracy even under harsh weather conditions.

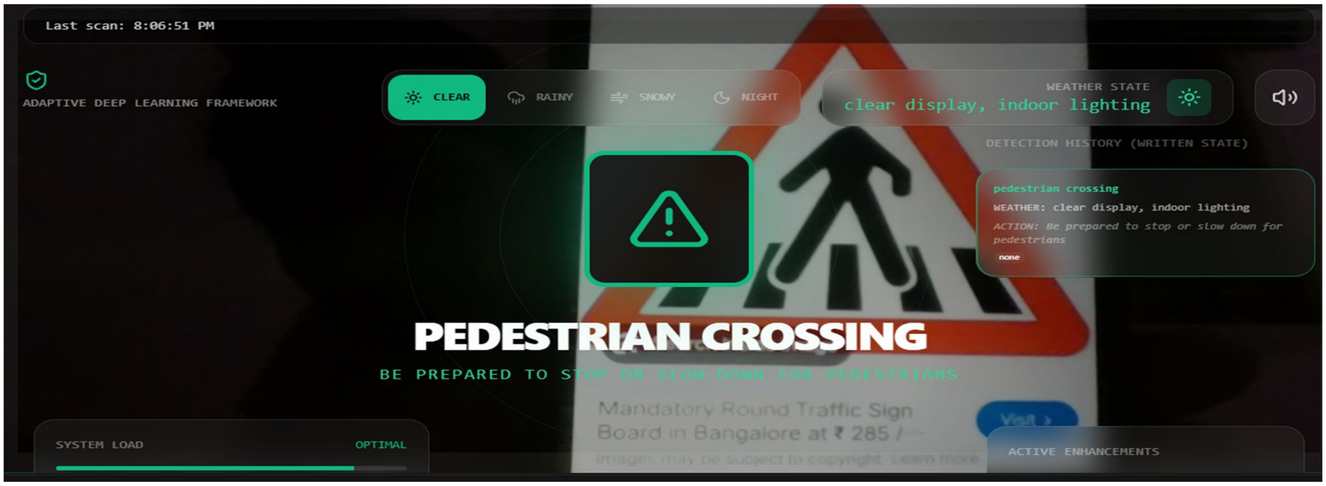

Fig. 2. Results and Performance Analysis

V. CONCLUSION

In conclusion, the proposed Adaptive Deep Learning Framework for Traffic Sign Recognition successfully improves the detection and classification of traffic signs under harsh weather conditions such as fog, rain, blur, and low illumination. By integrating deep learning techniques, image preprocessing, and weather-specific data augmentation, the system achieves higher accuracy, robustness, and real-time performance compared to traditional methods. The experimental results demonstrate the framework's ability to maintain reliable recognition even in challenging environments, making it suitable for Advanced Driver-Assistance Systems (ADAS) and autonomous vehicles. Overall, this project contributes toward enhancing road safety and intelligent transportation systems through adaptive and efficient traffic sign recognition.

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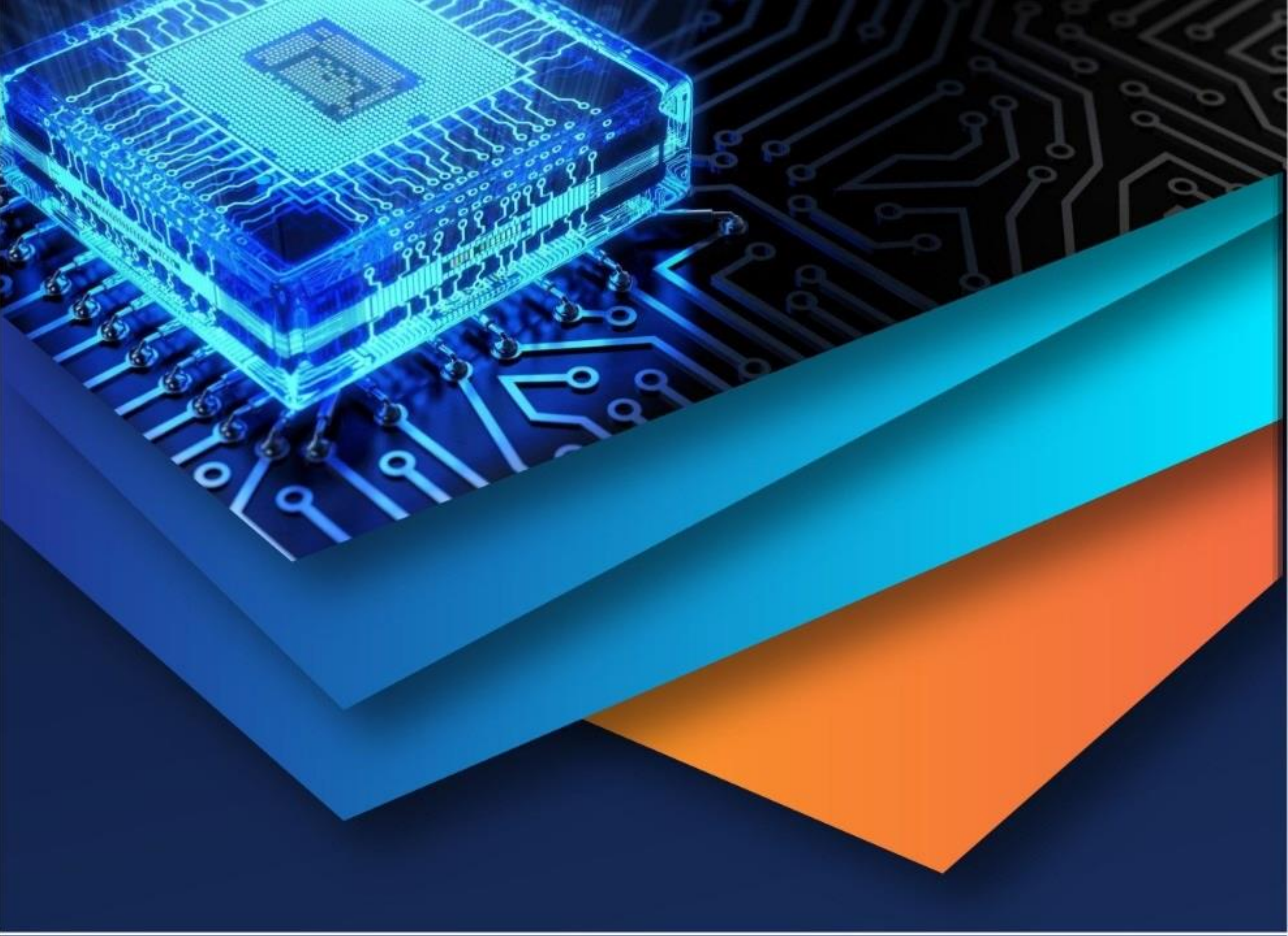

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