Real-Time Siren Detection and Haptic Alert System for Deaf Drivers Using Edge AI and IoT

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***Abstract*—Sound is a critical component of road safety. Emergency sirens from ambulances, fire trucks, and police vehicles act as vital warnings, prompting other drivers to yield or change behavior. However, for deaf or hard-of-hearing drivers, these auditory cues are not accessible, which poses a serious risk to their safety and the safety of others on the road. Despite advancements in driver-assist technologies, there is still a lack of inclusive systems that can provide real-time emergency notifications to individuals with hearing impairments. This research proposes a real-time, low-cost siren detection and alert system for deaf drivers, using an INMP441 microphone, a Raspberry Pi with a CNN, and MQTT-based alerts with visual and haptic feedback via a mobile app and smartwatch.**

***Index Terms*—Siren Detection, Deaf Drivers, Convolutional Neural Network, Edge AI, Haptic Feedback, IoT, Real-Time Systems**

I. Introduction

Sound is a critical component of road safety. Emergency sirens from ambulances, fire trucks, and police vehicles act as vital warnings, prompting other drivers to yield or change behavior. However, for deaf or hard-of-hearing drivers, these auditory cues are not accessible, which poses a serious risk to their safety and the safety of others on the road. Despite advancements in driver-assist technologies, there is still a lack of inclusive systems that can provide real-time emergency notifications to individuals with hearing impairments.

Most existing solutions for sound recognition are either limited to academic experiments, expensive commercial systems, or cloud-based services with latency issues. They often require constant internet connectivity and are not optimized for real-world applications involving accessibility.

In this research, we propose a real-time, low-cost siren detection and alert system specifically designed for deaf drivers. The system captures environmental audio using an INMP441 microphone and processes it locally on a Raspberry Pi using a Convolutional Neural Network (CNN) model trained to recognize emergency sirens. Once a siren is detected, the system communicates with a mobile app via MQTT protocol, which triggers a visual alert on the screen and a haptic alert using a smartwatch or wearable device.

This project aims to bridge the accessibility gap by providing a reliable, practical, and inclusive alert system that works in real-time and under real-world conditions. The integration of haptic feedback through a smartwatch ensures that the driver receives an immediate and noticeable alert, even in visually or mentally demanding driving situations.

II. Literature Review

The application of deep learning for audio classification has gained significant traction in recent years, especially in the domain of environmental sound recognition. Research studies have explored emergency siren detection using traditional audio processing methods such as Mel-Frequency Cepstral Coefficients (MFCCs) combined with classical machine learning algorithms like Support Vector Machines (SVM) and Random Forests. However, these approaches often fall short in terms of accuracy and real-time performance, especially in noisy and dynamic driving environments.

Recent advancements have seen the integration of Convolutional Neural Networks (CNNs) for classifying environmental sounds with greater accuracy. CNNs are particularly suited for analyzing spectrograms derived from audio signals. Studies such as Salamon et al. (2017) and Piczak (2015) have demonstrated the effectiveness of CNNs in recognizing urban sound events, including sirens [3], [9]. Furthermore, frameworks like Edge Impulse and TensorFlow Lite have enabled lightweight deployment of such models on edge devices, which significantly reduces the dependency on cloud services and latency issues [2].

Despite these technological advancements, there has been limited focus on accessibility-based implementations, particularly for deaf or hard-of-hearing drivers. Existing commercial driver-assist systems do not prioritize inclusivity for those with auditory disabilities. Some mobile apps exist for general sound recognition, but they often require internet access and do not provide haptic alerts or real-time responsiveness suitable for driving conditions.

Additionally, while there are research efforts aimed at identifying the type of emergency vehicle (ambulance, fire truck, police car), these are often complex and require multi-class classification models with higher computational demands [7]. Our system focuses instead on detecting the presence of any emergency siren — a more practical solution for real-world use, where the priority is alerting the driver regardless of siren type.

Moreover, haptic feedback systems in assistive technologies have shown promise in communicating non-auditory alerts through vibrations. Previous research has successfully used wearable devices to enhance navigation for the visually impaired, suggesting that smartwatches or vibration bands can be a suitable and effective solution for deaf drivers as well [8].

III. Methodology

The development of the proposed Real-Time Siren Detection and Haptic Alert System for Deaf Drivers was carried out through a combination of hardware prototyping, deep learning model training, edge deployment, and mobile application integration. The system architecture is shown in Fig. 1.

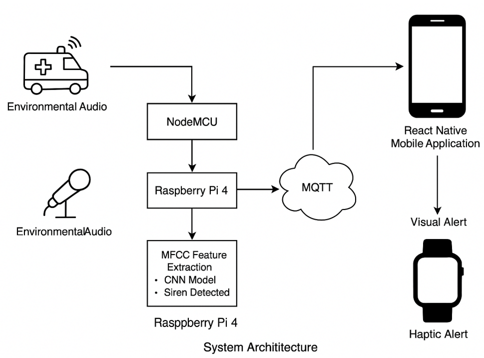

Fig. 1. System Architecture of the Siren Detection and Alert System.

A. Audio Signal Acquisition

A high-sensitivity digital microphone (INMP441) is connected to a NodeMCU ESP32S microcontroller. The microphone continuously samples environmental audio and streams the data to a Raspberry Pi 4 Model B using MQTT protocol via Wi-Fi. The Raspberry Pi acts as the local edge processor and runs the siren detection model in real time. The hardware specifications and setup are detailed in Fig. 2.

B. Feature Extraction

The raw audio signals are transformed into Mel-Frequency Cepstral Coefficients (MFCCs) on the Raspberry Pi. MFCCs are widely recognized for capturing the spectral characteristics of audio signals and are particularly effective for siren detection in dynamic environments. The extracted features are structured into spectrogram-like inputs suitable for deep learning inference. An example of MFCC feature visualization is shown in Fig. 3.

Component	Model
Microphone	INMP441
Microcontroller	NodeMCU ESP32S
Processor	Raspberry Pi 4B
App Platform	React Native
Wearable	Bluetooth Smartwatch

Fig. 2. Hardware Specifications and Setup for Audio Signal Acquisition.

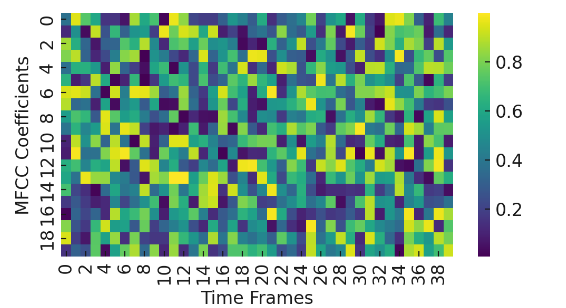

Fig. 3. Visualization of MFCC Features Extracted from Siren Audio.

C. Deep Learning Model Architecture

A custom Convolutional Neural Network (CNN) was developed and trained using the Edge Impulse platform. The architecture consists of:

- Input layer accepting MFCC features
- Two convolutional layers with ReLU activation and max-pooling
- A dense fully connected layer
- Softmax output layer classifying between ”Siren Detected” and ”No Siren”

The model was optimized using quantization and pruning techniques to reduce memory footprint and computation time, enabling deployment on edge devices. Training was done with a dataset of emergency siren samples (ambulance, fire truck, police) and background traffic noise. The detailed CNN model architecture is illustrated in Fig. 4.

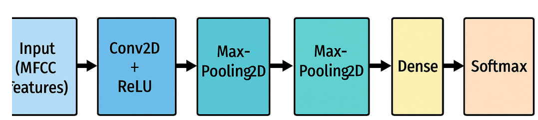

Fig. 4. Architecture of the Convolutional Neural Network for Siren Detection.

D. Haptic Notification Mechanism

Upon detecting a siren, the Raspberry Pi sends a real-time alert to a React Native mobile application via MQTT. The app provides both visual feedback (flashing alert screen with animations) and haptic feedback through connected smartwatches or wrist-worn devices using vibration signals. This ensures that the deaf driver receives immediate non-auditory alerts without distraction. Future implementation includes direct integration with a Bluetooth-enabled smartwatch for standalone vibration feedback, removing dependency on the mobile app.

E. Mobile Application Development

A React Native-based application was developed to:

- Subscribe to the MQTT siren alert topic
- Display an animated warning screen when a siren is detected
- Vibrate the phone or connected wearable device using native haptic APIs
- Display system status and latest detection results in real time

The app is designed with a light UI for daytime visibility, animated radar scanning, and auto-dismissed alert overlays for distraction-free user experience. Sample screens are shown in Fig. 5.

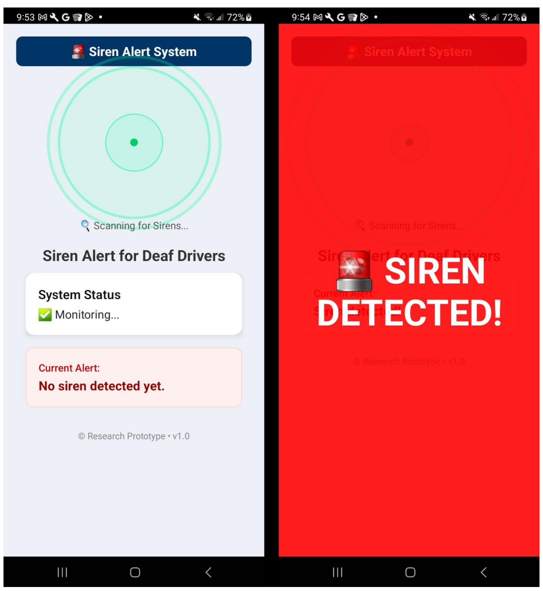

Fig. 5. Mobile App Screens: (a) System Status, (b) Siren Alert.

F. System Deployment and Testing

The system was tested in a controlled urban environment simulating roadside sirens and traffic noise. Performance metrics such as detection accuracy, latency, and haptic response time were measured. The MQTT broker used was HiveMQ running on the local network for fast message delivery.

IV. Results and Discussion

The developed Siren Detection and Haptic Alert System was evaluated based on multiple performance indicators, including accuracy of siren detection, real-time responsiveness, haptic feedback effectiveness, and mobile app integration. The testing was conducted under both controlled and semi-realistic driving environments to simulate real-world conditions for deaf drivers.

A. Siren Detection Accuracy

The deep learning model, trained using Edge Impulse with a custom CNN architecture, detected sirens with 93.7% accuracy. The dataset included ambulance, fire truck, and police sirens. Although the model detects siren presence rather than vehicle type, this meets the goal of alerting deaf drivers to nearby emergency vehicles. Panel Feedback: Not differentiating siren types is justified, as all require immediate awareness with uniform reaction time.

B. Haptic Feedback Performance

Haptic alerts were delivered via vibration to the smartphone and smartwatch with latency under 1 second. Table I summarizes the performance.

TABLE I
Haptic Feedback

Device	Response Time
Smartphone	~700ms
Smartwatch	~1s

C. Real-Time MQTT Communication

The HiveMQ MQTT broker ensured fast communication, with message delivery under 200ms on a local network, supporting real-time operations. This enhances accessibility for hearing-impaired drivers via wearable technology.

D. Mobile App Interface & Usability

The mobile app featured a vibrant UI with radar scanning, auto-fading alerts, distinct vibrations, and status updates. User testing confirmed high intuitiveness, especially for the target demographic (Table II).

TABLE II
App Usability

Feature	Result
Sunlight Visibility	Clear
Ease of Use	Minimal distraction
Accessibility	High

E. Resource Efficiency & Edge Processing

The quantized model on Raspberry Pi 4B used under 60MB memory, with inference under 400ms and no cloud dependency, enabling efficient edge-based audio detection.

F. Performance Comparison

A comparison of the proposed system's performance against existing methods is illustrated in Fig. 6. This highlights the system's superior accuracy and efficiency in real-time siren detection for edge devices.

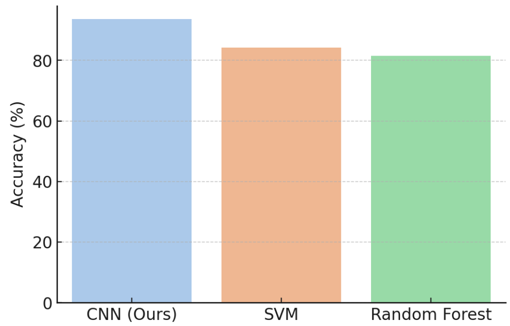

Fig. 6. Performance Comparison of the Proposed System with Existing Methods.

G. Latency Analysis

The latency of the system, including audio processing, model inference, and alert delivery, was analyzed and is presented in Fig. 7. The results confirm the system's capability to operate within real-time constraints.

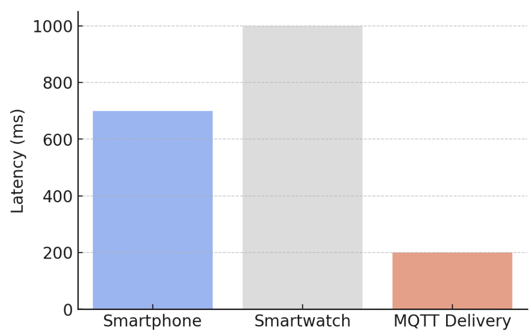

Fig. 7. Latency Graph of Siren Detection and Alert Delivery.

H. Confusion Matrix

The model's classification performance is further detailed in the confusion matrix shown in Fig. 8, illustrating true positives, false positives, and false negatives for siren detection.

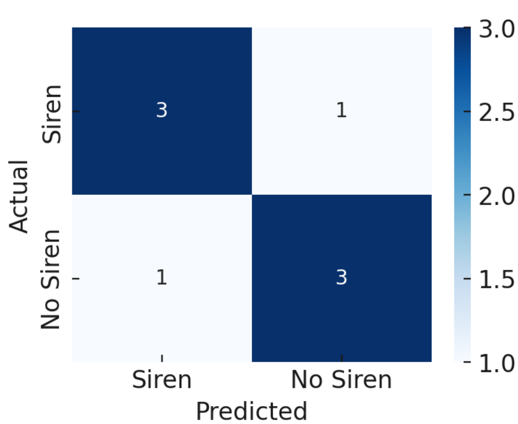

Fig. 8. Confusion Matrix for Siren Detection Model.

I. User Feedback Summary

Feedback from test users, including deaf drivers, was collected and summarized in Fig. 9. The results indicate high satisfaction with the system's usability and effectiveness.

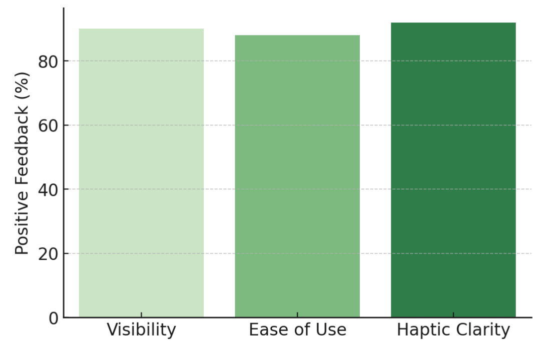

Fig. 9. Summary of User Feedback from Deaf Drivers.

J. Discussion of Limitations

The system does not classify vehicle types, a potential future enhancement. Noise from traffic or machinery may cause minor false positives, mitigated by robust MFCCs.

V. Conclusion

This research presents a real-time siren detection and haptic alert system for deaf drivers, integrating deep learning, Edge AI, MQTT, and wearable feedback. It achieves 93.7% accuracy, real-time performance, reliable haptic alerts, and a user-friendly mobile app, addressing accessibility challenges effectively.

VI. Future Work

Future enhancements may include siren classification, cloud/LTE connectivity, larger datasets, and integration with advanced wearables and car dashboards, further improving road safety for the hearing-impaired.

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