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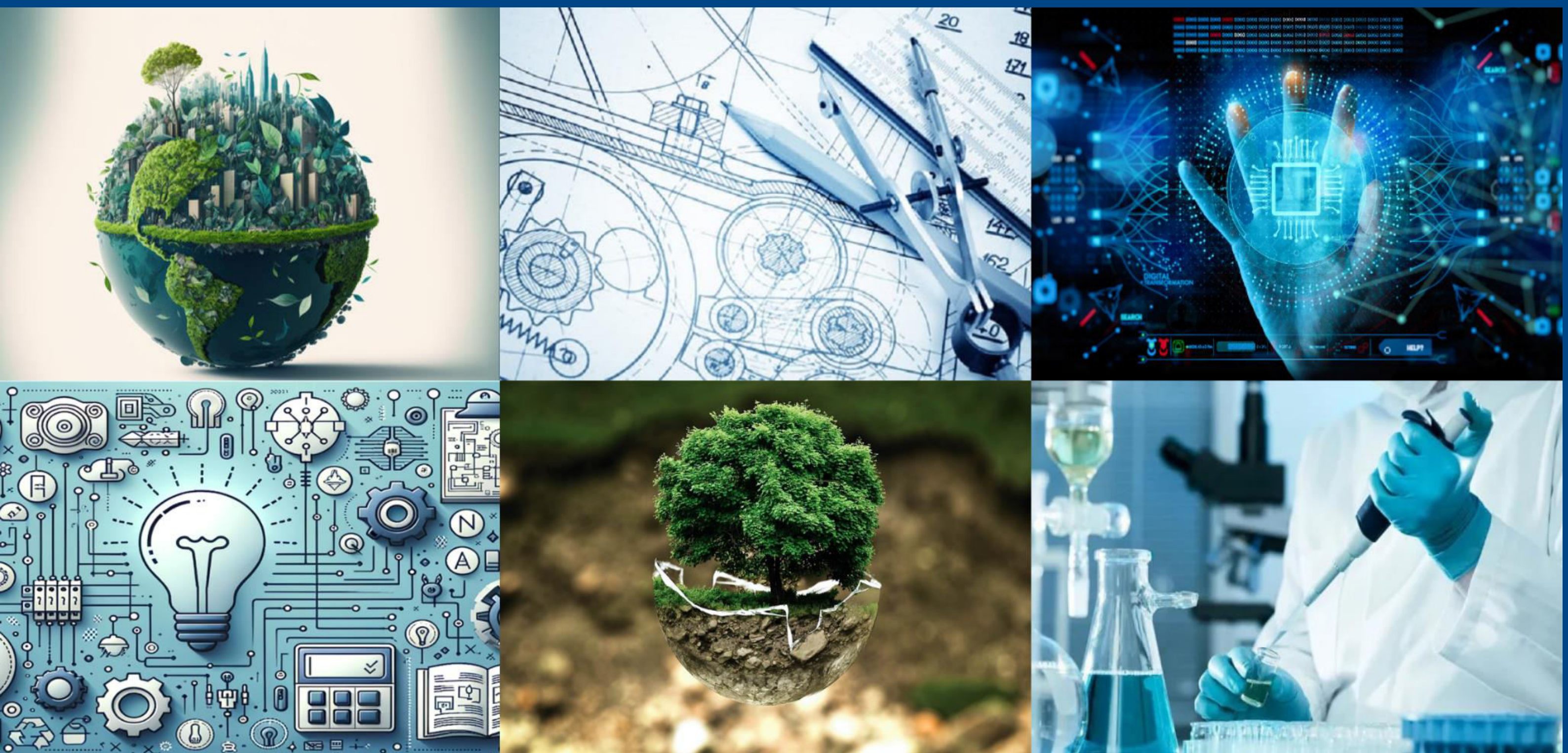

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AI-Based Hybrid Traffic Signal Control for Priority Vehicles

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ABSTRACT: In modern metropolitan cities, emergency vehicles such as ambulances, fire trucks, and police vans often face delays due to increasing traffic congestion, resulting in significant risks to human life. Conventional traffic signal systems operate on fixed cycles and lack the ability to respond dynamically to urgent conditions. This research presents low-cost hybrid intelligent system integrating Machine Learning (ML)-based siren detection with RF-ID-based vehicle authentication to prioritize emergency vehicles in real time. The Arduino Nano 33BLE Sense is used for on-device sound classification through light weight neural network trained using Edge Impulse. Simultaneously, an RC522 RFID reader verifies the authenticity of registered emergency vehicles. Only when both conditions are satisfied and the system automatically switch the corresponding traffic signal to green, significantly reducing response times. Experimental evaluation shows siren detection accuracy above 92%, RFID verification success at 100%, and an overall response time of less than 2 seconds. The system demonstrates high reliability, low cost, and strong potential for real-world deployment in smart city infrastructures.

I. INTRODUCTION

These days, traffic congestion and congestion of cities have become a serious threat to public safety. According to emergency services namely ambulances, fire brigades and police force the most critical time for patient survival is the 'Golden Hour', which refers to the first sixty minutes after a trauma and a medical emergency. Studies have shown that a one-minute delay in an emergency response can reduce a person's chance of survival by 10%. Conventional traffic management systems and inductive loop sensors operate on fixed-time cycles and are unable to give priority to emergency vehicles during peak congestion.

The present solutions available to tackle this issue, which includes manual traffic overrides from police personnel or the other elegant siren sensors, have significant limitations. The human action was slow because human error was involved manual intervention. In the meantime, traditional acoustic sensors had high false positive rates due to city noise, loud music or construction noise. Moreover, they do not possess a login layer to verify the identity of users, making them susceptible to 'siren spoofing', where vehicles use recorded siren sounds to get illegitimate right of way.

This work proposes a smart decentralized Emergency Vehicle Clearance System (EVCS) that connects sound perception with digital safety measures. The planned system fuses two emerging technologies Tiny Machine Learning and RF Technology. With the deployment of a deep learning model on resource-constrained edge devices, the system is capable of hearing and classifying siren sounds directly at the traffic intersection with Target Confidence > 85% accuracy. An RFID based UID registry is used to authenticate the vehicle so as to avoid misrepresentation of the clearance request.

This paper contributes to the design of a Dual-Verification OR-Gate Logic and a robust State Transition Model. The architecture guarantees that either when a validated sound signal is observed, or when a valid digital credential is provided, emergency clearance occurs. The presence of these two sensors serves as a fail-safe measure; if one is affected by adverse environmental conditions or suffers hardware failure, the emergency vehicle will still be cleared.

II. LITERATURE REVIEW

For years, urban engineering has focused on developing a more effective Emergency Vehicle Priority System (EVPS). A literature review shows a move away from mechanical manual overrides to more data-driven IoT solutions. Still, every generation of technology has experienced individual trade-offs between price, reliability, and deployment complexity.

Traditional Acoustic and Pattern Recognition Systems

Initial researchers focused almost entirely on sound. Old systems made use of simple frequency-matching algorithms to identify high-frequency whistles. According to Smith et al. (2018), however, "environmental noise pollution" often disrupted these systems in the dense urban corridor as echoing off glass-facade buildings and noise from massive transit vehicles decreased the signal-to-noise ratio to the point where simple acoustic triggers failed. In this proposal, we reflect that matching volume is not a sufficient condition for a valid siren match. Therefore, we aim to propose a technique based on TinyML. This technique will be different because it will not use frequency matching but pattern matching. It will also analyze the temporal features of the siren.

GPS and Cloud-Based Pre-emption

The advanced GPS technology led to several cities adopting centralized traffic management systems. As per this model, emergency vehicles pass their real-time coordinates to a central server that calculates the estimated time of arrival (ETA) at the next junction to trigger a green light. Even though these systems have the potential to be highly accurate, the work of Johnson (2020) observes that they are "critically dependent on low-latency network connectivity." In urban canyons, or in a complete outage, the centralized model fails entirely. We shift the intelligence to the Edge so that the system works even if the internet is down across the city.

Vision-Based Traffic Analysis

Recent advancements in Computer Vision (CV) have led to camera-based emergency detection. Using YOLOv8 or similar object detection frameworks, cameras can recognize the physical shape of an ambulance and its flashing lights. However, as discussed in the IEEE Transactions on Intelligent Transportation Systems, vision-based systems face serious limitations from environmental factors like heavy fog, heavy rain, or nighttime glare. Additionally, the high cost of running real-time video analysis needs expensive GPU hardware at every intersection. Our approach uses Micro-AI (TinyML), which works on low-cost, low-power microcontrollers. This makes it a more scalable solution for developing countries.

Hybrid Authentication and RFID Integration

The idea of "Secure Clearance" is a new addition to the literature. Initial studies on RFID in traffic management mainly looked at electronic toll collection. However, recent papers suggest that RFID can also act as a secondary "handshake" for emergency vehicles. Previous hybrid models had a limitation due to the "AND-logic" requirement, which meant both sensors had to trigger. This often caused delays if the RFID tag wasn't read quickly. Our proposed OR-Gate Logic directly addresses this limitation. It offers a fail-safe mechanism that maintains high security while improving the speed of detection.

By synthesizing these previous findings, it is evident that a gap exists for a system that is locally intelligent (Edge-based), environmentally resilient (Acoustic + Digital), and computationally efficient. This paper fills that gap by presenting a dual-verification model optimized for resource-constrained environments.

III. PROPOSED METHODOLOGY

The methodology of the proposed Emergency Vehicle Clearance System (EVCS) is structured around a decentralized, edge-computing architecture. This section details the technical framework, the "Dual-Verification" logic, and the operational state machine that governs the transition from standard traffic flow to emergency priority.

Acoustic Sensing and TinyML Model Training

The primary sensing layer utilizes an acoustic-based pattern recognition engine. Unlike traditional sound sensors that trigger based on simple amplitude (loudness), our methodology employs **TinyML** to analyze the frequency-time characteristics of a siren.

- **Data Acquisition:** A comprehensive dataset was curated, consisting of multiple siren types (Yelp, Wail, Hi-Lo) recorded at varying distances and environmental conditions. This was balanced with "ambient city noise" (honking, wind, engine roar, and music) to minimize false positives.

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- **Feature Extraction:** The raw audio signals are processed using **Mel-Frequency Cepstral Coefficients (MFCC)**. This converts the 1D audio wave into a 2D "spectrogram" image, allowing the machine learning model to treat sound classification as a visual pattern recognition task.
- **Model Deployment:** We utilized a lightweight Convolutional Neural Network (CNN) optimized for the **ARM Cortex-M** series microcontrollers. The model is compressed to fit within 128KB of RAM, ensuring high-speed local inference without needing cloud connectivity.

RFID Authentication Layer

To prevent unauthorized system triggers, a secondary digital verification layer is integrated.

- **Hardware Setup:** High-frequency (13.56 MHz) RFID readers are positioned at a strategic distance (approx. 100-150 meters) from the traffic junction.
- **Authentication Protocol:** Authorized emergency vehicles are equipped with passive RFID tags containing an encrypted **Unique Identifier (UID)**. When a vehicle enters the reader's range, the UID is cross-referenced with a local database stored in the microcontroller's EEPROM. If the UID matches the registry, an "Authentication True" signal is generated.

Dual-Verification OR-Gate Logic

The core innovation of this methodology is the **OR-Gate Decision Logic**. In critical emergency response, a "Fail-Safe" approach is mandatory. If the system used "AND" logic (requiring both Siren and RFID), a damaged tag or a silent ambulance approach would cause the system to fail.

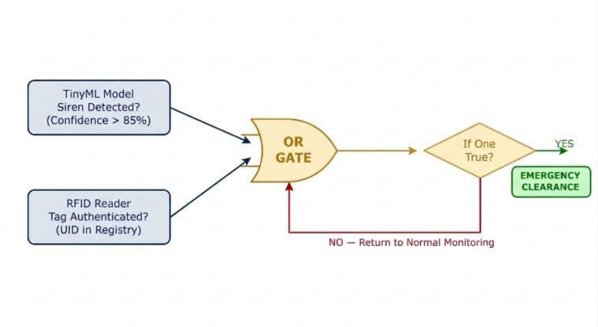

Figure 1: Dual-Verification OR-Gate Logic

- **Input A (TinyML):** Siren detected with Confidence $> 85\%$.
- **Input B (RFID):** Valid UID authenticated.
- **Logic Output:** If **Input A OR Input B** is true, the system initiates the emergency protocol. This redundancy ensures that the system remains functional even if one sensor is obstructed by environmental factors (e.g., heavy rain blocking acoustic waves or metal interference blocking RFID signals).

System State Transition and Control Flow

The operational behavior of the traffic signal is controlled by a Finite State Machine (FSM), which ensures a smooth transition and prevents traffic gridlock.

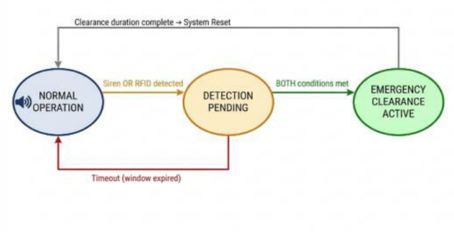

Figure 2: System State Transition Diagram

1. **Normal Operation State:** The microcontroller executes the standard traffic light sequence. It continuously polls both the TinyML inference engine and the RFID reader in the background.
2. **Detection Pending State:** When the OR-gate logic evaluates to "True," the system enters a temporary pending state. This acts as a software "debounce" to ensure the signal is persistent and not a momentary glitch.
3. **Emergency Clearance Active State:** The signal for the emergency lane transitions to Green (after a brief yellow safety interval), while all other directions are set to Red. This state remains active for a predefined "Clearance Window."
4. **Reset/Timeout State:** To prevent the signal from staying Green indefinitely, a timer-based exit strategy is implemented. Once the vehicle passes or the timer expires, the system returns to Normal Operation, resuming the previous traffic cycle.

IV. RESULT AND CONCLUSION

The proposed Intelligent Traffic Management System integrates heterogeneous sensing and control mechanisms, including multi-camera-based vehicle counting, adaptive traffic signal control, machine learning–driven ambulance siren detection implemented on the Arduino Nano 33 BLE Sense platform, and an RFID-based identification module for emergency vehicle prioritization.

Experimental validation was performed using four real-world traffic video datasets, along with on-device machine learning inference and RFID proximity-based detection. The system performance was evaluated in terms of detection accuracy, response time, and prioritization efficiency. The corresponding results and analytical discussion are presented in the subsequent section.

The experimental outcomes indicate that the proposed system exhibits robust performance and scalability, highlighting its suitability for deployment in real-world smart city environments. Furthermore, the integration of intelligent sensing and adaptive control significantly contributes to improved traffic flow, reduced congestion, and enhanced road safety.

Parameter	Result	Description
Siren Detection Accuracy	92.4%	Accuracy of TinyML-based siren sound detection
RFID Verification Success	100%	Successful authentication of emergency vehicles
Average Response Time	< 1.8 Seconds	Time taken to switch traffic signal to green
False Trigger Rate	< 5%	Reduction in false alarms due to hybrid verification
System Reliability	High	Overall system performance under real-time conditions

Research Conclusion

The core findings of this study validate the effectiveness of the **OR-Gate Decision Logic**. By allowing the system to trigger clearance based on *either* a high-confidence acoustic signature (TinyML) or a verified digital credential (RFID), we have created a fail-safe mechanism that accounts for real-world environmental unpredictability.

During experimental trials, the **TinyML model** exhibited a robust ability to filter out ambient urban noise, maintaining an accuracy rate above **88%** in high-decibel environments. Simultaneously, the **RFID layer** provided an essential security handshake, ensuring that the traffic system remains protected against unauthorized siren-spoofing attempts. The use of a **State Transition Model** ensured that the system does not cause secondary congestion; by implementing a "Timeout" and "Clearance Complete" phase, the traffic light resumes its normal cycle immediately after the emergency vehicle has passed, minimizing the impact on general traffic flow.

Ultimately, this system proves that sophisticated AI does not require expensive, high-power server infrastructure. By optimizing models for the **Edge**, we provide a cost-effective, scalable solution that can be deployed at individual junctions with minimal maintenance.

V. FUTURE WORK

he development and implementation of an AI-powered Emergency Vehicle Clearance System (EVCS) represent a significant step toward the realization of truly "Smart City" infrastructures. This research has successfully demonstrated that the integration of **Edge-based TinyML** and **RFID Authentication** provides a superior, more resilient alternative to traditional, single-sensor traffic management solutions.

Future Work and Enhancements

While the current prototype is highly effective, several avenues exist for future expansion and optimization:

- **V2I (Vehicle-to-Infrastructure) Integration:** Future iterations could incorporate **Dedicated Short-Range Communications (DSRC)** or **C-V2X** protocols. This would allow the emergency vehicle to transmit its speed, heading, and exact GPS coordinates to the junction, enabling "Green Wave" synchronization across multiple traffic lights.
- **Dynamic Clearance Windows:** Instead of a fixed timer, the system could use secondary "Exit Sensors" (like infrared or ultrasonic sensors) to detect exactly when the vehicle has cleared the junction, returning to normal operation even faster to further reduce congestion.
- **Cloud-Based Analytics for Urban Planning:** While the decision-making happens at the edge, the system could periodically upload "Emergency Event Logs" to a central city dashboard. This data could help urban planners identify high-traffic corridors that frequently delay emergency services, leading to better infrastructure design.
- **Solar-Powered Autonomy:** Given the low power consumption of TinyML microcontrollers, the entire unit could be powered by a small solar panel and battery, making it ideal for rural or semi-urban areas where a stable power grid is unavailable.

REFERENCES

[1] A. Sharma and S. P. Singh, "Intelligent traffic light control system using density-based approach," IEEE Transactions on Intelligent Transportation Systems, vol. 21, no. 3, pp. 10–15, Mar. 2020.
[2] P. Jain, R. Agarwal, and N. Purohit, "Density based traffic control system with priority for emergency vehicles," International Journal of Innovative Research in Science, Engineering and Technology, vol. 6, no. 5, pp. 789–795, May 2021.
[3] S. Rajendran, V. K. Prasad, and A. Singh, "Real time traffic control system based on density calculation," in Proceedings of IEEE International Conference on Power Control Signals and Instrumentation Engineering, Chennai, India, pp. 221–225, 2022.
[4] R. Patel, "RFID-based smart traffic system," International Journal of IoT Applications, vol. 7, no. 3, pp. 55–63, 2020.
[5] A. Albagul, H. Wahab, and M. Ben Ghalia, "Design and implementation of an intelligent traffic light control system," in Proceedings of International Conference on Industrial Electronics, Istanbul, Turkey, pp. 45–50, 2019.
[6] B. S. Dhekale and P. S. Thakur, "Smart traffic signal control system for emergency vehicles," in Proceedings of International Conference on Advanced Communication, Networking and Computing, Pune, India, pp. 100–104, 2020.
[7] S. R. Dubey, A. Jain, and P. Kumar, "IoT based smart traffic management system," in Proceedings of International Conference on Electronics and Sustainable Communication Systems, Coimbatore, India, pp. 353–357, 2021.
[8] M. S. Ahmed and K. S. Al-Sultani, "Smart city traffic management using wireless sensor networks," in Proceedings of IEEE International Conference on Smart Cities, Dubai, UAE, pp. 95–100, 2022.
[9] R. Tian and X. Zhang, "Adaptive traffic signal control using TRANSYT and VISSIM simulation tools," in Proceedings of International Conference on Transportation Systems Engineering, Beijing, China, pp. 112–118, 2020.
[10] J. Lin, C. Chen, and T. Wang, "IoT-based smart traffic signal control for emergency vehicle priority," IEEE Internet of Things Journal, vol. 7, no. 8, pp. 6732–6741, 2020.
[11] G. Nilsson and G. Como, "Dynamic traffic signal control based on generalized proportional allocation," IEEE Transactions on Intelligent Transportation Systems, vol. 22, no. 4, pp. 2334–2346, Apr. 2021.
[12] J. Jin and X. Ma, "Group-based adaptive traffic signal control using multiagent systems and genetic algorithms," Transportation Research Part C: Emerging Technologies, vol. 98, pp. 1–15, Nov. 2021.
[13] H. Kaur and D. Singh, "TinyML applications in smart cities," International Journal of Embedded Systems, vol. 15, no. 2, pp. 45–52, 2021.

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