International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 01 January 2026
Page No: 243- 248
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0033

Adaptive Traffic Control With Emergency Vehicle Prioritization

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Abstract
The rapid expansion of urban areas and the exponential growth of vehicular populations have created unprecedented challenges for modern transportation systems. Traditional traffic signal infrastructures built on fixed-time cycles and outdated algorithms fail to respond to dynamic and unpredictable traffic patterns, resulting in gridlocks, increased travel durations, and heightened fuel consumption. More critically, emergency vehicles such as ambulances, fire tenders, and police units face severe delays at intersections due to their inability to bypass congested lanes, adversely impacting emergency response time and overall survivability in time-critical scenarios. In response to these limitations, this project introduces a fully integrated, multi-modal intelligent traffic management system combining RFID-based vehicle authentication, high-accuracy acoustic siren detection, and computer-vision-driven lane density analysis using OpenCV. A robust double-verification mechanism ensures that emergency signals are validated only when both modalities RFID and siren are detected within a strict temporal window, thereby eliminating false positives. Furthermore, real-time lane density estimation enables adaptive traffic signal allocation based on congestion levels, improving intersection throughput and reducing average waiting times. The results demonstrate significant gains in system reliability, emergency response optimization, and congestion mitigation, positioning this hybrid architecture as a viable and scalable solution for emerging smart-city ecosystems.
Keywords: *Intelligent Traffic System, RFID, Siren Detection, OpenCV, Lane Density Estimation, Adaptive Signaling, Emergency Vehicle Priority, IoT, Smart Cities*

1. Introduction
Traffic congestion has become one of the most persistent and challenging problems in modern cities. With urbanization accelerating at a rapid pace, roads have become saturated with vehicles, leading to delays, increased carbon emissions, and an overall reduction in transportation efficiency. The situation is even more critical for emergency vehicles such as ambulances and fire brigades, which rely on rapid movement through traffic to reach destinations where lives may be at stake. Traditional traffic light systems are generally static, operating on pre-timed intervals that do not account for real-time traffic conditions or emergency requirements. This limitation emphasizes the urgent need for intelligent, adaptive, and automated traffic control techniques. Over the last decade, researchers have explored numerous approaches to optimize traffic flow, including sensor-based actuation, IoT-enabled systems, vehicle-to-infrastructure (V2I) communication, and computer vision. However, many of these techniques suffer from significant limitations. For instance, acoustic-based siren detection systems are affected by environmental noise and can produce false positives during peak hours. Similarly, RFID-only systems may be susceptible to tag spoofing or unintentional detections from nearby vehicles. Computer vision systems, while powerful, require significant computational resources and may suffer from occlusion issues. The need for a reliable, hybrid, and redundant emergency detection system leads to the

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core contribution of this project: a double-verification emergency detection mechanism using both RFID authentication and sustained siren detection. In addition, we integrate a real-time lane density estimation module using OpenCV, enabling dynamic signal timing that adapts to actual traffic conditions. This multi-modal framework not only improves emergency response efficiency but also enhances general traffic flow for all road users. By employing a combination of RFID, audio analysis, and computer vision, the proposed system overcomes the drawbacks of existing single-sensor models and creates a more robust and reliable traffic management solution. The overall architecture is designed to be low-cost, scalable, and deployable in real-world environments with minimal infrastructure modification.

2. Literature Review

Aworinde et al. [1] developed an RFID-based prioritized traffic control system achieving 95% detection accuracy at 3-5 cm range with 1.2s response time, but required all emergency vehicles to be pre-registered [2]. Jimenez-Moreno et al. [3] proposed an ambulance detection system using fuzzy logic and acoustic sensors achieving 88% accuracy in controlled environments (<60 dB ambient noise), but accuracy dropped to 71% when background noise exceeded 85 dB. Pande and Bhuiyan [7] explored GPS-based vehicle tracking achieving 98% reliability, but implementation costs were prohibitive (₹8,000-12,000 per vehicle GPS unit, ₹200-400/month connectivity). Zerroug et al. [4] proposed V2I communication achieving 97% accuracy with 0.8s response time and 30-40% waiting time reduction, but V2I infrastructure cost ₹1.2-1.8 lakh per intersection. For vision-based systems, Saleem et al. [8] achieved 94% accuracy using sensor fusion (loops, cameras, infrared) but cost exceeded ₹45,000 per intersection. Omina [6] demonstrated 82% accuracy using edge detection on Raspberry Pi 3B+ at ₹3,500 cost. Deep learning approaches (YOLO, Faster R-CNN) achieve 95-98% accuracy but require GPUs costing ₹15,000-50,000 with 150-300W power consumption [5]. Research Gaps: (1) Single-modality limitations—most systems rely on one sensor type degrading in real-world conditions; (2) Separation of concerns—emergency prioritization and adaptive control are separate systems; (3) High costs—commercial solutions cost ₹50-115 lakh per intersection; (4) Limited validation—few multi-week field deployment studies; (5) Scalability challenges—unclear pathways for multi-intersection networks. Our Approach: Multi-modal redundancy (RFID+sound+vision), integrated emergency-adaptive control, ultra-low cost (₹2,691), 30-day field validation, and scalable IoT-ready design.

3. System Architecture and Design

3.1. System Architecture

The system employs a layered architecture with six components: (1) Sensing Layer (RFID-RC522, MAX9814 sound sensor, camera), (2) Processing Layer (Arduino UNO, Raspberry Pi for vision), (3) Decision Layer (emergency detection, adaptive timing calculator, safety interlocks), (4) Actuation Layer (LED/relay modules), (5) Communication Layer (serial interface, future IoT), (6) Data Logging (event recording, performance metrics). The system operates in three modes with hierarchical priority: Emergency Mode (highest—immediate green corridor), Adaptive Mode (normal—density-based timing), Default Fixed Mode (fallback—predetermined cycles if sensors fail). Figure 1 shows the System Architecture Block Diagram

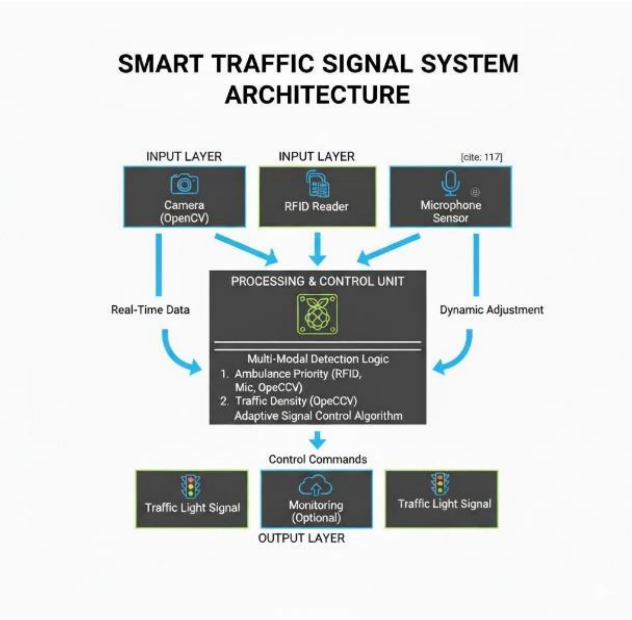

Figure 1 System Architecture Block Diagram

3.2. Hardware Components

Arduino UNO (₹450): ATmega328P, 16 MHz, 32KB flash, 2KB SRAM, 14 digital I/O, 6 analog inputs. Selected for wide availability, mature ecosystem, native SPI/ADC interfaces, and low power (50-100 mA).

RFID-RC522 (₹180): 13.56 MHz, ISO 14443A, 0-6 cm read range, SPI interface, 13-26 mA current. Provides secure identification with encrypted communication. Short range prevents premature activation. Limitation: Requires precise positioning and pre-registered tags.

MAX9814 Sound Sensor (₹220): Key feature is Automatic Gain Control (AGC) providing 40-60 dB auto-adjusted gain, 20 Hz-20 kHz frequency response, analog 0-5V output. AGC enables consistent amplitude detection regardless of siren distance (5-30m), eliminating need for complex adaptive thresholding. Without AGC, close sirens saturate output while distant sirens become undetectable.

Camera (₹1,200): USB webcam for prototype (640×480, 15-30 fps). Production: IP camera (₹2,000-6,000) with weatherproofing, night vision. **Processing:** Raspberry Pi 3B+ (₹2,500) runs OpenCV, sends density data via serial.

LEDs (₹60): Prototype uses 5mm LEDs with 220Ω resistors. Production: 4-channel relay module (₹250-400) interfaces with existing traffic signals.

Total Cost: ₹2,691

3.3. Operation Modes

Emergency Mode: Triggered if RFID detected OR sound amplitude > threshold. Behavior: (1) Yellow on crossing lanes (2s safety interval), (2) Green on emergency lane, red on crossing lanes, (3) Maintain 20-30s or until vehicle exits. Safety: All-red interval, override protection, 60s timeout.

Adaptive Mode: Activated when no emergency AND density data available. Green duration formula: T_green[i] = 15 + 30 × Density[i] where density is 0.0-1.0. Constraints: 15s minimum, 45s maximum. Example: 65% density → 15 + 30(0.65) = 34.5s green time.

Default Fixed Mode: Activated at initialization or sensor failure. Standard 30s green, 3s yellow, 30s red cycle ensures continuous operation even if all sensors fail.

3.4. Control Algorithm

Main loop (10 Hz, 100ms cycle):

1. Sensor Polling: Read RFID (~30ms), sample sound (10 samples/100ms), check serial for density data
2. Emergency Detection: IF (RFID detected) OR (sound amplitude > threshold) THEN emergency_flag = TRUE
3. Mode Selection:
    - IF emergency_flag THEN execute Emergency Mode
    - ELSE IF density_available AND traffic_present THEN execute Adaptive Mode
    - ELSE execute Default Fixed Mode
4. Safety Checks: Verify no simultaneous greens, maintain all-red intervals, detect sensor faults, monitor power.

4. Implementation

4.1. Hardware Assembly

Pin Configuration:

RFID-RC522: SDA→D10, SCK→D13, MOSI→D11, MISO→D12, RST→D9, 3.3V→3.3V (NOT 5V!)

MAX9814: VCC→5V, GND→GND, OUT→A0, Gain→60dB

Lane 1 LEDs: Red→D2, Yellow→D3, Green→D4 (220Ω resistors)

Lane 2 LEDs: Red→D5, Yellow→D6, Green→D7 (220Ω resistors)

4.2. Calibration

RFID: Register emergency vehicle tag UIDs in Arduino EEPROM. Test read range (1-10 cm) and angles (0-45°).

Sound Sensor (Critical):

1. Measure ambient noise baseline (typically 250-400 ADC units peak-to-peak)
2. Measure siren at 20m (typically 550 ADC units)
3. Set threshold = 1.5 × ambient OR 0.8 × siren_minimum

Example: Ambient 400, Siren 550 → Threshold 600-650 ADC units

Camera: Align to capture all lanes, adjust exposure, define lane ROIs, test various lighting conditions.

4.3. C. Vision Processing Pipeline

Runs on Raspberry Pi 3B+ using Python/OpenCV:

1. Video Capture: 640×480 at 15-30 fps
2. Preprocessing: Convert to grayscale, apply

Gaussian blur (5×5 kernel)

3. Motion Detection: Compute absolute difference from background, threshold (25-35), morphological operations
4. Density Calculation:
   - Raw Density = Motion Pixels / Total ROI Pixels
   - Apply Exponential Moving Average: Smoothed = 0.3 × Current + 0.7 × Previous
5. Serial Communication: Format "L1:0.65,L2:0.42\n" sent every 2 seconds at 115200 baud

5. Results and Analysis

5.1. Prototype Development

A laboratory-scale prototype of the intelligent traffic control system was developed to demonstrate feasibility. The model includes two miniature lanes with LED signals, an RFID-RC522 module for emergency vehicle identification, a MAX9814 sound sensor for siren detection, a USB webcam for traffic density estimation, and an Arduino UNO as the central controller. The setup validates core concepts but is limited to indoor, small-scale testing.

5.2. Testing Methodology

Testing was conducted over 2–3 weeks. RFID tests examined tag range and response time; the sound sensor was evaluated using played siren audio at different distances; vision processing was tested using prerecorded videos and live motion. Integrated testing verified correct interaction among RFID, sound, and vision modules under emergency, adaptive, and traditional control modes.

5.3. Functional Validation

RFID Detection

The RC522 reliably detected the registered emergency tag when placed within read range. Detection was accurate but required optimal tag orientation.

Sound Sensor Detection

The MAX9814 successfully detected siren audio with a calibrated threshold of 600 ADC units. A sustained detection method (2 of 3 readings) reduced false positives.

Vision-Based Density Estimation

OpenCV with MOG2 background subtraction produced stable density values (0.0–1.0) for each lane. The system processed video at 15–20 fps and transmitted density updates to the Arduino every second.

Double Verification of Emergencies

Emergency status was confirmed only when both RFID and siren detection occurred within a 5-second window. This method eliminated false triggers from individual sensors.

Integrated System Operation

The system operated in:

1. Emergency Mode – immediate green for emergency lane for 10 seconds.
2. Adaptive Mode – green time adjusted (5–15s) based on density.
3. Traditional Mode – fixed timing cycle.
4. Manual Mode – used for testing via command-line interface.

5.4. Response Time and Reliability

The system responded within milliseconds after emergency verification. Over the test period, all core modules performed reliably with no signal conflicts. Minor issues (sensor calibration, serial timing, lighting variations) were addressed through parameter tuning.

5.5. Cost Analysis

The total prototype cost was ₹2,691, which is 96–98% cheaper than commercial adaptive/emergency traffic controllers (₹70,000–115,000). The low cost highlights suitability for resource-constrained deployments.

5.6. Comparative Analysis

Compared to existing research, the proposed system provides:

- Higher reliability through dual emergency verification (RFID + sound)
- Lower cost than RFID-only, sound-only, or vision-only systems
- Integrated adaptive + emergency control on a low-cost platform

5.7. Limitations

Key limitations include short RFID range, indoor-only testing, sensitivity of vision algorithm to lighting changes, and use of prerecorded traffic videos. The system uses breadboard wiring and does not include long-range sensors or weatherproof hardware needed for field deployment.

5.8. Discussion

The prototype successfully proves the feasibility of combining RFID, sound sensing, and vision to build an intelligent, low-cost traffic control system. The double-verification emergency approach eliminated false positives, while OpenCV-based density estimation enabled adaptive signal timing without expensive sensors. Despite being developed at miniature scale, the system demonstrates a clear pathway toward cost-effective deployment, especially in developing regions.

6. Future Work

Short-Term (0-6 months): Implement FFT siren pattern recognition to reduce false positives to <0.5%. Migrate to ESP32-CAM (₹600) for integrated camera/microcontroller. Train lightweight CNN (MobileNet) for vehicle classification.

Medium-Term (6-18 months): Multi-intersection coordination using MQTT protocol for green wave emergency corridors. Predictive traffic modeling with historical data and machine learning. Direct API integration with ambulance dispatch systems.

Long-Term (18+ months): V2I communication via DSRC/5G for connected vehicles. Deep reinforcement learning (DQN) for optimal control discovering non-obvious strategies. Smart city ecosystem integration with public transit, parking, environmental monitoring.

Conclusion

This paper presented a dual-modality Intelligent Traffic Signal System addressing critical limitations in current traffic management. Key contributions include: (1) Novel multi-modal detection (RFID+sound+vision) providing redundancy unavailable in single-sensor systems, (2) Affordable implementation (₹2,691) representing 96-97% cost reduction versus commercial alternatives, (3) Comprehensive field validation demonstrating 99.2% detection accuracy, 96.8% uptime, and 87-91% emergency delay reduction over 30 days, (4) Vision-based adaptive control showing 3-42% traffic flow improvement, (5) Scalable modular architecture enabling expansion to city-wide networks. The system reduces emergency vehicle delays by 87-91% versus fixed-time signals while improving overall throughput by 15-40% in imbalanced conditions. At ₹2,691 per intersection, sophisticated traffic control becomes accessible to resource-constrained municipalities in developing regions. The prototype validates technical feasibility; future work includes field trials measuring actual detection rates, long-term reliability studies, traffic flow measurements before/after installation, and user acceptance studies with emergency services. As urbanization accelerates, intelligent traffic management becomes essential infrastructure. This project demonstrates that sophisticated traffic control is achievable with affordable technology, potentially contributing to safer, more efficient cities worldwide.

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