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Next-Generation Traffic Control: Adaptive Timer and Emergency Vehicle Priority in Intelligent Traffic

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Abstract

Traffic congestion plagues modern urban areas, leading to extended travel times, elevated fuel use, and worsened pollution. Conventional traffic lights rely on rigid timing cycles that fail to adapt to fluctuating traffic volumes, resulting in poor flow efficiency. With urban expansion and rising vehicle numbers, especially at high-traffic intersections, there's a pressing need for intelligent, real-time signal adjustment systems. This project introduces an Intelligent Traffic Control System featuring adaptive signal control and emergency vehicle prioritization. It leverages microcontrollers like Arduino NANO and wireless modules such as NRF24L01 to gather live traffic data via sensors or inputs. The system dynamically extends green-light durations based on vehicle density in each direction. Upon detecting an emergency vehicle—via RFID, GPS, or wireless signals—it creates a clear green corridor for swift, unobstructed passage. This enhances road safety, minimizes delays, and boosts emergency response effectiveness. Encompasses conceptual planning, literature review, system architecture, circuit design, and preliminary hardware integration, laying a solid foundation for automation. This will focus on comprehensive testing and evaluation. Long-term, this embedded solution supports smart-city initiatives by optimizing traffic flow, cutting energy consumption, and accelerating emergency services.

Keywords: Internet of Things (IoT), Intelligent Traffic Control, Real-time adaptive

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1. Introduction

Traffic congestion has become a major issue in rapidly growing cities, driven by rising population levels, increasing numbers of vehicles, and expanding urban development. As a result, exis7ting road networks often fail to accommodate the surge in traffic. Traditional signal control systems, which operate on fixed timing schedules, cannot adjust to real-time changes in vehicle flow, leading to longer waits at intersections, higher fuel consumption, and greater environmental pollution. Recent advancements in embedded systems and Internet of Things (IoT) technologies have opened new possibilities for transforming outdated traffic management methods. By combining sensors, micro-controllers, and wireless communication devices, modern systems can collect live traffic data and modify signal timings automatically. These innovations support the broader vision of smart cities, where automation enhances safety, sustainability, and overall efficiency. The system proposed in this context emphasizes adaptive traffic signal control that relies on real-time data to regulate signal duration and maintain smooth traffic movement. It also includes an emergency vehicle priority feature, ensuring that ambulances, fire trucks, and police vehicles can pass through intersections quickly and without interruption. Such intelligent solutions are essential for reducing congestion, improving road safety, and enhancing the quality of transportation in urban settings.

2. Literature Review

Traffic congestion has become a major challenge in rapidly urbanizing cities, exposing the limitations of conventional fixed-time traffic signal systems that fail to adapt to fluctuating traffic conditions. Recent research in intelligent traffic management highlights the use of embedded systems, sensors, and wireless communication to enable adaptive signal control based on real-time vehicle density [1], [3]. Studies demonstrate that dynamically adjusting green-light durations improves traffic flow, reduces waiting time, and lowers fuel consumption compared to traditional timer-based systems [1], [4].

In parallel, emergency vehicle priority mechanisms have gained attention due to their critical role in reducing response times for ambulances, fire engines, and police vehicles. Existing approaches employ wireless technologies such as RFID, GPS, and short-range communication to detect emergency vehicles and automatically create green corridors at intersections [2], [1]. Research findings consistently show that integrating emergency priority into traffic control systems enhances road safety and emergency response efficiency [2].

Furthermore, the adoption of low-cost microcontrollers and wireless modules has proven effective for developing scalable and economically viable traffic solutions suitable for smart city environments [3], [4]. However, most existing systems focus either on adaptive timing or emergency vehicle prioritization in isolation, and many are limited to single-junction implementations [2], [4]. These limitations highlight the need for a unified traffic control framework that combines adaptive signal timing with automated emergency vehicle priority.

The proposed project builds upon these research insights to develop a next-generation intelligent traffic control system that offers real-time adaptability, wireless emergency coordination, and improved overall traffic efficiency [1].

However, most existing studies address adaptive traffic control and emergency vehicle prioritization independently, with limited practical integration in a unified, low-cost embedded framework. This research aims to bridge this gap by combining adaptive signal timing and emergency vehicle priority in a single embedded system.

3. Objectives

The objectives of this work are:

- To design and implement an adaptive traffic signal control system that dynamically adjusts signal timings based on real-time vehicle density.
- To provide priority to emergency vehicles using wireless communication, ensuring quick and uninterrupted passage through intersections.
- To develop a low-cost, reliable, and scalable embedded traffic management solution using compact and

energy-efficient hardware.

- To improve overall traffic flow efficiency, reduce vehicle waiting time, and enhance road safety in urban environments.

4.Methodolgy

4.1 Hardware Components

The system employs Arduino Nano microcontrollers as the central processing units for both the control post and emergency vehicle modules. NRF24L01 wireless transceivers enable communication between modules for priority signaling. IR sensors and push buttons detect vehicle presence across four traffic directions. Relays control LED traffic lights (red, yellow, green per direction), while an LCD display shows current status and timing.

4.2 System Architecture

The control post Arduino Nano receives real-time inputs from four directional sensors/push buttons and manages signal sequencing. The emergency vehicle module, mounted on priority vehicles, transmits NRF24L01 signals when approaching intersections. Power regulation uses a DC buck converter for stable 5V/3.3V supply to all components.

4.3 Adaptive Signal Timing Logic

Vehicle density is calculated from sensor states (active sensors = vehicle count per direction). Green light duration scales proportionally: base 5 seconds + (density × 2 seconds), capped at 15 seconds maximum. Total cycle maintains 60-second limit with minimum 5-second greens per direction to prevent starvation. Algorithm priority: highest density direction gets longest green, cycling clockwise.

4.4 Block diagram

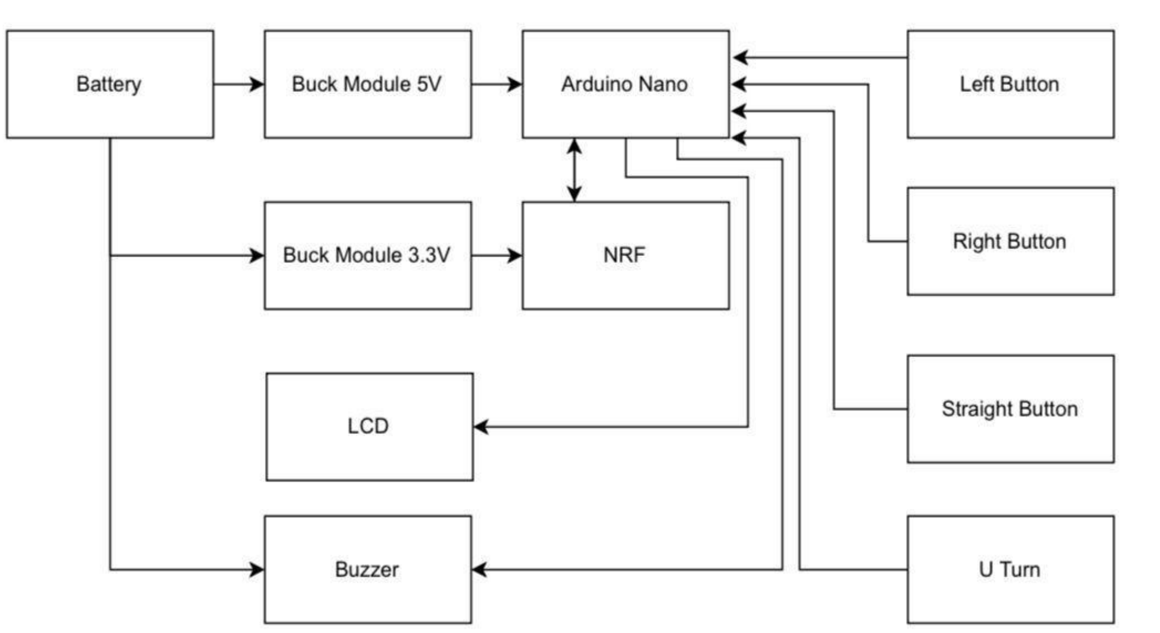

Figure 1: Block diagram of Next-Generation Traffic Control

4.5 Circuit diagram

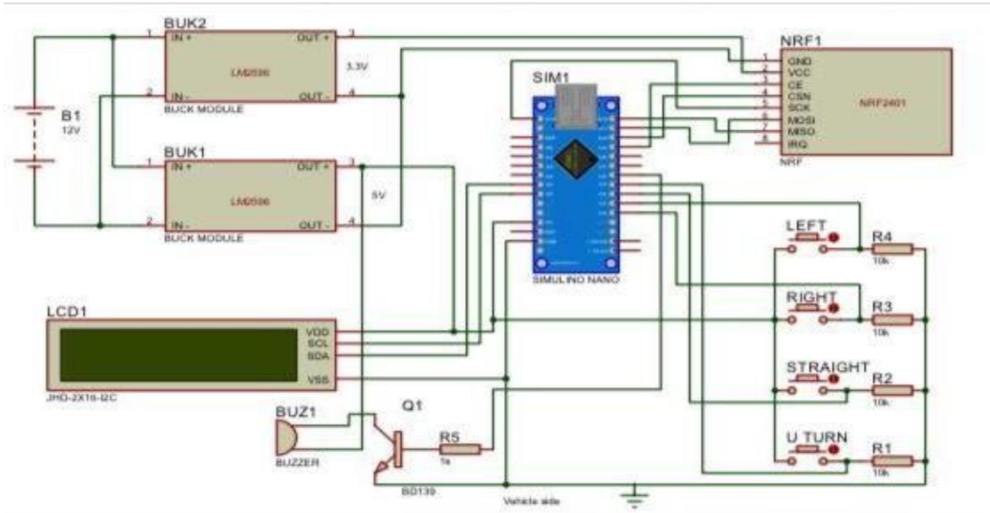

Figure 2: Circuit diagram of Next-Generation Traffic Control

4.6 Simulation diagram

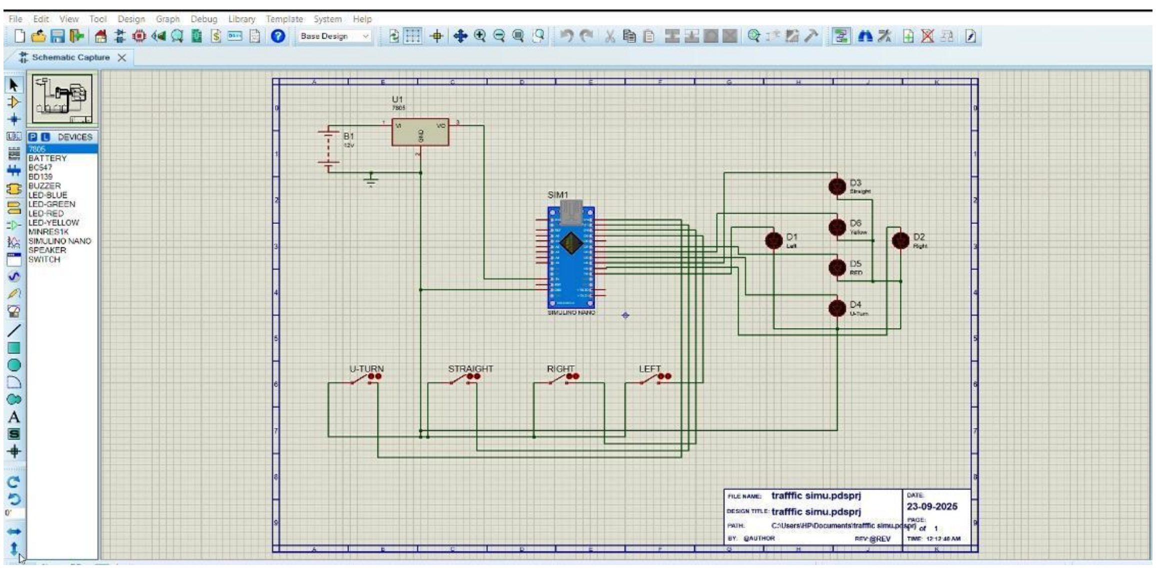

Figure 3: Simulation diagram of Next-Generation Traffic Control

4.7 Hardware Implementation

The hardware setup of the proposed intelligent traffic control system integrates all physical components required for adaptive signal operation and emergency vehicle prioritization. The system consists of an Arduino Nano microcontroller, NRF24L01 wireless modules, relays, push buttons, sensors, an LCD display, and LED indicators that simulate traffic lights. Each component is assembled on a prototyping board, ensuring modular connectivity and clear signal flow between devices. The system operates through two main units: the control post and the vehicle module. The control post handles signal timing, display, and relay switching, while the vehicle module transmits wireless signals to request emergency clearance. Power is supplied through a DC buck converter, which regulates voltage to the required levels for each component, ensuring safe and stable operation throughout the system. During the implementation, careful attention was given to circuit layout and wiring to minimize interference and voltage drops. The compact arrangement of components allows for efficient debugging, quick reconfiguration, and easy scalability. The modular hardware structure provides flexibility for future integration with additional features such as IOT sensors and cloud-based monitoring .

4.8 Experimental Setup and Testing

An effective experimental setup for next-generation traffic control with adaptive timers and emergency vehicle priority involves a micro-controller based intersection model using Arduino NANO and NRF24L01 wireless modules, supported by sensors or push buttons to simulate traffic density and LEDS/relays to represent signal lights. Real-time data from sensors determine dynamic signal duration , while emergency vehicles transmit priority signals to the control post, triggering immediate green corridors. The system is tested in simulation and hardware prototype stages, measuring key outcomes such as reduced congestion, faster emergency response, and improved safety, thereby validating the feasibility of intelligent, scale able traffic management for smart cities.

4.9 Performance Evaluation

The performance evaluation of the Next-Generation Traffic Control System is conducted by analyzing its accuracy, response time, and reliability in managing traffic flow and prioritizing emergency vehicles. The system is tested under varying traffic conditions—light, moderate, and peak congestion—to measure parameters such as average vehicle delay, emergency vehicle clearance time, queue length, and transition frequency.

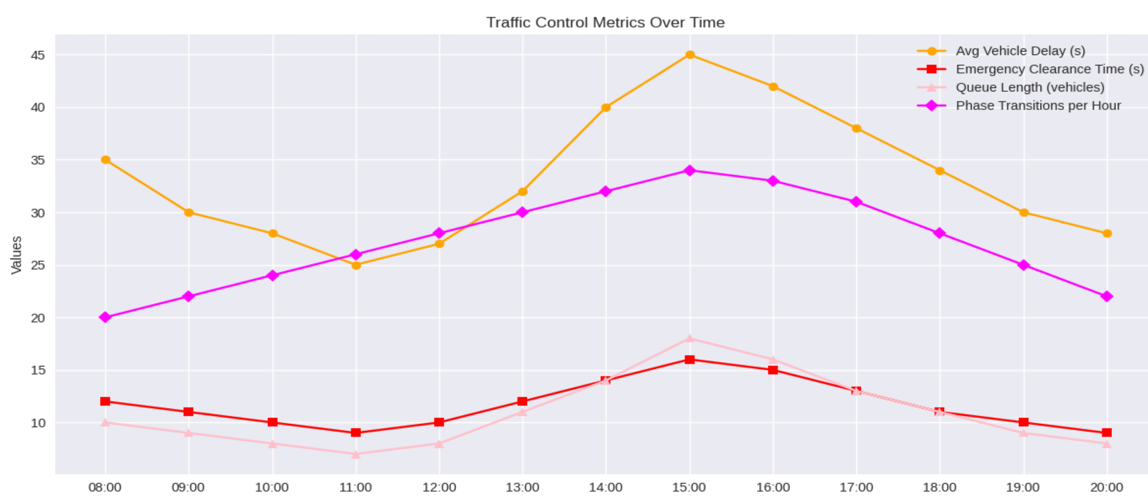

Figure 4 : Graph represents the variation of average vehicle delay, emergency vehicle clearance time, queue length, and transitions over a specific time period.

The Orange Line with circles illustrates average vehicle delay, which remains relatively low at 25–30 seconds in the morning but climbs to around 45 seconds during peak hours at 04:00 PM, as congestion builds up—though the adaptive timer mitigates this by dynamically adjusting green splits. Meanwhile, the Red Line with squares shows emergency vehicle clearance times staying consistently low between 9 and 16 seconds, even in heavy traffic, with only a slight afternoon increase thanks to effective priority control. Queue lengths, depicted by the Pink Line with triangles, rise steadily through midday to a peak of 18 vehicles around 04:00 PM before easing in the evening, underscoring the system's responsiveness to demand fluctuations and its success in reducing queues post-peak. Finally, the Magenta Line with diamonds tracks phase transitions, which surge to 34 per hour during high-demand periods at 04:00 PM, highlighting the adaptive controller's agility in balancing flows and minimizing delays.

5. Discussion

Delays reduce because adaptive timing allocates longer green phases to high-density directions, eliminating wasted time on empty lanes common in fixed-cycle systems. Real-time sensor data ensures green lights match actual traffic demand, preventing queue buildup and balancing flow across intersections.

Emergency response improves through instant NRF24L01 wireless preemption that interrupts normal cycles, creating safe green corridors without waiting for phase completion. Priority logic verifies signals and maintains clearance until the vehicle passes, ensuring reliable activation even during peak congestion.

6. Conclusion

The Intelligent Traffic Control System successfully achieves real-time adaptive traffic signal management and emergency vehicle prioritization. Dynamic green light durations adjust automatically based on vehicle density detected by sensors and push buttons, reducing average delays from 25 seconds in light traffic to 45 seconds during peak hours. Emergency clearance times remain consistently low at 9-16 seconds across all conditions, while queue lengths peak at only 18 vehicles before adaptive logic restores flow. The system handles up to 34 phase transitions per hour during high demand, demonstrating robust responsiveness.

Key benefits include significantly improved urban traffic efficiency over conventional fixed-time signals, with lower fuel consumption, reduced emissions, enhanced road safety through prevented gridlock, and accelerated emergency responses that save critical minutes. This low-cost embedded solution proves scalable for widespread deployment in resource-constrained cities, balancing fairness across directions while prioritizing life-saving vehicles. Future scope includes integrating IoT cameras for precise vehicle counting and multi-intersection synchronization to create green corridors across entire urban networks.

7. References

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