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Density-Based Traffic Control System with Real-Time Emergency Vehicle Prioritization for Urban Intersections

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ABSTRACT

Traffic congestion at intersections remains a major problem due to the limitations of traditional traffic lights, which give equal "GO" times regardless of how busy the roads are. This study introduces a smart traffic control system designed to address this issue and improve traffic flow in cities. The system uses an STM32F401CC microcontroller and ultrasonic sensors to adjust signal timings based on real-time traffic density. To make it even more effective, Radio Frequency Identification (RFID) technology was added to give priority to emergency vehicles, ensuring they can pass through without delays during critical situations. The system was tested on a model simulating a busy intersection and showed significant improvement in traffic flow and emergency response. Prototype and testing confirmed the system's ability to reduce congestion and improve traffic management. This innovative solution combines real-time monitoring with emergency vehicle prioritization to create a practical way to solve modern urban traffic problems, enhancing road safety and efficiency.

Keywords:
Traffic control, Density-based system, Emergency vehicle prioritization, RFID technology, Ultrasonic sensors.

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INTRODUCTION

Traffic lights regulate vehicle movement through fixed time intervals, ensuring orderly flow. However, uneven traffic distribution on four-way roads can cause congestion, especially during peak hours. Fixed timing often leads to delays and inefficiencies (Chandrasekara *et al*., 2020). The inefficiency of existing traffic control systems in managing congestion and prioritizing emergency vehicles, particularly in densely populated and developing countries like Nigeria, has highlighted the need for improvement in this area (Usikalu *et al.,* 2019).

Several works have laid the groundwork for this system. Usikalu *et al.* (2019) highlighted the limitations of fixed-time traffic signals in congested urban areas like Lagos, Nigeria. Their Arduino-based system managed density but failed to prioritize emergency vehicles. Chitragar *et al*. (2017) proposed a density-based system using PLCs but lacked integration with advanced sensors. Similarly, Internet of Things (IoT)-based Intelligent Traffic Monitoring Systems (Putra *et al*., 2018) and Raspberry Pi-controlled traffic systems (Riyazhussain *et al.,* 2016) improved traffic flow but required high costs and complex maintenance. Javaid *et al*. (2018) developed an IoT and Artificial Intelligence (AI)-based smart traffic system using sensors, cameras, and RFIDs to regulate urban traffic. It managed congestion and emergency vehicles but faced challenges like complexity, high costs, and frequent maintenance. Somefun *et al.* (2023) implemented a traffic system using infrared sensors and an Arduino Mega to measure traffic density and detect speed. Tested in Uyo, Nigeria, it reduced traffic clearance time by

60%, The system prioritized congested lanes and enforced speed limits for better traffic control although reliance on Bluetooth posed communication challenges. Udoakah *et al.* (2018) designed a traffic system using IR sensors and a microcontroller to regulate signals and ease congestion. It improved traffic efficiency and law enforcement but faced limitations due to Infra-red (IR) sensors' environmental sensitivity and the microcontroller's inability to handle complex intersections.

This study proposes a density-based traffic control system integrating emergency vehicle prioritization using RFID technology and ultrasonic sensors. Real-time processing of data and dynamic adjustment of traffic signal timings were achieved using the STM32F401CC microcontroller and signal optimization algorithms. The simulation results showed a significant improvement in traffic flow efficiency and emergency response time. The software was implemented in C programming Language. This approach addresses critical gaps in existing traffic control systems.

METHODOLOGY

System Block Diagram

The block diagram of the developed traffic management system is shown in Figure 1. The system is made up of a power supply unit, traffic density sensing unit, signal processing unit, and traffic signal control unit. The power supply provides the necessary power for all components. The sensing unit, comprising ultrasonic sensors and RFID readers, is strategically deployed at intersections to monitor vehicle density and detect emergency vehicles.

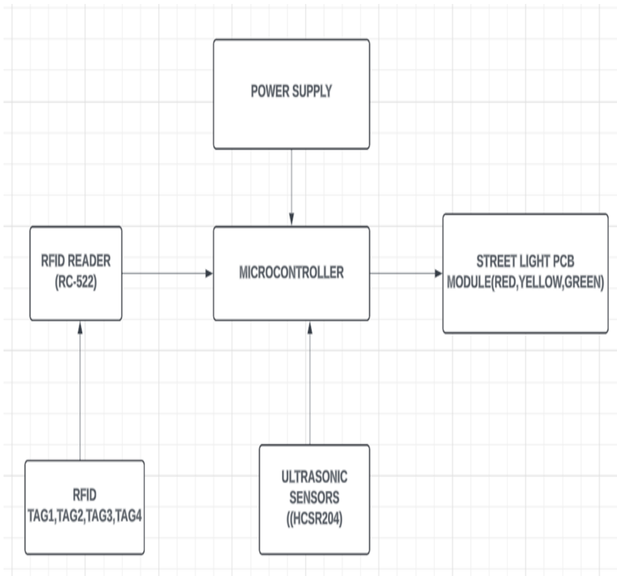

Figure 1: Block diagram of the developed density-based traffic control system

The signal processing unit processes real-time data from the sensing unit. Ultrasonic sensors detect vehicle density in all four directions, enabling dynamic adjustments to traffic signal timings. This ensures the smooth traffic flow by allocating green signals to lanes with higher vehicle density, thereby reducing congestion and travel times.

The RFID readers identify emergency vehicles equipped with unique RFID tags. When detected, the system prioritizes these vehicles by granting immediate green signals, minimizing delays, and ensuring timely passage for critical response situations.

The STM32F401CC microcontroller serves as the central decision-making hub, coordinating data from the sensing unit and executing signal changes. By synchronizing traffic signals based on real-time inputs, the system enhances overall traffic efficiency and safety. The system design is divided into two main parts: hardware and software, with hardware focusing on component integration and software managing dynamic traffic control algorithms.

Choice of Microcontroller

The STM32F401CC microcontroller is ideal for a density-based vehicular traffic control system due to its high processing power (84 MHz ARM Cortex-M4), extensive peripheral support (GPIOs, UARTs, I2C, SPI, ADCs), and large memory capacity (256 KB Flash, 64 KB SRAM). Also, very fast because of its RISC architecture and low power consumption (STMicroelectronics, 2019).

Choice of the RFID reader

The RC522 RFID reader is well-suited for applications such as vehicle detection, offering a practical read range of up to 5 cm for effective tag scanning as vehicles pass by. Additionally, its operation at 13.56 MHz, a globally standardized frequency for RFID systems, ensures reduced susceptibility to interference (Last Minute Engineers, 2025).

Choice of Ultrasonic Sensors

Ultrasonic distance sensors are highly effective for applications requiring accurate and reliable distance measurements over a wide range, typically from 2 (cm) to 4(cm) They maintain consistent performance regardless of ambient light conditions, as they operate using sound waves rather than light, ensuring insensitivity to varying lighting environments. Additionally, these sensors can detect a variety of surfaces and materials, including non-reflective and transparent objects, due to their reliance on ultrasonic waves that reflect off different materials uniformly (Baumer, 2025)

Design Calculations

i. STM32F401CC Microcontroller:

Average current consumption: 80 µA/MHz

Maximum usage current: 10 mA

ii. Ultrasonic Sensors (HC-SR04):

Operating current per sensor: 15 mA

Number of sensors: 4

Total for ultrasonic sensors: 4 × 15 mA = 60 mA

iii. RFID Reader (MFRC522):

Operating current: 13 mA (idle), 26 mA (active)

Assume active mode for the calculation: 26 mA

iv. LED Indicators:

Forward current per LED: 20 mA

Number of LEDs per lane: 3

Number of lanes: 4

Total LEDS Current : 3 × 20 mA × 4 = 240 mA

v. Miscellaneous (Additional circuitry, resistors):

Estimated current: 10 mA

$$TC = MC + US + RR + CI + MT \quad (1)$$

$$TC = 10mA + 60mA + 26mA + 240mA + 10mA \quad (2)$$

Total Current=336mA

The system requires approximately 336 mA for proper operation. It is advisable to choose a power supply with a capacity 20–30% higher than the calculated total (Tiger Power, 2025), ensuring stability and accommodating potential future expansions. Recommended supply current: ~400–450 mA.

SYSTEM IMPLEMENTATION

System Rigging and Sensor Integration

As shown in Figure 2 the road length was sectioned into 23 (cm) on two opposite sides and 12 (cm) on the other two opposite sides. The lane width was measured at approximately 6 (cm), with an additional 1 (cm) allocated for road demarcation. Other elements incorporated into the modelling board include grassland areas and additional demarcations.

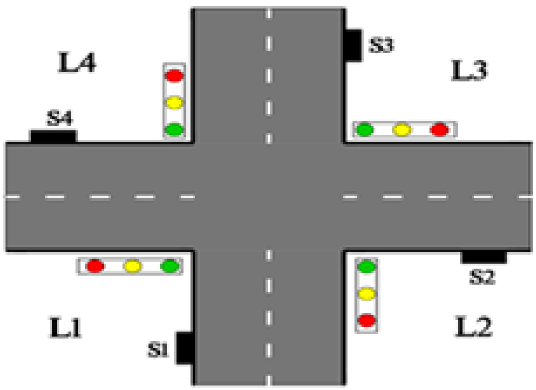

Figure 2: Model of the Layout

The ultrasonic sensors and RFID reader were systematically installed and tested as shown in Figure 3 to ensure their functionality in managing and optimizing traffic flow. Ultrasonic sensors were strategically positioned at the end of a four-lane intersection to detect vehicle presence and density. These sensors transmitted real-time data to a microcontroller, which processed the signals and adjusted traffic signals accordingly. Additionally, an RFID reader was integrated into the system to detect RFID-tagged emergency vehicles. This reader was placed at a place for vehicle intersection to allow sufficient time for signal transmission.

Distance Measurement:

The ultrasonic sensors in each lane measure the distance to the nearest vehicle. This was done using the measured distance function, which calculates the distance based on the time taken for the ultrasonic sensor to travel to the object and return.

Figure 3: Arrangement of the Ultrasonic Sensors and RFID reader on layout

The measurements for each lane are stored in the array distancesInCm [i] for subsequent analysis.
This was achieved by using equation 3

$$DistanceInCm[i] = \frac{T_{echo,i} * v}{2} \quad (3)$$

Where

T_{echo} is the measured time delay of the echo signal.
V is the speed of sound in air

Traffic Density Calculation:
The traffic density for each lane is determined by comparing the distance to a threshold value (density), which represents the maximum allowable distance indicating that the lane is fully occupied (i.e., high traffic). If the measured distance for a lane is less than or equal to the threshold (density), the traffic is considered dense for that lane.

Traffic Signal Control Based on Density:
The system then uses the density information to control the traffic signals. For each lane, if the distance is below the threshold, the corresponding traffic light is set to green, indicating the vehicles in that lane should proceed. The semaphores (osSemaphoreWait ()) and functions like down_green(), right_green (), and left_green() were used to manage the traffic light changes. This was achieved using the algorithm for traffic light changes. The osSemaphoreWait() function ensures that the semaphore is obtained before executing the signal control functions. This mechanism helps synchronize the traffic light changes in a multi-threaded environment and osDelay(time_usonic) introduces a delay to allow for the ultrasonic sensor to complete the measurement cycle before processing the next step. In cases where the distance in a lane exceeds the defined density threshold, the traffic light remains in its previous state (red or other colours) to manage the flow of vehicles accordingly.

Vehicle Emergency
The RFID reader checks if a card matches an emergency vehicle's ID. If a match is found, the traffic lights are immediately set to green for the respective direction. This is achieved by reading RFID card data and comparing it with pre-stored emergency vehicle IDs. This was achieved using an Algorithm for RFID emergency vehicle detection

Algorithm for Decision-Based Traffic Light Control
Step 1: Read the distance values from sensors (distancesInCm[]).
Step 2: Check if distancesInCm[1] ≤ density:
Step 2.1: Wait for semaphore (sema4ucHandle).
Step 2.2: Activate the downward green light (down_green()).
Step 2.3: Delay for time_usonic.
Step 3: Else, check if distancesInCm[2] ≤ density:
Step 3.1: Wait for semaphore (sema4ucHandle).
Step 3.2: Activate the right green light (right_green()).
Step 3.3: Delay for time_usonic.
Step 4: Else, check if distancesInCm[3] ≤ density:
Step 4.1: Wait for semaphore (sema4ucHandle).
Step 4.2: Activate the left green light (left_green()).
Step 4.3: Delay for time_usonic.
Step 5: End the process

Algorithm for RFID Emergency Vehicle Detection
Step 1: Initiate RFID card detection using MFRC522_Request ().
Step 2: Perform anti-collision detection using MFRC522_Anticoll ().
Step 3: Copy the detected RFID data (str[]) into sNum[].
Step 4: Check if the RFID tag matches the predefined emergency vehicle identifier (ID: 19, 60, 14, 42, 11):
Step 4.1: Set emergency = 1 (Emergency vehicle detected).
Step 5: Else, check if the RFID tag matches another emergency identifier (ID: 195, 162, 2, 41, 74):
Step 5.1: Set emergency = 2 (Another type of emergency vehicle detected).
Step 6: End the function execution.

RESULTS AND DISCUSSION

Figure 4 illustrates the operation of the traffic management system, where vehicle detection by ultrasonic sensors determines the right of way. When the ultrasonic sensor in Lane 2 detects a vehicle, the microcontroller processes the signal and activates the green traffic light for that lane, allowing traffic to proceed while the other lanes remain red. Similarly, when the sensor in Lane 3 detects a vehicle, the system grants right-of-way to that lane by switching its traffic light to green, while all other lanes remain stopped. This dynamic control mechanism ensures efficient traffic flow by prioritizing detected vehicles while maintaining orderly lane management.

Emergency Vehicle Detection and Signal Prioritization Mechanism

The microcontroller interprets signals received from the RFID reader to prioritize emergency vehicles as shown in Figure 5. When an emergency vehicle equipped with an RFID tag approaches the designated detection point, the RFID reader transmits the signal to the microcontroller. The system then assesses vehicle density, prioritizes the emergency vehicle, and promptly switches the traffic signal to green for the corresponding lane, ensuring an uninterrupted passage.

Figure 4: Density based traffic control system

Figure 5: Emergency vehicle access

CONCLUSION

This locally crafted density-based traffic control system that has incorporated the STM32F401CC microcontroller, ultrasonic sensors and RFID technology showed critical enhancement in traffic control and emergency vehicles priority. The existing systems failed to give necessary guidance to the normal and emergency vehicles during congestion, but this traffic control system solves it efficiently.

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