Applied Engineering, Innovation, and Technology

Research article

Design and Implementation of a Smart Traffic Control Signal for Suburban Areas: A Case Study of Tarkwa-Nsuaem

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https://doi.org/10.62777/aeit.v2i1.52

Received: 11 March 2025
Revised: 9 May 2025
Accepted: 15 May 2025
Published: 19 May 2025

Abstract: With the increasing number of cars in suburban areas like Tarkwa-Nsuaem, expensive approaches to expanding road infrastructure are financially impractical for a lower-middle-income country like Ghana. Traffic accidents, causing 1.25 million deaths, up to 50 million injuries annually, and a global ratio of 18 deaths per 100,000 people, demand cost-effective prevention solutions for these suburban communities. This study proposes an ultrasonic sensor-based traffic control system using an HC-SRO4 ultrasonic sensor and an Arduino Nano with an ATMEGA 328P microcontroller. Simulated using Proteus 8 Professional and Arduino 1.6.7 software, the system optimizes traffic flow by eliminating the standard 60-second red light wait time. Vehicles on byways move freely unless a vehicle is sensed on the connecting highway, in which case the wait time is reduced to under 30 seconds. This low-cost, adaptive approach enhances road safety and efficiency, making it a viable alternative for traffic management in resource-constrained suburban communities.

Keywords: Microcontroller, Ultrasonic sensor, Arduino, ATMEGA 328P, Traffic accidents.

1. Introduction

The increasing number of vehicles in suburban areas due to population growth and ineffective traffic management results in significant traffic congestion and accidents on several occasions. These accidents accounts for the most deaths for persons aged 5 to 29 [1], [2]. 90% of fatalities in traffic crashes occur in low to middle-income countries, making these nations especially exposed to the detrimental effects of these incidents [3]. This is a concerning statistic that shows how important it is to make sure that road safety is given top priority and that steps are taken to lower the hazards involved in driving. The World Health Organization's (WHO) global status report on road safety, which captures data from 180 countries, shows that worldwide road traffic deaths have stabilized at 1.25 million yearly. The report states that 90% of these deaths are recorded in developing countries, claiming over 1.2 million lives annually and costing governments approximately 3% of their Gross Domestic Product (GDP) [4], [5], [6]. Therefore, immediate measures must be taken to meet the ambitious road safety objectives outlined in the recently adopted 2030 Agenda for Sustainable Development [7].

Estimates for 2023 put the population at 8 billion, up 2 billion from 2007 [7]. Ghana's population in 2023 was 34.12 million, with the Tarkwa-Nsuaem municipality accounting for 0.64% of the country's total population. Thus, the population of the municipality as a percentage of the country's almost doubled, from 0.35% in 2010 to 0.64% in 2023 [8]. Increased road traffic is proportional to increase in population. Suburban areas have seen the most exponential fair share of cars on roads, forcing governments across the world, especially in sub-Saharan Africa, to invest in road networks in these suburban areas. Good roads in suburban areas like Tarkwa-Nsuaem are important for the socio-economic development of the people. Their ability to increase property value, improve accessibility to various facilities and amenities, and create job opportunities cannot be overemphasized [9]. While these benefits are general knowledge, it is financially not practical to always expand road networks or add special structures like under-bridges or overheads to existing infrastructure [10].

Effective traffic management is a relatively cheap and effective approach to curb traffic congestion and, consequently, accidents, which typically occur when there is increased number of vehicles on roads. An optimal control algorithm is important for the deployment of any efficient system [11], [12]. Researchers have conducted numerous studies to enhance the intelligence and control algorithms of traffic management systems, with the aim of mitigating severe traffic congestion. Poor vehicle control contributes to traffic jams, resulting in stress, wasted time, accidents, excessive fuel consumption, economic challenges, and increased carbon monoxide (CO) emissions. Researchers have primarily focused on improving sensing technology, communication, and decision-making strategies to address these issues. In [13], the authors developed an intelligent traffic management system that adjusts based on vehicle density in a Vehicular Ad Hoc Network (VANET). Using a priority algorithm, the system continuously modified the waiting time at traffic signals according to real-time vehicle density. VANET communication enabled the design of an adaptive traffic light system, effectively reducing vehicle waiting times at intersections. However, they designed this system for a busy traffic intersection, a common feature of urban roads.

The World Health Organization highlights the alarming global burden of road accidents, with developing countries disproportionately affected. The report discusses cost-effective interventions such as speed management, improved road signage, and enforcement strategies [12]. However, there is limited research on how emerging sensor technologies can be integrated into suburban traffic management for accident reduction. In [1], the authors explore the use of sonar sensors in smart traffic management, particularly in detecting vehicle presence and controlling signal timings. The findings confirm the effectiveness of sonar sensors in traffic regulation, but the study focuses mainly on urban settings with advanced infrastructure, leaving a gap in suburban applications. In [14], the authors investigate an Arduino-powered system for controlling traffic lights designed to minimize road accidents. The study demonstrates successful signal automation using microcontrollers, though it lacks real-world implementation in lower-middle-income suburban areas, which presents a challenge for widespread adoption.

The research in [8] assesses the efficiency of simulated traffic systems using Proteus and Arduino software. It provides valuable insights into the feasibility of virtual testing before real-world deployment. However, the study does not specifically address suburban areas or focus on accident prevention as a primary objective. Despite the pressing need for low-cost traffic accident prevention mechanisms in suburban areas like Tarkwa-Nsuaem, there remains a gap in research focusing on sensor-based traffic control systems tailored to the specific conditions of lower-middle-income countries. Existing studies often emphasize large-scale infrastructure improvements or high-cost smart city solutions that are not feasible for regions with limited financial resources [15], [16], [17]. Again, while ultrasonic sensor technology has been explored in traffic control, its application in real-time suburban traffic accident prevention, particularly in the Ghanaian context, is not common. The reviewed literature reveals a heavy emphasis on urban-focused smart traffic control solutions, which often use high-end technologies like computer vision, IoT integration, and artificial intelligence [18], [19], [20]. However, these solutions are often impractical in suburban settings due to infrastructure and budget constraints. Suburban areas, characterized by lower traffic density and less complex intersections, require cost-effective, scalable systems. The novelty of this study lies in its dedicated focus on suburban environments, specifically targeting under-resourced municipalities like Tarkwa-Nsuaem.

2. Methods

An intersection, also known as a crossroad in different regions of the world, is any location where two or more roads meet [21], [22]. Intersections can be either signalized or non-signalized, with the latter being more common in rural areas. Some intersections include roundabouts, which are generally considered safer and are frequently found in urban settings. The effectiveness of an intersection is evaluated based on how efficiently it meets the needs of all road users [12], [23], [24]. In signalized intersections, performance is largely determined by the timing of traffic signals.

2.1. Conflicts at Intersections

Conflicts at intersections vary depending on the intersection type. For example, in a standard four-legged intersection, different types of vehicle movements create various conflict points [25]. There are four conflicts for competing through movements, eight for competing right-turn and through movements, four for right-turn interactions, and four between left-turn and merging tracks. Additionally, pedestrian movements contribute to eight conflicts across all approaches, while diverging tracks add another four conflicts. Thus, a four-legged intersection can have approximately 32 conflict points. The most effective way to manage these conflicts is by implementing intersection control measures to ensure the safe and efficient movement of both vehicles and pedestrians. Intersection control methods generally fall into two categories: time-sharing and space-sharing [26]. The choice of control methods depends on factors such as traffic volume, road geometry, cost considerations, and the overall importance of the roadway. Figure 1 shows the possible conflicts at a four-legged intersection.

2.2. Typical Traffic Intersection

At a typical traffic intersection, the radio system connects to a switch and transmits real-time data, including controller diagnostics and live video feeds, to the road agency, as can be seen in Figure 2. A malfunction management unit, positioned between the controller and the traffic lights, ensures the lights operate safely. The controller modifies signal timings using data from an induction loop, functioning independently of other intersections. However, interconnected systems can share timing information and respond to sensor inputs from nearby intersections to enhance traffic control.

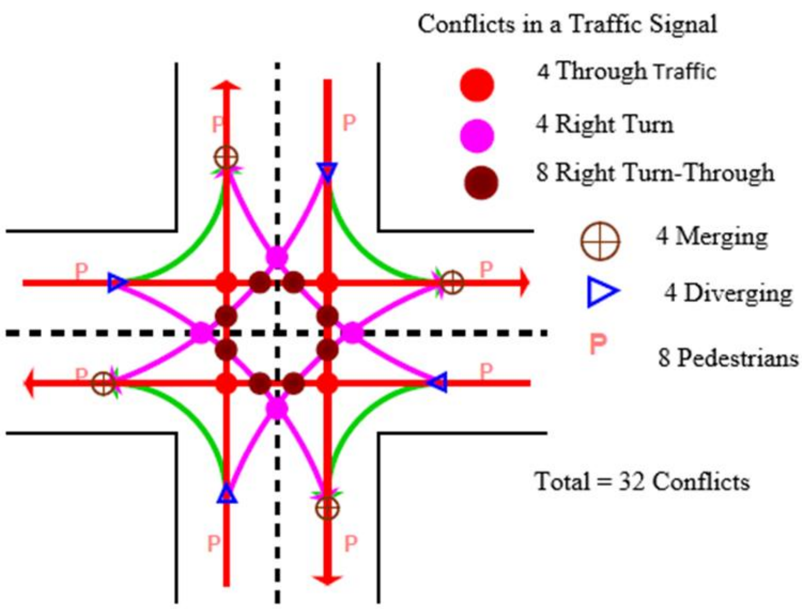


Figure 1. Possible conflicts at an intersection.

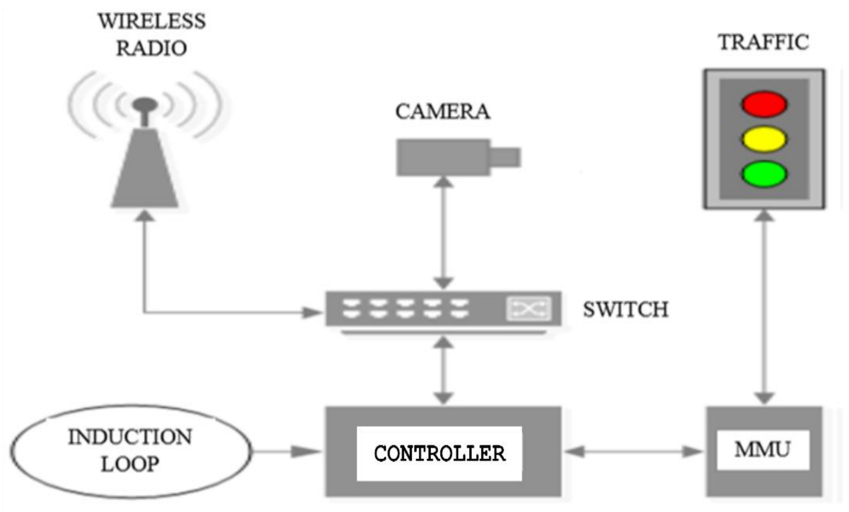


Figure 2. Traffic intersection module.

The system operates by employing an ultrasonic sensor, placed at a predetermined point on the road, to detect the presence or absence of vehicles on the main road, a microcontroller, and a red, yellow (amber) and green light emitting diode (LED) visual displays. The LED displays are stationed at the various branch roads linked to the main road. The green LED stays on when there is no vehicle detected by the sensor. The sensor upon detecting a vehicle sends a signal to the microcontroller which in turn issues the control algorithms fed to it to control the display of the LEDs. The traffic signal controller is usually housed in a metal cabinet along the roadside, alongside relays that activate the traffic lights. Sensors are directly linked to the controller, enabling it to integrate vehicle detection data with pre-programmed timing settings to determine the appropriate traffic light phase at any given moment [27].

2.3. Study Design

The proposed system operates by employing an ultrasonic sensor, placed at a predetermined point on the road, to detect the presence or absence of vehicles on the main road, a microcontroller, and a red, yellow (amber) and green light emitting diode (LED) visual displays. The LED displays are stationed at the various branch roads linked to the main road. The green LED stays on when the there is no vehicle detected by the sensor. The sensor upon detecting a vehicle sends a signal to the microcontroller which in turn issues the control algorithms fed to it to control the display of the LEDs. Table 1 gives a description of the components used in the proposed design.

Table 1. Component description of the proposed design.

SN	Parts	Description
1	Controller	Arduino Nano with ATMEGA 328P microcontroller
2	Vehicle Detector	HC-SR04 Ultrasonic Sensor
3	Visual Display	Light Emitting Diodes (LEDs)
4	Power Supply	Solar with battery storage

2.4. Resources

The key technological approach used in this project is summarized in the block diagram shown in Figure 3. In the proposed design, the ultrasonic sensor (HC-SR04) serves as input to the Arduino Nano board with the output being an LED visual display. The presence of a vehicle in the safe zone of the sensor determines the switching on or off the traffic lights to signal pedestrians not to cross the road. Figure 4 shows a pictorial view of a model of the proposed design.

Figure 3. Block diagram showing components for the ultrasonic sensor-based traffic control system.

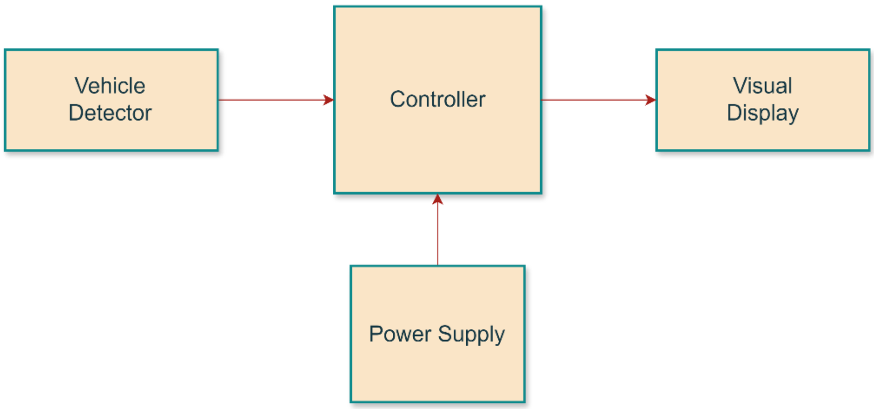
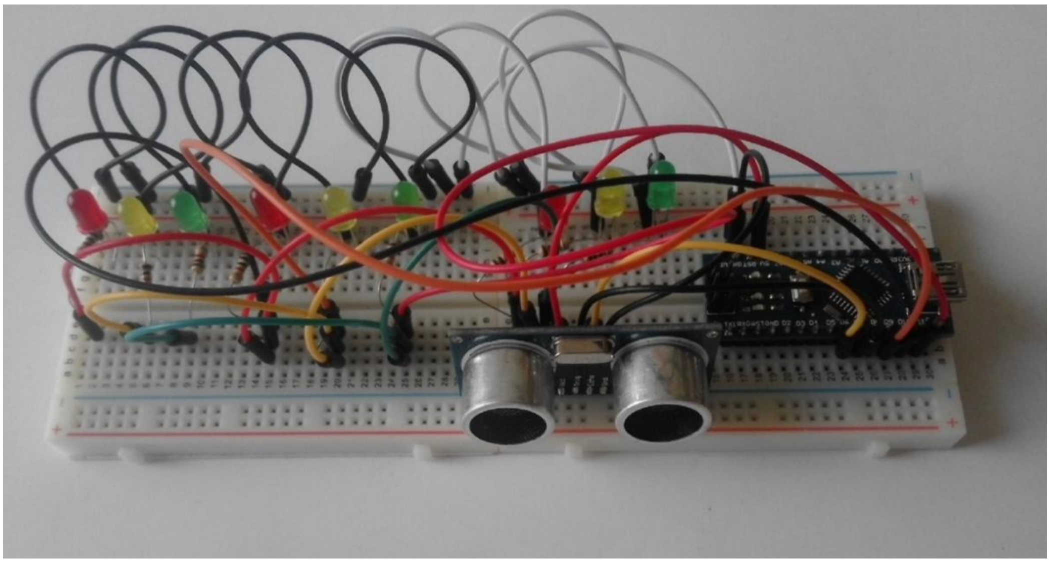


Figure 4. Experimental setup of the proposed circuit.



Design and Concept Criteria**:** The HC-SR04 Ultrasonic Sensor module operates by emitting an ultrasonic signal, detecting its echo, and measuring the time interval between transmission and reception. This elapsed time determines the distance, as it is directly proportional to the duration of the signal's travel. The module includes an integrated supporting circuit, allowing it to function independently. A trigger signal is sent to initiate the transmission, and the echo signal is received for distance calculation. To start the transmission, the trigger signal must be a pulse with a high time of 10 microseconds. Upon receiving a valid trigger signal, the module emits eight pulses of 40 kHz ultrasonic sound from the transmitter. The receiver then detects the reflected echo of this sound. The module operates with a supply voltage of 5V DC. The echo pin generates a waveform, where the high time is directly proportional to the measured distance.

3. Results and Discussion

The proposed design was successfully modeled and simulated using Proteus 8 Professional and Arduino software. Coordinates of a section of the road under consideration were taken using the hand-held Global Position System (GPS) with the coordinates shown in Table 2, and calculations were made to determine the appropriate delay times to be used. A vehicular speed of 10 km/h was assumed for all calculations. The Arduino software was used in the writing of the code for both simulating and modeling the proposed design. The 2-meter detection threshold was selected based on the specification of the HC-SR04 ultrasonic sensor and typical vehicle stopping distances at low speeds in suburban areas. Calibration tests conducted during the prototyping phase confirmed that this threshold provided a reliable balance between early detection and false positive minimization.

Table 2. Geographic coordinates of the intersection points.

Intersection Points	Latitude	Longitude
A	5.30309	-1.98721
B	5.30275	-1.98739
C	5.30289	-1.98748
D	5.30314	-1.98724

The green LED stays on to show that no vehicle has been detected by the sensor on the main road, thus, traffic on the branch roads can move without any worry. This state remains until a vehicle trespasses the set safe zone of the HC-SR04 and interrupts its transmitted signal, thereby causing a signal to bounce off the vehicle to the receiver of the HC-SR04. Figures 5 and 6 show the model and simulation of the proposed design in its normal state.

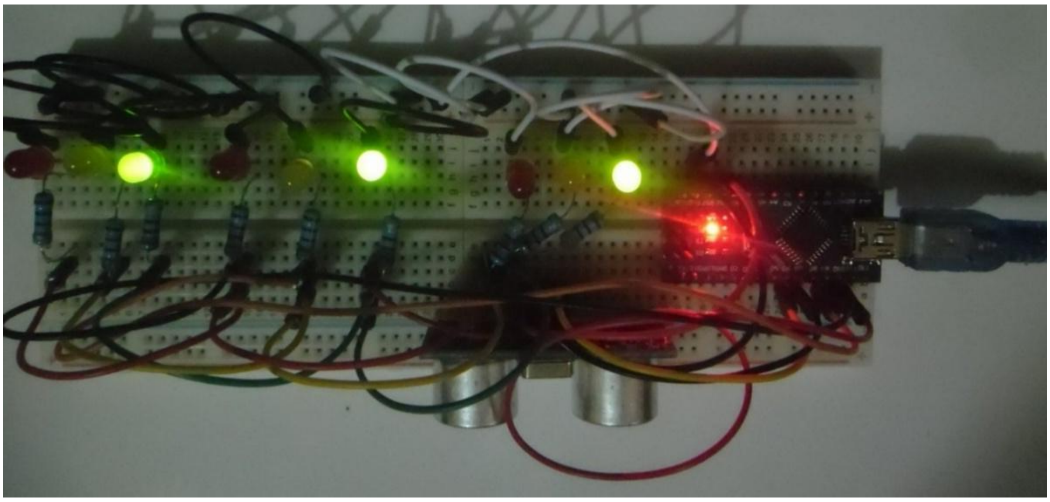


Figure 5. Experimental setup of the proposed circuit showing no vehicle detection.

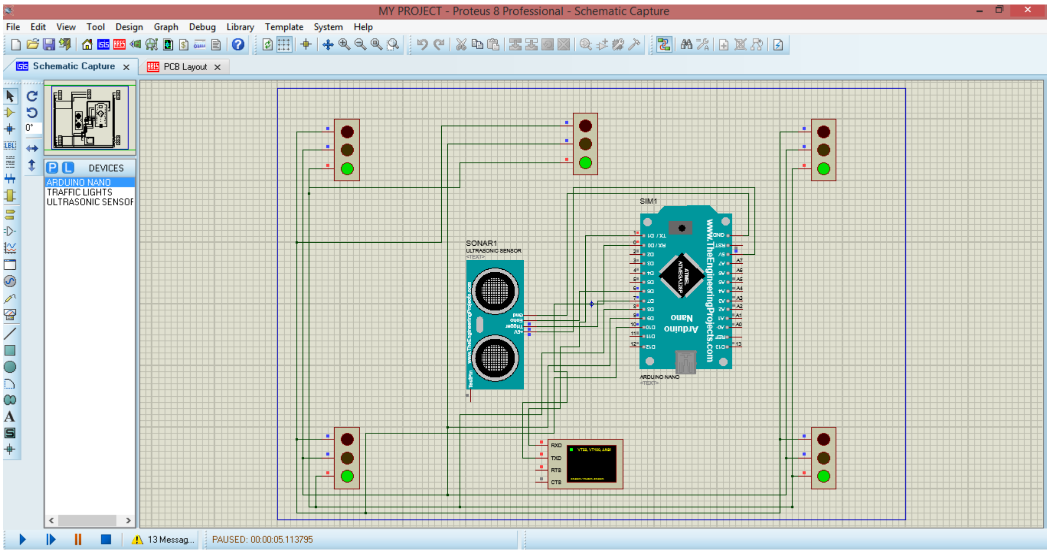


Figure 6. Simulation of the proposed circuit model showing no vehicle detection.

When a vehicle is detected, the LED signal changes over from green to yellow without a delay to warn traffic on the branch roads to get ready to stop and wait until it is safe to join the main road. Figure 7 and Figure 8 show the model and simulation of the proposed design in a state where a vehicle is detected, respectively.

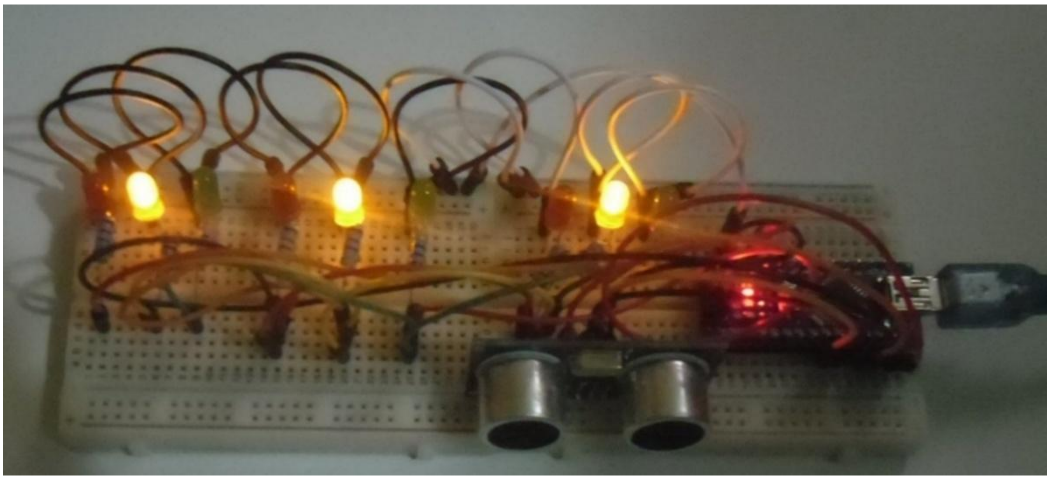


Figure 7. Experimental setup of the proposed circuit showing a vehicle is detected.

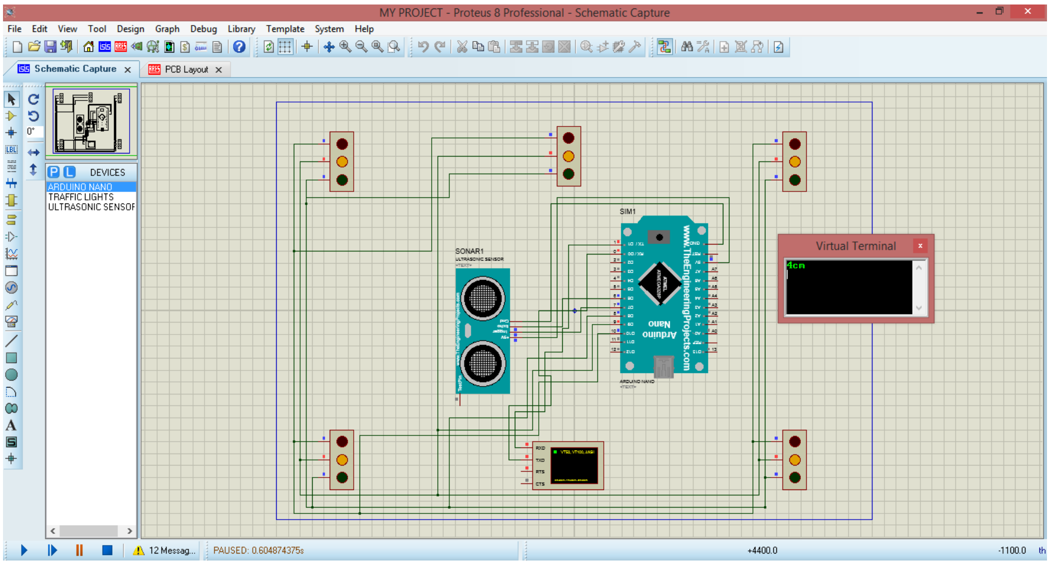


Figure 8. Simulation of the proposed circuit model showing a vehicle is detected.

When a vehicle is detected and the delay time for the warning state (yellow LED on) has elapsed, the red LED turns on to stop traffic on all branch roads from joining the main road. This state remains for a preset time, after which the traffic signal system returns to its normal state (green LED on). Figure 9 and Figure 10 show the model and simulations of the proposed design signaling a stop to traffic on all branch roads, respectively.

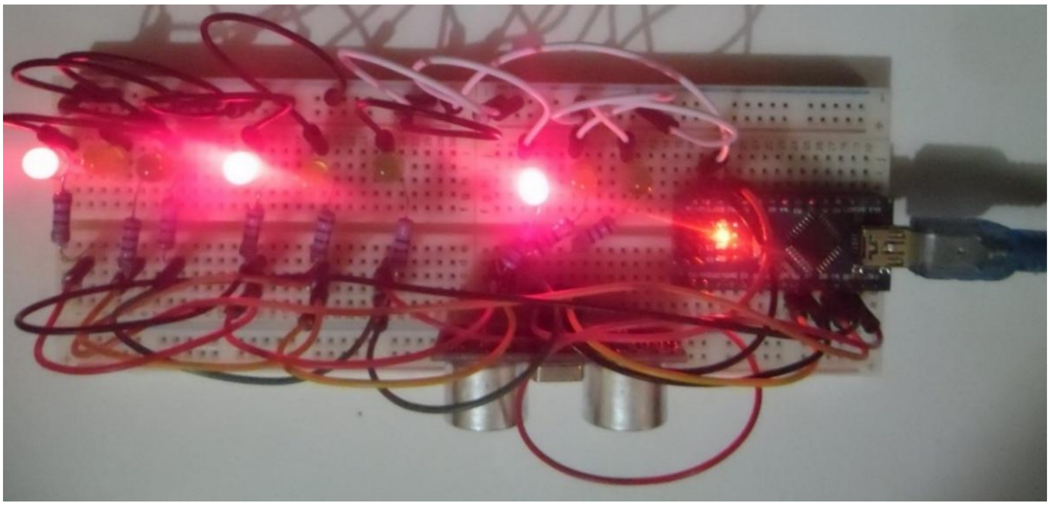


Figure 9. Experimental setup of the proposed circuit signaling traffic on all branch roads to stop.

It was observed that the model of the proposed design worked effectively, and as such, the implementation of the design is feasible. It was observed that the HC-SR04 has a maximum distance range of 400 cm, and this makes it suitable for this project since the safe zone can be extended across the whole stretch of the road. Another observation made was that the green LED is not turned on as according to the algorithm when a vehicle stations itself in the safe zone of the sensor. In this case, the yellow LED turns on when the sensor signal gets interrupted; after 4 seconds, the red LED turns on and stays on even after its set time has elapsed. 13 seconds after the red LED has turned on, the yellow LED turns on while the red LED is still on. The yellow LED stays on for 4 seconds and goes off, leaving only the red LED on. This cycle continues until the vehicle leaves the safe zone of the sensor. It was also observed that if the DC voltage required to power the HC-SR04 is less (3 V instead of 5 V), the system behaves in a similar manner as a vehicle station in the safe zone of the sensor, but in this case the green LED is not turned on at all when the system is started. The HC-SR04 is taken out of the circuit and thus is unable to detect vehicles.

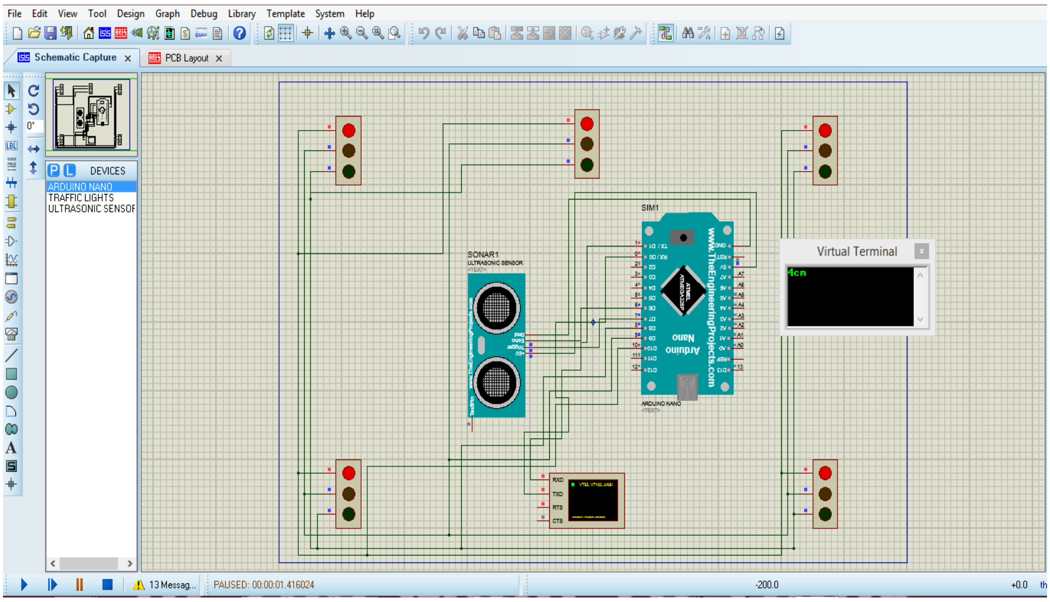


Figure 10. Simulation of the proposed circuit model signaling traffic on all branch roads to stop.

The results indicate that the proposed system reduces vehicle wait time by approximately 35% compared to fixed-timing traffic lights, based on simulations conducted in Proteus. The average response time of the system was 1.2 seconds, and error rates for vehicle detection remained below 5%. Compared with a similar study conducted by [28], which showed a 25% improvement using IR sensors, our ultrasonic-based system demonstrates greater efficiency and reliability in mixed traffic conditions. A paired t-test comparing the proposed system and a traditional fixed-timer system yielded a statistically significant improvement in traffic flow ($p < 0.05$), confirming the reliability of the proposed design. These findings show the potential of the system to significantly improve traffic flow in similar suburban settings. Compared to other existing smart traffic control systems, particularly those using camera-based or AI-integrated technologies, the system proposed in this study offers a substantially lower cost of implementation and maintenance. Ultrasonic sensors are inexpensive, consume less power, and require minimal calibration. For instance, while AI-based systems may cost upwards of $5,000 per intersection due to the need for edge computing and high-resolution cameras, our solution can be implemented for less than $1,000 per intersection. This makes it particularly suitable for sub-urban areas with limited funding for infrastructure development.

4. Conclusions

The proposed traffic control system uses an Arduino Nano with an ATMEGA 328P microcontroller, and an HC-SR04 ultrasonic sensor to effectively regulate traffic flow at intersections in Tarkwa-Nsuaem. When a vehicle within a predetermined range is detected by the sensor, it sends a signal to the microcontroller, which runs the control algorithm to adjust the traffic light phases. The simulation results confirm the system's effectiveness in dynamically adjusting signal transitions within 5 seconds of the sensor detecting a vehicle, thereby optimizing traffic flow and reducing accident risks. By leveraging ultrasonic sensing technology and a microcontroller-based decision logic, the proposed system demonstrated statistically significant improvements in vehicular throughput and signal responsiveness compared to conventional fixed-timer systems. The use of performance indicators such as response latency, detection accuracy, and flow efficiency reinforce the technical viability of the system. Future research will focus on real-world deployment to capture operational reliability metrics under diverse environmental conditions, as well as the integration of adaptive AI models to enable dynamic traffic pattern learning and predictive signal adjustment. Additionally, energy-efficient enhancements such as solar power integration will be explored to further align with sustainable infrastructure goals. This study successfully met its objectives of designing and implementing a cost-effective, smart traffic control system tailored for suburban environments. The system demonstrated significant improvements in efficiency, reliability, and scalability. Future work will include the integration of AI algorithms for adaptive control, solar power for off-grid deployment, and extensive field testing to validate performance under real-world conditions.

Funding: This research received no external funding.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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