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Research article

Design and Implementation of a Microcontroller-Based Adaptive Four-Way Traffic Light Control System for Traffic Optimization

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Abstract: This paper presents the design and construction of a microcontroller-based four-way traffic light control system aimed at optimizing traffic flow by automatically adjusting signal timing based on traffic density at each intersection. The system is built around an Arduino ATmega328 microcontroller inter-faced with break beam infrared (IR) sensors (transmitters and receivers) and LED displays. The IR sensors are installed on both sides of the lanes at regulated intervals to detect traffic density. The system is powered by a 12V DC battery and a 5V, 3A power supply is provided using a buck converter IC (LM2596), which steps down the 12V from the battery to 5V, 3A. This 5V power is used to run the Arduino microcontroller and the Darlington pair ICs for current sinking and sourcing. As vehicles pass through the areas monitored by the IR sensors, the traffic density is measured for each opposing lane, allowing the system to determine which lane should be prioritized for traffic flow. The corresponding LED indicators are then activated accordingly.

Keywords: Adaptive traffic light control, ATmega328, microcontroller, traffic density

1. Introduction

Over the years, the continuous migration of people from rural to urban areas in search of better opportunities has led to urban overpopulation and strained infrastructure. One such overstressed infrastructure is the road network, resulting in increased traffic congestion [1]. In areas where the traffic is heavy, various measures have been implemented to reduce pressure on roads and facilitate traffic flow. One of the common methods employed is the use of traffic lights [2].

Traffic lights are devices installed at road junctions to control opposing traffic flows. The operation of these signaling devices may vary, especially when managing turns, which often have specific lights or rules guiding action. Traffic lights typically consist of three signal indicators—red, yellow, and green—mounted on a vertical pole or suspended from overhead wires. Each signal is illuminated with a colored lens system, with red at the top, yellow in the middle, and green at the bottom. When in operation, the green light allows traffic to move in the indicated direction, the yellow light warns that the signal is about to change, and the red light instructs traffic to stop [3]. Some systems also include pedestrian signals and countdown timers.

Vehicular traffic is increasing worldwide, and many countries face challenges in managing traffic at intersections, especially at four-way junctions. This challenge can lead to delays and conflicts, particularly for emergency vehicles [4]. Four-way junctions in large cities require proactive traffic management due to their high potential for accidents. Studies show that accidents at four-way stops can be severe, with thousands of incidents occurring annually. Many of these accidents are due to drivers who either disobey the rules or are unfamiliar with four-way stop protocols [5].

Numerous techniques for designing traffic control systems have been proposed. A study in [6] developed a system to improve existing automatic signaling through image processing and adaptive signal control, using open-connected vehicles to measure traffic density. In [7], a study proposed a system using magnetic loop vehicle detection sensors on each lane, which adjusts the traffic light timing based on vehicle count. Moreover, a study in [8] evaluated a model that measures vehicle numbers in specific lanes to adjust traffic signal dormancy, using sensors connected to a microcontroller to count vehicles and manage LED signal timing. Another study demonstrated the use of reinforcement learning algorithms to optimize traffic light configurations, utilizing deep neural networks to reduce congestion [9]. Furthermore, another study provided a detailed review of state-of-the-art traffic signal optimization techniques, predicting that AI-based control will be the future trend [10]. Additionally, a study in [11] proposed a system using image processing algorithms to enhance the accuracy of traffic flow measurement.

An adaptive traffic light control system that minimizes delays through efficient communication between traffic light controllers was introduced in [12]. Another study examined a PIC microcontroller system with IR sensors to evaluate traffic density, addressing the issue of emergency vehicle delays in crowded environments [13]. In [1], a density-based traffic control system using an Arduino microcontroller, which activates the lane with the highest traffic was implemented. Similarly, PIC sensors and an Arduino microcontroller was used to adjust traffic light timing based on vehicle numbers in each lane [14]. Moreover, a study in [15] explored open connected-vehicle techniques for vehicle detection and timing adjustment. Additionally, a traffic light simulator that incorporates driver behavior was developed, enabling vehicles to seek alternative paths in the event of prolonged stops [16].

There is a growing need for efficient, responsive, and autonomous traffic control systems as traditional traffic light timing systems are often fixed and unable to adapt to real-time conditions. This study, therefore, presents a microcontroller-based four-way traffic control system designed to optimize traffic signal timing based on real-time traffic density. This system aims to improve road safety, reduce delays, optimize traffic flow, and alleviate congestion through a more adaptive traffic signal control mechanism.

2. Materials and Methods

This study focuses on the design and implementation of a microcontroller-based four-way traffic light system with vehicle counting functionality. The materials used include Arduino Uno ATmega328p, light-emitting diodes (LEDs), transistors, resistors, diodes, capacitors, a step-down transformer, voltage regulators, NPN Darlington transistor (ULN2003), 8-channel source drivers (UDN2981A), infrared (IR) sensors, a printed circuit board (PCB), Vero board, and soft wooden board.

2.1. Power Supply Unit

The power supply is a critical part of the system, providing the necessary electrical energy for the circuit components. A transformer steps down the 220V AC input to 12V AC. This is followed by rectification using four IN4007 diodes and smoothing via a 1000µF capacitor (rated 25V or higher). The resulting DC voltage is regulated to 5V using an LM2596 voltage regulator IC, which powers the main circuit, including the Arduino microcontroller.

2.2. Microcontroller Circuit using Arduino Uno ATmega328p

The Arduino Uno is an open-source microcontroller board based on the ATmega328p microcontroller unit (MCU), developed by Arduino.cc and first introduced in 2010. The board features 14 digital input/output (I/O) pins, 6 of which support pulse-width modulation (PWM); 6 analog input pins; and a USB Type-B connector for programming via the Arduino Integrated Development Environment (IDE). The ATmega328p has a 32KB flash memory, 2KB SRAM, and 1KB EEPROM. Resistors, along with other components such as transistors and diodes, were used throughout the circuit to regulate current flow and protect the microcontroller from excess voltage. The resistors, varying in their properties, were chosen carefully to ensure optimal performance of the circuit.

On the board, the ATmega328p is pre-programmed with a bootloader that enables new code to be uploaded without using an external programmer [17]. The resistors, placed in critical locations, helped control current flow and ensured that voltage remained within the operating limits of the microcontroller and associated components. Figure 1 shows the Arduino Uno ATmega 328p used in this study.

Figure 1. Arduino UNO ATmega 328p.

2.3. Infrared Sensor

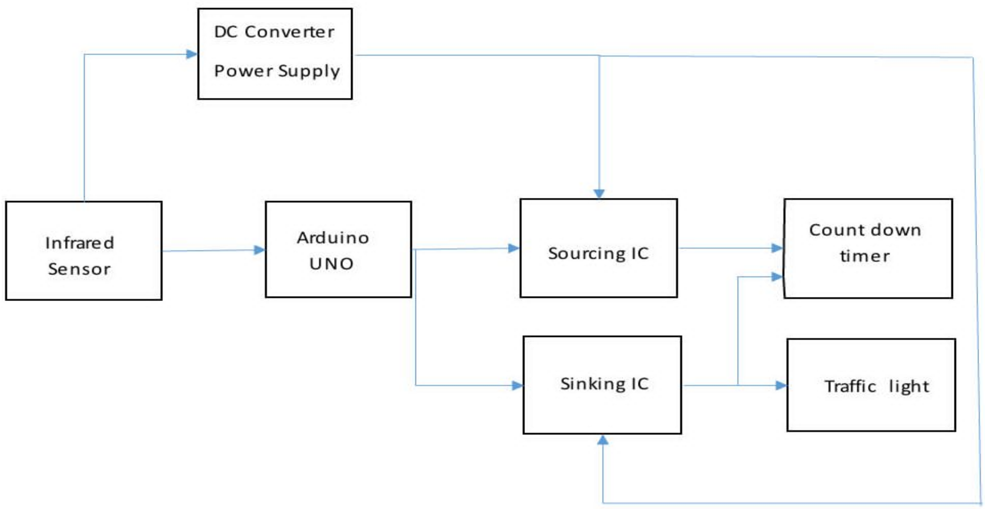
An infrared (IR) sensor, as shown in Figure 2, detects specific environmental characteristics by emitting and receiving infrared radiation. In this system, IR sensors are used to detect vehicle presence and measure traffic density. The IR transmitter emits radiation, which is reflected by vehicles, and the reflected signal is received by the IR receiver. The intensity of the reflected radiation is processed to detect the presence of a vehicle. As the output from the IR receiver is typically weak, it is amplified before being sent to the microcontroller for further processing.

Figure 2. Infrared sensor.

3. Modelling and Analysis

The design and construction of the traffic light system involved several key components, including the infrared sensors, a microcontroller, 7-segment displays, Darlington ICs, counters, and LEDs. These components were used to construct a traffic signal control system prototype based on vehicle density. The system block diagram is shown in Figure 3.

Figure 3. Block diagram of microcontroller-based traffic light control with vehicle counter.



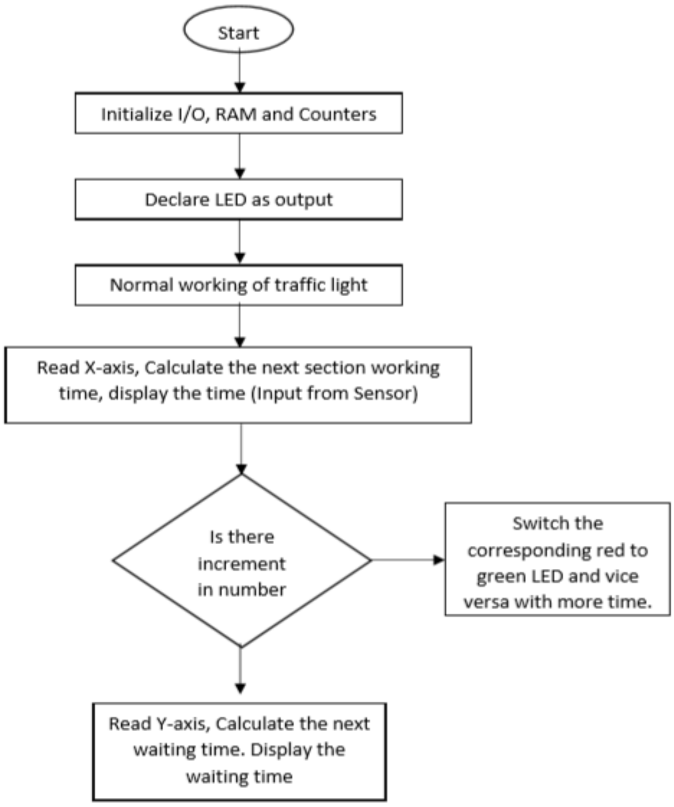
3.1. System Operation

To measure the vehicle count, 8 IR sensors were placed on each side of a four-way junction to detect vehicles moving through the sensor-monitored area. The system employs an infrared transmitter and a photodiode as the receiver. These sensors are strategically placed at predetermined intervals along the road. When no vehicle is present, the IR transmitter continuously emits infrared light, which is detected by the photodiode, allowing it to conduct and complete the circuit.

When a vehicle interrupts the IR beam, the photodiode is unable to detect the infrared signal, and this change is processed by the microcontroller. The signal interruption causes the base current of the transistor to decrease, sending a high logic signal to the microcontroller. Based on this input, the microcontroller adjusts the traffic signal timing. For example, if more vehicles are detected in a particular lane, the green light for that lane remains illuminated longer to accommodate the higher traffic density, while red LEDs light up in the other lanes.

As the microcontroller receives traffic data, it controls the countdown timer, LEDs, and other circuitry to manage the traffic flow efficiently. The operational flowchart of the system is shown in Figure 4.

Figure 4. Flow chart of microcontroller-based traffic light control system.



3.2. Circuit Implementation

The system is powered by a 12V DC battery, which is regulated to 5V using a bulk converter IC (LM2596) to provide a stable power supply for the Arduino Uno and the Darlington pairs IC (ULN2003A, UDN2981A). The Arduino runs a countdown timer that initializes upon startup (0–3 seconds) to process the input/output (I/O), RAM, and counters before activating the traffic control sequence.

The IR sensors are active-low devices, outputting 5V when no vehicle is detected and 0V when a vehicle interrupts the IR signal. The data gathered by the sensors is processed by the microcontroller to adjust the countdown timer, which controls how long the traffic lights (LEDs) remain illuminated.

A common cathode dual 7-segment display is used to show the countdown timer for each lane. The 7-segment display is connected to data lines and selector lines, with high logic supplied to the data lines and the selector lines grounded. The Arduino powers the data lines via the sourcing IC (UDN2981A), which amplifies the voltage to 5A. Pull-down resistors (1 KΩ) are used in the display circuit to discharge any residual voltage, ensuring quick response times.

The microcontroller also controls the selector pins via the sinking IC (ULN2003A), which grounds the selector lines to determine which data is displayed on the 7-segment display. Pull-up resistors (10 KΩ) are used in the sinking IC circuit to further stabilize the system and eliminate residual voltage.

The IR sensors are connected to the analog pins A0 through A5 on the Arduino, and the LEDs are connected to digital pins 9, 12, and 13. Figure 5 shows the schematic diagram of the circuit.

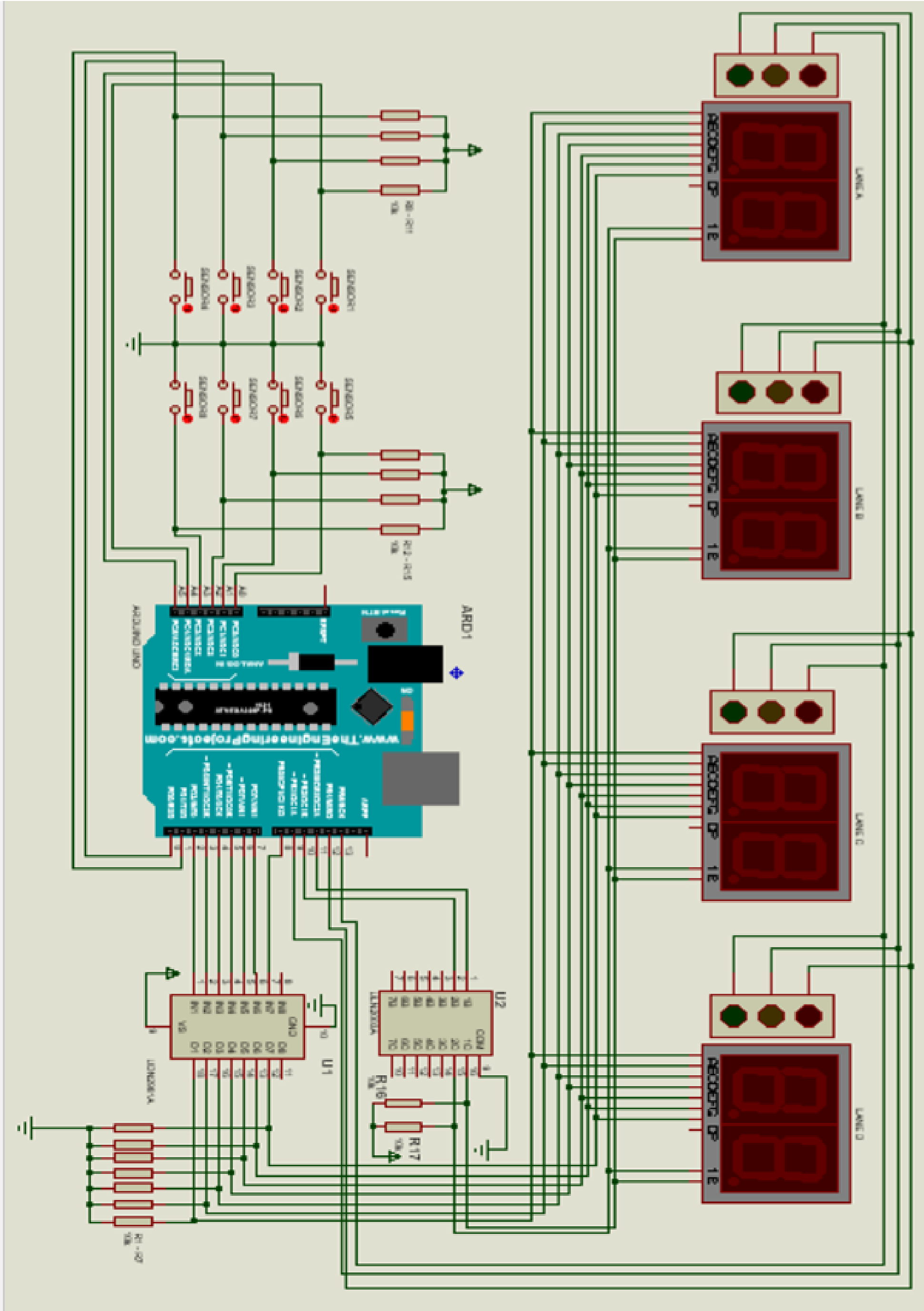


Figure 5. Complete system circuit schematic diagram.

4. Results and Discussion

4.1. Project Construction

The preliminary implementation of the project was first tested using a breadboard. Each block of the circuit, as shown in the system diagram, was tested separately on the breadboard to ensure proper functionality. Once the testing phase was completed, the components were transferred to a Vero board for final installation.

The final circuit construction was carried out on a Vero board as seen in Figure 6. Integrated circuit sockets were used to make troubleshooting and part replacement easier. The remaining components, including the 7-segment display, were soldered onto the Vero board for the final build. A wooden platform was used for the system's physical construction, considering the space required for the four-way traffic light demonstration.

The wooden platform used for the project measured 60 cm in width, 75 cm in height, and 2 cm in thickness, with all components mounted securely on top.

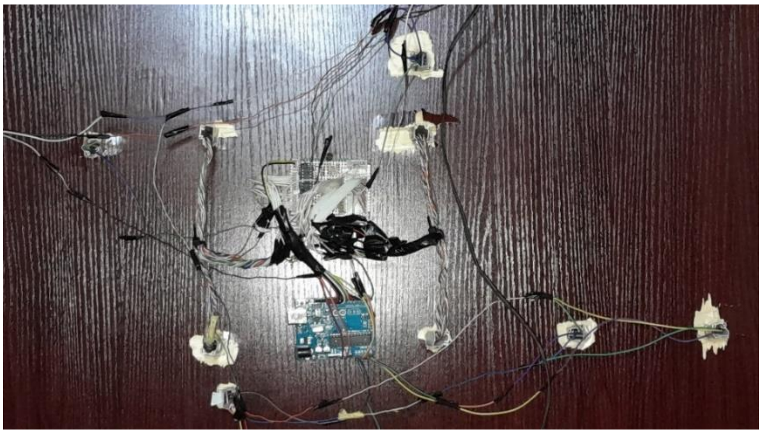


Figure 6. Circuit connection on vero board.

4.2. System Packaging

The final packaging of the system was designed for practical demonstration. A wooden platform supported the display, and plastic materials were used for traffic light supports, which were mounted at right angles on the board. Infrared sensors were placed strategically using glue to ensure stability. The completed system prototype is depicted in Figure 7.

Figure 7. Prototype of a four-way traffic light.

4.3. System Testing and Discussion

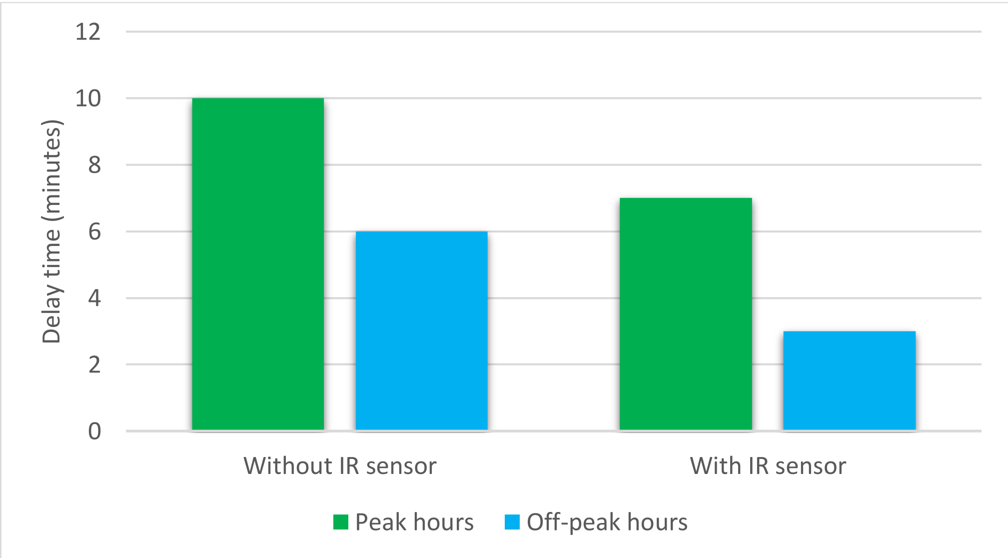
Each block unit of the system was tested separately for functionality. Key tests included power supply unit, infrared sensors, and system stability. The voltage consistency and temperature stability were tested, confirming that it met the required specifications. The infrared sensors were examined to ensure they provided adequate coverage for detecting vehicles in each lane. Furthermore, the entire system was powered up to test stability and verify the polarity of connections across all components.

Table 1 presents the reduction in traffic delay achieved by the system during peak and off-peak hours. A significant decrease in delay times was observed when using the IR sensor-based system, particularly during off-peak hours. The traffic delay reduction is seen in Figure 8.

Table 1. Traffic delay reduction.

Parameters	Delay without IR sensor (minutes)	Delay with IR sensor (minutes)	Delay time reduction (%)
Peak hours	10	7	30
Off-peak hours	6	3	50

Figure 8. Reduction in traffic delay.

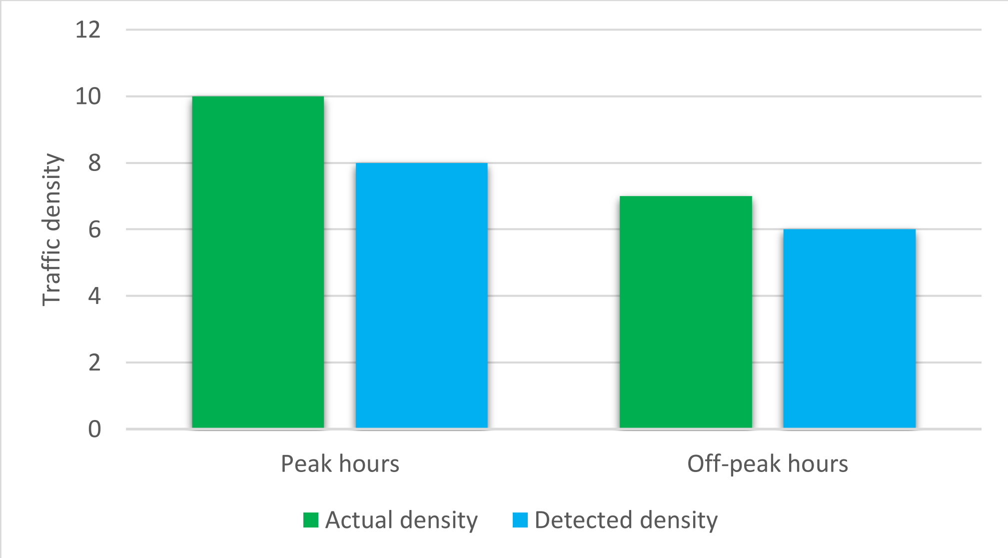


The system's performance in detecting traffic density was evaluated, with detection accuracy ranging between 80% and 85.71% during peak and off-peak hours, respectively. The performance of the system is dependent on some factors such as environmental, traffic and IR sensor conditions. The density detection accuracy is shown in Table 2 and Figure 9.

Table 2. Traffic density accuracy.

Condition	Actual traffic density	Detected traffic density	Accuracy (%)
Peak hours	10	8	80
Off-peak hours	7	6	86

Figure 9. Accuracy of traffic density detection.



The system's response time refers to the time taken for the sensors to detect an obstruction and send a signal to the microcontroller, which then adjusts the traffic light. Table 3 and Figure 10 show the response times recorded during six testing attempts, with an average response time of 38.17 milliseconds.

Table 3. System response time.

Number of attempts	Time (ms)
1	34
2	38
3	43
4	37
5	38
6	39
Average	38.17

Figure 10. System response time.

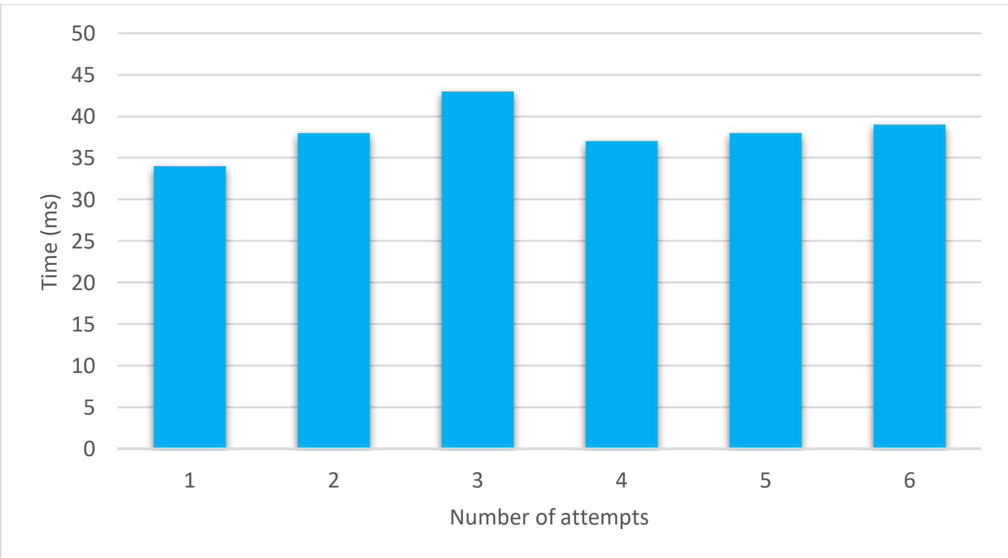


Table 4 shows how the traffic light timing changes based on the classified vehicle density levels—Low, Medium, and High. The system adapts the red, yellow, and green light durations according to the number of vehicles detected.

Table 4. Traffic light timing based on density classification.

Density	Light timing (s)		
	Red	Yellow	Green
Low	20	4	30
Medium	30	4	45
High	50	4	60

5. Conclusions

This study demonstrates the effective use of a microcontroller to regulate traffic at a road junction, specifically focusing on a four-lane intersection. We explored the optimization of traffic light controllers through the integration of Infrared sensors and the Arduino Uno ATmega 328p microcontroller. Our objective was to reduce traffic delays associated with conventional traffic signals, and our design successfully achieved this goal. The traffic light system was designed, implemented, and integrated with the necessary hardware and software components, resulting in a user-friendly interface that enhances overall functionality. Furthermore, this project has the potential to be automated, providing a robust solution for monitoring and managing traffic control, thereby contributing to the development of an efficient road system.

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

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