Tanzania Journal of Engineering and Technology 2025, **44**(1):190-203
OPEN ACCESS articles distributed under Creative Commons
Attribution Licence [CC BY-ND]
Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

Copyright © 2025 College of Engineering and Technology, University of Dar es Salaam
ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v44i1.1141

Regular Research Manuscript

Development of a Microcontroller-Based Intelligent Traffic Light Control System for Vehicular Movement in T-Junctions

Frederick Ojiemhende Ehiagwina[†], Seun Musiliu Olatinwo, Abdultawwab Ayotunde Ibiyeye, Lateef Olashile Afolabi, Olusina Teslim Olumbe-Salau

Department of Electrical/Electronic Engineering, Federal Polytechnic Offa, Kwara State, Nigeria

[†]Corresponding Author: frederick.ehiagiwna@fedpoffaonline.edu.ng; ORCID: 0000-0002-1527-4376

ABSTRACT

This research is devoted to the issue of regulating traffic congestion in major cities using light-dependent resistors coupled with the PIC16F877A microcontroller. This study proposes an intelligent traffic control system for T-Junctions, utilizing sensing and control to optimize traffic flow through dynamic phase adjustments and congestion reduction, enabled by a microcontroller-based decision-making system. The proposed system reduces traffic congestion, automates control, and enhances safety, minimizing accidents and lowering infrastructure costs. Under simulated environment, it demonstrates an average response time of 50 ms and achieves 99% accuracy in displaying the correct countdown. Finally, the number of state transitions handled per minute is 60 transitions per minute under normal traffic conditions.

ARTICLE INFO

Submitted: **Dec. 13, 2024**

Revised: **Mar. 5, 2025**

Accepted: **Apr. 8, 2025**

Published: **Apr. 2025**

Keywords: *Traffic congestion, Microcontroller, Intelligent system, Automated control, Road safety.*

INTRODUCTION

The rapid urbanization and the significant rise in vehicle numbers have led to severe traffic congestion in modern cities, highlighting the inadequacies of conventional traffic control systems. Intelligent Traffic Control Systems (ITCS) offer a promising alternative by leveraging modern technology to enhance traffic flow, alleviate congestion, and improve road safety (Lieberthal *et al*., 2024; Lu *et al*., 2021). As urban road networks expand and existing infrastructure resources remain constrained, the intelligent management of traffic has emerged as a critical technical challenge. While optimizing traffic flow can yield environmental and economic benefits, it may also inadvertently increase demand, necessitating careful consideration of the implications of such improvements (Agatz *et al*., 2021; Khan & Ivan, 2023; Pompigna & Mauro, 2022).

The conventional traffic control systems exhibit significant inefficiencies, including unresponsiveness to real-time scenarios, prolonged queues, and increased fuel consumption, that heightened carbon emissions. This has created an urgent need for alternative methods that effectively address these weaknesses, thereby improving the reliability, cost-effectiveness, and efficiency of transportation networks in urban areas

(Kumar, 2023; Xiao *et al*., 2024). This research aims to develop an intelligent traffic system using light-dependent resistors (LDRs) and the PIC16F877A microcontroller. The objectives are to design an LDR network for vehicle detection, implement real-time traffic signal control, and evaluate system performance. By dynamically adjusting traffic signals based on real-time vehicle data, the system aims to improve traffic flow, particularly at congested T-junctions, and enhance road safety.

Overview of Intelligent Traffic Systems

T-junctions can often experience congestion and delays due to the conflicting traffic flows from different directions. Effectively managing the traffic flow and signalling at such junctions are crucial for improving overall traffic efficiency and reducing wait times for vehicles. Conceptually, ITCS is designed to manage traffic flow dynamically using advanced technologies. This research aims to develop an intelligent traffic control system that can efficiently manage the traffic at a T-junction. The existing ITCS implementation strategies are reviewed in this section of the paper.

Vehicle Detection Technologies: A range of vehicle detection methods are employed in Intelligent Transportation Systems (ITS), including inductive loop sensors, infrared sensors, light-dependent resistors (LDRs), and cameras. These technologies play a crucial role in monitoring traffic flow and enabling real-time traffic management. This section discusses these technologies, focusing on their advantages and limitations.

Inductive Loop Sensors

Inductive loop sensors are commonly used in traffic control systems to detect the presence of vehicles at intersections and other points on the road. They operate based on the principle of electromagnetic induction. They consist of a loop of wire embedded in the pavement or road surface. The loop is typically made of insulated copper or aluminum wire and is installed in a slot cut into the pavement. The slot is then filled with a sealing material to protect the wire and ensure durability (Klein, 2024; Oluwatobi *et al*., 2021).

When an electric current flows through the loop, it creates a magnetic field around it. This field is stable when there are no metal objects (like vehicles) in the vicinity. When a vehicle, which contains a large amount of metal, passes over or stops on the loop, it alters the magnetic field due to its inductive properties. This change in the magnetic field induces a change in the electrical characteristics of the loop. The changes in the magnetic field are detected by the sensor's control unit, which processes the signal to determine the presence or absence of a vehicle.

The sensor then sends a signal to the traffic control system, indicating that the loop is occupied by a vehicle. Inductive loop sensors are widely used to control traffic lights at intersections. They can detect the presence of vehicles waiting at a red light or approaching an intersection. This information helps in adjusting the signal timing, reducing wait times, and improving traffic flow (Marszalek *et al*., 2018; Ripka *et al*., 2021).

These sensors can also be used for vehicle counting and traffic monitoring purposes. By tracking vehicle movements, they provide valuable data on traffic volume, speed, and patterns, which can be used for traffic management and planning. In some traffic systems, inductive loops are used to prioritize certain types of vehicles, such as emergency vehicles or public transportation. The presence of these vehicles can trigger special signal patterns to ensure quicker passage.

Inductive loop sensors are known for their reliability and durability, offering accurate vehicle detection, including presence, count, and classification, while functioning effectively in various weather conditions.

Their non-intrusive installation minimizes traffic disruption, and they require low maintenance compared to other sensor types. However, the installation process can be complex and time-consuming, often necessitating road closures and specialized equipment. Additionally, their performance may be influenced by environmental factors such as pavement conditions and temperature variations, leading to potential detection errors. The limited detection zone restricts their coverage to vehicles directly over the loop, which may result in missed detections in adjacent lanes, particularly for stopped or slow-moving vehicles (Finley *et al*., 2024; Klein, 2024).

Infrared Sensors

Infrared sensors are another technology used in traffic control systems, offering an alternative to inductive loop sensors. Infrared (IR) sensors operate based on the emission and detection of infrared light. They use either active or passive infrared technologies to detect vehicles. Active infrared sensors emit a beam of infrared light towards roads or intersections, detecting vehicles by measuring the intensity and timing of the reflected light when a vehicle enters the beam path. In contrast, passive infrared sensors identify changes in infrared radiation levels caused by the heat emitted from vehicles. These sensors process the detected signals to ascertain vehicle presence, speed, and direction. The information gathered from both types of sensors is transmitted to traffic control systems, facilitating the management of traffic lights, monitoring traffic flow, and collecting data for traffic management. This data is crucial for optimizing signal timings, reducing congestion, and aiding in traffic planning by providing insights into vehicle volume, speed, and occupancy (Nellore & Hancke, 2016; Tasgaonkar *et al*., 2020).

Infrared sensors offer a wide detection range, enabling the monitoring of multiple lanes simultaneously and effectively identifying stopped or slow-moving vehicles, which is a limitation of inductive loops. They are less influenced by pavement changes and temperature variations, and they are easier to install and maintain. However, they face challenges including susceptibility to interference from other infrared sources, reduced accuracy in adverse weather conditions, higher initial costs, reliance on a clear line-of-sight, and the potential for false detections (Klein, 2024; Simbeye, 2023).

Light Dependent Resistors in Traffic Systems

Light dependent resistors (LDRs) are increasingly utilized for vehicle detection due to their affordability and simplicity. They operate on the principle of photoconductivity, where their electrical resistance decreases in response to light exposure, generating electron-hole pairs that enhance conductivity. The degree of resistance change is directly proportional to light intensity, making LDRs effective for ambient light detection and potential traffic signal adjustment. LDRs primarily detect light presence rather than vehicle identification and are sensitive to environmental lighting changes, which can lead to inconsistent detection. Despite their cost-effectiveness and minimal electronic requirements, LDRs exhibit limitations such as slow response times and nonlinear resistance changes, which can hinder accurate light measurement. (Agramelal *et al*., 2023; Jadhav *et al*., 2022). Consequently, while they are valuable in various applications, their use in modern traffic control systems is often overshadowed by more advanced sensor technologies that address these limitations. Hence, in this research a microcontroller-based data logger system was incorporated with LDRs for enhance and intelligent vehicle detection and traffic control system. The microcontroller-enhanced system enables real-time traffic monitoring by collecting and recording data, allowing controllers to assess flow and make informed decisions. LDRs detect light intensity changes from vehicles, enabling the microcontroller to accurately measure traffic volume and optimize signal timing, while dynamic adjustments based on real-time data reduce congestion and wait times. Additionally, the data logger stores historical data for pattern analysis, empowering controllers to identify trends and refine traffic management strategies.

This system also improves safety and efficiency. Real-time data helps controllers detect hazards like congestion or accidents, enabling proactive interventions. Optimized signal timings and traffic flow reduce congestion, shortening travel times and improving air quality. Furthermore, the microcontroller-based system can integrate with intelligent transportation systems (ITS) for a holistic traffic management solution. By leveraging this technology, traffic controllers can make data-driven decisions, enhance safety, and boost the overall efficiency of the transportation network (Modieginyane *et al*., 2018; Sarrab *et al*., 2020).

Related Works on Intelligent Traffic System

ITCS offers various approaches to addressing urban traffic congestion and reducing accidents. However, traditional traffic signals are not able to react instantly to changing traffic patterns, which frequently results in congestion and lengthier travel times (Wu *et al*., 2018). Thus a fog computing-based intelligent traffic light control system to get around these restrictions was proposed by Wu et al. (2018). Using a fog computing platform, the system computes and disseminates traffic flow data at intersections and other locations. An intelligent control method was created to coordinate lights across crossings using traffic flow at these intersections as essential parameters. This increases traffic efficiency and reduces congestion across the network. According to simulation data, this technology improves intersection efficiency and lessens problems with traffic flow in general.

Bali *et al*. (2020) noted that because emergency vehicles like fire trucks and ambulances find it difficult to get to their destinations on time, urban road congestion has led to a considerable increase in accidents and a greater death toll. The authors suggested a solution to this problem by establishing "Green Corridors" for emergency vehicles utilising IoT-enabled technologies. Emergency vehicles may avoid traffic thanks to this system, which could save lives and cut down on delays. By using an RFID reader to scan the ambulance's RFID tag and notify traffic lights to turn green, the IoT offers a clever traffic control solution. Additionally, it warns cars up ahead to yield so the ambulance can pass. By reducing delays and speeding up reaction times in emergency circumstances, this integrated system guaranteed that emergency vehicles may arrive at their destinations on time.

Jayalakshmi (2024) presented a real-time traffic control system that utilizes computer vision and embedded computing technologies. By leveraging OpenCV and pre-trained cascade classifiers, the system detected vehicles in live traffic footage. Integrated with cameras and Raspberry Pi devices, it captures real-time data on traffic density and flow in urban areas. The system processed video frames to assess traffic conditions and identify congestion. This information was used to dynamically adjust traffic signals, optimizing flow and reducing congestion. The research detailed the system's architecture, algorithms, and integration, demonstrating its effectiveness in improving urban traffic management. By combining computer vision and embedded computing, this system offers real-time insights and responsive control to enhance road safety and ensure smoother traffic movement.

Intelligent Traffic Control Systems (ITCS) have demonstrated notable benefits, including significant efficiency improvements, such as enhanced traffic flow and reduced congestion through real-time data and adaptive signal control. By leveraging various data sources like sensors, cameras, and GPS, these systems enable more accurate traffic predictions and management strategies, while adaptive algorithms help adjust control measures based on real-time conditions, optimizing traffic flow. Additionally, ITCS solutions can reduce environmental impacts by minimizing stop-and-go traffic, thereby decreasing fuel consumption and emissions.

However, challenges exist, including high implementation and maintenance costs, complexities in integrating new technologies with existing infrastructure, and concerns about data privacy and security, particularly with the collection of personal data. Scalability is also an issue, as certain solutions may struggle to accommodate the demands of rapidly growing urban areas with dynamic traffic conditions.

METHODS AND MATERIALS

System Architecture

The system architecture outlines the overall design of the intelligent traffic system, including the placement of sensors, microcontroller configuration, and traffic signal control logic.

The system aims at managing traffic at a T-junction using a PIC16F877A microcontroller, which controls traffic lights and 7-segment displays to show countdown timers. The PIC16F877A microcontroller is a versatile, cost-effective solution for applications like robotics, automation, and internet of things (IoT) projects. It features a high-performance reduced instruction set computing (RISC) processor with fast instruction execution, 14.3 KB of flash program memory for complex code, and 33 input/output (I/O) pins for flexible peripheral connectivity. Equipped with a 10-bit, 8-channel analogue to digital converter (ADC), it ensures precise analogue signal conversion, while (universal asynchronous receiver-transmitter (UART), serial peripheral interface (SPI), and inter-integrated circuit (I2C) support seamless serial communication. With 14 interrupt sources, low power modes, and a wide operating voltage range (2.0V to 5.5V), it efficiently handles asynchronous events and suits battery-powered designs. Operating at up to 20 MHz and backed by extensive development tools, documentation, and a large developer community, the PIC16F877A delivers robust performance and broad applicability.

The system also uses LDR sensors to detect the presence of vehicles and adjust the traffic light timings accordingly. The block diagram of a typical traffic control system is shown in Figure 1.

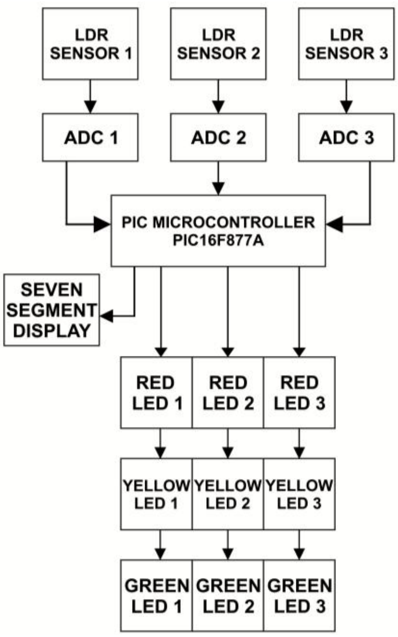

Figure 1: Block diagram of a traffic control system.

a. Components and Materials

This section lists and describes the hardware and software components used in the project, including LDR sensors, the PIC16F877A microcontroller, traffic lights, and additional circuitry.

b. Microcontroller Programming

Describes the programming of the PIC16F877A microcontroller to process sensor data and control traffic signals. Includes flowcharts and code snippets to illustrate the control logic. The pin layout of PIC16F877A microcontroller is shown in Figure 2.

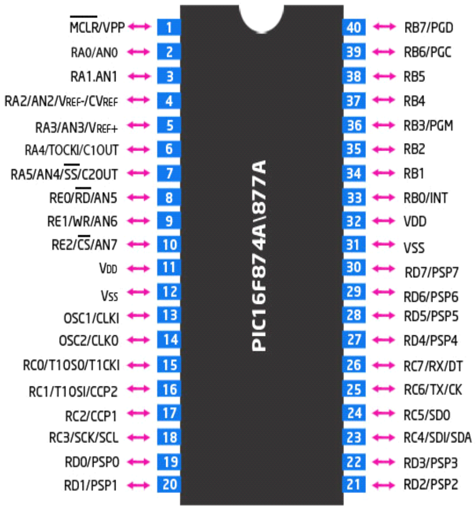

Figure 2: Pin Layout of PIC16F877A.

c. *Features:* 40-pin microcontroller with multiple I/O ports, ADC channels, timers, and serial communication interfaces.

d. *Programming*: Typically programmed in C using MPLAB X IDE and XC8 compiler.

e. *Peripheral Interface*: This can interface with a variety of sensors and output devices, making it suitable for embedded control applications.

The photograph of a 7-segment display (chip) is shown in Figure 3, while that of a LDR is shown in Figure 4.

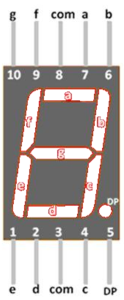

Figure 3: Segment Display (chip).

f. Seven-Segment Display Control

- **Multiplexing**: Reduces the number of I/O pins required by controlling one digit at a time very quickly. The seven-segment is interfaced directly to the microcontroller.
- **Display Logic**: Update display values based on timer values calculated in the control logic.

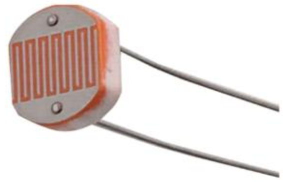

Figure 4: Photograph of LDR.

g. LDR Vehicle Sensors

- **Operation**: LDRs change resistance based on light intensity; used in a voltage divider to produce a varying voltage signal.
- **ADC Conversion**: PIC16F877A's ADC converts the analogue voltage to a digital equivalent value for processing.
- **Calibration**: Adjusted sensor thresholds to detect vehicle presence accurately under varying light conditions.

h. System Integration

Integrating sensors, microcontrollers, and traffic signals into a cohesive Intelligent Traffic System (ITS) involves a systematic approach that ensures effective communication and control. This setup typically includes sensors for vehicle detection, a microcontroller for processing and decision-making, and traffic signals for managing vehicular flow. The PIC16F877A microcontroller, with its versatile I/O capabilities, is well-suited for this application.

Integrating sensors, a microcontroller, and traffic signals into a cohesive ITS involves careful planning and precise implementation. The PIC16F877A microcontroller is well-suited for this application, providing the necessary processing power and I/O capabilities. By following the described setup and using the provided code, an effective and efficient ITS can be developed, improving traffic flow and enhancing safety.

The system should be able to adapt to changing traffic conditions in real time, adjusting the signal timings and countdown displays accordingly.

This dynamic control and responsiveness are essential for effectively managing traffic flow and minimizing congestion at the T-Junction. By addressing these key aspects, the intelligent traffic control system aims to enhance the overall efficiency of the T-junction, reduce waiting times for vehicles, and provide a more user-friendly interface for drivers through the use of countdown timers and visual displays. The complete circuit diagram of the proposed automatic traffic, T-Junction traffic control system is shown in Figure 5.

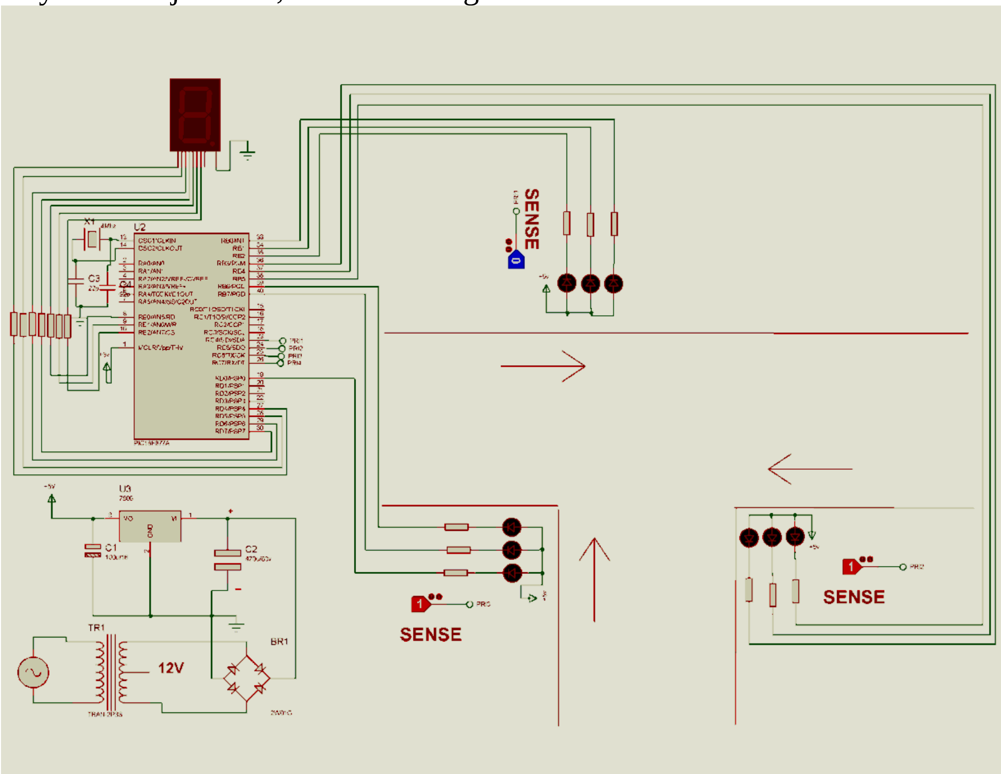

Figure 5: Circuit diagram of a traffic lights system.

System Design

Voltage and Current Calculations:
When reading from the ADC, the LDR voltage divider provides a voltage proportional to the light intensity.

Voltage Calculation:

- $ADC\ Value\ Range: 0\ to\ 1023\ (10-bit\ ADC)$
- $Reference\ Voltage: 5V$
- $Voltage\ =\ \left(\frac{ADC\ Value}{1023}\right)\ \times\ 5V$

Current Calculation: Using a current sensor (ACS712), the output voltage from the sensor is proportional to the current.

- $Sensor\ Output\ Voltage\ =\ (Current\ \times\ Sensor\ Sensitivity)\ +\ Sensor\ Zero\ \ Current\ Voltage$

Timer Calculations:
Using Timer0 for 1-second intervals.

- $Prescaler: 256$
- $Clock\ Frequency: 4\ MHz\ (assuming\ 4\ MHz\ crystal)$
- $Instruction\ Cycle: 1\ \mu s\ \left(\frac{4\ MHz}{4}\right)$
- $Timer0\ Overflows\ every\ 256\ \mu s$
- $Preload\ Timer0\ with\ 6\ to\ achieve\ \ 1\ second\ delay$:

$$Preload\ Value\ =\ 256\ -\ (256 \times 1\ \mu s)\ =6\ units$$

IMPLEMENTATION AND TESTING

Prototype Development

This section of the paper describes the step-by-step process of building the prototype, which include assembly, wiring, and initial setup are described in this section. Figure 6 outlines the flowchart of system implementation. Figure 7 depicts the features of the proposed hardware implementation of the traffic control system.

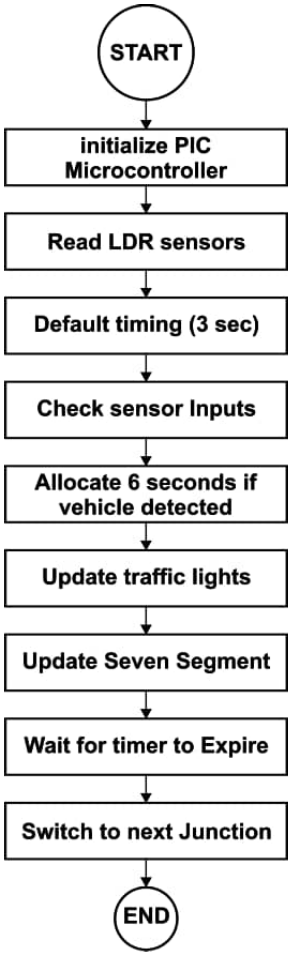

Figure 6: Flowchart of an Intelligent Traffic System.

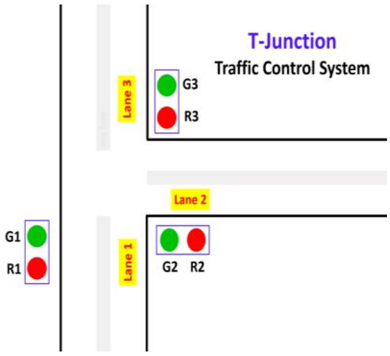

Figure 7: Proposed T-junction traffic system.

Hardware Connections

LDR Sensors:

Connection: Each LDR is connected in a voltage divider circuit to one of the PORTC pins of the PIC16F877A (RC4, RC5, RC6).

Connection of the 7-Segment Displays

The segments of 7-segment display are connected to PORTD and E (RD4, RD5, RD6, RD7, RE0, RE2, RE2), with current-limiting resistors of 100Ω.

Switch Mode Power Supply Used for powering the project is a 220 AC to 5V DC switch mode power supply unit.

The control logic involves managing the states of traffic lights and updating the countdown timers based on sensor inputs and pre-defined intervals.

State Machine

- **GREEN:** Vehicles can pass.
- **YELLOW:** Warning state before switching to RED.
- **RED:** Vehicles must stop.

Transitions: The state transitions are time-based, with the possibility of adjusting based on LDR sensor input (e.g., extending green time if vehicles congestion are present).

Timers and Counters:

- Timer used to manage the duration of each traffic light state.
- 7-segment display shows the countdown of the current light state.

This design ensures efficient traffic control at the T-junction by dynamically adjusting the traffic light timings based on real-time vehicle detection, thereby enhancing traffic flow and reducing congestion.

Software Development

The development of the control software, including sensor data acquisition, signal processing algorithms, and traffic light control logic are presented in details in this section of the paper.

Software Development Steps

The following steps were involved in the software development.

Initialization:

The pseudocode for initializing all peripherals, including the Analog-to-Digital Converter (ADC) for Light-Dependent Resistor (LDR) sensors, I/O pins for traffic lights and 7-segment displays, and timers for 1-second intervals is shown in Table 1.

Table 1: Peripheral initialization pseudocodes

```
// Function to initialize the Analog-to-Digital Converter (ADC) for LDR sensors
FUNCTION init_ADC
   CONFIGURE ADC:
      ENABLE ADC
      SELECT Channel 0 // For LDR sensor input
      SET Clock Source to Fosc/32 // For appropriate conversion speed
END FUNCTION

// Function to initialize I/O pins for traffic lights and 7-segment displays
FUNCTION init_pins
   CONFIGURE PORTB:
      SET as Output // For controlling 7-segment displays
   CONFIGURE PORTC:
      SET as Output // For controlling traffic lights
   CONFIGURE PORTA:
      SET as Input // For reading LDR sensor data
END FUNCTION

// Function to initialize timers for 1-second intervals
FUNCTION init_timers
   CONFIGURE Timer0:
      SET Clock Source to Internal Instruction Cycle
      ASSIGN Prescaler to Timer0
      SET Prescaler Value to 256 // For timing scaling
      SET Preload Value to 6 // To achieve 1-second delay
      ENABLE Timer0 Interrupt // To trigger on timer overflow
      ENABLE Global Interrupts // To allow interrupt handling
      ENABLE Peripheral Interrupts // To support timer interrupts
END FUNCTION
```

Reading LDR Sensors

Table 2 shows the pseudocode for reading LDR values using the ADC and converting the readings to digital values representing vehicle presence.

Table 2: LDR sensor reading pseudocodes

```
// Function to read ADC value from a specified channel
FUNCTION read_ADC(channel)
   CLEAR Previous Channel Selection
   SET ADC Channel to channel // Select the specified channel
   WAIT 2 milliseconds // Allow acquisition time for ADC
   START ADC Conversion
   WHILE Conversion is in Progress
      // Wait until conversion completes
   ENDWHILE
   READ ADC Result // Combine high and low bytes for 10-bit value
   RETURN ADC Result
END FUNCTION

// Function to determine vehicle presence based on LDR reading
FUNCTION get_vehicle_presence
   SET adc_value = CALL read_ADC(0) // Read from channel 0 (LDR connected to AN0)
   IF adc_value > VEHICLE_THRESHOLD THEN
      RETURN True // Vehicle is present
   ELSE
      RETURN False // No vehicle detected
   ENDIF
END FUNCTION
```

Traffic Light State Machine

The pseudocode for implementing a state machine to control traffic lights, transitioning between GREEN, YELLOW, and RED states.

Table 3: Traffic light state machine pseudocodes

```
// Define traffic light states
ENUM TrafficState = {GREEN, YELLOW, RED }

// Initialize global variables
SET currentState = GREEN // Start with green light
SET timer = 0 // Tracks seconds in current state
SET greenDuration = 10 // Green light duration in seconds
SET yellowDuration = 3 // Yellow light duration in seconds
SET redDuration = 10 // Red light duration in seconds

// Function to update traffic light states and control
FUNCTION update_traffic_lights
   SWITCH currentState
      CASE GREEN:
         ACTIVATE Green Light // Turn on green light
         DISPLAY (greenDuration - timer) // Show remaining time on 7-segment display
         IF timer >= greenDuration THEN
            SET currentState = YELLOW
            SET timer = 0
         ENDIF
         BREAK
      CASE YELLOW:
         ACTIVATE Yellow Light // Turn on yellow light
         DISPLAY (yellowDuration - timer) // Show remaining time on 7-segment display
         IF timer >= yellowDuration THEN
            SET currentState = RED
            SET timer = 0
         ENDIF
         BREAK
      CASE RED:
         ACTIVATE Red Light // Turn on red light
         DISPLAY (redDuration - timer) // Show remaining time on 7-segment display
         IF timer >= redDuration THEN
            SET currentState = GREEN
            SET timer = 0
         ENDIF
         BREAK
   ENDSWITCH

   INCREMENT timer // Increment timer for next second
   WAIT 1 second // Delay to maintain 1-second countdown
END FUNCTION
```

7-Segment Display Update

To use multiplexing to update the 7-segment displays with the countdown timer, the following pseudocodes shown in Table 4 is applied.

Table 4: Pseudocodes for the 7-segment display update

```
// Define segment map for 7-segment display (0-9)
CONSTANT segment_map = [patterns for digits 0 to 9] // Maps digits to 7-segment patterns

// Function to display a number on 7-segment displays using multiplexing
FUNCTION display_number(number)
   SELECT First Digit // Activate first 7-segment display
   SET Display Output to segment_map[number / 10] // Show tens place
   WAIT 5 milliseconds // Allow display to persist
   SELECT Second Digit // Activate second 7-segment display
   SET Display Output to segment_map[number % 10] // Show units place
   WAIT 5 milliseconds // Allow display to persist
END FUNCTION

// Main loop to read sensor data, update traffic lights, and display countdown
FUNCTION loop
   WHILE True
      IF get_vehicle_presence() THEN
         SET greenDuration = 15 // Extend green light duration if vehicle detected
```

```
        ELSE
            SET greenDuration = 10 // Default green light duration
        ENDIF
        CALL update_traffic_lights // Update traffic light states and countdown
    ENDWHILE
END FUNCTION
```

The constructed prototype is shown in Figure 8.

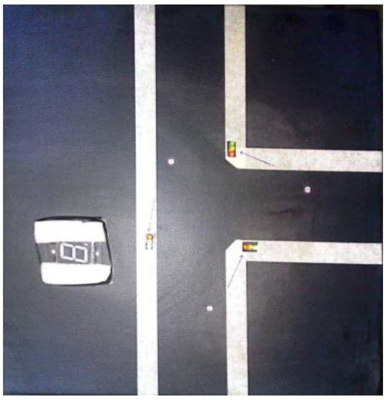

Figure 8: Construction of the traffic control system.

Testing Methodology

The testing procedures used to evaluate the performance of the traffic light control system include unit testing, integration testing, and system testing, each focusing on different aspects of functionality. In unit testing, individual components, such as LDR analog readings, traffic light state transitions, and 7-segment display updates, were tested in isolation to ensure they function correctly. Integration testing followed, where the interactions between components were assessed to verify that LDR readings accurately influenced traffic light timings and that the countdown display worked as expected. System testing involved simulating real-world scenarios, including varying traffic conditions, to observe the overall system's response and confirm it met the specified requirements. This comprehensive testing methodology is crucial for ensuring the reliability and safety of the system, particularly in traffic light control applications. It helps identify issues early, ensuring the system operates as intended, handles edge cases, and maintains robustness under diverse conditions, ultimately enhancing system quality and reliability.

Results and Analysis

The results of the testing phase are presented which include, data on system responsiveness, accuracy of vehicle detection, and effectiveness in managing traffic flow. The results shown in Table 5 were analyzed to assess the system's performance. This is crucial for understanding how well the system performs and identifying areas for improvement. It involves presenting the outcomes of the testing phase, interpreting the results, and providing insights into the system's behavior.

- Total Tests Carried out = 50
- Passed = 45
- Failed = 5

Reliability is 0.9 (= 90%).

Table 5: Developed system tests

Test Case ID	Description	Expected Result	Actual Result	Status	Comments
TC-01	Test ADC value range	ADC value between 0 and 1023	ADC value within range	Pass	
TC-02	Test traffic light state transition	Lights transition correctly	Lights transition correctly	Pass	
TC-03	Test LDR sensor input	Adjusts green light duration	Incorrect adjustment	Fail	Sensor input handling issue
TC-04	Test 7-segment display countdown	Correct countdown display	Correct countdown display	Pass	

TC-05	Test power failure recovery	Recovers to correct state	Incorrect state after power	Fail	Issue with state restoration

Successes

The traffic light system functions correctly, transitioning smoothly between states, while the 7-segment display accurately shows the countdown, ensuring a reliable and efficient operation.

Performance Metrics

The system demonstrates strong performance, with an average response time of 50ms and a maximum response time of 75ms after sensor input, while the 7-segment display achieves 99% accuracy in displaying the correct countdown. The system's throughput, that is, the number of state transitions handled per minute was 60 under normal traffic conditions.

Result Discussion

The development and implementation of the PIC16F877A-based T-junction traffic light control system have demonstrated the feasibility and effectiveness of using micro controller-based solutions for traffic management. The integration of a 7-segment display for countdown timers and LR sensors for vehicle detection enhances the system's functionality and provides clear benefits for traffic flow optimization. The traffic light system successfully manages the flow of vehicles at the T-junction. The transition between different traffic light states is smooth, and the countdown timers provide clear visual cues to drivers, improving their ability to anticipate changes and react accordingly. The system's accuracy in detecting vehicles using LDR sensors is generally reliable, but some discrepancies were noted. These discrepancies highlight the need for further refinement in sensor placement and sensitivity adjustment. The system's reliability was tested under various conditions, and while it performed well in most scenarios, issues were identified, such as incorrect handling of sensor inputs and failure to restore the correct state after power interruptions.

CONCLUSION AND RECOMMENDATION

Conclusion

The current implementation of the PIC16F877A-based T-junction traffic light control system has shown promising results, demonstrating the potential for microcontroller-based traffic management solutions. By addressing the identified areas for improvement and pursuing the outlined future work, the system can be further refined to provide more accurate, reliable, and scalable traffic control. This will contribute to better traffic management, reduced congestion, and enhanced road safety, ultimately benefiting drivers and pedestrians alike.

Recommendations

The following are suggested recommendations for future improvement of the microcontroller-based traffic light control system:

Advanced State Management and Sensors

Building on the current implementation, several avenues for future work can enhance the system's performance, reliability, and scalability. These include refining sensor logic by improving algorithms for better vehicle presence detection and adjusting traffic light durations more accurately, as well as calibrating LDR sensors to enhance detection under various lighting and weather conditions. Additionally, enhancing state management through the implementation of a robust state-saving mechanism, such as EEPROM or other non-volatile memory, would ensure the system can resume the correct state after power interruptions. Thorough state restoration testing should be conducted to validate this process in various scenarios. System optimization can be enhanced through refinements in microcontroller code, which would minimize latency in state transitions and sensor processing. Additionally, the integration of advanced sensors, such as infrared or ultrasonic sensors, could further improve vehicle detection accuracy.

Incorporating Artificial Intelligence (AI) for Enhanced Decision-Making

The proposed vehicle detection system, utilizing light-dependent resistors (LDRs), may be compromised by varying lighting conditions. Integrating AI-driven computer vision or machine learning algorithms, leveraging real-time video feed analysis, can significantly enhance detection accuracy. In addition, AI models leveraging historical and real-time traffic data can dynamically predict congestion and adjust signal timings, enhancing system intelligence and responsiveness compared to rule-based microcontroller approaches. For improved accuracy in traffic monitoring, consider implementing convolutional neural networks (CNNs) for vehicle detection.

Integration of Internet of Things (IoT) for Real-Time Monitoring and Remote Control

Future systems could leverage IoT integration for remote traffic signal monitoring and management via a cloud-based platform. IoT-enabled sensors (ultrasonic, infrared, or camera-based) with wireless connectivity enhance real-time data collection and decision-making. An IoT dashboard enables traffic authorities to monitor congestion, adjust signal timings, and receive performance or failure alerts.

Utilizing More Powerful Microcontrollers for Enhanced Performance

The PIC16F877A microcontroller used in the present system has limitations in processing power, memory, and connectivity. Upgrading to advanced microcontrollers like Arduino Mega 2560, ESP32, or ESP8266 would enhance system capabilities. Specifically, ESP32 offers better connectivity, faster processing, and lower power consumption, making it an ideal replacement for seamless AI and IoT integration.

Enhancing Communication via Wireless Protocols

The system lacks real-time interconnectivity between traffic lights. Implementing wireless communication protocols like LoRa, Zigbee, or MQTT would enable coordinated traffic signal control, optimizing city-wide traffic management.

ACKNOWLEDGEMENT

The authors are grateful to the reviewers for their useful suggestions that have enhanced the manuscript.

REFERENCES

Agatz, N., Hewitt, M., & Thomas, B. W. (2021). “Make no little plans”: Impactful research to solve the next generation of transportation problems. *Networks*, **77**(2), 269–286.

Agramelal, F., Sadik, M., Moubarak, Y., & Abouzahir, S. (2023). Smart Street Light Control: A Review on Methods, Innovations, and Extended Applications. *Energies*, **16**(21), 7415.

Bali, V., Mathur, S., Sharma, V., & Gaur, D. (2020). Smart traffic management system using IoT-enabled technology. *2020 2nd International Conference on Advances in Computing, Communication Control and Networking (ICACCCN)*, 565–568.

Finley, M. D., Venglar, S. P., Florence, D., Charara, H., Brydia, R. E., & Brewer, M. A. (2024). *Evaluation of Wrong-Way Driving Detection Technologies*. Texas A&M Transportation Institute.

Jadhav, A. S., Joshi, V., & Pawar, R. V. (2022). Automatic headlight intensity control using light dependent resistor. *Journal of Physics: Conference Series*, **2325**(1), 12001.

Jayalakshmi, M. (2024). Density Based Traffic Management System. *2024 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*, 1–6.

Khan, A. B. F., & Ivan, P. (2023). Integrating Machine Learning and Deep Learning in Smart Cities for Enhanced Traffic Congestion Management: An Empirical Review. *J. Urban Dev. Manag*, **2**(4), 211–221.

Klein, L. A. (2024). Roadside Sensors for Traffic Management. *IEEE Intelligent Transportation Systems Magazine*.

Kumar, V. (2023). *An Urban Sensing Architecture as Essential Infrastructure for Future Smart Cities Research*. University of Bristol.

Lieberthal, E. B., Serok, N., Duan, J., Zeng, G., & Havlin, S. (2024). Addressing the urban congestion challenge based on traffic bottlenecks. *Philosophical Transactions A*, **382**(2285), 20240095.

Lu, J., Li, B., Li, H., & Al-Barakani, A. (2021). Expansion of city scale, traffic modes, traffic congestion, and air pollution. *Cities*, **108**, 102974.

Marszalek, Z., Zeglen, T., Sroka, R., & Gajda, J. (2018). Inductive loop axle detector based on resistance and reactance vehicle magnetic profiles. *Sensors*, **18**(7), 2376.

Modieginyane, K. M., Letswamotse, B. B., Malekian, R., & Abu-Mahfouz, A. M. (2018). Software defined wireless sensor networks application opportunities for efficient network management: A survey. *Computers & Electrical Engineering*, *66*, 274–287.

Nellore, K., & Hancke, G. P. (2016). A survey on urban traffic management system using wireless sensor networks. *Sensors*, *16*(2), 157.

Oluwatobi, A. N., Tayo, A. O., Oladele, A. T., & Adesina, G. R. (2021). The design of a vehicle detector and counter system using inductive loop technology. *Procedia Computer Science*, *183*, 493–503.

Pompigna, A., & Mauro, R. (2022). Smart roads: A state of the art of highways innovations in the Smart Age. *Engineering Science and Technology, an International Journal*, **25**, 100986.

Ripka, P., Mirzaei, M., & Blažek, J. (2021). Magnetic position sensors. *Measurement Science and Technology*, *33*(2), 22002.

Sarrab, M., Pulparambil, S., & Awadalla, M. (2020). Development of an IoT based real-time traffic monitoring system for city governance. *Global Transitions*, *2*, 230–245.

Simbeye, D. S. (2023). Deployment of Inductive Loop Vehicle Traffic Counters Along Trunk Roads in Tanzania. *Tanzania Journal of Engineering and Technology*, **41**(4).

Tasgaonkar, P. P., Garg, R. D., & Garg, P. K. (2020). Vehicle detection and traffic estimation with sensors technologies for intelligent transportation systems. *Sensing and Imaging*, **21(**1), 29.

Wu, Q., He, F., & Fan, X. (2018). The intelligent control system of traffic light based on fog computing. *Chinese Journal of Electronics*, **27**(6), 1265–1270.

Xiao, M., Chen, L., Feng, H., Peng, Z., & Long, Q. (2024). Smart City Public Transportation Route Planning Based on Multi-objective Optimization: A Review. *Archives of Computational Methods in Engineering*, 1–25.