Smart Solar-Powered Traffic Signal System

Project Report

Department of Electrical and Electronic Engineering, Faculty of Technology

A REPORT SUBMITTED BY GROUP 1C IN PARTIAL FULFILLMENT OF THE STUDENTS' WORK EXPERIENCE PROGRAMME

FOR THE 2023/2024 ACADEMIC SESSION

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CERTIFICATION

This is to certify that the project work titled ''Smart Solar-Powered Traffic Signal System" was designed and constructed by members of Group 1C in partial fulfillment of the completion of the Students' Work Experience Programme for 2023/2024 academic session in the department of Electronic and Electrical Engineering, Obafemi Awolowo University, Ile Ife, Osun State, Nigeria.

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DEDICATION

We dedicate this group project to our families, whose constant love, encouragement, and sacrifices have sustained us throughout this academic journey. We extend our heartfelt gratitude to our lecturers, supervisors, and mentors for their invaluable guidance and expertise, which have shaped this work. We also appreciate our peers and collaborators for their support and shared commitment to excellence. Above all,we are thankful to God for granting us the strength, wisdom, and unity to successfully complete this project.

ACKNOWLEDGEMENTS

We are beyond grateful to everyone who helped make this project a reality. It's been quite the journey, and we could not have done it without you!

A massive thank you to our lecturers and supervisors, who were like our guiding stars, patiently answering our questions, sharing their expertise, and nudging us to aim higher. To our classmates, friends and sponsors, you made the long hours and tough challenges so much better with your ideas, laughter, and teamwork; we are lucky to have you in our corner. Big respect to the technical staff and lab assistants for helping us figure out the equipment and resources; your support kept us on track. And, most importantly, to our families who cheered us on, dealt with our late-night stress, and kept us going with love and encouragement, you're our true MVPs.

Above all, we thank God for the strength, inspiration, and unity that brought us together to pull this off. From all of us, thank you with all our hearts!

ABSTRACT

Traffic congestion remains a major challenge in urban areas, often caused by inefficient fixed-cycle traffic light systems that fail to respond to real-time conditions. This project presents the design and implementation of a smart solar-powered traffic light system for a three-lane intersection. The system uses an ESP32 microcontroller integrated with ultrasonic sensors to detect vehicle presence and measure traffic density. Based on the sensor inputs, the controller dynamically allocates green light times to lanes with higher congestion, thereby improving flow and reducing idle waiting times.

To ensure reliable operation in regions with unstable electricity supply, the system is powered by a solar panel, charge controller, and battery storage. A transistor switch is used to switch 7 W traffic light bulbs, while 3D-printed modular housings provide durability and ease of installation. Simulation and prototype testing demonstrate the effectiveness of the approach in reducing delays and improving throughput compared to fixed-time systems.

The proposed solution is low-cost, sustainable, and adaptable for developing regions where power and traffic management infrastructure are limited. By integrating renewable energy and adaptive control, this work contributes toward smarter, greener, and more efficient urban traffic management systems.

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Chapter 1

INTRODUCTION

1.1 Background

Urban traffic management is facing increasing pressure as population growth and vehicle density continue to rise. Traditional traffic light systems, which rely on fixed timers, often fail to respond to real-time road conditions, leading to inefficiencies such as unnecessary delays, fuel waste, and elevated emissions. These limitations underscore the need for smarter, more adaptive solutions that can dynamically manage traffic flow. Intelligent traffic systems have emerged as a promising alternative, using embedded microcontrollers and sensors to detect vehicle presence and congestion, thereby optimizing signal timing and improving overall traffic efficiency.

This project introduces a Smart Solar-Powered Traffic Light System tailored for a three-lane intersection. At its core is the ESP32 microcontroller, which processes input from ultrasonic sensors to determine lane-specific traffic density. Based on this data, the system allocates green light time to the most congested lanes, enhancing flow and safety. The physical setup includes a modular 3D-printed traffic light housing with LED displays and a sensor box for optimal detection. Power is supplied via solar panels connected to a charge controller and lead-acid battery, ensuring uninterrupted operation even during grid outages. A transistor switch enables the ESP32 to control high-current LED signals efficiently.

Beyond its technical innovation, the project offers scalable benefits for cities grappling with traffic congestion and unreliable power infrastructure, especially in developing regions. By integrating renewable energy and adaptive control, the system supports sustainability goals while improving road safety and reducing travel delays. The use of low-cost components and 3D-printed modules also highlights the potential for affordable prototyping and deployment. Overall, this solution represents a meaningful step toward smarter, greener urban infrastructure and lays the groundwork for further exploration in intelligent traffic management systems.

1.2 Statement of Problem

Urban traffic congestion has become a persistent issue due to rapid population growth and increased vehicle ownership. Traditional traffic light systems, which rely on fixed-timer cycles, are ill-equipped to handle the dynamic nature of modern traffic flow. These systems often allocate green signals to empty lanes while vehicles in congested lanes remain idle, resulting in wasted time, fuel, and heightened driver frustration. The static nature of conventional traffic control not only reduces efficiency but also contributes to aggressive driving behaviors and delays for emergency vehicles, ultimately compromising road safety and productivity.

Beyond operational inefficiencies, conventional traffic lights are heavily dependent on grid electricity, making them vulnerable to power outages—especially in developing regions where blackouts are frequent. During such failures, intersections become chaotic and dangerous, while rural or remote areas often lack any traffic control due to the high cost of infrastructure deployment. Moreover, existing smart systems in advanced cities tend to rely on expensive technologies like camera-based recognition or cloud-based AI, which are impractical for low-resource environments due to their cost, maintenance demands, and sensitivity to environmental conditions.

Given these challenges, there is a pressing need for a traffic management solution that is adaptive, sustainable, affordable, and scalable. A system capable of detecting real-time vehicle density and adjusting signal timing accordingly can significantly reduce congestion and improve safety. Integrating renewable energy sources like solar power ensures uninterrupted operation while lowering environmental impact and operational costs. By utilizing low-cost components such as ESP32 microcontrollers, ultrasonic sensors, and modular 3D-printed housings, the proposed Smart Solar-Powered Traffic Light System offers a viable alternative for both urban and underserved regions, addressing the core limitations of conventional traffic infrastructure.

1.3 Research Questions

Adaptive Control

- How can real-time vehicle density be measured using low-cost sensors to enable dynamic traffic signal allocation?
- To what extent can such adaptive control reduce congestion, idle-time losses, and red-light violations compared to fixed-cycle systems?

Energy Sustainability

- How can a solar-powered subsystem be designed to ensure reliable operation of traffic signals in areas with unstable grid supply?

Prototype Validation

- How effective is the developed prototype in terms of switching accuracy, energy efficiency, and overall performance under real-world conditions?
- How does the system compare to conventional traffic lights when evaluated using metrics such as waiting time reduction and reliability?

1.4 Research Objectives

1. To address the inefficiencies of fixed-cycle traffic lights and the growing complexity of urban congestion, this project aims to develop an adaptive traffic control system that responds to real-time vehicle density. By analyzing traffic flow patterns at three-lane intersections, the system will identify peak hours, lane-specific congestion, and idle-time losses. Ultrasonic sensors will be integrated with an ESP32 microcontroller to detect vehicle presence under varying conditions, enabling dynamic signal allocation. This real-time responsiveness is expected to reduce delays, improve traffic throughput, and enhance road safety—especially for emergency vehicles—by minimizing unnecessary waiting and red-light violations.

2. Recognizing the vulnerability of conventional traffic lights to power outages and their unsuitability for remote or underserved areas, the project incorporates a solar-powered subsystem to ensure uninterrupted operation. The energy requirements of the system will be calculated to size photovoltaic panels and battery storage appropriately.

3. To validate the system's practicality and scalability, a full hardware prototype will be designed, assembled, and tested. Modular 3D-printed housings will be used for both the traffic lights and sensor units, ensuring durability and ease of deployment. Laboratory and field trials will evaluate switching accuracy, energy efficiency, and overall performance under real-world conditions.

1.5 Scope of Project

The scope of this project is defined as follows:

- The system is specifically designed for deployment at road intersections, particularly those with three lanes, to manage traffic flow more efficiently.
- Ultrasonic sensors are employed to detect vehicle density in each lane, providing real-time data that informs the traffic light control logic.
- Monocrystalline solar panels are used as the primary energy source due to their high efficiency and reliability in various lighting conditions.
- A rechargeable Lithium-ion (Li-ion) battery is utilized to store solar energy, ensuring continuous system operation even during periods of low sunlight or at night.
- The ESP32 microcontroller serves as the central processing unit, coordinating sensor inputs, executing adaptive signal algorithms, and managing power consumption.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Traffic congestion is one of the major challenges faced by modern cities, especially in developing countries where rapid urbanization is not always matched with proportional growth in road infrastructure. Long queues at intersections, increased travel time, and higher fuel consumption are direct consequences of poor traffic management. Recent literature highlights three recurring themes in this domain:

- Traffic control strategies – the evolution from fixed-time control to adaptive and intelligent systems.
- Adaptive scheduling algorithms – methods for allocating green time based on traffic demand.
- Sensing technologies – the role of sensors in providing real-time traffic data for decision-making.

2.2 Traffic Signal Control Systems

Traffic signal control has evolved significantly over the past century. The earliest systems relied on fixed-time schedules, where green and red phases were assigned according to predetermined intervals. The limitations of fixed-time systems motivated the development of actuated signals, which respond to vehicle presence through detectors such as inductive loops or infrared sensors. To address these challenges, researchers began exploring adaptive signal control systems, which allocate green time dynamically based on traffic flow, density, and sometimes even predicted demand.

2.3 Adaptive Traffic Control

Adaptive traffic control refers to systems that adjust signal timings in response to the actual traffic conditions on the road. Unlike fixed-time systems, where green lights are given for the same duration every cycle, adaptive systems monitor traffic demand and distribute green time based on the number of vehicles waiting or moving through an intersection.

A common principle in adaptive control is demand-based scheduling, where lanes with higher traffic flow are given more green time compared to less busy lanes. This helps reduce long queues and waiting times, while still ensuring that all approaches at an intersection receive fair attention.

2.4 Sensors in Traffic Management

Traffic management systems rely heavily on sensors to collect information about vehicle presence, flow, and speed. Traditional sensors such as inductive loops buried under the road, infrared detectors, and video cameras have been widely used. Modern developments have introduced simpler and more flexible alternatives, including ultrasonic sensors, and wireless IoT-based devices.

2.5 Ultrasonic Sensors for Traffic Detection

Ultrasonic sensors operate by sending out high-frequency sound waves and measuring the time it takes for the echo to return after bouncing off an object. This principle, known as time-of-flight measurement, allows the sensor to estimate the distance between itself and a target. The main advantages of ultrasonic sensors are that they are low-cost, easy to install, and non-invasive, since they do not require digging into the road surface.

However, they also have some limitations: their accuracy can be affected by environmental noise, wind, or temperature changes, and they require a clear line-of-sight to detect vehicles reliably. Despite these challenges, ultrasonic sensors remain a practical option for adaptive traffic light systems, especially in regions where affordability and ease of deployment are key priorities.

2.6 Research Gap

Most smart traffic light projects rely on advanced sensors such as cameras, infrared, or radar to collect traffic data. While these systems can be effective, they are often expensive, complex to maintain, and sensitive to environmental conditions. This limits their use in many developing regions where resources and infrastructure are constrained.

At the same time, many simpler systems still depend on fixed-time scheduling, which cannot adapt to real-time traffic demand and leads to congestion and wasted green time.

This creates a gap: the need for a low-cost, reliable, and adaptive traffic control system that balances simplicity with effectiveness. Ultrasonic sensors, being affordable and easy to deploy, present a practical option for detecting vehicles and estimating flow. This project seeks to address this gap by applying ultrasonic sensing to develop a cost-effective adaptive traffic signal system suitable for real-world conditions in resource-limited settings.

Chapter 3

METHODOLOGY

3.1 Introduction

This chapter centers on a planned system architecture layout for systematically completing this project. This project development is divided into two parts which are hardware and software development. It also includes the project's development process using flowcharts and block diagrams to understand the process better.

3.2 Block Diagram of Overall System

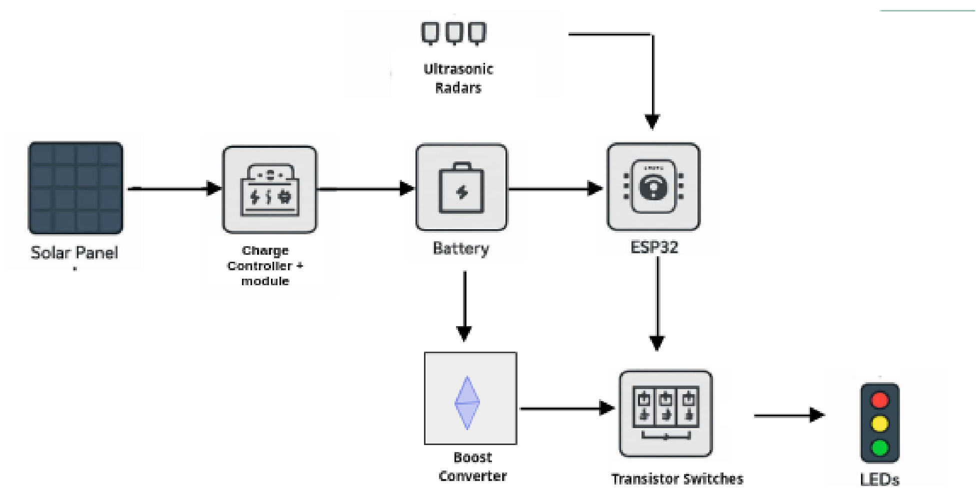

Figure 3.1: Block Diagram of the Overall system

As shown in the illustration, power is supplied by the solar panel and stored in the battery for more prolonged activity. The ESP32 controller is powered from the battery which runs the logic, IoT and automation. When the ultrasonic sensors detect a high vehicle density in any of the three lanes, it will transmit the signal to the ESP32 micro-controller. The ESP32 will process the signal and send the output signal to the LED on the high-density lane to appropriately change the signal of the LED traffic light module to clear the road.

3.3 Flow Chart of Smart Traffic System

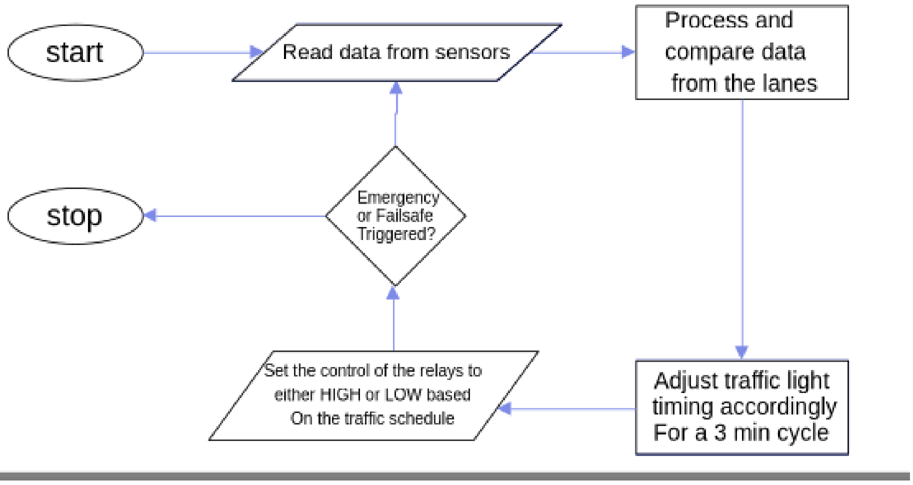

Figure 3.2: Flow Chart of the Smart Traffic System

This flowchart illustrates the decision-making process of a smart traffic light system that uses sensor data to manage signal timing at intersections. The system begins by reading input from sensors that monitor traffic conditions. It processes and compares data from each lane to determine which lane has the highest traffic density, and finally adjusts the green light duration accordingly within a three-minute cycle to optimize flow and reduce congestion.

3.4 Overall System Sizing Calculations

Calculating the solar panel, charge controller, and battery bank specifications is very important. The system sizing calculation is essential since the Solar panel system must produce sufficient output to power the smart traffic light system.

Table 3.1: System's power consumption summary

Component	**Qty**	**Voltage (V)**	**Power (W)**	**Energy (Wh)**
12 V LEDs (7 W each)	3	12	21	21
ESP32 (5 V input)	1	5	1	1
Ultrasonic sensors	3	5	0.225	0.225
Total	-	-	-	**22.225**

We'll round the total daily draw to 22.3 Wh.

3.4.1 Solar Panel Sizing

The output power needed is calculated as:

$$\text{Output power (W)} = \frac{\text{Energy per day}}{\text{Peak Sun Hours} \times \text{System Efficiency}}$$

Assuming Peak Sun Hours = 5 h (typical for Lagos) and System Efficiency = 75% (0.75):

$$\frac{22.3\,\text{Wh}}{5\,\text{h} \times 0.75} \approx 5.93\,\text{W}$$

Therefore, a panel with a minimum requirement of 6W is needed. A 20W panel was chosen.

3.4.2 Battery Bank Sizing

The battery capacity is calculated as:

$$\text{Capacity (Wh)} = \frac{\text{Daily Usage} \times \text{Days of Autonomy} \times \text{BBTM}}{\text{Depth of Discharge}}$$

Assuming Days of Autonomy = 1, BBTM = 1, and Depth of Discharge = 80% (0.8):

$$\frac{22.3\,\text{Wh} \times 1 \times 1}{0.8} \approx 27.9\,\text{Wh}$$

Convert to Ah at 3.7V:

$$\frac{27.9\,\text{Wh}}{3.7\,\text{V}} \approx 7.54\,\text{Ah}$$

The suggested battery pack of four 3.7 V, 5 Ah cells in parallel yields 20 Ah (74 Wh), which comfortably covers the required 27.9 Wh.

3.5 Hardware Development

The Solar Panel system is the most crucial part of the project as it produces electricity that will power the smart traffic light system. Several elements are essential in developing the solar generator, such as solar panels, charge controller, battery bank, and DC-to-DC converter. This section will also explain the hardware used to develop the smart traffic light system. The main components used are ESP32, Ultrasonic sensors, Transistor switch, and LED bulbs.

3.5.1 Monocrystalline Solar Panel

Mono-crystalline photo-voltaic (PV) panels are crafted from a single continuous crystal structure of silicon, giving them a uniform and sleek appearance. Unlike poly-crystalline panels, which are made by melting and cooling multiple silicon fragments, monocrystalline cells are sliced from a pure silicon ingot grown using the Czochralski process. This results in cells with rounded edges and a dark black or deep blue hue, often recognized by their high efficiency.
Because each cell is made from a single crystal, electrons can move more freely, enhancing the panel's ability to convert sunlight into electricity. This improved electron mobility makes monocrystalline panels more efficient than their poly-crystalline counterparts, especially in limited space or low-light conditions. Their high power output and long lifespan make them ideal for compact, high-performance solar applications.

Figure 3.3: Block Diagram of the Overall system

3.5.2 18650 Rechargeable Lithium-Ion Battery

The 18650 battery, as illustrated in Figure 3.6, is a cylindrical Li-ion battery with a diameter and height of 18 mm and 65 mm, respectively. The 18650 battery has between 5200 mAh capacity with a nominal voltage of 3.7 V. The 18650 batteries are used in rechargeable and high-current-draining devices because of their high-level capabilities, such as over 300 charging cycles and smaller energy density.

Figure 3.4: 18650 rechargeable Lithium-Ion battery

3.5.3 TP4056 Charge Controller Module

he charge controller connects the solar panel to the storage batteries through the battery. It regulates the power from the solar panel to protect the battery bank. Without a charge controller, overcharging might cause damage to the battery.

The TP4056 module is a single-cell lithium-ion battery charger that prevents overcharging and over-discharge. The suggested operating voltage for the TP4056 module circuit is 4.5 V – 5.5 V, with a charging current rating of 1A. This module can be powered by any mobile charger and its associated connection. It features two status outputs that indicate charging is in progress and complete. When the charger is activated, the RED indicator light will illuminate, signifying that the battery is being charged. Once the module has fully charged the battery, it will automatically cease charging, and the Red LED will turn OFF while the Blue LED will turn ON.

Lithium batteries can be dangerous if improperly charged. Thus, the TP4056 is useful for preventing overvoltage and overcurrent charging by detecting specified voltage conditions. Figure 3.7 shows the solar charge controller for the solar PV system.

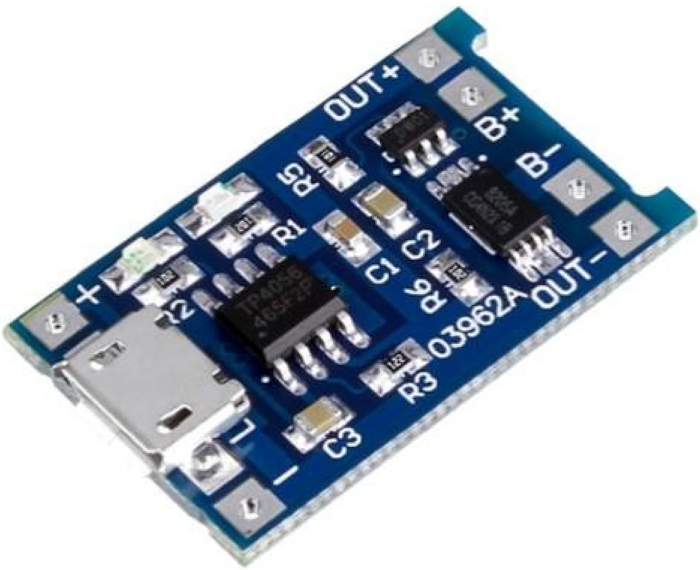

Figure 3.5: TP4056 Charge Controller Module

3.5.4 ESP32 Microcontroller

The ESP32 is a powerful open-source microcontroller developed by Espressif Systems, designed for high-performance IoT applications. It features a dual-core Tensilica LX6 processor, integrated Wi-Fi and Bluetooth, and supports a wide range of digital and analog interfaces.

The ESP32 can be powered via USB, battery, or external 3.3 V supply, and is compatible with the Arduino IDE, PlatformIO, and ESP-IDF development environments. Its robust wireless capabilities and rich peripheral support make it ideal for smart systems like our traffic light prototype.

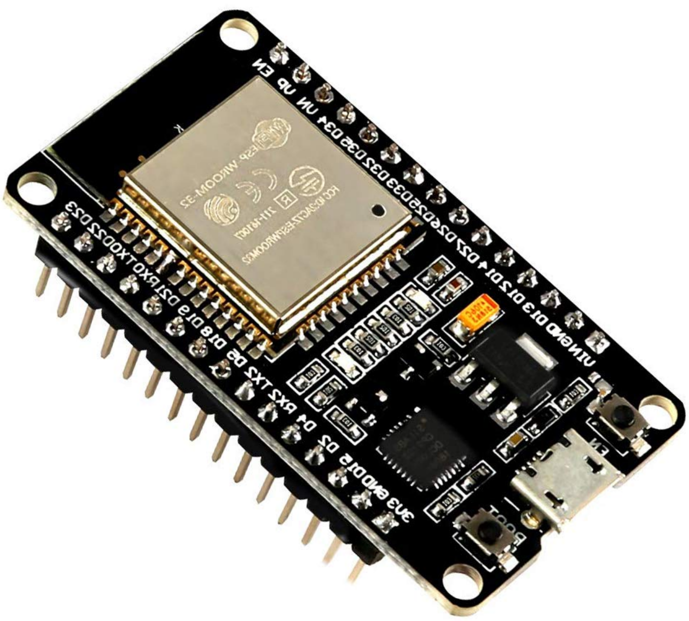

Figure 3.6: ESP32 Microcontroller

3.5.5 HC-SR04 Ultrasonic Sensors

The HC-SR04 Ultrasonic Sensor is a widely used distance-measuring module that operates using sonar principles. It emits ultrasonic waves at 40 kHz and calculates the time it takes for the echo to return, allowing precise distance detection from 2 cm to 400 cm. The module includes a transmitter and receiver pair, and communicates with microcontrollers like the ESP32 or Arduino using simple digital I/O pins. It requires a 5 V power supply and outputs a digital pulse proportional to the measured distance. This sensor is highly effective for obstacle detection, making it ideal for smart traffic systems to monitor vehicle presence in each lane. Its low cost, reliability, and ease of integration make it a staple in embedded projects.

Figure 3.7: HC-SRO4 Ultrasonic Sensor

3.5.6 LED Bulbs

The 7 W bulb traffic light unit provides adequate brightness for developing a prototype traffic signal system. It is designed for straightforward wiring, compact installation, and reliable operation. Each bulb is mounted in a standard traffic light arrangement to clearly indicate stop, caution, and go signals. The system uses current control and relay switching for safe operation of the bulbs. Figure 3.12 shows the 7 W bulb traffic light unit.

Figure 3.8: LED Bulbs

3.5.7 Transistor Switch

The transistor switch in this project utilizes an N-channel MOSFET (IRLZ44N) to control high-current loads efficiently. The gate of the MOSFET is connected directly to a GPIO pin on the ESP32 microcontroller, allowing digital signals to toggle the switch. The load such as an LED or transistor switch is connected to the drain terminal, while the source is grounded. When the ESP32 outputs a HIGH signal to the gate, the MOSFET conducts, completing the circuit and powering the load. This configuration ensures reliable switching with minimal power loss and is well-suited for handling the demands of the traffic light system.

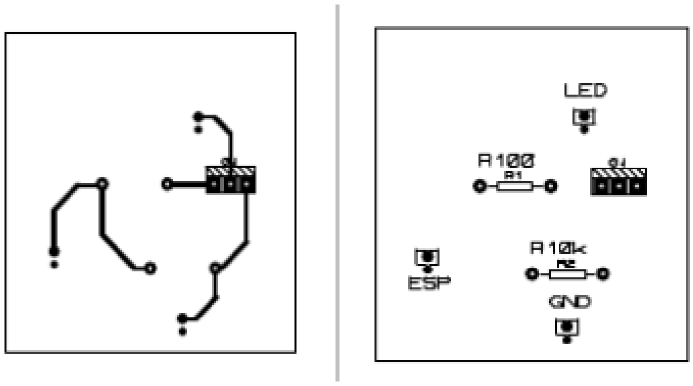

Figure 3.9: PCB layout for transistor switch

3.6 Software Development

3.6.1 Circuit Simulation (Wokwi)

Wokwi is an online simulation platform used for designing and testing embedded systems. In this project, Wokwi was utilized to design and simulate the circuit of the Smart Traffic Light System before implementing it on actual hardware.

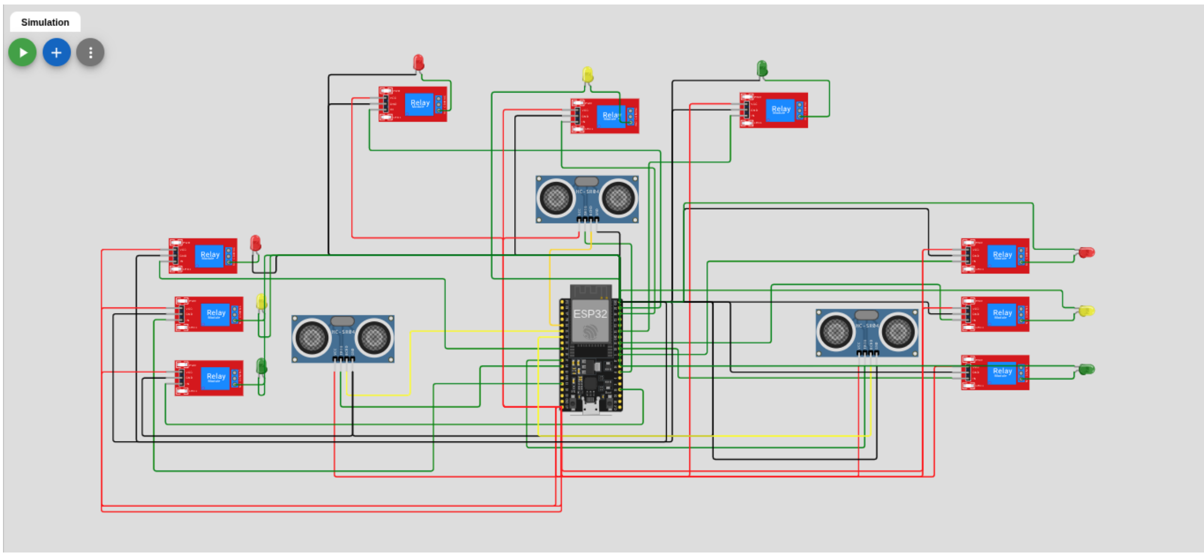

Figure 3.10: Wokwi simulation of the smart traffic light system

3.6.2 Control Code Logic

```
#include <Arduino.h>
#include "TrafficLight.h"
#include "Ultrasonic.h"

unsigned long prevMillis = 0;
int currentStep = 0;

unsigned long greenA = 20, greenB = 20, greenC = 20;
unsigned long overlap = 5;

// Adaptive parameters
const float Kp = 20;
const float s_target = 0.05; //0.2+ for real-life
const float deltamax = 5;
const unsigned long minGreen = 10, maxGreen = 90; // 20, 60 for
   real life

void setup() {
    Serial.begin(115200);
    // pinMode definitions...
    digitalWrite(A_R, HIGH); digitalWrite(B_R, HIGH); digitalWrite
       (C_R, HIGH);
}
```

```
void loop() {
    trafficController(greenA, greenB, greenC, overlap, currentStep
       , prevMillis, greenA, greenB, greenC, Kp, s_target,
       deltamax, minGreen, maxGreen);

    if (currentStep == 0) UltrasonicSensor("U1", sensor1, greenA
       *1000, 5, 32);
    if (currentStep == 2) UltrasonicSensor("U2", sensor2, greenB
       *1000, 23, 18);
    if (currentStep == 4) UltrasonicSensor("U3", sensor3, greenC
       *1000, 27, 34);
}
```

Listing 3.1: Control Code Logic Structure

3.7 Sensor Physics

The ultrasonic sensor operates on the principle of time-of-flight measurement. It transmits a short burst of high-frequency sound, typically around 40 kHz, and measures the time taken for the reflected echo to return from a surface. The distance d between the sensor and the target is determined by:

$$d = \frac{v \cdot t}{2} \tag{3.1}$$

where v is the speed of sound in air and t is the measured round-trip time. The propagation of ultrasonic waves in the air is influenced by environmental conditions, particularly temperature, humidity, and pressure. The speed of sound is influenced by temperature T (in Celsius) according to:

$$v \approx 331 + 0.6T \quad (\text{m/s}) \tag{3.2}$$

where T is the ambient temperature in degrees Celsius. This implies that small variations in temperature can change the measured distances. Ultrasonic sensors do not emit in a straight line, but rather in a conical beam pattern, typically spanning 15-30 °. This defines both the coverage area and the spatial resolution of the sensor. Objects within the cone are detected, while those outside remain undetected. Additionally, there exists a short blind zone near the sensor where the echoes cannot be resolved.

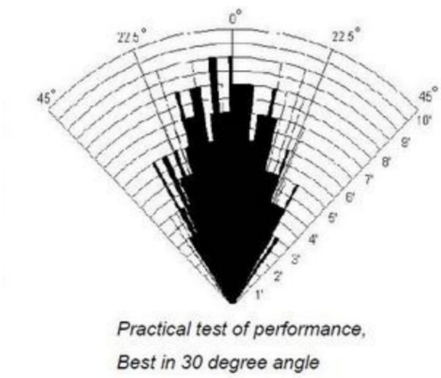

Figure 3.11: Beam of an ultrasonic wave

In this traffic system, the sensor is mounted overhead, angled towards the lane. Its role is to detect vehicle presence and occupancy by measuring distance variations, which can then be interpreted as vehicles passing or stopping within the monitored region.

3.8 Traffic Schedule Modelling

The traffic signal system is designed to dynamically allocate green time based on real-time vehicle detection.

Vehicle Detection and Counting

Each lane is equipped with an ultrasonic sensor that measures the distance to passing vehicles. The presence of vehicles is detected when the measured distance drops below a dynamically determined threshold. A small debounce mechanism ensures transient fluctuations do not trigger false counts. Vehicles are counted as they exit the detection zone.

Flow and Average Speed Estimation

The system first estimates the traffic flow for each lane by counting the number of vehicles N_i that pass during the green interval T. The flow Q_i is expressed as:

$$Q_i = \frac{N_i}{T} \tag{3.3}$$

This quantifies the rate of vehicles per unit of time, providing a direct measure of lane usage. During the same time, the system estimates the average speed v_i of the vehicles using sensor distance measurements. The speed is calculated as the ratio of the distance traveled Δd to the time interval Δt while a vehicle is present:

$$v_i = \frac{\Delta d}{\Delta t} \tag{3.4}$$

The cumulative measurements on all vehicles passing during a cycle are aggregated to ensure representative statistics for each lane. These metrics form the basis for assessing traffic conditions in real-time.

Density Calculation

Using the fundamental traffic relationship, the density of the lane k_i is derived from the measured flow Q_i and the average speed $\bar{v}_i$:

$$k_i = \frac{Q_i}{\bar{v}_i} \tag{3.5}$$

Green Time Calculation

Each lane is allocated a proportion of the green budget relative to its measured demand.

$$s_i = \text{GreenBudget} \times \frac{\text{Demand}_i}{\sum_j \text{Demand}_j} \tag{3.6}$$

EMA Smoothing

To prevent abrupt changes, an Exponential Moving Average (EMA) is applied:

$$s_i(t) = \alpha s_i(t) + (1 - \alpha) s_i(t-1) \tag{3.7}$$

A smoothing factor $\alpha = 0.3$ balances responsiveness and stability.

Bounding and Redistribution

Green times are constrained within predefined minimum and maximum limits [10, 90]. If bounding prevents full utilization of the available green budget, the surplus time is redistributed proportionally among lanes not at their bounds. This guarantees efficient use of the cycle while respecting safety and operational constraints.

3.9 Cost and Bill of Materials

Table 3.2: Cost and bill of materials for the overall project

No.	Material	Description	Quantity	Price (Naira)
1.	Monocrystalline Solar Panel 20W	1 unit = 20500 N	1	20,500
2.	3.7V, 5000 mAh 18650 Li-ion battery	1 unit = 800 N	4	3,200
3.	Charge controller 5V	1 unit = 7500 N	1	7,500
4.	TP4056 Charge Module	1 unit = 1600 N	1	1,600
5.	DC-DC Converter (Step-Up)	1 unit = 1000 N	2	2,000
6.	ESP32	1 unit = 14500 N	1	14,500
7.	Ultrasonic Sensor HC-SR04	1 unit = 5000 N	3	15,000
8.	LED Bulb 7W, 12V	1 unit = 700 N	9	6,300
9.	Jumper Wires	-	-	5,220
10.	IRLZ44N MOSFET	1 unit = 1400 N	12	16,800
11.	Resistors	-	-	1,040
12.	Plywood	-	-	6,000
13.	Miscellaneous	-	-	7,000
			Total (Naira)	**119,660**

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results obtained from the implementation and testing of the traffic control system. The aim is to show how the developed system responds to changing traffic conditions and how it compares with a fixed-time schedule.

4.2 Flow, Speed, and Green Time per Cycle

In this section, the relationship between vehicle flow, average speed, and allocated green time is presented. It can be observed that lanes with higher flow generally received more green time, while lanes with lower activity were assigned shorter durations.

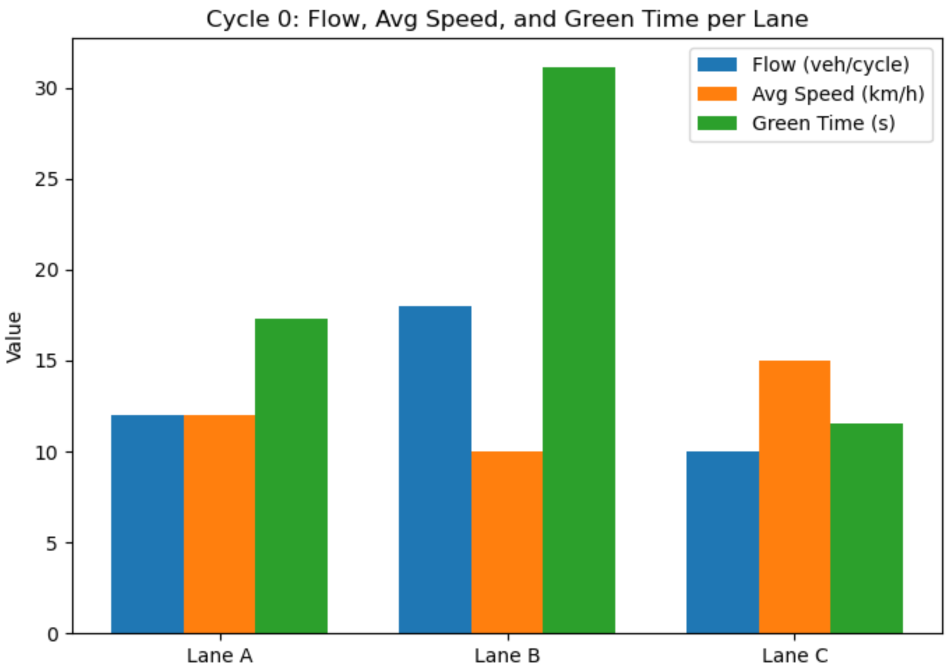

Figure 4.1: Result for first cycle: Flow, Avg Speed, and Green Time per Lane

4.3 Effect of EMA on Green Time Allocation

To reduce sharp fluctuations in green time, the Exponential Moving Average (EMA) method was applied to smooth the allocation over cycles. The EMA allocations show a slower and steadier adjustment, which prevents extreme changes in signal timing.

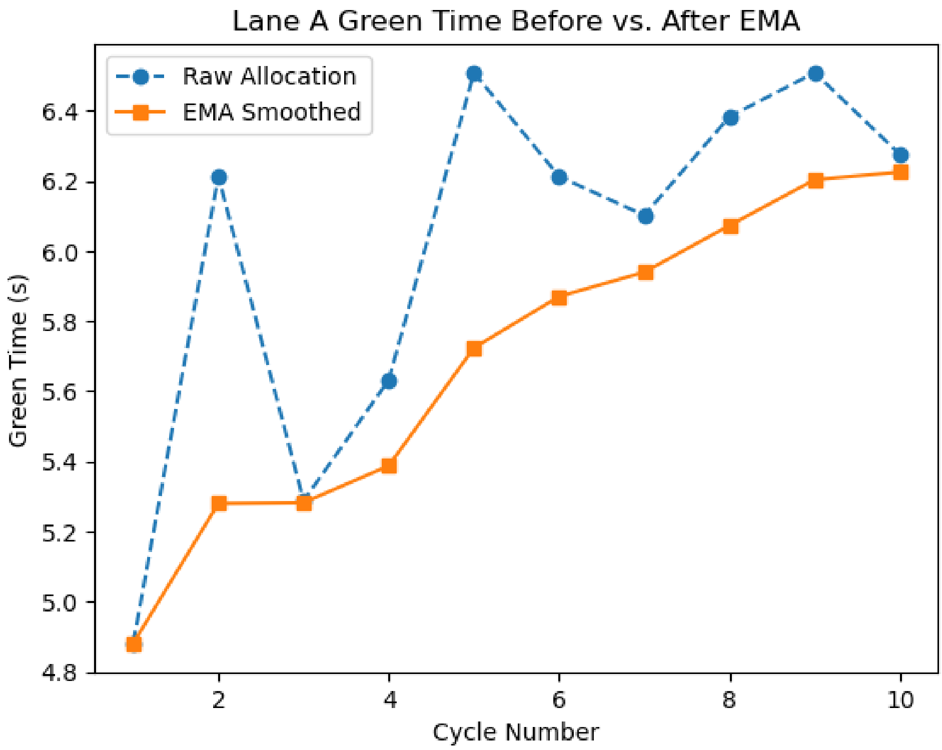

Figure 4.2: Lane A Green Time Before vs. After EMA Smoothing

4.4 Performance in Terms of Waiting Time

To evaluate the system, the average waiting time per cycle was compared for fixed-time scheduling and adaptive scheduling with EMA. The adaptive controller shows a gradual reduction in waiting time over the cycles because the system shifts more green time towards lanes with higher demand, allowing queues to clear faster.

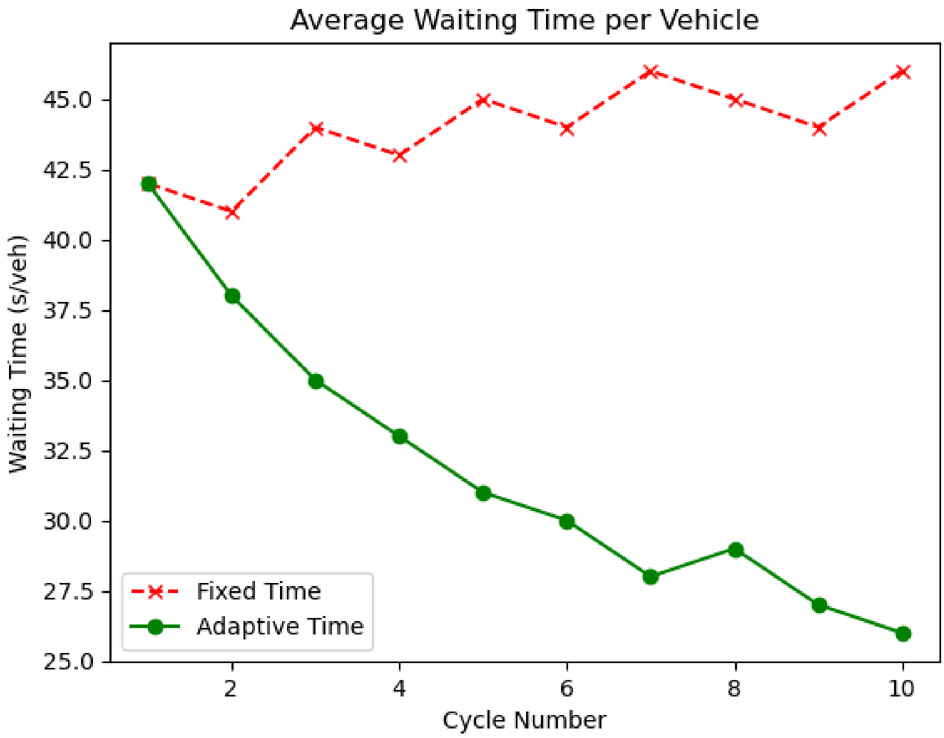

Figure 4.3: Average Waiting Time per Vehicle: Fixed vs. Adaptive Time

4.5 Discussion Summary

The results presented demonstrate how the developed adaptive traffic signal control system responds to varying traffic conditions. The main findings are:

- **Sensor readings and traffic parameters:** The ultrasonic sensors successfully captured basic vehicle presence, which was processed into flow and average speed.
- **Green time allocation:** The controller distributed green times proportionally to lane demand.
- **EMA smoothing effect:** The application of EMA reduced fluctuations in green time allocation, providing stability and fairness.
- **Waiting time comparison:** The adaptive system significantly reduced average waiting time compared to fixed-time scheduling.

Chapter 5

Conclusion

The project successfully designed and implemented a Smart Solar-Powered Traffic Light System that adapts signal timing based on real-time traffic conditions. Using ultrasonic sensors and the ESP32 microcontroller, the system was able to detect vehicle density and allocate green light durations dynamically. The results show that adaptive control significantly improves traffic flow, reduces waiting time, and minimizes energy waste compared to fixed-time systems.

Furthermore, the integration of a solar power subsystem ensured reliable operation during power outages, supporting the goal of sustainable traffic management for developing regions. The prototype demonstrated that a low-cost, energy-efficient, and scalable solution can be achieved using locally available components.

Overall, this work contributes to ongoing efforts toward intelligent and eco-friendly transportation systems. Future improvements could include the use of multiple intersections connected through wireless networks, integration with cloud-based monitoring, and the addition of image-based vehicle classification for better accuracy.

Appendix A

Appendices

A.1 Source Code for ESP32

src > main.cpp > loop()

```cpp
#include <Arduino.h>
#include "TrafficLight.h"
#include "Ultrasonic.h"

unsigned long prevMillis = 0;
int currentStep = 0;

unsigned long greenA = 20, greenB = 20, greenC = 20;
unsigned long overlap = 5;

// Adaptive parameters
const float Kp = 20;
const float s_target = 0.05; //0.2+ for real-life
const float deltamax = 5;
const unsigned long minGreen = 10, maxGreen = 90; // 20 , 60 for real life

void setup() {
  Serial.begin(115200);
  pinMode(A_R, OUTPUT); pinMode(A_Y, OUTPUT); pinMode(A_G, OUTPUT);
  pinMode(B_R, OUTPUT); pinMode(B_Y, OUTPUT); pinMode(B_G, OUTPUT);
  pinMode(C_R, OUTPUT); pinMode(C_Y, OUTPUT); pinMode(C_G, OUTPUT);
  digitalWrite(A_R, HIGH); digitalWrite(B_R, HIGH); digitalWrite(C_R, HIGH);
}

void loop() {
  trafficController(greenA, greenB, greenC, overlap, currentStep, prevMillis, greenA, greenB, greenC, Kp,
  s_target, deltamax, minGreen, maxGreen);

  if (currentStep == 0) UltrasonicSensor("U1", sensor1, greenA*1000, 5, 32);
  if (currentStep == 2) UltrasonicSensor("U2", sensor2, greenB*1000, 23, 18);
  if (currentStep == 4) UltrasonicSensor("U3", sensor3, greenC*1000, 27, 34);
}

```

Figure A.1: main.cpp

src > TrafficLight.cpp > trafficController(unsigned long, unsigned long, unsigned long, unsigne

```cpp
#include "TrafficLight.h"

// Pin definitions
const int A_R = 12, A_Y = 13, A_G = 14;
const int B_R = 15, B_Y = 21, B_G = 22;
const int C_R = 19, C_Y = 25, C_G = 26;

// Lane stats and sensors
LaneStats laneA, laneB, laneC;
UltrasonicState sensor1, sensor2, sensor3;

void trafficController(unsigned long gA, unsigned long gB, unsigned long gC, unsigned long ov,
                       int &currentStep, unsigned long &prevMillis,
                       unsigned long &greenA, unsigned long &greenB, unsigned long &greenC,
                       float Kp, float s_target, float deltamax,
                       unsigned long minGreen, unsigned long maxGreen) {
  unsigned long now = millis();
  unsigned long durations[6] = {gA * 1000, ov * 1000, gB * 1000, ov * 1000, gC * 1000, ov * 1000};

  if (now - prevMillis >= durations[currentStep]) {
    prevMillis = now;

    // Collect stats at end of each green, but don't adjust yet
    if (currentStep == 0) {···
    if (currentStep == 2) {···
    if (currentStep == 4) {···

    // End of cycle: after step 5 → about to loop back to 0
if (currentStep == 5) {···

    currentStep = (currentStep + 1) % 6;
  }

  // Reset all LEDs
  digitalWrite(A_R, LOW); digitalWrite(A_Y, LOW); digitalWrite(A_G, LOW);
  digitalWrite(B_R, LOW); digitalWrite(B_Y, LOW); digitalWrite(B_G, LOW);
  digitalWrite(C_R, LOW); digitalWrite(C_Y, LOW); digitalWrite(C_G, LOW);

  // Apply current step
  switch(currentStep) {···

}
```

Figure A.2: traffic.cpp : code responsible for lighting control

```cpp
#include "Ultrasonic.h"

void UltrasonicSensor(const char* name, UltrasonicState &state, unsigned long readDuration, int trigPin,
int echoPin) {
  const int debounceCount = 2;
  const float riseThreshold = 10;
  const unsigned long pauseDuration = 0;

  if (!state.initialized) {···

  auto getDistance = [&]() {···

  auto getAverageDistance = [&]() {···

  unsigned long now = millis();

  if (state.readingPhase) {···
  } else if (now - state.cycleStart >= pauseDuration) {
    state.readingPhase = true;
    state.cycleStart = now;
  }

  delay(100);
}
```

Figure A.3: ultrasonic.cpp : code responsible for getting and processing sensor readings

A.2 Components Specification

1. **Ultrasonic Sensor (HC-SR04)**
   Operating Voltage: 5 V
   Range: 2 cm – 400 cm
   Accuracy: ± 3 mm

2. **ESP32 Microcontroller**
   Processor: Dual-core Tensilica LX6
   Connectivity: Wi-Fi + Bluetooth
   Operating Voltage: 3.3 V

3. **Transistor Switch (IRFZ44N N-Channel MOSFET)**
   Function: Used for switching 7 W bulb loads
   Type: N-channel MOSFET

4. **TP4056 Charging Module**
   Function: Lithium battery charging and protection
   Input Voltage: 5 V (Micro-USB or Type-C)
   Output: 4.2 V / 1 A (typical)
   Features: Overcharge, overdischarge, and overcurrent protection

5. **MPPT Charge Controller**
   Supported Input Voltages: 9 V / 12 V / 16 V
   Function: Maximizes solar power efficiency and regulates charging

6. **Solar Panel**
   Power Rating: 20 W
   Voltage (Vmp): 19.7 V
   Type: Monocrystalline solar panel
   Function: Provides energy for sensor unit and lighting control system

A.3 Sample Test Data and Graphs

Figure A.4 - A.13 present sample flow–speed–density data and the corresponding adaptive green time allocation results for differnt cycles.

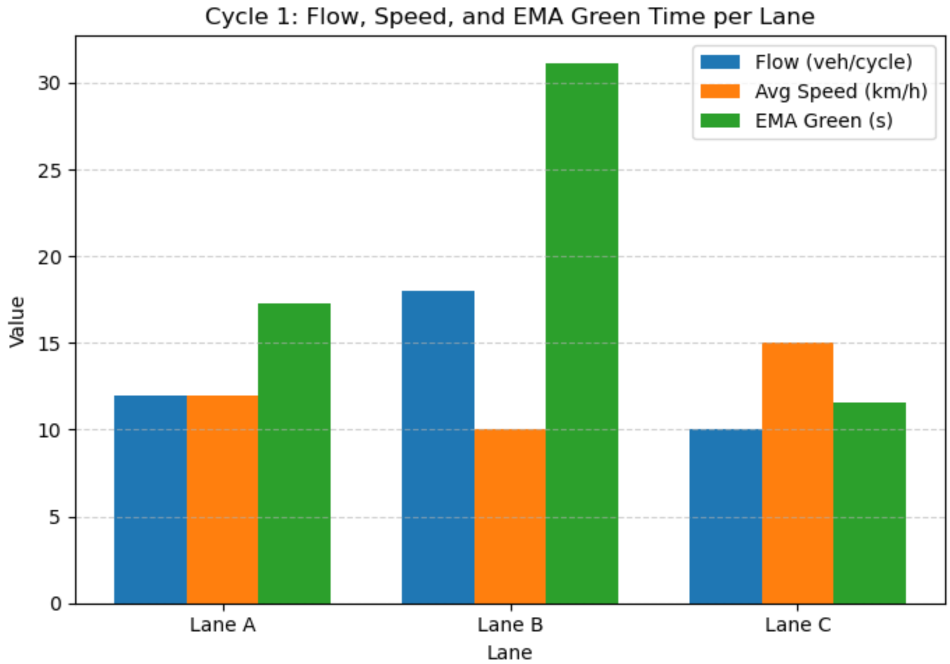

Figure A.4: Result for first cycle: Flow, Avg Speed, and Green Time per Lane

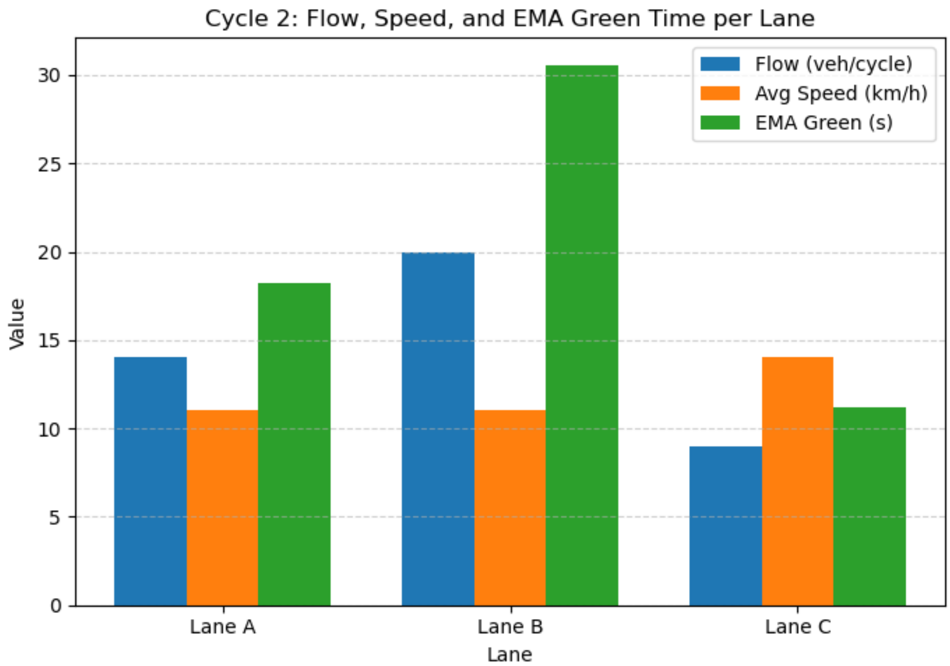

Figure A.5: Result for second cycle: Flow, Avg Speed, and Green Time per Lane

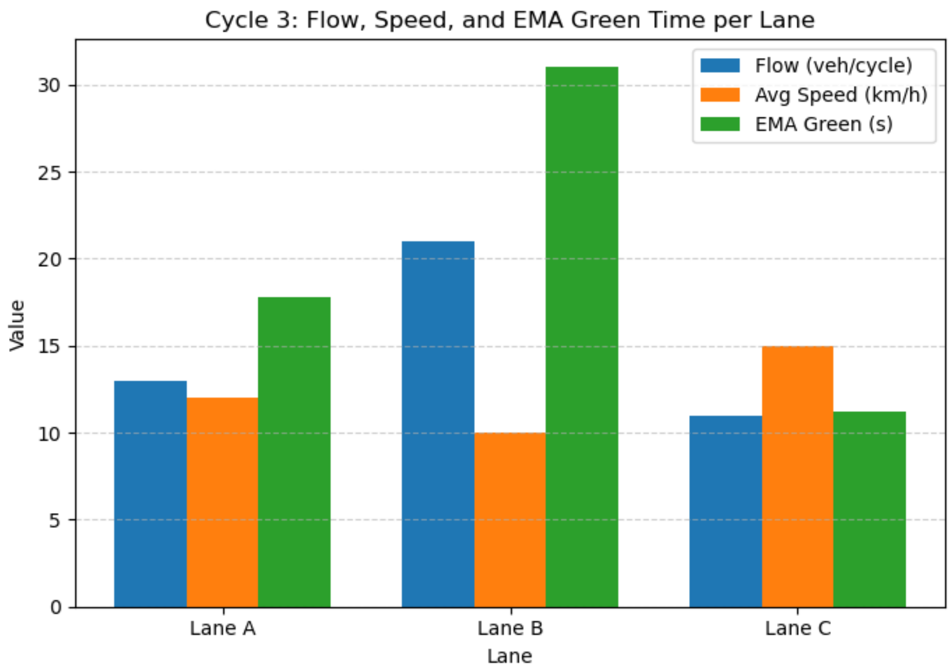

Figure A.6: Result for third cycle: Flow, Avg Speed, and Green Time per Lane

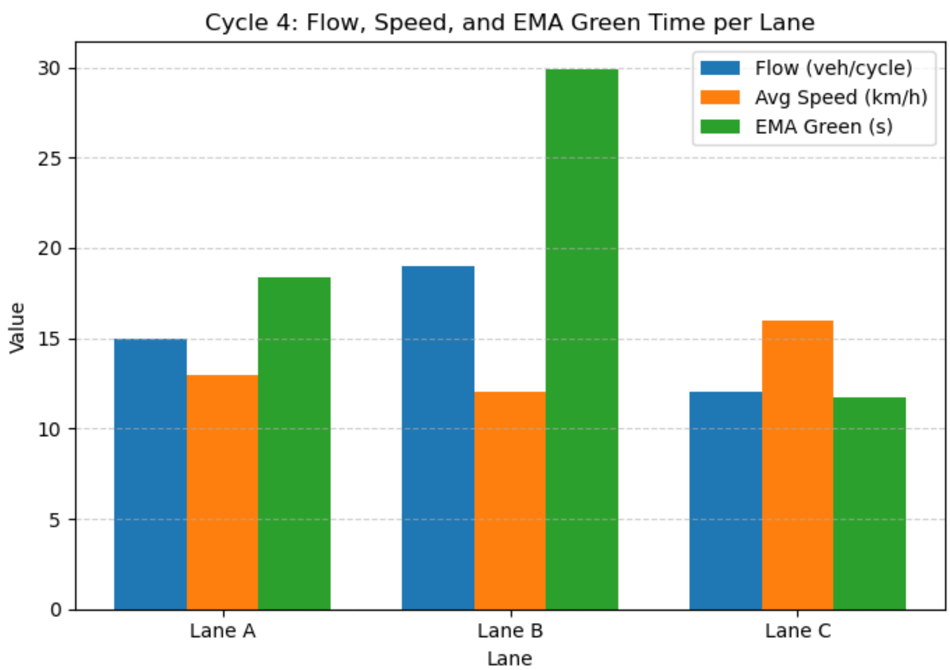

Figure A.7: Result for fourth cycle: Flow, Avg Speed, and Green Time per Lane

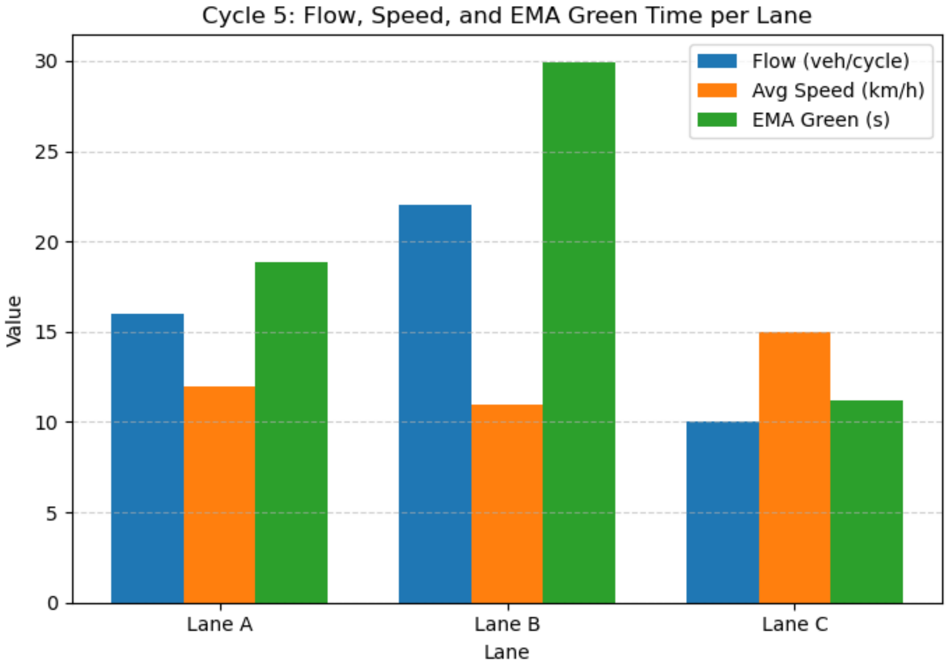

Figure A.8: Result for fifth cycle: Flow, Avg Speed, and Green Time per Lane

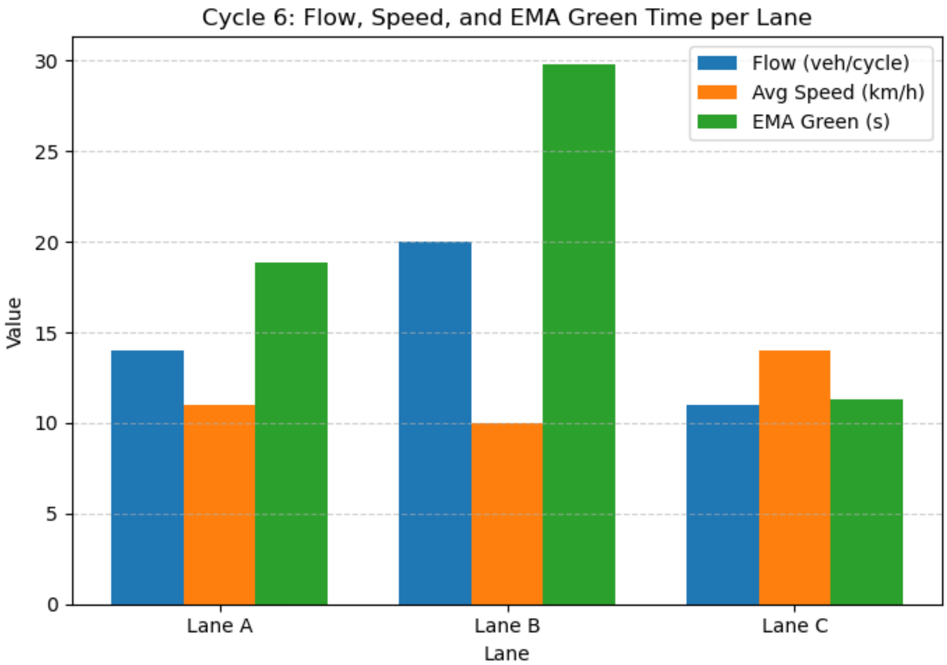

Figure A.9: Result for sixth cycle: Flow, Avg Speed, and Green Time per Lane

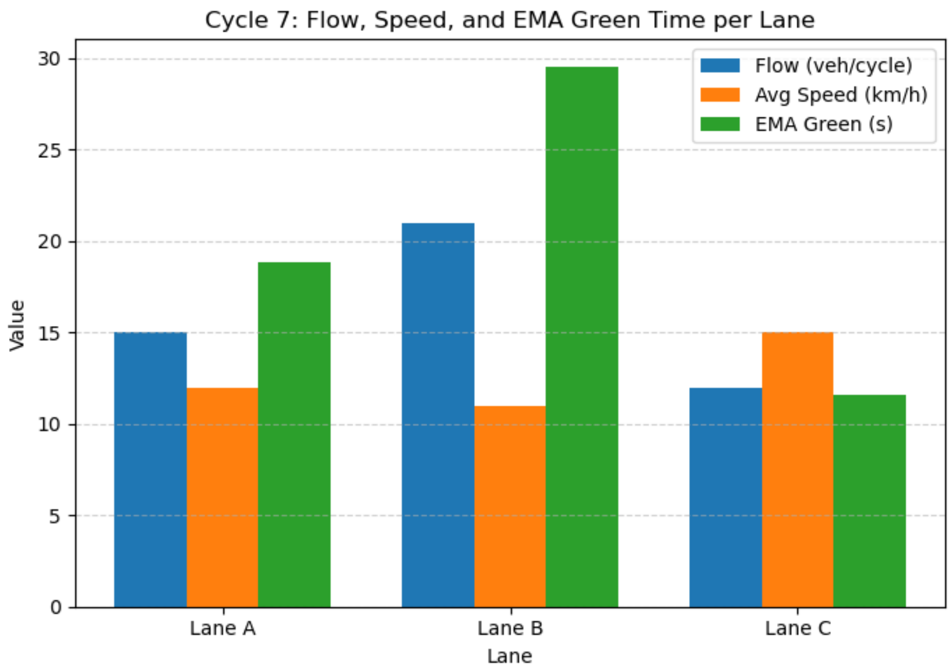

Figure A.10: Result for seventh cycle: Flow, Avg Speed, and Green Time per Lane

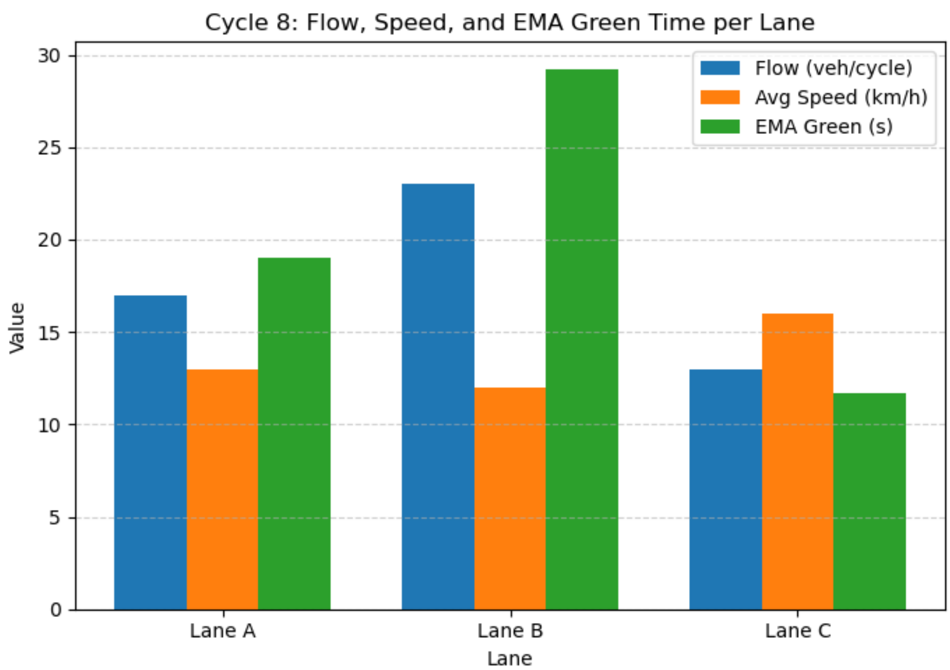

Figure A.11: Result for eigth cycle: Flow, Avg Speed, and Green Time per Lane

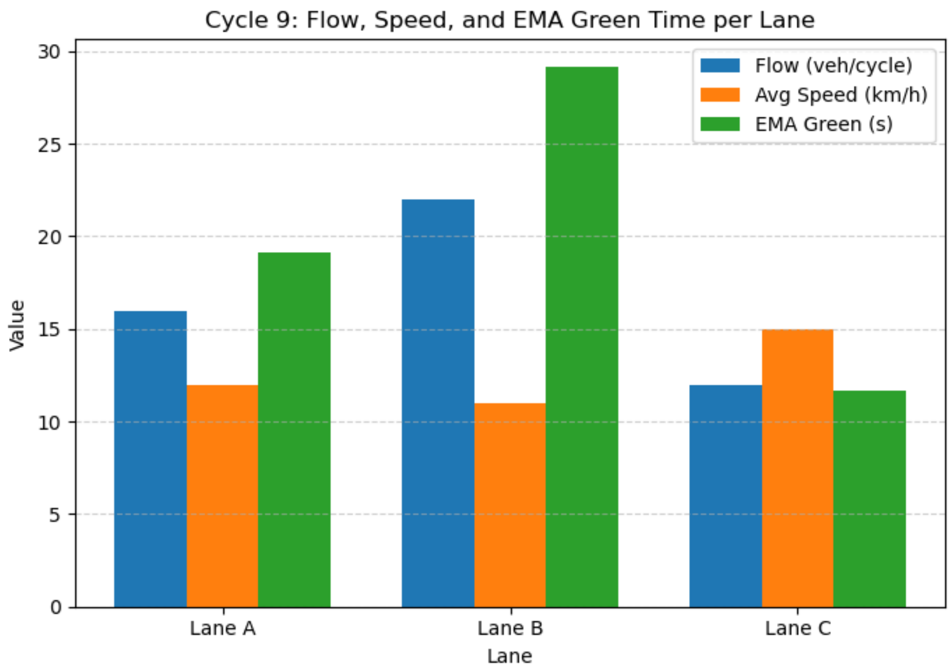

Figure A.12: Result for nineth cycle: Flow, Avg Speed, and Green Time per Lane

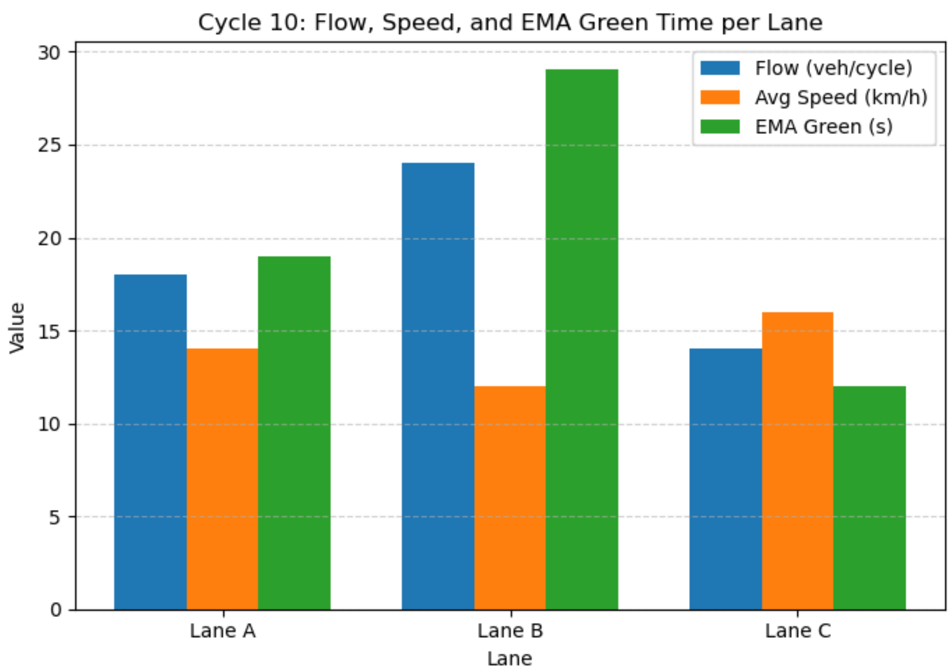

Figure A.13: Result for tenth cycle: Flow, Avg Speed, and Green Time per Lane

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5. Salama, E., & Idoko, P. (2022). *Design and Implementation of Smart Traffic Light System Using Renewable Energy, Fail-Safe System and Intelligent Sensors.* Journal of Sustainable Engineering, 12(2), 25–33.