

Smart Traffic and Congestion Control System Using IoT

Course: SE322 – Internet of Things

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1. Introduction

1.1 Background

Traffic congestion is one of the biggest challenges faced by growing cities. Traditional traffic light systems work on fixed timers and do not react to actual road usage. This means green lights may be given to empty roads, while vehicles pile up in other directions. The result is wasted time, increased fuel consumption, and inefficient road use.

With the development of IoT (Internet of Things), it is now possible to build smarter traffic systems that react to live data. By monitoring vehicle queues using sensors and controlling signals dynamically, traffic can be managed much more efficiently. Our project aims to do exactly that using real, physical components.

1.2 Project Goal

We built a smart traffic control system using **ESP32**, **ultrasonic sensors**, and **LED traffic lights**. The system detects vehicles, counts how many are waiting in each direction, and automatically adjusts the traffic light behavior to reduce congestion. It also displays realtime traffic light states and queue sizes on a **live dashboard**, using **MQTT** for communication.

2. Problem Statement

In a real city, different roads receive different amounts of traffic at different times of the day. A fixed 10-second green light might be too short for a busy road or unnecessarily long for an empty one. Most intersections today cannot adapt to that.

This project solves that problem by using **real-time vehicle detection** and **adaptive timing logic**. Instead of static intervals, the system gives more green time to the busier direction. It does this using sensors, microcontrollers, and internet-based communication—all tested on real hardware.

3. Hardware and Software Used

| Tool/Component | Description |
|------------------------------------|---|
| ESP32-WROOM-32S | Main microcontroller running traffic logic, sensors, and MQTT publishing. |
| Ultrasonic Sensors | Measure distance to detect vehicle presence at entry and exit points. |
| LEDs (Traffic Lights) | Red, Yellow, Green lights for both WE and EW directions. |
| Breadboard + Jumper Wires | Physical circuit connections. |
| Wi-Fi Network | ESP32 connects to MQTT broker through local Wi-Fi. |
| HiveMQ Public Broker | Used for MQTT publish/subscribe communication. |
| HTML, JavaScript, Bootstrap | Used to build the dashboard UI. |
| MQTT.js | JavaScript library used to connect web dashboard to MQTT. |
| Arduino IDE | Used to write and upload C++ code to the ESP32 board. |

4. System Design

The project simulates a 2-way traffic intersection:

- **West to East (WE)**
 - **East to West (EW)** Each direction has:
 - **Entry Sensor:** Detects vehicles entering the lane.

- **Exit Sensor:** Detects vehicles leaving the intersection.
- **3 LEDs:** Green, Yellow, Red to control flow.
- **Queue Counter:** Tracks how many vehicles are currently waiting.

Every few seconds, the system:

1. Checks both queue counts.
 2. Decides which direction has more traffic.
 3. Gives that direction the green light.
 4. Displays the result on a web dashboard.
-

5. Methodology

This section explains how the system was physically built and how the logic was implemented and executed in real time using the ESP32 microcontroller, ultrasonic sensors, LED-based traffic lights, and MQTT communication. All work was performed on a real breadboard using physical components.

5.1 Hardware Assembly

The hardware was assembled on a breadboard using the following layout for each direction (West-East and East-West):

For each direction:

- **Entry Sensor (Ultrasonic):** Detects vehicles approaching the intersection.
- **Exit Sensor (Ultrasonic):** Detects vehicles leaving the queue.
- **Traffic Light:** 3 LEDs (Green, Yellow, Red) connected to digital pins on the ESP32.
- **Queue Counter:** A variable stored in memory.

The ESP32 was connected via USB for power and uploaded with the Arduino code. Each sensor was connected to a 5V and GND rail, with TRIG and ECHO connected to GPIOs. Each LED was wired in series with a resistor and connected to its assigned GPIO.

5.2 Queue Counting Logic

Each direction maintains a **queue count** of how many vehicles are currently waiting.

Vehicle Entry:

When the **entry sensor** detects an object within 20 cm (simulating a car arriving), the counter increases by one.

Vehicle Exit:

When the **exit sensor** detects an object within 20 cm (simulating a car passing the light), the counter decreases by one—only if the queue is greater than 0.

Code Logic: if (readDistance(WE_TRIG_ENTRY,

```
WE_ECHO_ENTRY) < 20) { queueWE++;  
}
```

```
if (readDistance(WE_TRIG_EXIT, WE_ECHO_EXIT) < 20 && queueWE > 0) { queueWE--;  
}
```

This logic runs inside the main loop and gives a **live vehicle count** in both directions.

5.3 Traffic Direction Decision Logic

Every complete cycle (after both directions have had a green turn), the system compares the current queue values to decide which direction gets green next.

Rules:

- If queueWE > queueEW, give green to West-East.
- If queueEW > queueWE, give green to East-West.
- If equal, alternate to avoid starvation.

A simple boolean toggle (`lastDirection`) is used to remember who had the last turn and resolve ties.

5.4 Timing Control: How Green Duration Is Calculated

This is the **core adaptive logic**. Instead of using a static time like 10 seconds, we calculate the green duration dynamically based on how many cars are waiting.

Timing Formula:

Green Time = **BASE_GREEN_DURATION** + (Queue Size × **TIME_PER_CAR**) **Constants:**

- **BASE_GREEN_DURATION** = 5000 ms (5 seconds)
- **TIME_PER_CAR** = 2000 ms (2 seconds per car)

This value is then used in the light control logic to delay the signal for that amount of time before transitioning.

5.5 Traffic Light Phase Logic

Each light follows a strict 3-phase pattern:

1. Green Phase:

- Green LED ON
- Red on other side
- Duration: based on queue calculation above

2. Yellow Phase:

- Green OFF
- Yellow ON for 2 seconds

3. Red Phase:

- Yellow OFF
- Red ON
- Other direction takes over

The process then repeats for the opposite direction.

5.6 MQTT Communication Logic

After every cycle, the ESP32 **publishes** updated values to the MQTT broker. These updates include:

- Traffic light status per direction
- Current queue size **MQTT Topics Used:**
- iot/traffic/WE/state
- iot/traffic/EW/state

- iot/traffic/WE/queue
- iot/traffic/EW/queue **In Code:** client.publish("iot/traffic/WE/state",
currentDirection == "WE" ? "GREEN" : "RED"); client.publish("iot/traffic/WE/queue",
String(queueWE.c_str()));

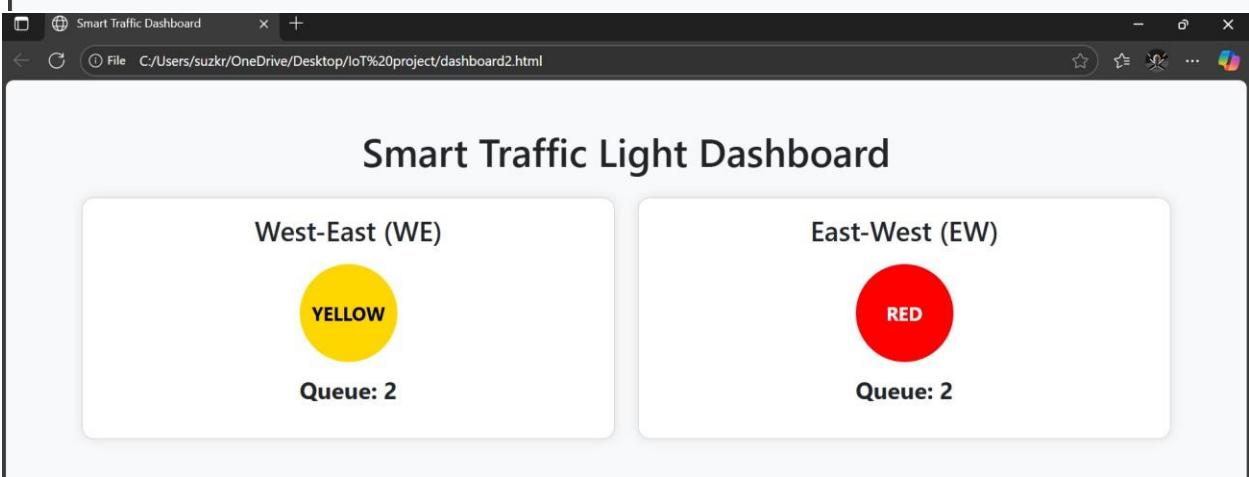
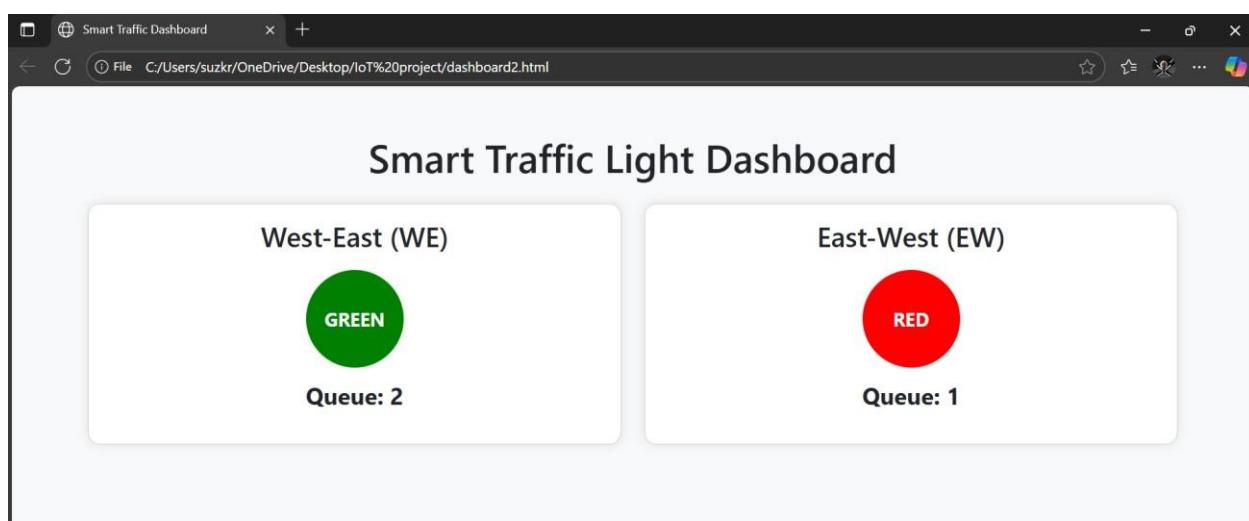
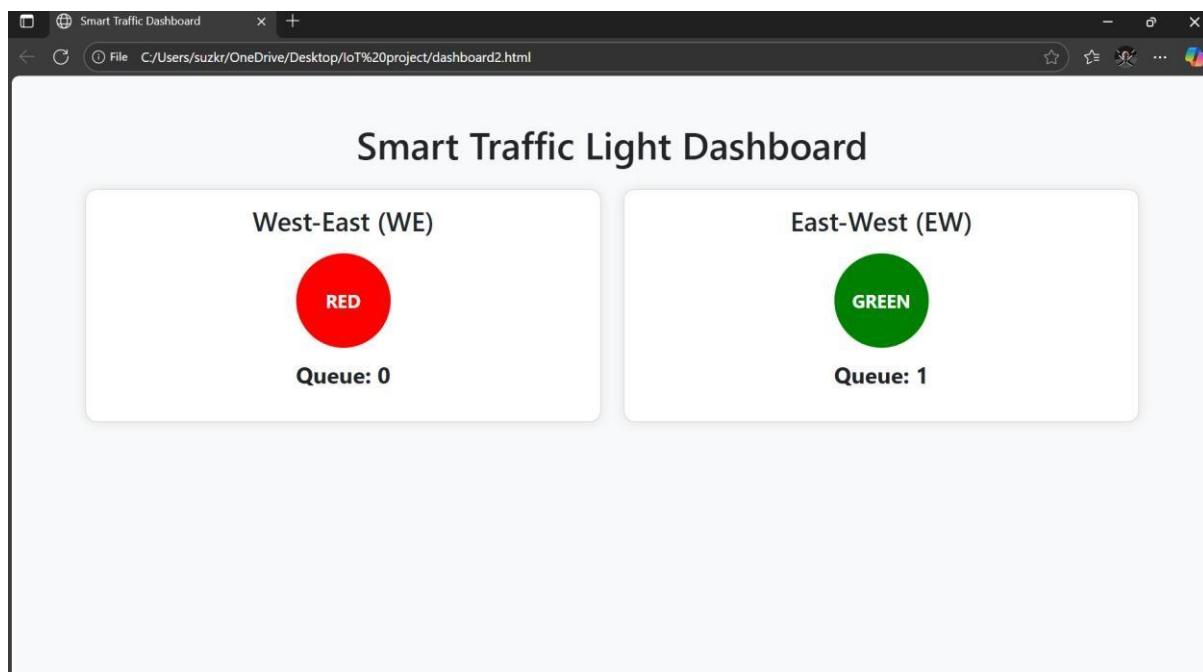
This ensures that the web dashboard is always in sync with the real physical system.

5.7 Real-Time Dashboard Integration

The dashboard is built using HTML, Bootstrap, and JavaScript.

- **MQTT.js** handles the broker connection.
- Each message triggers a visual update.
- Colored circles represent each direction's state.
- Queue values are displayed live.

Example Dashboard:



The system responds within milliseconds of any change.

5.8 Complete ESP32 Code

Below is the actual Arduino code running on the ESP32. This code handles everything: sensor reading, queue updates, traffic light control, MQTT publishing, and delay timing based on queue size.

```
#include <WiFi.h>
#include <PubSubClient.h>
const char* ssid = "Zakariya's Galaxy S22
Ultra"; const char* password = "chgr3080"; const
char* mqtt_server = "broker.hivemq.com";
WiFiClient espClient;
PubSubClient client(espClient);

void setup_wifi() {
delay(10);
Serial.println();
Serial.print("Connecting to ");
Serial.println(ssid);
WiFi.begin(ssid, password);
while (WiFi.status() != WL_CONNECTED) {
delay(500);
Serial.print(".");
}
Serial.println("WiFi connected");
```

```
} void
reconnect() {
    while (!client.connected()) {
        Serial.print("Attempting MQTT connection...");
    if (client.connect("ESP32Client_Traffic")) {
        Serial.println("connected");
    } else {
        Serial.print("failed, rc=");
    Serial.print(client.state());      delay(5000);
    }
}
} void publishState(const char* dir, const char* state, int
queue) {  char topicState[50];  char topicQueue[50];
sprintf(topicState, "iot/traffic/%s/state", dir);
sprintf(topicQueue, "iot/traffic/%s/queue", dir);
client.publish(topicState, state);  client.publish(topicQueue,
String(queue).c_str());
}

// SENSOR PINS
// WE
#define TRIG_ENTRY_WE 19
#define ECHO_ENTRY_WE 18
#define TRIG_EXIT_WE 5
#define ECHO_EXIT_WE 21

// EW
#define TRIG_ENTRY_EW 2
#define ECHO_ENTRY_EW 4
#define TRIG_EXIT_EW 22
#define ECHO_EXIT_EW 23

// RAFFIC LIGHT PINS
// WE
#define GREEN_WE 14
#define YELLOW_WE 27
#define RED_WE 26

// EW
```

```
#define GREEN_EW 25
```

```
#define YELLOW_EW 33
#define RED_EW 32

// VARIABLES int
queueWE = 0; int
queueEW = 0;
bool entryWE_Prev =
false; bool exitWE_Prev =
false; bool entryEW_Prev =
false; bool exitEW_Prev =
false;

// PHASE STATE
enum Phase { PHASE_GREEN_WE, PHASE_YELLOW_WE, PHASE_GREEN_EW, PHASE_YELLOW_EW };
Phase currentPhase = PHASE_GREEN_WE;
unsigned long phaseStartTime =
0;
const unsigned long BASE_GREEN_DURATION =
5000; const unsigned long MAX_GREEN_DURATION =
15000; const unsigned long TIME_PER_CAR =
1000; const unsigned long YELLOW_DURATION =
2000;
unsigned long greenDurationWE =
BASE_GREEN_DURATION; unsigned long greenDurationEW
= BASE_GREEN_DURATION;

void setup() { Serial.begin(9600);
setup_wifi();
client.setServer(mqtt_server, 1883);

pinMode(TRIG_ENTRY_WE, OUTPUT); pinMode(ECHO_ENTRY_WE, INPUT);
pinMode(TRIG_EXIT_WE, OUTPUT); pinMode(ECHO_EXIT_WE, INPUT);
pinMode(TRIG_ENTRY_EW, OUTPUT); pinMode(ECHO_ENTRY_EW, INPUT);
pinMode(TRIG_EXIT_EW, OUTPUT); pinMode(ECHO_EXIT_EW, INPUT);

pinMode(GREEN_WE, OUTPUT); pinMode(YELLOW_WE, OUTPUT); pinMode(RED_WE,
OUTPUT); pinMode(GREEN_EW, OUTPUT); pinMode(YELLOW_EW, OUTPUT);
pinMode(RED_EW, OUTPUT); }
long readDistanceCM(int trigPin, int echoPin) {
digitalWrite(trigPin, LOW); delayMicroseconds(2);
digitalWrite(trigPin, HIGH); delayMicroseconds(10);
digitalWrite(trigPin, LOW);
```

```
long duration = pulseIn(echoPin, HIGH, 50000);
```

```

    if (duration == 0) return -1;
    return duration * 0.034 / 2;
} void handleQueue(bool detectedNow, bool &prevDetected, int &queue, const
char* label) { if (detectedNow && !prevDetected) { queue++;
    Serial.print("ENTER "); Serial.print(label); Serial.print(" → queue++ → ");
} Serial.println(queue); prevDetected = true;
} if (!detectedNow &&
prevDetected) { prevDetected =
false;
}
} void handleExit(bool detectedNow, bool &prevDetected, int &queue, const
char* label) { if (detectedNow && !prevDetected) { if (queue > 0)
queue--;
    Serial.print("EXIT "); Serial.print(label); Serial.print(" → queue-- → ");
} Serial.println(queue); prevDetected = true;
} if (!detectedNow &&
prevDetected) { prevDetected =
false;
}
}
void updateQueues() {
    long entryWE = readDistanceCM(TRIG_ENTRY_WE, ECHO_ENTRY_WE);
    long exitWE = readDistanceCM(TRIG_EXIT_WE, ECHO_EXIT_WE);
    handleQueue((entryWE > 0 && entryWE < 8), entryWE_Prev, queueWE, "WE");
    handleExit((exitWE > 0 && exitWE < 8), exitWE_Prev, queueWE, "WE");

    long entryEW = readDistanceCM(TRIG_ENTRY_EW, ECHO_ENTRY_EW);    long
exitEW      =      readDistanceCM(TRIG_EXIT_EW,           ECHO_EXIT_EW);
    handleQueue((entryEW > 0 && entryEW < 8), entryEW_Prev, queueEW, "EW");
    handleExit((exitEW > 0 && exitEW < 8), exitEW_Prev, queueEW, "EW"); } void
switchToWE() {

```

```
digitalWrite(GREEN_WE, HIGH); digitalWrite(YELLOW_WE, LOW);
```

```
digitalWrite(RED_WE, LOW); digitalWrite(GREEN_EW, LOW);
digitalWrite(YELLOW_EW, LOW); digitalWrite(RED_EW, HIGH);
} void switchToEW() { digitalWrite(GREEN_WE, LOW);
digitalWrite(YELLOW_WE, LOW); digitalWrite(RED_WE, HIGH);
digitalWrite(GREEN_EW, HIGH); digitalWrite(YELLOW_EW, LOW);
digitalWrite(RED_EW, LOW);
} void switchToYellowWE() { digitalWrite(GREEN_WE, LOW);
digitalWrite(YELLOW_WE, HIGH); digitalWrite(RED_WE, LOW);
digitalWrite(GREEN_EW, LOW); digitalWrite(YELLOW_EW,
LOW); digitalWrite(RED_EW, HIGH);
} void
switchToYellowEW() {
    digitalWrite(GREEN_WE, LOW); digitalWrite(YELLOW_WE, LOW);
digitalWrite(RED_WE, HIGH); digitalWrite(GREEN_EW, LOW);
digitalWrite(YELLOW_EW, HIGH); digitalWrite(RED_EW, LOW);
} void loop() {
updateQueues();

// MQTT HANDLING
if (!client.connected()) reconnect();
client.loop();

// MQTT HANDLING if
(!client.connected()) reconnect();
client.loop();
if (currentPhase == PHASE_GREEN_WE) {
publishState("WE", "GREEN", queueWE);
publishState("EW", "RED", queueEW);
} if (currentPhase ==
PHASE_YELLOW_WE) { publishState("WE",
"YELLOW", queueWE);
publishState("EW", "RED", queueEW);
```

[REDACTED]

}

```

    if (currentPhase == PHASE_GREEN_EW) {
publishState("EW", "GREEN", queueEW);
publishState("WE", "RED", queueWE);
    } if (currentPhase ==
PHASE_YELLOW_EW) { publishState("EW",
"YELLOW", queueEW);
publishState("WE", "RED", queueWE);
}
}

Serial.print("queueWE: "); Serial.print(queueWE);
Serial.print(" | queueEW: "); Serial.println(queueEW);
greenDurationWE = BASE_GREEN_DURATION + queueWE * TIME_PER_CAR; if
(greenDurationWE > MAX_GREEN_DURATION) greenDurationWE = MAX_GREEN_DURATION;
greenDurationEW = BASE_GREEN_DURATION + queueEW * TIME_PER_CAR; if
(greenDurationEW > MAX_GREEN_DURATION) greenDurationEW = MAX_GREEN_DURATION;
unsigned long now = millis(); unsigned
long elapsed = now - phaseStartTime;
switch (currentPhase)
{
    case
PHASE_GREEN_WE:
        switchToWE(); if (elapsed >=
greenDurationWE) { if (queueEW >
0) { currentPhase =
PHASE_YELLOW_WE;
phaseStartTime = now;
        } }
break; case
PHASE_YELLOW_WE:
switchToYellowWE();
        if (elapsed >= YELLOW_DURATION) {
currentPhase = PHASE_GREEN_EW;
phaseStartTime = now;
        } break;
case PHASE_GREEN_EW:
        switchToEW();
        if (elapsed >= greenDurationEW) {
if (queueWE > 0) {
currentPhase = PHASE_YELLOW_EW;
phaseStartTime = now;
}
}
}

```

```
        }
    }      break;      case
PHASE_YELLOW_EW:
switchToYellowEW();      if (elapsed
>= YELLOW_DURATION) {
currentPhase = PHASE_GREEN_WE;
phaseStartTime = now;
}
break;
}
delay(200);
}
```

5.9 Full Dashboard Code (Web Interface)

Below is the complete HTML, CSS, and JavaScript code used to implement the real-time dashboard. This connects to the HiveMQ broker using MQTT.js and listens for traffic updates from the ESP32.

```
<!DOCTYPE html>
<html lang="en">
<head>
  <meta charset="UTF-8" />
  <meta name="viewport" content="width=device-width, initial-scale=1.0" />
  <title>Smart Traffic Dashboard</title>
  <link
    href="https://cdn.jsdelivr.net/npm/bootstrap@5.3.0/dist/css/bootstrap.min.css"
    rel="stylesheet">
  <style>
body {
  background-color: #f5f5f5;
}
.card {
border-radius: 12px;
  box-shadow: 0 0 12px rgba(0,0,0,0.1);
}
.light-circle {
width: 100px;
height: 100px;
border-radius: 50%;
```



```

        margin: 10px auto;
display: flex;      align-
items: center;      justify-
content: center;      font-
weight: bold;      color:
white;      font-size:
1.2rem;
    }
.GREEN { background-color: green; }
.YELLOW { background-color: gold; color: black; }
.RED { background-color: red; }

.fw-bold {
font-size: 1.5rem;
font-weight: bold;
}
</style>
</head>
<body class="bg-light">
<div class="container py-5">
<h1 class="text-center mb-4">Smart Traffic Light Dashboard</h1>
<div class="row">
<div class="col-md-6">
<div class="card text-center p-3">
<h3>West-East (WE)</h3>
<div id="stateWE" class="light-circle">--</div>
<p id="queueWE" class="fw-bold">Queue: --</p>
</div>
</div>
<div class="col-md-6">
<div class="card text-center p-3">
<h3>East-West (EW)</h3>
<div id="stateEW" class="light-circle">--</div>
<p id="queueEW" class="fw-bold">Queue: --</p>
</div>
</div>
</div>
</div>

<script src="https://unpkg.com/mqtt/dist/mqtt.min.js"></script>
<script>
const client = mqtt.connect("wss://broker.hivemq.com:8884/mqtt");
client.on("connect", () => {
client.subscribe("iot/traffic/WE/state");

```

```

        client.subscribe("iot/traffic/EW/state");
client.subscribe("iot/traffic/WE/queue");
client.subscribe("iot/traffic/EW/queue");
    });
    client.on("message", (topic, message) => {
const val = message.toString();      if
(topic.includes("WE/state")) {      const elem =
document.getElementById("stateWE");
elem.textContent = val;           elem.className =
"light-circle " + val;
}      if (topic.includes("EW/state")) {
const elem = document.getElementById("stateEW");
elem.textContent = val;           elem.className =
"light-circle " + val;
}      if (topic.includes("WE/queue")) {
document.getElementById("queueWE").textContent = "Queue: " + val;
}      if (topic.includes("EW/queue")) {
document.getElementById("queueEW").textContent = "Queue: " + val;
}
});
</script>
</body>
</html>
```

6. Testing and Evaluation

6.1 Hardware Testing Procedure

The complete circuit was assembled on a breadboard and tested using real hand gestures to simulate vehicle motion:

- A hand passed over the **entry sensor** increased the queue.
- A hand passed over the **exit sensor** decreased it.
- LEDs responded by changing light states.
- ESP32 output was monitored via serial.
- Dashboard showed real-time queue and signal updates.

6.2 Behavior Verification

- **Queue counts** updated correctly with entry and exit events.
- **Traffic light switched** accurately based on queue comparison.
- **Green duration** increased proportionally with queue size.
- **Yellow phase** always lasted exactly 2 seconds.
- **MQTT messages** were received instantly by the dashboard.

6.3 Results SCENARIO OBSERVED BEHAVIOR

| | |
|------------------------------------|--|
| 3 CARS IN WE, 0 IN EW | WE green ~11 seconds; EW red |
| EQUAL CARS (2 VS 2) | Direction alternated as expected |
| NO CARS IN EITHER DIRECTION | Green still given with minimum duration (5s + 2s yellow) |
| RAPID CAR ARRIVAL | Queue counter scaled correctly, green time extended |
| DISCONNECT/RECONNECT WI-FI | ESP32 reconnected automatically and resumed publishing |

7. Challenges and Fixes

| Challenge | How We Solved It |
|--|---|
| <i>Ultrasonic interference (false positives)</i> | Delayed queue increment; used basic debounce logic |
| <i>Queue overflow with repeated hands</i> | Added conditional to prevent double-counting on entry |
| <i>MQTT messages not appearing on dashboard</i> | Used WSS port 8884 and ensured correct topic formatting |

LED flickering during transitions Enforced exclusive state (one light ON per direction max)

Wi-Fi drop during operation Retried connection in loop until MQTT reconnected

8. Security Considerations

- MQTT communication uses **WSS** (WebSocket Secure), providing basic TLS encryption.
- The broker is public (HiveMQ), so no authentication or access control.
- For deployment in real cities, a **private broker with full TLS and client authentication** would be required.

9. Future Improvements

| Improvement Area | Plan |
|-------------------------|---|
| Physical deployment | Use IR sensors or inductive loops for more accurate vehicle detection |
| Multi-direction support | Add North-South lanes and 4-way logic |
| Mobile dashboard | Build Flutter or Android app for real-time control |
| Emergency override | Add button or priority input for ambulance/fire signals |
| Advanced timing | Use machine learning to predict traffic buildup |

10. Conclusion

This project demonstrated a fully functional smart traffic and congestion control system using IoT principles. By combining real vehicle detection via ultrasonic sensors, queuebased adaptive timing, MQTT communication, and a live dashboard, the system achieved real-time control and visualization. The use of **Green Time = Base + (2 seconds per car)** created a realistic traffic response. All work was implemented and tested on real hardware using the ESP32 microcontroller and common electronic components.

This system proves that IoT solutions for traffic management can be built affordably and reliably—and lays the groundwork for more advanced smart city applications.