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Development of an IoT-Enabled Rule-Based Adaptive Traffic Signal System Using Discrete Vehicle Queue-State Detection and ESP32

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ABSTRACT

Purpose – This study aims to develop and evaluate an IoT-enabled, rule-based adaptive traffic signal prototype that responds to discrete vehicle queue states at a four-way intersection. The system is designed as a low-complexity alternative to fixed-time signal control by associating detected vehicle presence at predefined spatial points with different green-light durations.

Methods – The prototype was developed using ESP32 microcontrollers and eight infrared (IR) sensors, with two detection points assigned to each of four approaches. The physical prototype uses spatially separated detection points to represent different queue states. Sensor inputs are processed locally by the ESP32 and classified into predefined traffic states. The controller assigns green-light durations of 20, 25, or 30 s according to the detected state. The prototype was evaluated under five laboratory-scale traffic configurations using simulated vehicles to verify sensor detection, traffic-state classification, signal response, and IoT communication functionality.

Findings – The experimental evaluation verified that the controller responded according to the predefined queue-state rules. When neither detection point was active, the corresponding traffic state was classified as normal and a 20-s green duration was assigned. Activation of the first detection point resulted in a 25-s green duration, while activation of both detection points resulted in a 30-s green duration. The five predefined scenarios demonstrated that the controller could apply different timing levels according to the traffic-state distribution among the four approaches. Repeated-cycle testing resulted in 49 successful detection-and-control responses out of 50 cycles, corresponding to a 98% successful-cycle rate under the tested laboratory conditions.

Research implications – The results demonstrate the functional feasibility of integrating discrete IR-based queue-state detection, local ESP32 processing, traffic-signal control, and wireless communication in a laboratory-scale prototype. However, the study does not establish a quantitative reduction in real-world delay, queue length, or congestion because the evaluation does not include field testing or a comprehensive fixed-time performance baseline.

Originality – The contribution of this study lies in the implementation of a low-complexity two-point queue-state detection architecture that translates spatial vehicle-presence information into rule-based green-time selection on a four-approach prototype. The architecture provides a basis for subsequent development involving repeated quantitative experiments, additional detection zones, improved traffic-state estimation, and field-based evaluation.

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INTRODUCTION

The increasing number of vehicles in urban areas has created significant challenges for traffic management, particularly at signalized intersections. Intersections represent critical points in urban transportation networks because traffic streams from different approaches compete for limited right-of-way. When traffic demand varies considerably between approaches, a fixed signal-timing plan may allocate green time inefficiently, resulting in unnecessary waiting, queue accumulation, and underutilization of available intersection capacity [1].

Traffic signal control strategies can generally be distinguished into fixed-time, actuated, and adaptive control. Fixed-time control determines signal timing in advance based on predetermined plans and historical traffic conditions. Although this approach is relatively simple to implement, its performance may decrease when actual traffic demand differs substantially from the assumed demand pattern. Actuated control introduces real-time detector information and applies predefined control rules, such as phase calls, green extensions, minimum green, and maximum green. Adaptive traffic signal control extends this concept by using real-time traffic information to modify signal timing according to traffic conditions and, in more advanced systems, optimization objectives [2].

Recent research has increasingly focused on adaptive traffic signal control because traffic demand is dynamic and may vary across time and intersection approaches. Contemporary approaches include model-based optimization, connected-vehicle-based control, reinforcement learning, and other data-driven methods. For example, recent research has investigated model predictive control using connected-vehicle information to estimate queue conditions and optimize signal timing, while other studies have applied deep reinforcement learning to minimize queue length and waiting time. [3]. These approaches demonstrate the potential of real-time traffic information for improving intersection control, but they generally require more extensive traffic-state information, computational resources, simulation environments, or communication infrastructure than is necessary for a basic embedded prototype.

Another important direction is the development of low-cost sensing and distributed traffic-control architectures. Infrastructure-based detectors remain important sources of traffic information for signal control, but detector selection affects installation cost, sensing resolution, reliability, and system complexity. Recent research has explored wireless adaptive signal architectures using ESP32 controllers and distributed communication, including architectures that incorporate explicit fail-safe mechanisms to prevent conflicting traffic movements [4]. This indicates that embedded wireless controllers can provide a practical platform for experimental traffic-control systems, provided that their control and safety limitations are clearly defined.

The distinction between actuated and adaptive control is particularly important for the present study. The proposed system does not perform continuous optimization of cycle length, phase split, or offset, nor does it estimate traffic demand using a continuous traffic-flow model. Instead, the system applies a rule-based multi-level control mechanism. Vehicle presence is detected at two predefined spatial points on each approach, and the combination of sensor states is converted into a discrete queue-state classification. The resulting state determines the corresponding green-light duration. Therefore, the proposed architecture is more appropriately understood as a queue-state-responsive, rule-based adaptive signal prototype rather than a full adaptive traffic-signal optimization system [5].

Low-complexity sensing is particularly relevant for prototype development because advanced computer-vision systems can provide detailed vehicle information but generally require additional computational and sensing resources. Recent traffic-signal studies have investigated video-based detection and fuzzy or learning-based control to obtain more detailed traffic-state information. Such approaches can estimate vehicle queues or traffic flow more continuously, but they also introduce additional processing and sensing requirements. The use of infrared sensors in the present study is therefore motivated not by an expectation that they provide complete traffic-state estimation, but by their suitability for implementing a simple binary vehicle-presence detector on a microcontroller-based prototype.

The proposed two-point sensing architecture represents queue conditions through discrete detection zones. The first detection point represents the presence of a vehicle closer to the intersection, whereas activation of both detection points represents a vehicle presence extending farther upstream. This approach does not provide a continuous measurement of queue length in meters. Instead, it provides a coarse classification of queue state that can be processed locally by an ESP32. The advantage of this approach is its low computational complexity and relatively straightforward relationship between sensing and signal control. Its limitation is the relatively low spatial resolution of the traffic information available to the controller [6].

The literature also indicates that contemporary adaptive traffic-signal research increasingly emphasizes measurable traffic-performance objectives. Queue length, delay, waiting time, throughput, and related measures are commonly used to evaluate whether a control strategy provides an actual transportation benefit. For example, recent adaptive-control studies compare proposed strategies against fixed-time or other baseline strategies using queue and delay measures rather than relying solely on successful execution of signal-control rules [7]. Consequently, verifying that a controller changes green duration in response to sensor activation is necessary for demonstrating functional correctness, but it is not sufficient to establish an improvement in intersection performance.

Based on this perspective, the research gap addressed in this study concerns the implementation of a low-complexity, discrete queue-state-responsive traffic signal architecture that integrates local sensing, embedded decision-making, and wireless communication within a four-approach prototype. The contribution is therefore not the use of ESP32, infrared sensors, or wireless communication individually, as these technologies are already established. Instead, the study investigates how two spatially separated IR detection points can be used as a simple queue-state representation and directly translated into rule-based signal timing at the prototype level.

The proposed architecture also emphasizes local decision-making. The ESP32 processes sensor information locally so that the basic signal-control function does not depend entirely on network availability. Wireless communication is incorporated as an IoT monitoring layer for transmitting traffic-state information to the monitoring interface. This separation between local control and communication is important because a temporary communication failure should not inherently prevent the basic traffic-control function from operating.

The physical implementation is evaluated using a laboratory-scale four-way intersection prototype. Four traffic-light modules represent the approaches, while two IR detection points are assigned to each approach. The experimental evaluation focuses primarily on functional verification: whether the sensors can provide the intended input states, whether the controller classifies those states according to the predefined rules, and whether the corresponding signal timing is generated. The study therefore does not interpret successful timing changes as direct evidence of reduced real-world congestion.

Fixed-time, actuated, and adaptive traffic-signal control represent progressively different levels of responsiveness to real-time traffic demand [8], while recent adaptive approaches increasingly incorporate connected vehicles and real-time traffic-state information [9], [10]. More advanced adaptive traffic-signal systems employ optimization, connected-vehicle information, or reinforcement learning to optimize delay, queue length, or network performance [9], [11], [12], [14]. In contrast, the present study uses a low-complexity rule-based mechanism based on two discrete IR detection points.

This limitation also defines the scope of the contribution. The present prototype provides an initial experimental platform for studying discrete queue-state-responsive control using low-complexity embedded hardware. More advanced evaluation is required to establish transportation performance through repeated trials, fixed-time comparison, detector reliability measurements, communication-performance analysis, and eventually field testing. Such an evaluation would allow future versions of the system to move from functional prototype verification toward quantitative intelligent transportation system assessment.

Recent research has also investigated wireless and distributed traffic-signal architectures using embedded controllers and communication networks, including systems incorporating ESP32-based controllers and fail-safe mechanisms [13].

Accordingly, this study aims to develop and evaluate an IoT-enabled, rule-based adaptive traffic signal prototype using discrete vehicle queue-state detection and ESP32 microcontrollers. The specific objectives are to:

1. develop a four-approach traffic signal prototype using ESP32 microcontrollers and infrared vehicle-detection sensors.
2. classify traffic conditions using two spatially separated detection points on each approach.
3. implement predefined green-light timing responses according to the detected queue state.
4. evaluate the functional response of the prototype under different traffic distributions across four approaches.
5. examine the feasibility of integrating local traffic-signal control with wireless IoT communication.

METHOD

Research Design

This study employed an experimental prototyping approach to develop and evaluate an Internet of Things (IoT)-enabled rule-based adaptive traffic signal system. The system was designed to adjust the green-light duration according to the discrete vehicle queue state detected at each approach of a four-way intersection.

The prototype consisted of four traffic-signal modules representing four approaches. Each approach was equipped with an ESP32 microcontroller, red, yellow, and green LED indicators, and two infrared (IR) detection points. The ESP32 performed local processing of the sensor inputs and controlled the corresponding traffic-signal sequence. Coordination between the traffic-light modules was implemented through a wired connection. Wi-Fi and MQTT were implemented separately as a monitoring layer for transmitting traffic-state information to the MQTT monitoring interface.

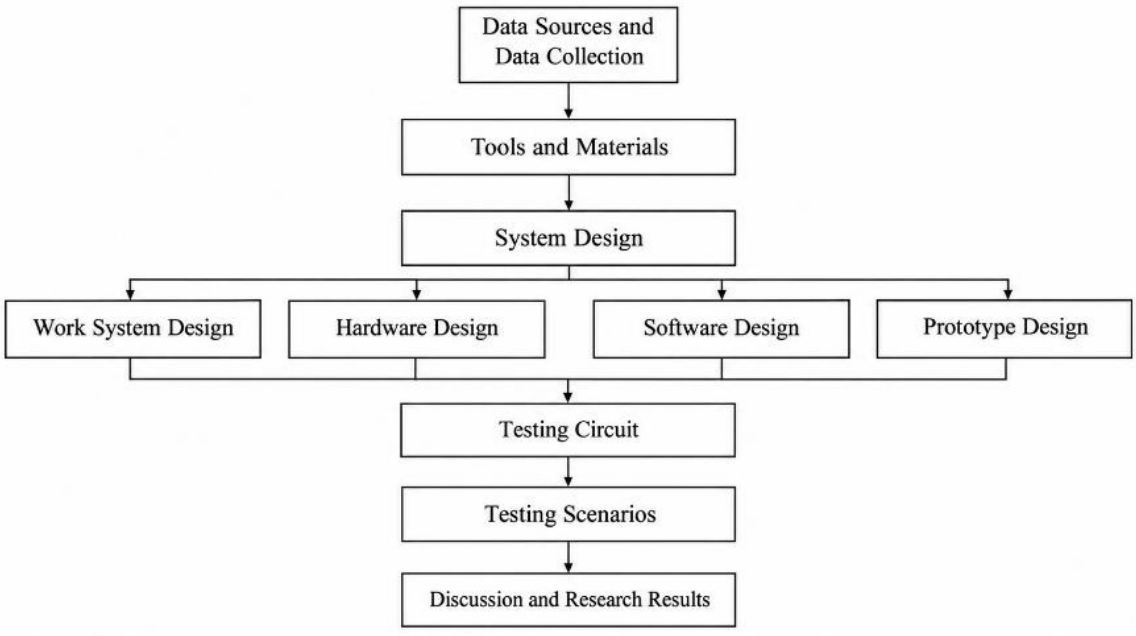


Figure 1. Research flowchart

The evaluation was conducted at prototype scale using simulated vehicles. The main purpose of the experiment was to verify whether the proposed detection mechanism could consistently identify the predefined traffic states and whether the controller could apply the corresponding green-light duration. In addition, repeated-cycle testing was performed to evaluate the consistency of the detection and control response.

The study therefore focuses on functional verification and prototype-level reliability, rather than claiming a reduction in real-world traffic congestion, waiting time, or vehicle delay. A quantitative comparison with a conventional fixed-time traffic signal under real traffic conditions was not included in the present experiment.

Prototype Configuration and Sensor Placement

The prototype represents a four-way signalized intersection. Each approach contains two IR-based vehicle detection points, namely S1 and S2.

Unlike the conceptual distances used in the initial manuscript, the distances reported in this study refer to the actual physical dimensions of the prototype. The distance from the traffic signal to S1 is approximately 10 cm, while the distance from S1 to S2 is approximately 10 cm. Thus, S2 is located approximately 20 cm from the traffic signal.

The two detection points are used to represent different queue states rather than to provide continuous measurements of queue length. S1 represents a vehicle reaching the first detection zone, whereas activation of S2 indicates that the detected traffic condition has extended to the second detection zone.

The physical distance between the sensors is a prototype design parameter and should not be interpreted as a direct representation of a fixed 10 m or 30 m distance in a real intersection. For future field implementation, the distance between detection zones would need to be determined according to the physical geometry of the intersection, lane length, expected queue formation, and desired congestion thresholds.

Table 1. Prototype sensor configuration

Parameter	Prototype configuration
Number of approaches	4
IR sensors per approach	2
Total IR sensors	8
Distance from traffic signal to S1	10 cm
Distance from S1 to S2	10 cm
Approximate distance from traffic signal to S2	20 cm
Vehicle representation	Toy vehicles
Controller	ESP32
Communication	Wired coordination; Wi-Fi/MQTT monitoring

This clarification directly addresses the reviewer's concern regarding the difference between the conceptual field distances and the actual physical dimensions shown in the prototype.

Discrete Queue-State Classification

The proposed system does not continuously calculate the physical length or number of vehicles in a queue. Instead, it uses the activation states of two spatially separated IR sensors to classify the traffic condition into discrete levels. The control relationship is defined as follows.

Table 2. Discrete queue-state classification and green-light timing

S1	S2	Traffic state	Green duration
Inactive	Inactive	Normal	20 s
Active	Inactive	Congestion Level I	25 s
Active	Active	Congestion Level II	30 s
Inactive	Active	Normal	20 s

The controller determines the traffic state based on the activation combination of S1 and S2. When both sensors are inactive, the approach is classified as normal and receives a 20-second green phase. When S1 is active while S2 remains inactive, the system classifies the approach as Congestion Level I and increases the green duration to 25 seconds. When both S1 and S2 are active, the system classifies the condition as Congestion Level II and applies a 30-second green duration. When S1 is inactive and S2 is active, the system maintains the normal traffic classification and applies a 20-second green duration.

This four-state input table reflects the actual control logic implemented in the prototype. The two IR sensors therefore provide discrete input combinations that are translated directly into predefined signal-timing responses. The system does not use these sensor states to continuously estimate queue length; instead, they serve as simplified indicators for determining the appropriate traffic-state category.

IoT Communication

The IoT communication subsystem was implemented using the Wi-Fi connectivity of the ESP32 and the MQTT communication protocol. MQTT was implemented and operated during prototype testing as a monitoring mechanism for transmitting traffic-state information from the traffic-light controllers to the monitoring interface.

Each ESP32-based traffic-signal module was connected to the local Wi-Fi network to publish traffic-state information through the MQTT broker. The transmitted information represented the traffic condition detected by the local controller and could be observed using an MQTT client such as MQTT Explorer. MQTT was therefore used for monitoring and visualization rather than for coordinating the traffic-light modules.

Local sensor processing and traffic-signal control were performed by each ESP32 independently. Coordination between the traffic-light modules was implemented through a wired connection, while Wi-Fi and MQTT provided a separate monitoring layer. This architecture separates the primary traffic-signal control function from the IoT communication layer.

During prototype testing, the MQTT monitoring subsystem operated successfully under the local network environment. The measured communication latency was below 100 ms on average under the tested conditions. However, the availability of the monitoring function remained dependent on Wi-Fi connectivity, MQTT broker availability, and power-supply stability.

For real-world deployment, additional communication-recovery and fault-handling mechanisms would be required to improve monitoring reliability under network disconnection, broker interruption, and power disturbances. The effect of communication failure on traffic-signal operation is addressed separately in the Signal Coordination and Fail-Safe Considerations section.

Signal Coordination and Fail-Safe Considerations

The coordination of the four traffic-light modules is implemented through a wired connection rather than through MQTT communication. The wired connection is used to support the exchange of control information between the traffic-light modules during normal operation. Therefore, the primary traffic-signal control mechanism does not depend on Wi-Fi or MQTT connectivity.

MQTT is implemented as a separate communication layer for monitoring purposes. Traffic-state information generated by the ESP32-based controllers is transmitted through the Wi-Fi network to the MQTT broker and can be observed using an MQTT client such as MQTT Explorer. This separation

between control and monitoring is designed so that network interruptions do not directly stop the traffic-signal control process.

During normal operation, the traffic-light modules continue to execute their local control logic and wired coordination even when the Wi-Fi network or MQTT connection is unavailable. If the Wi-Fi connection is interrupted, the monitoring function becomes unavailable and updated traffic information cannot be displayed through MQTT Explorer; however, the basic traffic-light control remains operational.

This architecture also reduces the dependency of traffic-signal operation on the IoT communication layer. MQTT is therefore considered a monitoring channel rather than a safety-critical control channel. A temporary loss of MQTT connectivity does not directly determine the traffic-light state.

In the prototype, the traffic-state information observed through the MQTT monitoring interface provides an additional overview of the traffic condition at the approaches. This enables the operator to observe whether congestion is occurring across one or multiple approaches and to identify conditions in which congestion becomes more widespread. The monitoring result can therefore support system observation and evaluation without replacing the local traffic-signal control mechanism.

Experimental Procedure

Testing was conducted by placing toy vehicles on the approaches of the prototype intersection to represent different queue conditions. Five traffic configurations were used to represent increasing levels of traffic demand. The first configuration represented low traffic on all approaches. The subsequent configurations introduced congestion level I on one or more approaches, followed by a configuration combining congestion level I and level II.

The experimental procedure consisted of several stages. First, the power supply and electronic connections were checked to ensure that all modules could operate. Second, the IR sensors were tested to determine whether vehicle presence could be detected at the designated points. Third, the LCD output was observed to verify that system information was displayed according to the operating condition. Finally, the complete traffic-control system was operated under the predefined traffic configurations.

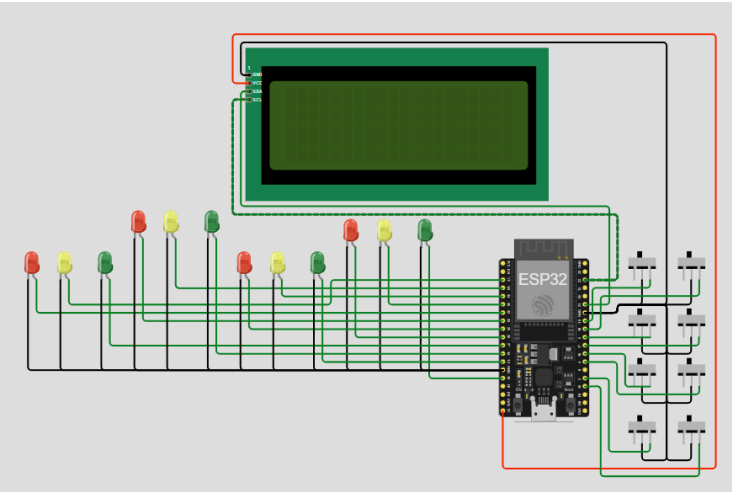


Figure 2. Prototype wiring diagram

For each configuration, the sensor states, traffic classification, signal sequence, and resulting green-light duration were observed. The same basic control rules were applied to all four approaches, allowing the response of different approaches to be compared under different traffic distributions. The original experimental design defines five configurations ranging from all approaches being uncongested to a condition in which one approach reaches congestion level II while two other approaches experience congestion level I.

Data Analysis

The collected observations were analyzed descriptively to evaluate three main aspects: traffic-state detection, adaptive signal response, and IoT communication. Detection performance was evaluated by comparing the intended traffic condition with the sensor state recognized by the controller. Adaptive control was evaluated by examining whether the green duration changed according to the predefined traffic category. The communication component was assessed from the transmission and monitoring behavior of the ESP32-based system.

In addition, the response of the four approaches was compared across the experimental configurations to examine whether the controller could provide different green durations when traffic conditions were unequal. Any communication interruption, unstable power condition, or sensor detection error observed during testing was also recorded as part of the system evaluation.

Ethical and Experimental Considerations

The study involved a laboratory-scale prototype and simulated traffic using toy vehicles; therefore, no personal information or human-subject data were collected. The experimental results were limited to the physical prototype and simulated intersection conditions and should not be interpreted directly as field performance under real traffic conditions. Environmental factors that may affect IR-based detection, as well as Wi-Fi and power-supply stability, were considered as technical limitations requiring further evaluation before real-world deployment.

RESULTS AND DISCUSSION

Results

The developed prototype was evaluated using a four-approach intersection model in which each approach was equipped with two infrared (IR) detection points. The experimental evaluation focused on the ability of the controller to identify different queue conditions and automatically modify the green-light duration. In addition to the traffic scenarios, the prototype was also evaluated through power-supply, IR-sensor, LCD, and IoT communication tests.

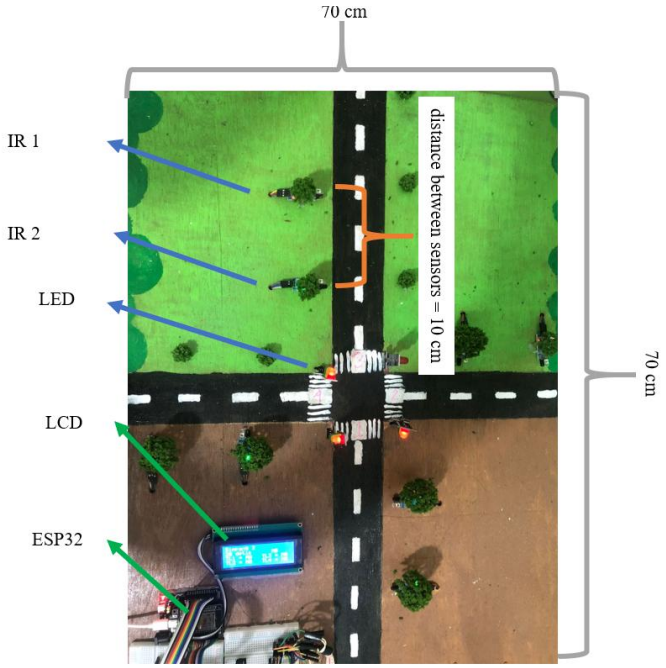


Figure 3. System Design

The traffic-state classification was determined from the activation pattern of the two sensors. When neither sensor detected a vehicle, the approach was categorized as a normal condition and assigned a 20-second green phase. Activation of the first sensor indicated congestion level I and increased the

green phase to 25 seconds. When both sensors were active, the system classified the approach as congestion level II and assigned a 30-second green phase. The resulting control relationship is presented in Table 3.

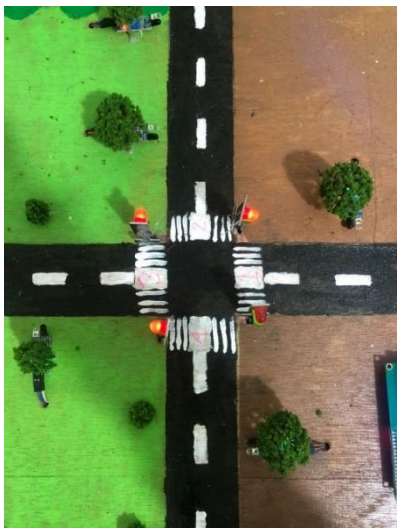


Figure 4. Operational condition of the traffic light prototype under a normal traffic scenario

Table 3. Queue-based traffic classification and signal timing

S1	S2	Traffic condition	Green duration	Control response
Inactive	Inactive	Normal	20 s	Successfully applied
Active	Inactive	Congestion Level I	25 s	Successfully applied
Active	Active	Congestion Level II	30 s	Successfully applied
Inactive	Active	Normal	20 s	Successfully applied

The experimental scenarios were subsequently organized according to the distribution of traffic conditions across the four approaches. This arrangement allowed the controller to be observed not only under uniform traffic conditions but also when congestion occurred selectively on particular approaches.



Figure 5. Simulated queue-state detection during congested conditions

Table 4. Traffic configurations used for system evaluation

Scenario	Approach 1	Approach 2	Approach 3	Approach 4
S1	Normal	Normal	Normal	Normal
S2	Normal	Normal	Normal	Level I
S3	Normal	Normal	Level I	Level I
S4	Normal	Level I	Level I	Level I
S5	Normal	Level I	Level I	Level II

The first scenario represented an uncongested intersection. All approaches received the basic 20-second green duration. In the second scenario, congestion level I was introduced at Approach 4, resulting in a 25-second green phase for that approach while the remaining approaches retained the normal timing.

As congestion was introduced into more approaches, the controller continued to apply the corresponding timing rule independently. In Scenario 3, Approaches 3 and 4 were assigned the level-I timing, while Approaches 1 and 2 remained under normal conditions. Scenario 4 introduced level-I congestion to Approaches 2–4. The final scenario represented a more demanding condition in which Approach 4 reached level II while Approaches 2 and 3 remained at level I. The thesis reports the corresponding final timing as 20 s, 25 s, 25 s, and 30 s for Approaches 1–4, respectively.

The LCD test showed that the display could present information corresponding to the operating condition of the prototype. The IR-sensor test was used to verify object detection at the designated detection points, while the complete scenario tests demonstrated that the traffic-light controller changed its timing according to the sensor state.

The communication subsystem was implemented using the Wi-Fi capability of the ESP32. The experimental evaluation recorded an average communication latency below 100 ms under local-network conditions. It also observed that communication and controller stability were affected by Wi-Fi conditions and power-supply stability; voltage-drop conditions could cause the ESP32 to reset.

The MQTT monitoring function was tested to verify whether traffic-state information generated by the ESP32 controllers could be transmitted and observed through the MQTT monitoring interface. MQTT Explorer was used as the monitoring client to display the messages published by the traffic-light system.

The monitoring interface successfully displayed traffic-related information from the prototype modules, allowing the operating condition of the four approaches to be observed through the MQTT topics. The monitoring output provides an overview of the traffic state detected at each approach and can be used to identify conditions in which congestion occurs simultaneously or becomes more widespread across the intersection.

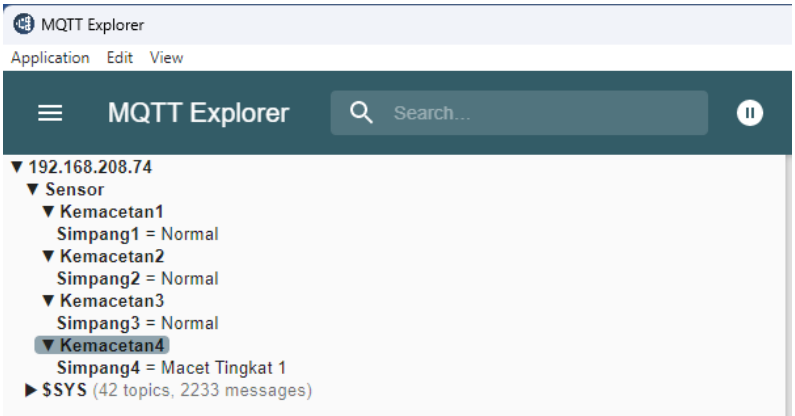


Figure 6. MQTT Explorer monitoring interface showing traffic-state information from the four traffic-light modules.

Figure 6 presents the MQTT Explorer monitoring interface during prototype operation. The displayed topics correspond to the traffic-light modules and their reported traffic conditions. This result confirms that the MQTT communication layer successfully transmitted monitoring information from the ESP32-based system to the monitoring client.

The MQTT communication was implemented independently from the primary traffic-light coordination mechanism. Consequently, the monitoring function is not required for the basic operation of the traffic signals. When the Wi-Fi network or MQTT connection is unavailable, the monitoring information cannot be updated in MQTT Explorer, but the traffic-light system continues to operate using its wired coordination and local control logic.

Repeated-Cycle Reliability

A repeated-cycle experiment was subsequently performed to assess the consistency of the prototype. A total of 50 cycles were conducted.

Table 5. Repeated-cycle test results

Evaluation parameter	Result
Total experimental cycles	50
Successful queue detections/control responses	49
Detection/control failures	1
Successful cycle rate	98%
Failure rate	2%

Of the 50 tested cycles, 49 cycles successfully detected the intended queue condition and produced the corresponding control response, while 1 cycle failed to detect the queue condition, causing the system to interpret the approach as a non-congested condition. The resulting successful detection/control-cycle rate was:

$$\boldsymbol{Succes\ Rate} = \frac{\mathbf{49}}{\mathbf{50}}\boldsymbol{x}\ \mathbf{100\%} = \mathbf{98\%}$$

The system successfully detected and responded to the intended queue condition in 49 of the 50 cycles. One cycle resulted in a missed queue detection, causing the controller to classify the condition as non-congested.

The 98% successful-cycle rate indicates that the prototype operated consistently in the tested laboratory environment, although one detection failure demonstrates that the IR-based detection mechanism was not completely error-free.

Importantly, this result does not establish that the sensor has 98% accuracy under real traffic conditions. The experiment was conducted using a prototype and simulated vehicles, and therefore the result represents the reliability observed within the tested experimental configuration.

Discussion

The experimental results indicate that the proposed system can implement a rule-based adaptive traffic signal mechanism using discrete vehicle queue-state detection. The main characteristic of the proposed approach is that the controller does not attempt to continuously estimate the physical length of a vehicle queue. Instead, two spatially separated IR detection points are used to represent different queue states.

The use of two detection points provides a simple relationship between vehicle position and signal timing. When vehicles do not reach either detection point, the system maintains the normal 20-second green duration. When the first detection point is activated, the green duration is increased to 25 seconds. When both detection points are activated, the green duration is increased to 30 seconds.

This architecture represents a rule-based multi-level actuated control mechanism rather than a full adaptive traffic optimization system. The timing values are predetermined and do not continuously

optimize the signal cycle based on traffic arrival rate, queue length, throughput, or delay. This distinction is important because advanced adaptive traffic-signal systems may use continuous traffic measurements, optimization models, connected-vehicle information, or machine-learning techniques.

The principal advantage of the proposed approach is its relatively low computational complexity. Vehicle-state information is obtained directly from IR sensors and processed locally by an ESP32. This reduces the computational requirements compared with vision-based systems that require image processing or machine-learning inference.

However, the low complexity is accompanied by lower traffic-state resolution. Because only two detection points are used, the system cannot determine the exact number of vehicles or continuous queue length. Different vehicle distributions may produce the same sensor activation pattern and consequently the same signal-timing decision.

The repeated-cycle experiment provides additional evidence regarding the functional reliability of the prototype. Of the 50 tested cycles, 49 produced the intended detection and control response, corresponding to a 98% successful detection-and-control-cycle rate. One missed detection demonstrates that the sensing mechanism remains susceptible to detection errors even under prototype conditions.

The result therefore supports the feasibility of the proposed sensing and control concept but should not be interpreted as evidence that the system reduces real-world traffic delay or congestion by a specific percentage. Such claims would require a controlled comparison with a fixed-time baseline using traffic-performance measures such as average waiting time, maximum queue length, queue-clearance time, throughput, and number of stops.

The MQTT implementation further demonstrates that the ESP32-based controller can be incorporated into an IoT communication architecture. The local communication latency observed during testing was below 100 ms on average. Nevertheless, communication should not be considered the sole basis for traffic-signal safety. Loss of Wi-Fi or MQTT communication should not cause conflicting signal states, and future field implementation should therefore incorporate fail-safe operation, watchdog mechanisms, communication-status monitoring, and appropriate signal interlocking.

Implications

Several limitations should be considered when interpreting the findings of this study.

First, the proposed system uses only two IR detection points per approach. Consequently, the system provides discrete queue-state information rather than continuous measurements of queue length or the exact number of vehicles.

Second, the experimental distance between the traffic signal and the detection points was defined according to the physical dimensions of the prototype, with S1 positioned approximately 10 cm from the signal and S2 approximately 10 cm farther from S1. These dimensions cannot be directly transferred to an actual intersection. A field implementation would require recalibration of detection-zone distances according to road geometry and expected queue characteristics.

Third, the experiment used simulated traffic represented by toy vehicles. Real traffic involves substantially greater variation in vehicle size, speed, spacing, road-user behavior, weather, lighting, and vehicle composition.

Fourth, although the repeated-cycle experiment produced a 98% successful detection-and-control-cycle rate, the current study did not separately quantify false-positive and false-negative detection rates, sensor specificity, or detection performance across systematically varied environmental conditions.

Fifth, the adaptive timing values of 20, 25, and 30 seconds are predefined rules. The controller does not currently perform continuous optimization based on traffic arrival rates, queue discharge rates, pedestrian demand, turning movements, or neighboring intersections.

Sixth, MQTT communication was successfully implemented in the prototype, but communication performance was evaluated primarily under a local Wi-Fi environment. Additional testing is required under packet loss, network disconnection, broker interruption, reconnection, and power-reset conditions.

Finally, the present study does not provide a fixed-time traffic-signal baseline with quantitative traffic-efficiency measurements. Therefore, the results demonstrate functional feasibility and prototype-level reliability, rather than statistically validated improvements in traffic efficiency.

Research contribution

The main contribution of this study is the development and experimental evaluation of an ESP32-based IoT traffic-light prototype that integrates queue-state detection, adaptive green-light control, and MQTT-based communication. Rather than treating traffic sensing, signal control, and IoT communication as independent components, the proposed architecture combines these functions into a single prototype system. Vehicle detection becomes the basis for traffic-state classification, the classified condition determines the signal timing, and the ESP32 provides local processing and wireless communication capabilities within the IoT architecture.

A second contribution is the implementation of a discrete queue-classification mechanism using two spatially separated IR sensors. The first sensor represents the initial detection point, while activation of both sensors represents a more extended detected traffic condition. Based on the implemented control logic, the system distinguishes three operational traffic states: normal traffic, Congestion Level I, and Congestion Level II. These states are translated into green-light durations of 20, 25, and 30 seconds, respectively. The approach provides a relatively lightweight alternative to traffic-monitoring systems that require continuous image processing or more computationally intensive vehicle-detection methods.

The use of two detection points also establishes a direct relationship between the physical position of vehicles and the controller's decision-making process. Instead of requiring the system to estimate queue length continuously, the controller uses the activation combination of S1 and S2 as a simplified representation of queue development. This makes the decision algorithm relatively straightforward and suitable for implementation on a microcontroller-based platform. At the same time, the study identifies the resulting spatial resolution as a limitation that can be addressed through additional detection points or more advanced sensing technologies.

A further contribution is the multi-approach experimental evaluation. The prototype was not evaluated under only a single congestion condition. The experimental design included different traffic distributions across four approaches, ranging from an entirely normal condition to combinations of Level I and Level II congestion. This enables the system's adaptive logic to be examined when traffic demand is distributed unevenly between approaches. The final scenario, for example, combines normal traffic on one approach, Level I congestion on two approaches, and Level II congestion on another approach.

This multi-approach configuration is relevant because adaptive traffic control is concerned with differences in traffic demand between competing approaches. The prototype demonstrates how a common control rule can produce different green-light allocations according to the detected state of each approach rather than applying an identical extension to every direction.

Another contribution is the implementation of MQTT-based IoT monitoring within the traffic-control architecture. The ESP32 provides Wi-Fi connectivity in addition to its local control function, while MQTT is used to transmit traffic-state information to the monitoring interface. Coordination between the traffic-light modules is implemented through a wired connection, separating the IoT monitoring layer from the primary signal-control mechanism. The communication subsystem was successfully operated during prototype testing, with the measured local-network communication latency

reported below 100 ms on average. This implementation demonstrates the feasibility of combining local traffic-signal control with MQTT-based communication in a distributed prototype architecture. Although the system does not constitute a complete city-scale traffic-management platform, the implemented communication layer provides a basis for further development toward centralized monitoring, data logging, and broader traffic-management integration.

Limitations

Several limitations should be considered when interpreting the results of this study. These limitations primarily relate to the sensing configuration, experimental environment, communication infrastructure, and the simplicity of the adaptive control algorithm.

First, the proposed system employs only two detection points for each traffic approach. The first sensor (S1) represents an initial queue-detection point, while the second sensor (S2) represents a more distant detection point. This configuration allows the controller to distinguish among predefined traffic conditions: normal traffic, Congestion Level I, and Congestion Level II. However, it does not provide a continuous measurement of the actual number of vehicles or the physical length of the queue. For example, several vehicles positioned between the two detection points may produce the same classification as a different number of vehicles, provided that the same sensors are activated. Therefore, the system should be interpreted as a discrete queue-state detection system rather than a continuous queue-length measurement system.

Second, the use of infrared (IR) sensors introduces environmental limitations. IR-based detection depends on the ability of the sensor to distinguish the intended object from its surrounding environment. In an outdoor traffic environment, direct sunlight, surface reflection, weather conditions, dust, and changes in sensor orientation may influence detection performance. These effects may be less apparent in the controlled prototype environment but could become more significant when the system is installed at an actual intersection. Sensor installation height, detection angle, distance, and calibration would therefore become important factors in maintaining reliable vehicle detection.

Third, the experimental evaluation was conducted using a prototype intersection and simulated traffic represented by toy vehicles. Although this configuration is useful for verifying the relationship between sensor states and traffic-light responses, it does not reproduce the full complexity of real-world traffic. Actual vehicles differ considerably in size, shape, speed, spacing, acceleration, and stopping behavior. In addition, real intersections involve interactions among vehicles, pedestrians, turning movements, lane changes, and other road users. Consequently, the experimental results demonstrate the technical feasibility of the proposed control concept, but they should not yet be interpreted as evidence of operational effectiveness under real traffic conditions.

Fourth, although MQTT communication was successfully implemented and operated during the prototype evaluation, the communication performance was assessed primarily under a local Wi-Fi network environment. The present study does not comprehensively evaluate communication reliability under packet loss, network congestion, broker interruption, prolonged disconnection, or reconnection conditions. In addition, communication disturbances and voltage instability may affect the operation of the ESP32 controller. The system therefore requires additional mechanisms, such as automatic recovery, watchdog-based fault handling, stable power regulation, communication-status monitoring, and appropriate fail-safe operation before continuous field deployment.

Fifth, the current adaptive controller applies predefined timing increments based on the detected traffic state. The green-light duration is adjusted using fixed values of 20 seconds for normal conditions, 25 seconds for Congestion Level I, and 30 seconds for Congestion Level II. This rule-based approach provides a simple and predictable control mechanism, but it does not dynamically optimize signal timing according to continuously changing traffic demand. Variables such as vehicle arrival rate, vehicle classification, turning movements, pedestrian demand, emergency-vehicle priority, and traffic conditions at neighboring intersections are not incorporated into the current decision process.

Another limitation concerns the scale of the experimental evaluation. The documented scenarios represent several combinations of traffic conditions across the four approaches, but they do not cover the full range of traffic patterns that may occur in an operational intersection. In particular, highly unbalanced traffic demand, rapid changes in queue conditions, simultaneous congestion across multiple approaches, and repeated fluctuations in sensor states require additional testing. Although 50 repeated cycles were conducted and 49 cycles successfully produced the intended detection and control response, further testing under more varied conditions would be necessary to establish broader statistical measures of detection reliability and controller consistency.

Finally, although MQTT-based monitoring was successfully implemented, the current system provides monitoring functionality rather than a complete centralized traffic-management platform. The MQTT layer allows traffic-state information from the prototype modules to be observed through an MQTT client, but it has not yet been extended to centralized historical data management, multi-intersection coordination, or large-scale traffic-management functions. In addition, MQTT communication was evaluated primarily under the local Wi-Fi environment, and further testing under network disconnection, packet loss, broker interruption, and reconnection conditions is required.

Suggestions

Future development should focus on improving the quantitative evaluation, sensing capability, communication reliability, and real-world applicability of the proposed system.

First, future experiments should employ a larger number of trials for each traffic condition. Rather than relying primarily on scenario-based observation, each experimental condition should be repeated several times under controlled and varied conditions. The evaluation should record measurable parameters such as vehicle-detection accuracy, false detection rate, missed detection rate, sensor response time, controller response time, communication latency, successful data-transmission rate, and queue-clearance time. These measurements would provide a stronger quantitative basis for evaluating system performance and comparing different configurations.

Second, the sensing architecture could be expanded by increasing the number of detection points along each approach. Additional sensors would allow the system to distinguish more traffic states instead of relying on only three predefined conditions. For example, multiple detection zones could be used to represent short, medium, long, and very long queues. However, increasing the number of sensors would also increase hardware complexity, wiring requirements, calibration requirements, and maintenance needs. Therefore, future research should evaluate whether the additional information obtained from more detection points provides sufficient improvement in control performance.

Third, alternative vehicle-detection technologies should be investigated for applications that require continuous queue-length estimation. Camera-based computer vision could provide information about vehicle count, vehicle position, and potentially vehicle classification, while LiDAR could provide distance-based information without relying on the same optical detection mechanism as conventional IR sensors. The thesis also identifies LiDAR and vision-based approaches as potential directions for improving vehicle-detection capability. A comparative experiment between IR, computer vision, and LiDAR would therefore be useful for determining the trade-offs among accuracy, cost, processing requirements, and environmental robustness.

Fourth, the IoT communication layer could be developed into a centralized monitoring architecture. An MQTT-based communication system could be implemented to transmit traffic-state information from multiple ESP32 controllers to a central dashboard. Such a platform could provide real-time visualization of traffic conditions, historical data storage, and system-status monitoring. Importantly, future research should not only demonstrate data transmission but also measure communication reliability under different network conditions, including increased distance, network congestion, temporary disconnection, and reconnection events.

Fifth, additional fault-tolerance mechanisms should be incorporated into the controller. Because the prototype depends on electrical power and wireless communication, the next version could include watchdog timers, automatic system restart procedures, voltage monitoring, communication-reconnection routines, and appropriate power-regulation mechanisms. These features would help maintain stable operation when temporary communication or power disturbances occur. The system should also be designed so that a temporary IoT communication failure does not unnecessarily interrupt the basic local traffic-light control process. Sixth, the adaptive algorithm could be extended beyond fixed 5- and 10-second timing increments. Future research could investigate algorithms that dynamically calculate green-light duration from real-time traffic demand. The controller could incorporate variables such as the estimated number of vehicles, queue growth rate, arrival rate, waiting time, and traffic conditions on competing approaches. This would allow the traffic signal to respond not only to the existence of congestion but also to its changing intensity.

Finally, field testing at an actual intersection would be an important stage before the proposed system could be considered for operational traffic management. Field experiments should be conducted under different traffic conditions and compared with an appropriate existing or baseline signal-control strategy. The evaluation should use measurable indicators such as average queue length, average waiting time, maximum waiting time, throughput, cycle utilization, number of stops, and queue-clearance time. Such testing would help determine whether the adaptive strategy observed in the prototype can be maintained under real-world traffic conditions and would also reveal practical issues related to sensor installation, weather exposure, communication infrastructure, electrical reliability, and interaction with existing traffic-management equipment.

Overall, future development should progress from prototype validation toward quantitative testing, improved sensing, reliable IoT communication, more adaptive control algorithms, and finally field-based evaluation. This progression would provide a structured pathway for transforming the current proof-of-concept system into a more robust intelligent traffic-signal platform.

CONCLUSION

This study developed and experimentally evaluated an IoT-enabled rule-based adaptive traffic signal prototype using discrete vehicle queue-state detection, IR sensors, and ESP32 controllers. The system classified traffic conditions into normal, Congestion Level I, and Congestion Level II based on the activation of two detection points and assigned green-light durations of 20, 25, and 30 seconds, respectively.

The prototype was implemented at laboratory scale using four traffic approaches, with an actual sensor spacing of approximately 10 cm between the traffic signal and S1 and 10 cm between S1 and S2. MQTT-based monitoring was successfully implemented to transmit traffic-state information from the ESP32-based controllers to the monitoring interface, while coordination between the traffic-light modules was maintained through a wired connection.

Repeated testing over 50 experimental cycles resulted in 49 successful detection-and-control cycles and one missed detection, corresponding to a 98% successful detection-and-control-cycle rate. This result demonstrates the functional feasibility and prototype-level consistency of the proposed mechanism under the tested conditions.

However, the proposed system should be considered a discrete queue-state-based rule controller rather than a complete traffic optimization system. The study does not yet establish improvements in real-world traffic delay, waiting time, queue length, throughput, or congestion reduction because a fixed-time baseline and field-scale traffic evaluation were not conducted.

Future research should therefore focus on fixed-time comparative testing, larger and dynamically varying traffic scenarios, detailed sensor error analysis, fail-safe signal coordination, MQTT reliability testing, and field-scale validation. Additional detection points, computer vision, LiDAR, or other sensing technologies could also be investigated to improve traffic-state resolution.

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AUTHOR CONTRIBUTION STATEMENT

JAR: Conceptualization, methodology, system design, prototype development, data collection, experimental testing, data analysis, and manuscript preparation.

AUAW: Supervision, research guidance, validation, interpretation of results, critical review, and revision of the manuscript.

MD: Technical review, validation, system evaluation, interpretation of results, and critical revision of the manuscript.

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AI DISCLOSURE STATEMENT

The authors used ChatGPT (OpenAI) during the preparation of this manuscript for language editing, manuscript structuring, paraphrasing, and improving the clarity and organization of the academic writing. After using the tool, the authors thoroughly reviewed and edited the generated content, verified it against the research materials and experimental findings, and take full responsibility for the content, accuracy, and integrity of this publication.

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