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Smart Traffic Management at Intersections

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RESEARCH ARTICLE

Smart Traffic Management at Intersections

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ABSTRACT

Effective traffic control methods, whether at intersections or other nodes within the road network, play a critical role in ensuring traffic quality and safety. An inappropriate choice of traffic control techniques or poorly optimized light signal programming at intersections often leads to unsatisfactory service levels. This study specifically addresses the issues related to intersections controlled by traffic lights. It aims to identify the key factors influencing the regulation and programming of traffic lights, with a focus on using different microcontrollers, particularly the Raspberry Pi. The primary objective of this research is to develop a methodology and an adapted programming approach to the Raspberry Pi microcontroller to improve traffic performance at intersections and provide sustainable mobility. To achieve this goal, a prototype of a traffic light-controlled intersection was constructed and managed by a Raspberry Pi Model microcontroller. The prototype integrates sensors to collect real-time traffic data, enabling adaptive and efficient signal control. This prototype is now part of the Laboratory of Traffic and Transport at the University of Prishtina. It is used as a model for responsible institutions for motorized traffic management in urban areas. Our findings support scalable deployment in developing countries with minimal infrastructure. Comparative results and reproducible Python code enhance reliability and transparency. The study further includes a comparative analysis of results, presented through diagrams, to evaluate the system's efficiency.

Keywords: Smart traffic, Artificial intelligence, Sensor, Vehicle delay, Microcontroller

1. Introduction

With the rapid development of technologies and their implementation in vehicles, communication and interconnection with essential processes in traffic management have been enabled. The practical implementation of traffic signals has enabled traffic control by applying control algorithms [1–4].

Urban mobility in general and motorized traffic in particular constitute a challenge for developing countries that require adequate treatment [2–6]. In this regard, Kosovo remains at the basic level of treatment, and the fixed-time traffic control system is applied as a form of traffic light control at intersections. This means that these systems are often

inefficient, especially when traffic nonlinearity is high [2].

Other traffic-related impacts, traffic delays, and other safety aspects are some of the issues of particular importance that require proper treatment to improve the quality of traffic operations and the quality of life [2].

Promoting innovative ideas to solve these problems is the right way for developed cities to respond to changing mobility demands with adequate solutions [4].

In most developing nations, including Kosovo, traffic control systems rely on outdated fixed-time controllers.

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The systems do not adapt to current traffic in real-time, so they have long queues of cars, heavy pollution, and inefficiency.

This research addresses this by introducing a low-cost, scalable, and urban area-specific Raspberry Pi-based real-time adaptive traffic light controller with budgetary and infrastructural constraints.

We differentiate ourselves from previous works by embracing the following:

- IR and ultrasonic sensor fusion
- Green light extension based on queue length;
- Pseudo-coded Python logic for transparency;
- Coupling with day/night cycle and error handling.

Traffic problems in urban areas, especially in Kosovo, are highlighted regarding sustainable mobility. As a result, time delays and conflicts between specific directions of movement become the source of many other problems that negatively affect the quality of life in urban areas [1–4]. In many cases, the solutions implemented by the responsible entities do not meet the real demands for movement in urban areas and do not provide an offer harmonized with the real demand. In the conventional traffic control approach, traffic at an intersection is regulated by signs or signaling other traffic signals. Vehicles are often forced to stand still and make frequent stops, thus limiting the total capacity of the intersection. The forms of traffic control at intersections are usually inadequate and exceed the capacity to meet the movement demands. In these conditions, road users face long delays in motorized traffic and other safety-related issues [1, 2, 5–7, 22, 27].

The main goal of the research is to apply the appropriate methodology, namely the appropriate programming language for programming the Raspberry Pi microcontroller, through which the improvement of traffic operation indicators at intersections will be achieved.

Other objectives within the framework of this research include:

- Intelligent traffic control based on real demand for movement (as an innovative solution).
- Functionalize the prototype for traffic control using appropriate sensors and the “Raspberry Pi” controller.
- Effective traffic management through “Smart” techniques.

The research questions that the research project should answer are as follows:

- Research Question 1: How can traffic be controlled through sensors and the Raspberry Pi controller?

- Research Question 2: What is the methodological approach for programming with the controller for traffic control purposes?
- Research Question 3: What impact can the implementation of sensors and the Raspberry Pi controller have on improving urban mobility?

Various researchers, through their studies, have addressed the traffic problems that the whole world is facing due to the high concentration in urban centers and the high mobility of people in these areas, recommending that the need for the use of intelligent, automatic traffic control systems in real-time be increased [7, 8].

Improving the quality of traffic operations and improving safety are among the essential objectives and targets of many countries that face traffic problems similar to Kosovo [9–12]. Statistics from previous research conducted by the Fatal Accident Reporting System suggest that about 40% of all accidents occur near intersections, and about 22% of accident deaths are intersection-related [13, 22].

The research results by many authors prove the importance of using the traffic light management system at intersections through remote intelligent systems or smart cameras. According to these authors, directly in those moments when we have a change in the density of vehicle traffic at the intersection, using intelligent systems or a Raspberry PI microcontroller, different functional algorithms can be used with two working modes: day and night mode [14–19].

Amid the persistent tension between socioeconomic progress and environmental conservation, concepts like sustainable development, the circular economy, and smart growth have become central themes in today’s environmental discussions [26].

Other research proves the environmental benefits of smart traffic management, in which case, referring to the total values obtained from the study (Smart traffic light to reduce CO₂) over a year, through smart traffic signal systems, vehicles emit 136t less carbon dioxide, and waiting times are shortened [6, 20].

Operational performance at signalized intersections can be significantly improved by optimizing phasing and signaling plans using intelligent traffic control methods [21, 22].

All advancements in transportation occur naturally. These advancements are not confined solely to technological innovations, nor are they limited to technological progress in general [25]. Sensor technology and data analytics improvements have also opened up new possibilities for real-time monitoring and predictive capabilities [28].

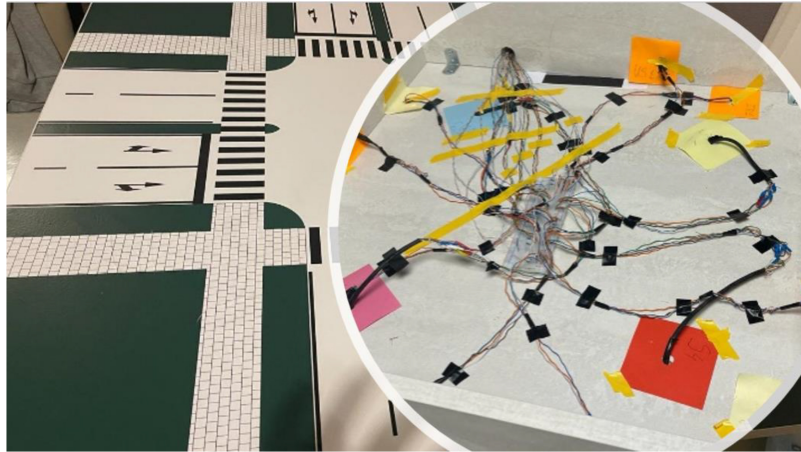


Fig. 1. Prototype platform built for research purposes.

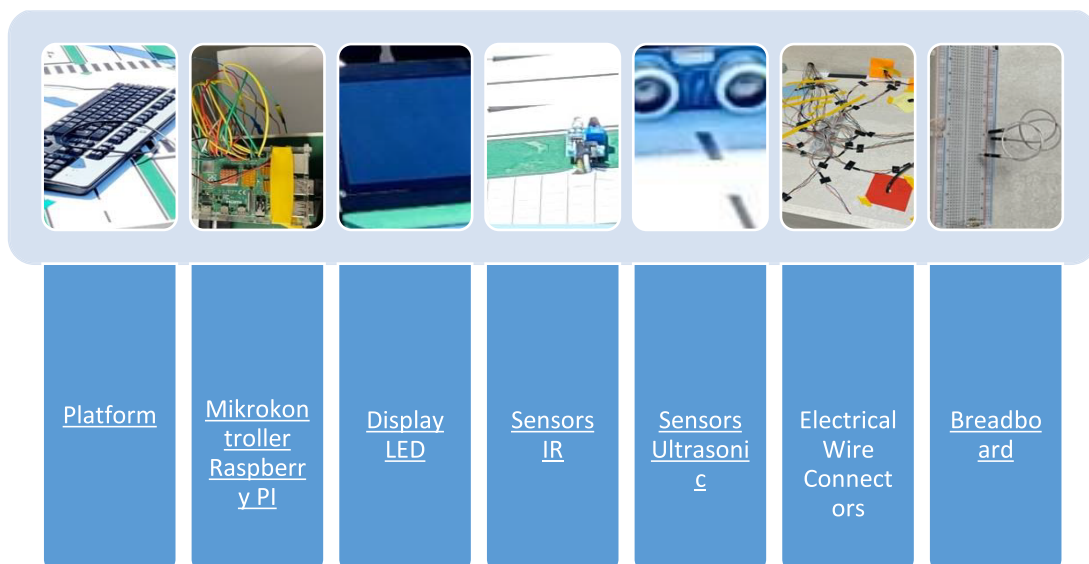
2. Methodological approach for automatic control and traffic management through smart techniques

The research was developed to solve the congestion problems at intersections and to utilize the space better, thereby reducing overall traffic delays as a primary effect, pollution, increasing safety, and improving quality of life as secondary effects. To achieve this goal, we have created a prototype of managing an intersection with light signaling through automatic control. Initially, several different forms of control were considered, and then the form we considered the most appropriate was chosen. The most frequent problems that affect the irrational use of intersection spaces were analyzed, and a plan for their management was created, which will be explained below. The intersection was considered to be the one

with four entrances and exits since it has more problems that need to be addressed than other, simpler intersections. Also, this represents the most frequent shape of intersections we encounter in everyday life (Fig. 1).

We have used a prototype to show the functional principle of traffic control and management concretely. A “+” shaped intersection and traffic lights have been built, providing the priority of passage and the duration of traffic light times based on the prepared and implemented algorithm. Traffic management, respectively, the control of traffic light times, has been carried out based on real data obtained from sensors, which were then processed in the program applied to the Raspberry Pi microcontroller.

Various devices have been used to build the prototype, such as:



Programming and selecting the most appropriate algorithm to provide the most effective traffic control solutions at intersections is enabled through the Python programming language.

A four-way intersection was simulated with a Raspberry Pi controlling sensor input and light timing. Every entry point had a single IR sensor for detecting presence and an ultrasonic sensor for detecting queue length.

3. Functional prototype construction for traffic control

The functional prototype was constructed to test the proposed functional solution and the implemented algorithmic model. Through the application of this model, traffic quality indicators are significantly improved, including the level of recovery and the

reduction of unnecessary time delays through the adaptation of the program applied to control traffic lights according to the program applied to control traffic lights according to real traffic requirements. The working principle of the microcontroller and its connection to sensors and traffic lights are presented in the diagram below.

Initially, the connection scheme of the necessary techniques in the functional prototype was prepared, and then the prototype was built and functionalized for intelligent traffic control using advanced “SMART” techniques.

The functional prototype offers real solutions, and during the application, it can adjust traffic light intervals depending on the number of vehicles circulating on the entrance branches of the intersection.

In the construction of the prototype, four IR sensors were used, one sensor at each entrance of the branches of the intersection. These sensors are connected to the microcontroller, where they send

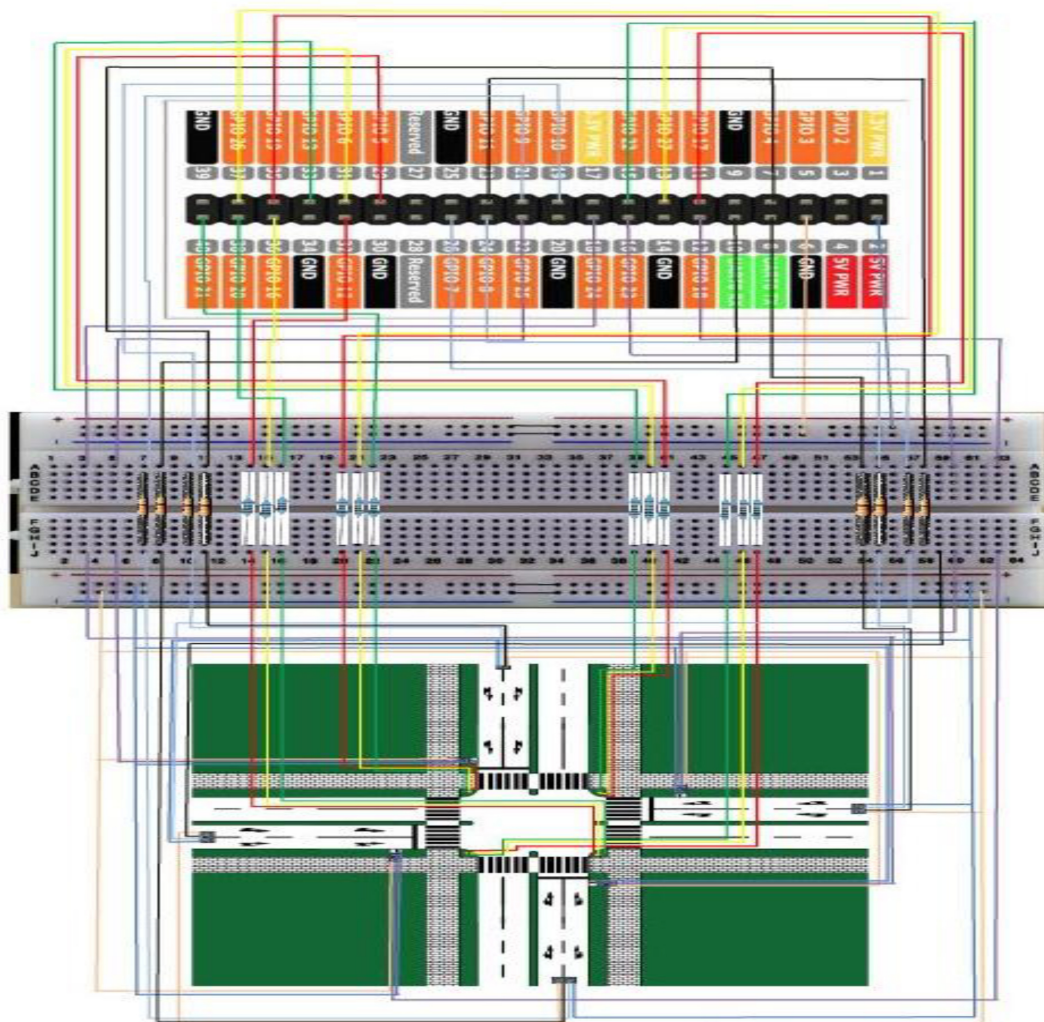


Fig. 2. Connection scheme of the technical elements of the prototype.

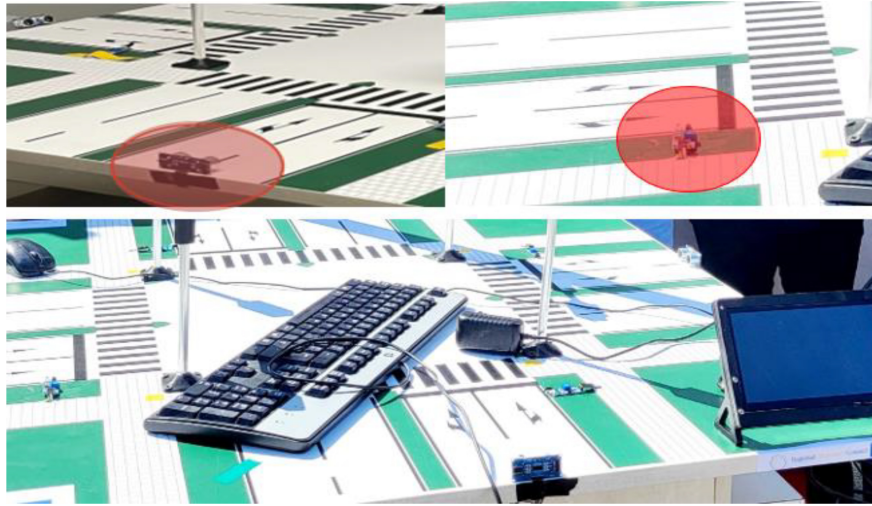


Fig. 3. Data collection by sensors.

the information they collect. Their presence in each branch is related to their role in understanding the presence of vehicles in front of them, an essential procedure for starting the cycle we apply in case we have a load on one branch and not the others. Through it, we also understand the arrival times of the vehicles, data that serves us to determine which branch the green line opens first. Since the information received from this sensor is about the presence of vehicles waiting to connect to the intersection, and the place where these vehicles wait to pass is in the entrance part near the intersection, the position of the sensor should also be in this area.

Compared to Santos et al. (2023) and Ramazani et al. (2023), our system introduces [23, 24]:

- Two-sensor input for time control dependent on queues;
- Cost-effective hardware implementation verified under laboratory conditions;
- Simulated day/night logic to minimize red-time off-peak hours.

In addition to IR sensors, which play a significant role in receiving information about vehicles moving at the intersection, their combination with “Ultrasonic” sensors allows us to have information about the length of the queues of vehicles waiting to enter the intersection. This data is needed to adjust the time, namely the green intervals at the traffic lights according to the branches at the intersection [20]. Their role is related to the controller’s algorithm’s programming function. After the microcontroller receives information about vehicles waiting in front of the intersection, it needs to receive information about the number of vehicles waiting to determine the increase in the duration of the green time.

4. Functionalization of the prototype and traffic control

Based on the abovementioned concept, the intersection prototype’s functionalization shows the control system’s implementation and operation. In this system, vehicles arriving first at the intersection are detected by infrared (IR) red-beam sensors, and priority is given to these vehicles by activating the green light for their lane.

During the green phase, ultrasonic sensors measure the distance of vehicles within their coverage area to assess the possibility of extending the duration of the green light. Suppose the sensors detect longer distances (indicating queues). In that case, the green phase can be extended by 40 to 50 seconds (up to a predefined maximum limit) to allow more vehicles to pass through the intersection. Conversely, the microcontroller does not extend the green light duration if the ultrasonic sensors measure very short distances (indicating no significant queue). Instead, it transitions to the next phase, operating the traffic signal cycles with the minimum red interval time.

Fig. 4 illustrates the prototype platform that was built and functionalized. The traffic signal operations are managed through a Raspberry Pi microcontroller with IR and ultrasonic sensors.

The program executed on the microcontroller integrates detecting IR red light sensors and measuring distances via ultrasonic sensors (displayed in centimeters). This functionality is demonstrated in Fig. 5.

The system executed a Python program that dynamically changed signal timing. For instance, if an ultrasonic sensor detected > 100 cm of queued cars, the green phase was prolonged by 40–50 seconds. The flow chart for the algorithm is presented in the new

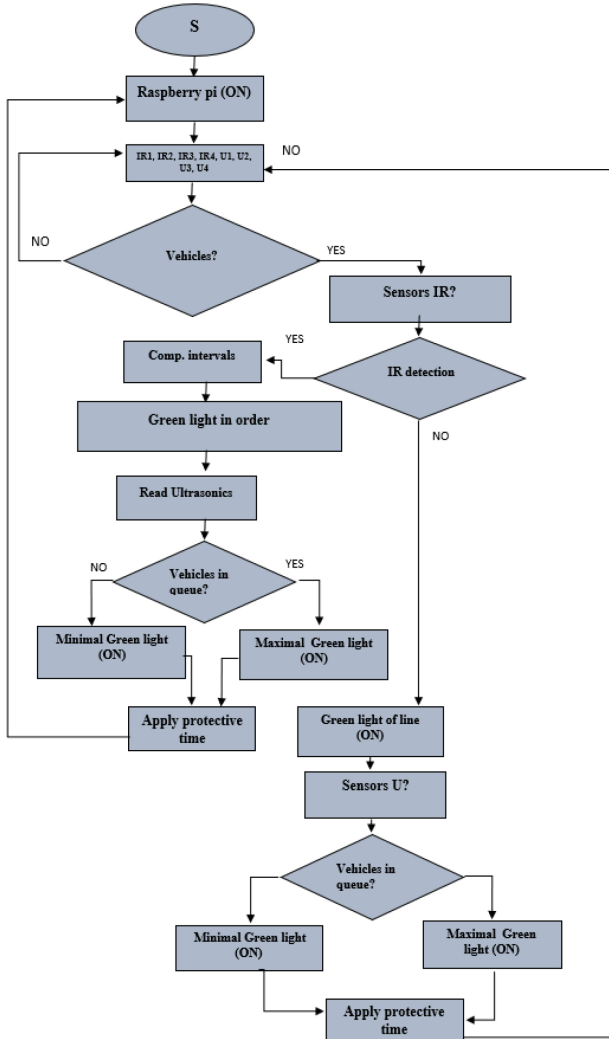


Fig. 6. Flow chart algorithm [1].

The mathematical representation of the implemented pseudo-code is provided below.

Initialization:

```

» Num_parts = 4
» red_pins = [17, 5, 19, 12]
» yellow_pins = [27, 6, 26, 16]
» green_pins = [22, 13, 21, 20]
» ir_sensor_pins = [18, 23, 24, 25]
» ultrasonic_trigger_pins = [7, 8, 9, 10]
» ultrasonic_echo_pins = [11, 14, 15, 4]
» distance_threshold = 10 cm

```

Set up GPIO:

```

»  $\forall i \in [0, \text{num\_parts} - 1]$ , setup(red_pins[i], OUTPUT)
»  $\forall i \in [0, \text{num\_parts} - 1]$ , setup(yellow_pins[i], OUTPUT)
»  $\forall i \in [0, \text{num\_parts} - 1]$ , setup(green_pins[i], OUTPUT)
»  $\forall i \in [0, \text{num\_parts} - 1]$ , setup(ir_pins[i], INPUT)
»  $\forall i \in [0, \text{num\_parts} - 1]$ , setup(ultrasonic_trigger_

```

```

pins[i], OUTPUT]

```

```

»  $\forall i \in [0, \text{num\_parts} - 1]$ , setup(ultrasonic_echo_pins[i], INPUT)

```

Function Definitions:

Set Traffic Lights:

Set_traffic_lights (part, red, yellow, green)

```

{
    output(red_pins[part], red)
    output(yellow_pins[part], yellow)
    output(green_pins[part], green)
} ==>

```

Ultrasonic Distance:

Ul_distance(part) ==>

```

{
    output(Ul_trigger_pins[part], True)
    delay(0.00001)
    output(Ul_trigger_pins[part], False)
    pulse_start = time()
    pulse_end = time()
    while(input(Ul_echo_pins[part]) == 0)
        pulse_start = time()
    while(input(Ul_echo_pins[part]) == 1)
        pulse_end = time()
    pulse_duration = pulse_end - pulse_start
    distance = pulse_duration * 100
    return distance
}

```

Main Loop:

While True ==>

```

{
     $\forall \text{part} \in [0, \text{num\_parts} - 1]$ 
    if (input(ir_sensor_pins[part]) == HIGH)
        print("Vehicle detected by IR sensor in Part", part)
        set_traffic_lights(part, 0, 0, 1)
        delay(5)
        continue
    distance = Ul_distance(part)
    print("Distance (Part ", part, "):", distance, "cm")
    if (distance < distance_threshold)
        set_traffic_lights(part, 0, 0, 1)
        delay(5)
    else
        set_traffic_lights(part, 1, 0, 0)
        delay(2)
        set_traffic_lights(part, 0, 1, 0)
        delay(2)
        set_traffic_lights(part, 0, 0, 1)
        delay(5)
}

```

Exception Handling:

except KeyboardInterrupt ==> {cleanup() }

Fig. 8 shows error bars for variance across 10 cycles of testing. Statistical significance was tested ($p < 0.05$) using a two-sample t-test.

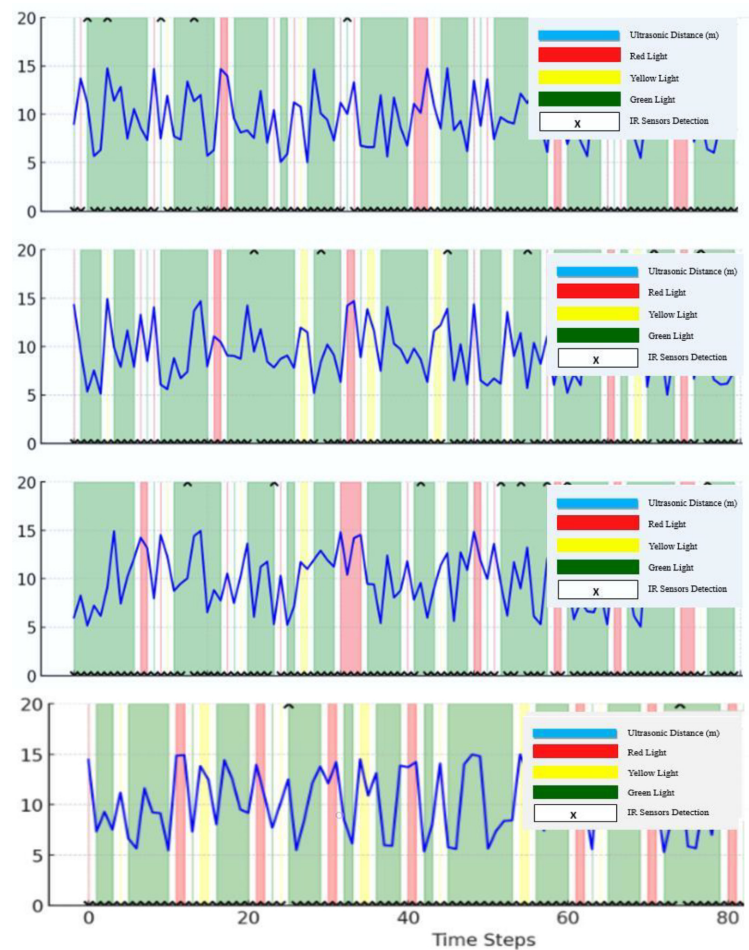


Fig. 7. Testing the functioning of the built system according to several scenarios.

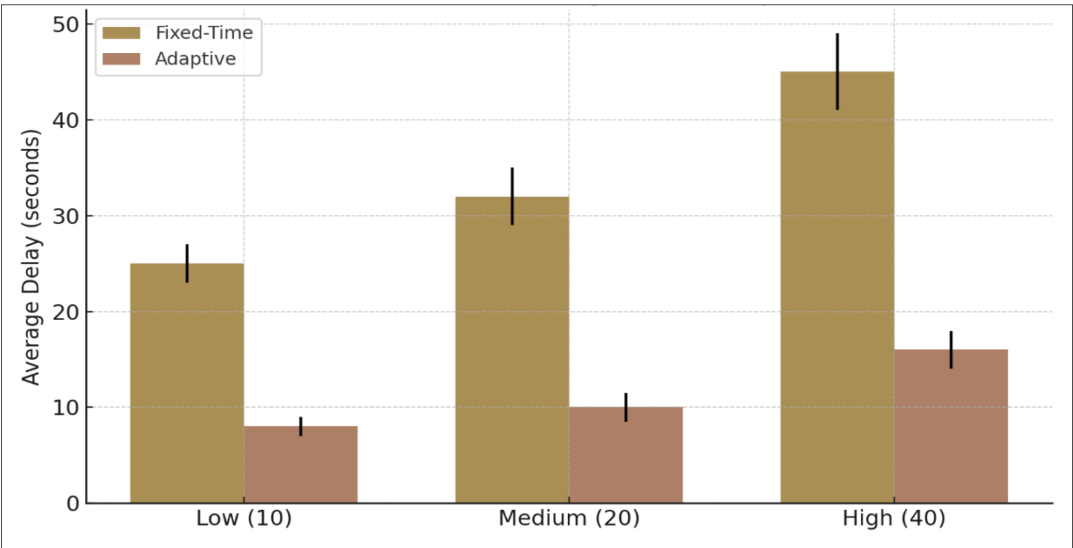


Fig. 8. Traffic delay.

- Average delay reduced from 32s (fixed-time) to 9.6s (adaptive);
- Peak queue length: 14 vehicles (fixed) vs. five vehicles (adaptive);
- The system was tested using simulated densities of 10, 20, and 40 vehicles per branch.

5. Conclusions

Testing various scenarios based on the functionalized algorithm, applied to the prototype designed for traffic light control and efficient traffic management (aligned with real-time movement demands), reveals a highly rational utilization of traffic time across intersection branches and significantly reduced delays.

The results demonstrate that the management plan, employing automated control and “smart” techniques, is approximately 50% more effective under average traffic loads. Furthermore, it reduces unnecessary waiting times by over 70% during low-load conditions, such as nighttime traffic, when movement demands from certain branches are minimal.

This approach enables more efficient use of the green interval and minimizes the red interval for branches with low demand for movements at the intersection. It also shortens waiting queues by dynamically adapting signals to real-time demand, facilitated through communication between sensors and the Raspberry Pi microcontroller. Consequently, vehicles avoid unnecessary waiting when no movement requests from other intersection branches exist.

Other benefits include improved safety, which results from precise phase planning and adaptation to real movement demands from each branch of the intersection. Better traffic performance metrics about intersection capacity and service level result from improved traffic operations quality at the intersection.

The method helps safeguard the environment by preventing unnecessary crossing waits drastically lowering dangerous emissions. Reducing red time and junction lines, minimizing the time to 5–7 seconds per phase within the cycle (when there is no demand for movement) directly helps to lessen environmental damage since cars that linger at red lights release more pollutants such as carbon dioxide, nitrogen oxide, carbon monoxide, and hydrocarbons.

Conflicts of interest

The authors of this research paper declare no conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

“Conceptualization, G.H.; methodology, G.H., P.G., Sh.Th and R.L; software, G.H., Sh.Th, and F.C.; validation, G.H., P.G., R.L, and Sh.Th, F.C.; investigation, G.H., and P.G.; resources, G.H., P.G., R.L, and Sh.Th, F.C.; investigation, G.H, and P.G.; resources, G.H and Sh.Th.; formal analysis, Sh.Th and F.C.; investigation, G.H, and P.G.; writing—original draft preparation, G.H; writing—review and editing, G.H and P.G.; visualization, F.C., and Sh.Th.; supervision, G.H; project administration, G.H, and R.L; funding acquisition, G.H and R.L. All authors have read and approved the final version of the manuscript”.

Limitations and future work

- Limitations: Lab-tested prototype, not field deployment; Sensor inaccuracy in rainy or foggy weather (± 5 cm); No integration with pedestrian signals.
- Future work: Field testing in city intersections. Adaptive prediction using traffic patterns with AI; Integration with smart city IoT dashboards.

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