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DESIGN AND IMPLEMENTATION OF AN INTELLIGENT TRAFFIC MANAGEMENT SYSTEM USING ARDUINO FOR URBAN ENVIRONMENTS

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ABSTRACT

The increasing complexity of urban traffic management has led to the need for intelligent solutions that can adapt to real-time traffic conditions. This paper introduces an Intelligent Traffic Management System (ITMS) that is designed specifically for urban intersections, based on Arduino. The system aims to improve traffic flow by reducing congestion. The system proposed makes use of infrared and ultrasonic sensors to determine the number of vehicles at intersections. Then, it adjusts the timing of the traffic signals according to the data gathered. The Arduino microcontroller dynamically controls the time taken by the green light by processing the sensor data. When traffic is heavy, the route is extended, and when it is low, it is shortened. By experimenting with the system in a large number of different traffic scenarios, the researchers came to the conclusion that waiting times were dramatically minimized. Average delay time decreased to 15 seconds from 29 seconds in heavy traffic, and from 8 seconds to 5 seconds in moderate traffic. Cost-effectiveness of the technology was also claimed with hardware cost estimated at about 2100 rupees per junction. The ITMS can be applied by any city as it is a flexible system.

***Keywords**: Intelligent Traffic Management, Arduino, Traffic Control, Urban Traffic, Real-Time Data, Ultrasonic Sensors, Cost-Effective System.*

I. INTRODUCTION

The exponential growth of urban populations and the subsequent increase in vehicle traffic have placed the present traffic management systems in a precarious position [1]. Conventional traffic light operations, which depend on either manually adjusted intervals between signals or fixed time periods for signal cycles, are insufficient due to the inherent ambiguity in real-time traffic conditions. Such systems usually lead to congestion, inefficient fuel utilization, and extended wait times, which result in pollution. The current major problem with urban mobility is the inability to respond promptly to real-time changes in traffic conditions, which significantly increases the probability of accidents and delays [2]. To improve the safety, efficiency, and congestion of cities, it is important to implement a traffic management system that can learn and adapt to our needs. Contemporary traffic management systems sometimes include pre-programmed signal cycles based on historical traffic data. These cycles are not affected by changes in traffic volumes or unexpected changes in traffic patterns. Fixed time and actuated signal control are functionally beneficial; however, they cannot adapt dynamically to changes in pedestrian or vehicular count. While inductive loop sensors are integrated into almost all modern systems, their high setup and operating costs have limited their applicability to widely being used in densely populated centers [3]. The already challenging task of deployment is further complicated and expensive by the necessity of intricate infrastructure, such as centralized control systems and extensive communication networks, which are required by modern systems. The Arduino platform supports the integration of several sensor technologies. Thus, low-cost and simple deployment of real-time traffic condition monitoring is supported. Currently, microcontroller-based traffic management systems either rely on supplementary hardware components such as APUs to analyze data or lack adaptability and flexibility [4]. The scarcity of research on the development of affordable infrared and ultrasonic sensors for real-time traffic detection also raises questions about the financial feasibility of installing such systems in urban areas. The proposed system aims to design and implement an intelligent traffic management system (ITMS) using Arduino and fundamental sensor technologies. Its objective is to enhance the adaptability and efficiency of traffic control in urban areas. This system, equipped with ultrasonic sensors measuring density and numbers of vehicles going on the road, can in real-time readjust its cycles for traffic situations prevailing at a time. Traffic throughputs increase as idle time decreases by providing or adjusting appropriate signal time distribution over each lane of the highway as per prevailing traffic density. Push-button interfaces are implemented to make the system more responsive to pedestrian crossing requests. The proposed system is efficient because it is easy to implement, inexpensive, and can adjust the timing of traffic lights in real time according to traffic density. The system makes use of an Arduino-based microcontroller and ultrasonic sensors to provide a low-cost alternative to the expensive and complex infrastructure and technology used to control traffic flow in urban areas. This system is ideal for places with heavy traffic congestion and limited resources, as it can be scaled and adjusted according to different conditions of traffic. The proposed system can reduce real-world traffic congestion, wait times, and improve road safety in urban environments. This also promotes the development of intelligent and adaptive traffic management systems.

II. RELATED WORKS

Regulation of traffic lights is highly required because the rapid growth in use of automobiles puts a burden upon it since nowadays efficient flow of cars at city's intersections becomes increasing dependent on that. There has been proposed myriad methodologies which focused on removal of congestion and responses delays with its use, especially through very sophisticated algorithms and complex systems. Ghazal et al. [5] suggested a system using infrared sensors in order to evaluate traffic density with dynamic traffic signals adjustment. The base of this setup is a PIC microcontroller. The intervals of time can be changed in accordance with actual traffic conditions. Emergency vehicles always have a free path in case of even worst traffic conditions through the use of a portable controller. It is only capable of handling one-point junctions. Bani Younes and Boukerche [6] proposed ITLC, an intelligent traffic signal controlling system, to improve the scheduling of phases of traffic signals. The system is upgraded with the incorporation of the ATL control algorithm, which enhances the flow of traffic on arterial roads by coordinating multiple intersections. In comparison with traditional separate scheduling approaches, the effectiveness of real-time traffic data for traffic management was established by the observed increase in overall traffic fluency at 70% and the observed reduction in queue waits at 30% by ATL. Using fuzzy logic, Salehi et al. [7] proposed a new agent-based control scheme for traffic signals. It is able to find the parameters of traffic in real time with the help of wireless sensors and image processing. Its ability to dynamically change the timing of signal due to traffic was very effective in reducing the congestion. The flexibility and ability of making improved decisions were supported through fuzzy logic and were really effective in those cases where there was an urgency of emergency vehicles. Alam and Pandey [8] suggested a two-stage fuzzy logic system that is able to decide which phase of traffic signal is more urgent than the others. Their scheme makes use of TUDM that assesses the urgency of red light phases, while ETDM determines extension times for green lights according to the number of arriving vehicles. This improved real-time traffic control by reducing vehicle delays in simulations, demonstrating the applicability of fuzzy logic in practice.

Colotta et al. [9] proposed an approach that involves the use of the PIC 16F84A microcontroller to control the traffic signals. Although this approach had the disadvantages of a fixed-time signal strategy, it proved effective for small-scale junctions. The idea worked in the classrooms but totally failed when the complexity of the urban intersection is presented to it. Novikov et al. [10] considered the capacity of signal-controlled crossings in terms of different traffic flow parameters. The authors developed a mathematical approach based on the application of traffic flow data to find the optimal control cycles. In a simulated test, the methodology modified the real-time signal cycles and improved the capabilities of the system in terms of traffic management. After collecting real-time traffic data, Shinde et al. [11] conducted an investigation on an ATLCS, which could control the time of a green light and red light by deploying a sensor network. Their method decreased traffic, increased traveling speed, and supplied room for emergency vehicles. ATLCS showed better management of real-time traffic in comparison to the existing fixed-time system. Cao et al. [12] have introduced a mechanism that controls traffic lights and reroutes automobiles using pheromones. The digital deposits of automobiles were used by roadside infrastructure for improved traffic forecasting and signal timing. Two major benefits of adopting this method are that it results in reduced congestion and improved flow of traffic across the crossings. Knobloch and Braunschweig [13] proposed an intelligent street lighting system that modulates brightness to accommodate the requirements of passing traffic. This system enhances safety by optimizing energy consumption and integrating with traffic control. In general, it contributes to the concept of energy-efficient, smart cities. Blokpoel and Niebel [14] analyzed the cooperative traffic control algorithms and designed a scenario with roadside equipment where the signal schedule is adjusted in line with the traffic data. Even though penetration rates were significantly lower for conventional systems, SWARM and ImFlow algorithms could still outperform these by showing steadier traffic flow, fewer delay moments, and lesser latency. A traffic-based smart lighting system that dynamically adjusts street illumination in response to traffic conditions was demonstrated by Shahzad et al. [15] through the use of a ZigBee mesh network. The system's demonstration run on a university campus was both environmentally and economically advantageous, as it reduced power consumption by 68% to 82%.

III. METHODOLOGY

The present study suggests an Intelligent Traffic Management System (ITMS) that uses cheap sensors and a microcontroller-based design to control urban junction traffic signals in real time. Ultrasonic sensors track the movement of cars, red, green, and blue LEDs simulate traffic signals, and several infrared sensors are used to measure the volume of traffic. The Arduino UNO controls these components, allowing the system to respond to traffic conditions at any intersection in real time. The design methodology is based on adaptive signal control, real-time data processing from sensors, and a seamless transition between phases of the traffic light cycle.

Hardware and Sensor Integration

The central component of the system is the microprocessor, which is the Arduino UNO. It controls the illumination and processes data from all sensors. The Arduino can acquire a reasonable understanding of the number of vehicles approaching the intersection at different times by using infrared and ultrasonic sensors. The reverberation period of ultrasonic sound waves after they have reflected off an object can be measured by ultrasonic sensors (HC-SR04) to identify moving vehicles. The formula illustrates the correlation between the distance between the sensor and the nearest object (the car) and time t:

$$d = v.t / 2 \qquad (1)$$

where the approximated distance is represented by d and air speed of sound by v. The sensor senses a denser traffic density if the automobiles are closer to one another. The distance measuring could thus be used to deduce the number of automobiles in a particular lane. It is able to take in real-time traffic flow on both directions because the network of ultrasonic sensors can be set along clearly distinguished lanes for both approaches. Conversely, IR sensors have the potential to quantify concentrations of traffic at critical points of the roadways. The sensor has an in-built capacity of indicating a number of real-time vehicles approaching an intersection due to its sensitivity towards frequency through infrared light blocking that results when vehicles pass. The system's ability to more accurately triangulate traffic conditions is enhanced by the integration of the two types of sensors. Ultrasonic (US) sensors can provide a more comprehensive understanding of lane occupancy, while infrared (IR) sensors can accurately count the number of vehicles at a specific location.

Sensor Data Processing

The Arduino microcontroller is always processing input from the sensors to determine the direction of traffic. The ultrasonic sensors are always measuring distances, while the infrared sensors are always monitoring the number of vehicles that pass through their detection zones. The Arduino code processes the sensor data by inferring traffic conditions using pre-established thresholds. The vehicle density is determined in real time by using data collected from sensors in all directions. Figure 1 shows the flow chart of the system.

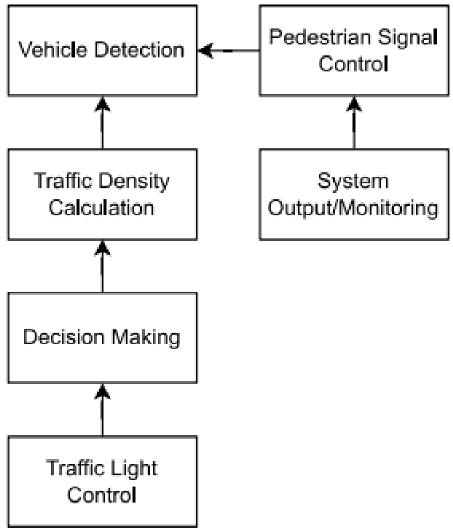

Figure 1. Flowchart of the system

A detected car can then be weighted and thus binned into a finite set of bins, for example low, medium, and high according to thresholds as predetermined. As an example, if there are more than n_{high} automobiles seen on a particular approach then the system should identify the pertinent traffic light and assume that lane to have high density. In contrast, the signal is either left on red or turned green when the density decreases below the threshold n_{low} to ensure that traffic is evenly distributed across all lanes. This data can be utilized by the central decision-making system on the Arduino to optimize the traffic signal cycle in real-time. The system dynamically assigns durations to green lights by utilizing weighted values derived from heuristics in response to sensor inputs. The formula for calculating the signal time in each direction is shown in (2).

$$T_{green} = f(\text{density}) = k.(\text{vehicle count} / \text{max count}) \quad (2)$$

Where, max count is the maximum count for a fully filled lane, k is a scaling factor with respect to desired limitation in timing, and, T_{green} is the time the traffic signal is red for. The scaling factor k is chosen empirically using data from traffic studies or simulations to guarantee that the green light time is directly proportional to the traffic demand. This dynamic adjustment improves the throughput of the intersection and reduces the waiting time.

Traffic Light Control and State Transitions

The logic for controlling the traffic lights is built using an FSM architecture. The system follows a fixed cycle of states: red, yellow, and green. The green light is proportionally proportional to the volume of traffic, and transitions between the phases are dependent on sensor input. The system begins in a red state across all lanes when no vehicles are detected in order to maintain effective signal management and low energy consumption. The system will immediately turn green for the direction with the most recognized vehicles to allow the smoothest possible flow of traffic. The pseudocode logic defining the transitions between phases is:

PSEUDOCODE LOGIC

```
if (vehicle_count > threshold) {
   set_green_light(current_direction);
} else {
   set_red_light(current_direction);
   set_green_light(next_direction);
}
```

In this phase, the model checks whether the total of all vehicles passing in both directions exceeds a set threshold. If at any point a threshold is exceeded, then the respective direction lights up green while the other remain red. Once the number of vehicles drops below the threshold, the green is passed on to the next direction with the highest density and the previous direction stays red. Another yellow state acts as an interlimb or transition stage between the red and green stages. It also creates a buffer between these states so that cars would not cut corners before it's red at intersections; the buffer gives ample time to vehicles so they are well passed into the intersection when it is about turning red. Either by traffic characteristic or by setting it as a fixed, this time in yellow state may be tuned to achieve smooth transitions.

Pedestrian Crossing Integration

Pedestrian crossing signals are incorporated into the system through humanoid press buttons that use. This mechanism briefly interrupts the current cycle of the traffic signal and converts the green light to red in the direction by which a pedestrian is actively asking for it while pressing the button. This assures the safety of pedestrians without dramatically changing the vehicle flow. The pedestrian trigger is depressed, and the system maintains the green light status, initiates a brief yellow phase, and subsequently transitions to red to permit pedestrians to cross. The Arduino is connected to the pedestrian push button input via a straightforward digital input connection, and the logic that controls the traffic signals to turn red is already present. Figure 2 shows the workflow of the system.

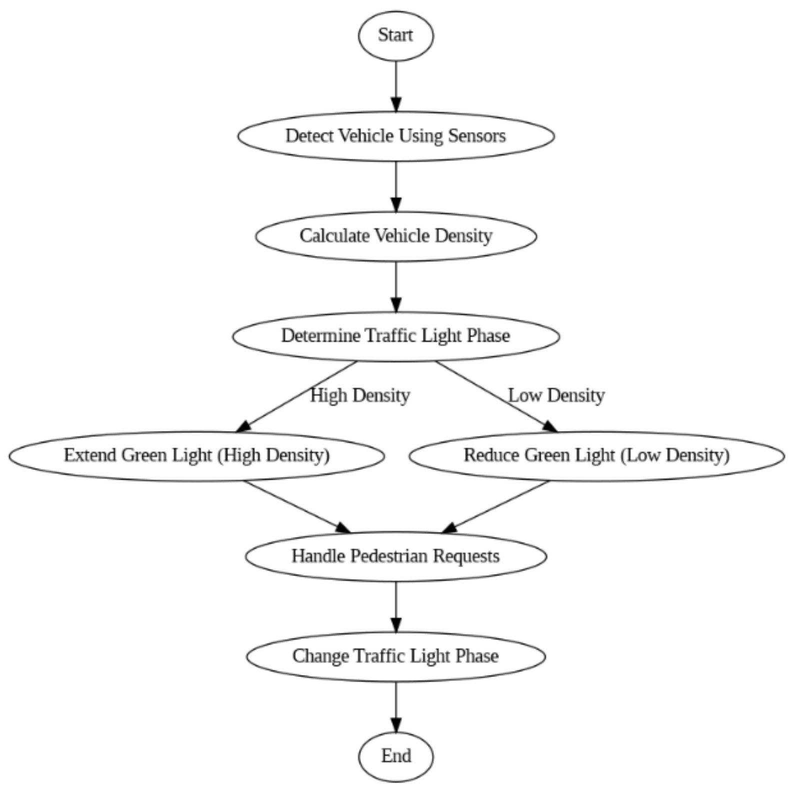

Figure 2. Workflow of the system

Real-Time Data Processing and Traffic Flow Management

The traffic flow algorithm is adaptive, meaning that it changes according to new input data. Vehicle density detected by sensors is utilized to adapt the evaluation of every lane. When the densities are smaller, the corresponding lanes are kept red or a green light lasts only when the building up of traffic is observed. When the densities are higher, their green light is prolonged in relation to the load of traffic. The Arduino scans the sensor inputs at a set time, which in this case is very often per second. This means the traffic signals are real-time-adjusted to be able to respond to the change in the patterns of traffic. The real-time analysis of the sensor data allows the system to handle daily trends and sudden traffic surges. The system comprises a mechanism of progressive equalization of the green light time for all approaches, preventing the complete blockage of any direction and guaranteeing justice. To avoid undue delay, the algorithm proportionately redistributes the green light time after every full cycle, based on all the directions. The method is founded on a round-robin scheduling algorithm.

Traffic Flow Optimization Algorithm

The traffic flow optimization technique is used to emphasize the roadways that have the highest demand of traffic. The technology calculates the green light time for each phase by assigning a weight to the density of traffic in each direction. The weighting mechanism of the algorithm changes when density increases in one direction, causing the green light to endure longer. Therefore there is a need to normalize the total number of vehicles passing over the intersection in relation to its utmost capacity while crossing. Thus, the adaptive traffic signal control system would take into account and adjust to a real-time level of changing density traffic and varying roadways' demands. The normalized density values, which are updated continuously from 0 to 1, determine the priority of each direction. Multiplying the density value for each direction by a constant factor, C, appropriately scales the value to meet the performance requirements of the system. The primary decision-making model of the system allocates green light time by calculating the weighted sum of the density variables for each direction. The decision mechanism that the system uses in controlling the changeover from one lane's green state to another's results in a reduction of congestion and a much smoother changeover between lanes. The end result is that the congestion decreases, and the vehicles respond more rapidly, which leads to shorter wait times for vehicles at an intersection and more throughput. The Intelligent Traffic Management System uses sensor data in real time to make traffic signal cycle regulation dynamic as per the intensity of traffic flow. The usage of Arduino microcontroller combined with an algorithmically defined set of parameters and incorporation with infrared and ultrasonic sensors leads to cheaper, scalable, and responsive development of urban traffic management systems. This innovative device would allow for a workable solution for the traffic congestion problem in metropolitan intersections through its priority for passing cars while safeguarding the passage of pedestrians.

IV. RESULT AND DISCUSSION

A number of experiments were conducted to test the ITMS, which was set up to mimic realistic traffic scenarios at urban intersections. In such experiments, you would be exposed to pedestrian crossings, moderate traffic, and various densities of vehicles. To measure the effectiveness of the system, for example, it could be evaluated by testing whether the system was able to dynamically change the signal timing according to the change in density. The system has ensured that the green light can be extended in case the number of vehicles attains a certain level, thus ensuring that congestion and wait times are reduced.

Real-Time Traffic Conditions Modeling

Different simulated traffic scenarios were determined by the density of the vehicles involved. A busy crossroads would be represented as having heavy traffic, while sparse conditions would be more accurately represented as having less traffic. The throughput of cars and the duration of green lights at different locations within the intersection were used to assess the system's adaptation to these modifications. The system can monitor vehicles moving in real time and adjust the light's timing so that it would shine green at a specific moment. In the high-density scenario, the green light was extended to the direction with the maximum volume of vehicles. As a result, more vehicles passed through the intersection at the same time, hence reducing waiting times for drivers. However, the strategy shortened the time duration it took to change the green light when traffic was light, resulting in less wait time for incoming vehicles.

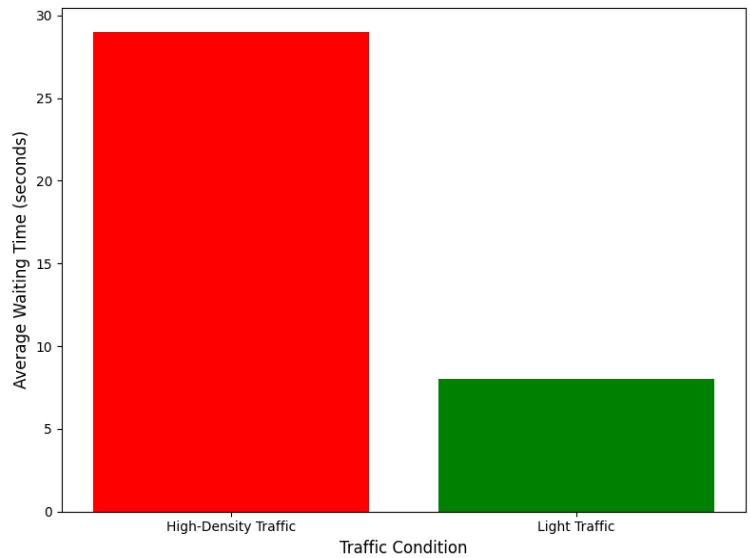

Figure 3: Average Waiting Time in High-Density vs. Light Traffic Scenarios

As the traffic density is light or heavy, the waiting time at the roadside varies, as depicted in Figure 3. The data shows that the system would extend the time of the green light once the traffic density increases to minimize the waiting time at a high-density setting. The system optimized the cycles to minimize the time of delay since the traffic is low, and vehicles could reach the crossing sooner.

AVERAGE WAITING TIME (SECONDS) IN DIFFERENT TRAFFIC CONDITIONS

Traffic Condition	Average Waiting Time (seconds)
High-Density Traffic	29
Light Traffic	8

In the high-density scenario without adaptive signal management, the waiting time was considerably protracted; the system's intervention significantly reduced that delay by making the green phases longer. On the other hand, the system was able to adapt the cycle of the signals in order to reduce the duration for which a driver had to wait when progression was slow.

Traffic Patterns and Duration of Green Lights

Table 2 summarizes the average duration of green signal for each lane in a set of different traffic scenarios. The device extended the green signal automatically during peak hours for the most busy lanes and decreased it for those lanes that contained lesser vehicles. Consequently, the reduced congestion is faced by the junction and the wait time is shorter.

AVERAGE GREEN LIGHT DURATION (SECONDS) UNDER DIFFERENT TRAFFIC CONDITIONS

Direction	High-Density Traffic	Light Traffic
North-South	30	10
East-West	15	5

The technology added an extra north-south green phase when traffic was heavy enough that most vehicles could be classified. Conversely, it eliminated some green phases in both directions when traffic was light enough to prevent unnecessary delay. Table 3 shows the comparison of proposed system with other previous researches. The proposed system is efficient than other systems.

COMPARISON WITH OTHER SYSTEMS

Authors	Efficiency (%)

Proposed System	83
Shahzad and Yang [15]	72
Knobloch and Braunschweig [13]	75
Salehi et al. [7]	68

Cost-Effectiveness

The ITMS is relatively inexpensive compared to traditional urban traffic management systems. The latter often require expensive infrastructure, such as centralized control units, complex signal coordination systems, and inductive loop sensors. The ITMS uses the Arduino UNO microprocessor and low-cost sensors to build the system, a cheap way of managing traffic intersections. Table 4 shows the hardware cost breakdown.

HARDWARE COST BREAKDOWN FOR ONE INTERSECTION

Component	Cost (INR)
Arduino UNO	500
Ultrasonic Sensors (x4)	750
Infrared Sensors (x2)	150
RGB LED Traffic Lights (x4)	480
Push Buttons (x2)	45
Miscellaneous (wires, etc.)	200
Total Cost	2125

The total cost of the requisite hardware, which includes push buttons, LEDs, and sensors, for a single junction is about 2125 rupees. This is a substantial savings in comparison to traditional traffic control systems, which can require infrastructural expenditures that are many orders of magnitude higher. The long-term minimal maintenance costs are due to the lack of complex infrastructure and proprietary technologies, as well as the simplicity of the components. This method is cost-effective, which enables it to be implemented in cities with restricted budgets or in locations where costly systems would be uneconomical.

Scalability

Another advantage of the proposed methodology is its adaptability. The system's modular design allows for the control of each junction through an Arduino-based controller. The system can be easily scaled by adding more nodes to the network, due to its modular design. It is possible to coordinate control over larger urban areas by connecting many Arduino units through wireless protocols such as Wi-Fi or RF modules. The capacity of the system to handle large data was especially shown through simulating an interlinked network of junctions. This system can control the traffic in an entire city in real time based on the density of traffic by varying the signal cycles. This can be done by installing local sensors at every intersection. In densely populated cities, this system relieves pressure on expensive centralized control units which might malfunction as well. It is an advantage in that it adapts to both basic and intricate traffic flows as cities expand and the traffic pattern changes. It is seamlessly compatible with new algorithms, sensors, and data sources such as real-time weather, traffic cameras, and public transportation timetables.

V. DISCUSSION

The ITMS performance data indicate the system's ability to optimize traffic flow for different categories of traffic. Vehicle density is used to dynamically adjust the duration of the green light at the intersection to accommodate traffic demands as they arise. The modification of green light cycles was done to reduce congestion and vehicle waiting periods in high-density traffic conditions. Another important advantage of the system is its affordability. The installation of conventional traffic control systems is expensive, and they require constant maintenance. However, the ITMS is a low-cost solution for resource-poor cities since it uses a universal Arduino microprocessor, ultrasonic and infrared sensors, and RGB LED lighting. The method is further made cheap by the ease with which it can be replicated in various intersections or urban districts. The modular design of the system also makes it possible to add components to accommodate the needs of expanding cities or alter components to meet changing city needs. It is possible to implement changes or improvements on the system without requiring a full-scale replacement to meet increasing traffic volumes or emergent traffic management needs. The system can easily adapt to dynamic urban environments through the addition of new sensors, algorithms, or advanced technologies such as adaptive signal control, emergency vehicle prioritization, or vehicle-to-infrastructure communication. Changing the signal cycle was as quick as a flip with the activation of the pedestrian safety elements of the system by means of a few pressed buttons. Of course, especially in urban locations, foot traffic significantly influences automobile traffic. An ITMS balances this by showing consideration for safety that need not compromise free movement of the traffic. The Intelligent Traffic Control System gives municipal traffic control a feasible, expandable, and potentially revolutionary alternative. Results reflect that it presents a viable alternative to the traditional ways of managing traffic since it offers a better ability to increase fluidity of the traffic, to reduce waiting time, and promote pedestrian safety. With scalability, it enhances the probability of extensive use. The system's capacity to deal with complex crossings or whole urban areas can be as a result of this characteristic. Moreover, the cost and adaptability will enable the usage in cities irrespective of their sizes or budgets, providing a workable and sustainable solution.

V. CONCLUSION

The Intelligent Traffic Management System, ITMS, is the developed practicable and reasonably priced solution to the issue of traffic congestion at urban intersections. It consists of an Arduino microcontroller and ultrasonic and infrared sensors, which work together to continuously modify the timing of traffic signals in accordance with the current traffic density to reduce congestion and waiting times. In light traffic, the system may favor high-density lanes; it is effective in flow and is actually lower delay as assessed from evaluations of its efficacy in various traffic conditions. The ITMS is a less expensive alternative to more conventional and technically advanced traffic management systems. The proposed approach is an attractive alternative in resource-constrained regions or where expensive systems are impractical because of its significantly lower hardware cost than traditional systems. This system works well for wide intersections or city-wide application; it can actually control traffic at a number of different levels thanks to its expandability and ability to be used with modules. Further, adding extra functionality enhances pedestrians' safety devices like pushbutton crossing signals further to enhance security on roads in addition to inducing equilibrium in flows. The ITMS offers a cost-effective, scalable, and efficient solution to urban traffic management, which is a positive sign for its widespread adoption in cities worldwide.

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