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IoT-based Adaptive Traffic Signal Controller to Optimize the Flow of Traffic and Reduce Congestion

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***Abstract*— The traffic management system is a fundamental element of a Smart city, as the growing population increases road traffic. We present an adaptable traffic light control system that adjusts the timing of traffic signals in real-time based on the flow of traffic to improve traffic flow at intersections and reduce traffic congestion in Kuwait. The proposed system uses ultrasonic sensors to measure the queue length indicating congestion, data analysis, and smart algorithms to adjust the traffic signal's timing. All the signals at the intersection are allocated a fixed default green time of 60 seconds. The proposed controller varies the time of the signals adapting to the queue length. A working prototype was developed, and system performance was evaluated. The proposed system improved the traffic flow and reduced the wait time at the intersection. An accompanying smartphone application offers real-time information on congestion levels at various intersections, aiding users in making informed decisions about their travel routes.**

Keywords— Adaptive controller; traffic signals; IoT; smart cities; ultrasonic sensors; road congestion.

I. INTRODUCTION

Despite only making up 3% of the total surface area of the planet, metropolitan areas are responsible for producing 80% of all greenhouse gas emissions. The urban population is expected to rise to 70% by 2050. Because of poor traffic signals and insufficient laws, developing nations frequently struggle with the problem of traffic congestion. Kuwait is no exception and complaints about traffic are on the rise because of restricted infrastructural growth. Kuwait's population is expected to be 7 million in 2030. Due to the lack of public transport infrastructure, the use of personal cars is preferred over mass transport due to privacy concerns, harsh weather conditions, and accessibility. On average 83.72% of people use the car for commuting to school and work in Kuwait City. The escalating number of vehicles poses a challenge for efficient management that can lead to congestion, pollution, and delays. Poor traffic management in congested spots results in elongated traffic jams [1]. This situation all negatively impacts the economy, environment, and general quality of life. The global economy loses 8.15 million hours in traffic jams, and at least 40% of this is working hours and 30% of global air pollution comes from the burning of fossil fuels by vehicles on the road [2]. Various restrictions are imposed to limit the number of drivers on the road to ease congestion which include restrictions on issuing driving licenses to expats, changing the office times, and variable signal times.

To reduce carbon emissions and waste of natural resources, many countries have proposed the idea of smart cities. Smart cities are urban environments that leverage advanced technologies and data-driven solutions to enhance the quality of life, efficiency of services, and sustainability of urban living. These cities deploy various interconnected systems and technologies to address urban challenges and improve overall functionality. This concept has already been adopted by many first worlds that have created and adopted intelligent city projects to handle the tremendous growth in traffic due to the increasing demand. Smart cities would monitor the components that make up their infrastructure (such as roads, buildings, etc.) for better management of their resources, plan preventative maintenance tasks, and oversee security while maximizing services to their residents. Smart transportation systems focus on improving traffic flow, reducing congestion, and providing efficient public transportation. This includes intelligent traffic management, smart parking solutions [3], and the promotion of alternative transportation modes [4].

Different traffic signal operation modes are used for controlling traffic, including pre-timed, semi-actuated, fully actuated, hybrid, adaptive, or traffic-responsive systems. In pre-timed signals, the right-of-way for movements is granted based on a predetermined allocation of time. Pre-timed signals adhere to predetermined cycle lengths and green splits, operating independently or in coordination with neighboring traffic signals. Actuated control, on the other hand, offers flexible durations of green timing for phases equipped with detectors contingent on intersection characteristics and timing parameters determined by demand at the intersection. Adaptive signal control technology consistently modifies signal timing, including cycle lengths, in response to evolving traffic patterns.

Most traffic control systems now in use are often pre-timed which provides fixed constant phases for red/yellow/green for each signal cycle. In situations of heavy traffic density, these static systems are unable to adapt to the changing environment. This situation can be handled by deploying traffic police; this is not only expensive but also not feasible due to limited staff. There is an urgent need to develop a smart system that can automate and manage traffic.

The term "intelligent transportation system" (ITS) refers to a set of advanced technologies and communication systems that aim to improve transportation networks' security, effectiveness, and efficiency. Ongoing advancements in artificial intelligence, big data analytics, and the Internet of Things contribute to the continuous development of ITS. It utilizes information from various sources, including sensors, cameras, and GPS devices, to monitor traffic congestion, events, and road conditions. This data allows real-time adjustments to traffic signal control systems, ultimately enhancing traffic flow.

Queue length on specific roads often rises because of inefficient traffic signal controllers, resulting in traffic disturbances such as congestion. To address this issue, a more practical approach involves allowing more vehicles to pass during the green light interval. This approach works by dynamically adjusting the green light time based on real-time changes in traffic load at each road within a 4-way junction. There are numerous ways to deal with this problem, including video data processing, infrared sensors, inductive loop detection, and wireless sensor networks. However, installing and maintaining these solutions can be expensive and time-consuming, which could be a disadvantage. In this paper we present an ultrasonic sensor-based solution for adapting the green light duration of the traffic based on the congestion level on the road. We installed three ultrasonic sensors for detecting four congestion levels. The ultrasonic sensors have been found effective for this task, and due to this reason, they are widely deployed in Japan. The proposed system only improved the traffic flow but also reduced the wait time at the intersection. An accompanying smartphone application offers real-time information on congestion levels at various intersections, aiding users in making informed decisions about their travel routes.

The rest of this paper is organized as follows. Section II provides an overview of related work. Section III delves into the features of the road intersection under study, while Section IV presents the architecture of the proposed system. The methodology employed to address this issue is detailed in Section V. Section VI examines the results, and Section VII concludes the paper.

II. RELATED WORK

A. *Methods for Traffic Congestion Detection*

There are several algorithms that can be used for traffic congestion detection. Traffic flow analysis algorithm uses data from traffic sensors, such as loop detectors or cameras, to measure traffic flow parameters such as speed, volume, and density. By analyzing changes in these parameters over time, traffic congestion can be detected. For example, if the speed drops below a certain threshold or the volume exceeds a certain capacity, it may indicate congestion. The Traffic Volume Analysis method involves analyzing the volume of traffic passing through a road segment over a certain period. Traffic congestion can be detected when the traffic volume exceeds the capacity of the road or is significantly higher than the normal volume for that time of day or day of the week. The Speed Analysis method analyzes the speed of vehicles on a road segment using radar guns, GPS data from vehicles, or analyzing video footage from traffic cameras. When the average speed drops below a certain threshold or is significantly lower than the posted speed limit, it may indicate congestion. The Density Analysis method checks the number of vehicles per unit length of the road and traffic density can be calculated by dividing the traffic volume by the road length or by using other methods such as using vehicle lengths or areas occupied by vehicles. High traffic density may indicate congestion, especially when it exceeds the capacity of the road or is significantly higher than the normal density for that road. Occupancy Analysis tracks the percentage of time that a traffic lane or road segment is occupied by vehicles [5]. Occupancy can be calculated by dividing the time during which a detector or sensor detects a vehicle by the total time of observation. High occupancy rates may indicate congestion, especially when they are consistently high over time. Queue Length Analysis analyzing the length of queues or lines of vehicles that form due to congestion [6]. Queue length can be measured by manually observing the length of the queue or by using video footage from traffic cameras. Long queue lengths may indicate congestion, especially when they are longer than usual or extend beyond the normal queueing area. Travel Time Analysis analyzes the time taken by vehicles to travel through a road segment or a specific corridor which can be measured using GPS data from vehicles, toll booth data, or other methods. An increase in travel time compared to historical data or expected travel time may indicate congestion.

There exist many different optimization strategies to deal with traffic congestion, including Queuing Theory [7], Genetic Algorithms [8], Ant Colony Optimization [9], Particle Swarm Optimization [10], and Queuing Theory. Queuing theory is best suited for solving this issue because congested queues are used for modeling traffic congestion. To find a more efficient path to shorten wait times, the field of optimization known as queuing theory investigates the dynamics of queues.

Many techniques are used for detecting traffic congestion and optimizing traffic flow to mitigate congestion impacts. Often GPS data collected from the vehicles on the road such as taxis is used to identify congestion patterns. If vehicles are moving slowly on the same road segment, this may indicate congestion [11]. The content uploaded by the user on social media platforms can also provide information about traffic conditions. analysis of social media platforms, such as Twitter or Instagram, can provide real-time information about traffic congestion from user-generated content. By analyzing hashtags, geotags, and keywords related to traffic, congestion can be detected [12]. Sharing posts mentioning traffic jams or sharing images of congested roads can be used to identify areas experiencing congestion. Cellular data analysis Mobile phone data, such as call detail records (CDRs) or location data, can be used to detect traffic congestion by analyzing changes in location, speed, and density of users.

Accurately estimating the number of vehicles on the roads is a fundamental prerequisite for the successful deployment of an adaptive traffic light control system. This can be achieved through various sensors including wireless sensor networks, magnetic loop detection, infrared sensors, video data analysis, and infrared sensors. RFID systems can be incorporated into the existing signaling system by installing RFID tags on cars, which relay information to controllers installed at each signal. By counting the number of cars entering and leaving a road segment, the system can detect traffic congestion and dynamically adjust the signal timers to optimize traffic flow [13], [14]. The authors in [15] proposed a density-based traffic light control system that uses IR sensors and an Arduino microcontroller. IR sensors are placed at each side of the traffic junction to detect the density of traffic. The Arduino controller receives input from the sensors and adjusts the traffic light timings accordingly. The author of [16] employs inductive loops and a programmable micro-controller to evaluate traffic density and synchronize the timers of traffic lights in real-time enhancing the smooth flow of vehicles by reducing delays. Furthermore, the system integrates a pre-emption mechanism that utilizes infrared sensors to give priority to emergency vehicles over others in the same lane. Researchers also used a wireless sensor network installed in the road to collect information to estimate the length of the queue and reduce the waiting time by adjusting the green light time and the sequence of lights [17]. The study described in [18] uses video surveillance-based traffic control mechanisms through the deployment of cameras at junctions to capture live videos, where background differentiation and morphological operations are applied for the detection and identification of vehicles. The researchers in [19] employed radar sensors for vehicle detection, primarily chosen for their resilience to varying weather conditions and high accuracy in detection. Subsequently, they implemented a traffic conditions identification algorithm that integrates spectral clustering and neural network techniques to achieve classification of road congestion levels. Tyagi et al. utilized a single omnidirectional microphone at road junctions for traffic congestion detected by capturing acoustic signals from the environment including engine noise, honking, tire noise, and air turbulence [20]. The congestion is determined by analysing the Mel-Frequency spectral coefficients of the recorded sound waves and comparing them with the statistical patterns of previous congestion behaviour. However, in noise-restricted areas such as schools and hospitals, where honking is not allowed, the absence of honk sounds may lead to potential misinterpretation in terms of acoustic patterns.

Video cameras presently stand as the predominant sensing system in traffic surveillance, leveraging their capability to visually capture image information. Analysis of traffic congestion employs either conventional vision systems [21] or deep learning systems to address congestion issues [22]. Certain researchers adopt multisensory fusion techniques, incorporating video and LIDAR, to tackle this problem [23]. However, cameras, despite their widespread use, present challenges such as expense, limited access to direct distance information, and vulnerability to light and weather conditions. We used ultrasonic sensors in this research as they are cheap and easy to deploy. Furthermore, these sensors have proven large scale functionality as they have been extensively used in Japan due to alignment with government policies discouraging pavement cutting on existing highways.

III. Road Intersection Scenario

An overview of the structure of a signalized road intersection under study with traffic lights on each intersection approach is shown in Figure 1. It consists of 8 roads, with 4 roads having traffic approaching the intersection and 4 roads leaving the intersection. The roads R_1, R_2, R_3, and R_4 in the figure are approaching the intersection, and traffic signals S_1, S_2, S_3, and S_4 are installed on these roads (overhead on signal poles) to control the flow of traffic by providing instructions in the form of red, yellow, and green lights. Traffic signals are electrically operated control devices for guiding roadway users by assigning right-of-way to different approaches and movements. They facilitate shared road space by managing conflicting movements, allocating delays, and enhancing the safety and mobility of various traffic actions. The ultrasonic sensors (presence detectors) are placed at the close proximity to the stop line at the upstream approach to the intersection to inform the signal controller of the presence of motor vehicles. These detectors are designed to notify the controller when vehicles are waiting at the intersection during the red interval. In response to this detection, the controller can initiate actions such as calling for additional green time, allowing for the passage or extension of the green interval to accommodate the movement of waiting vehicles. The sensors are labeled according to the roads where they are installed and their location on the road, with the lower number indicating that the sensor is closer to the signal. Each intersection has standard signals and there are no separate signals for pedestrians and bicyclists.

Each road has 3 lanes including one right-turn lane, one straight-through lane, one straight-through/left-turn lane (not shown in Figure 1), and one U-turn Lane. A signal control cabinet located near the intersection houses the electronic equipment and controllers that manage the traffic lights. The control cabinet connects to the traffic lights through underground or overhead cables. To monitor the traffic condition, three ultrasonic sensors are installed on the U-turn Lane of each approaching road. There are no dedicated signal phases for the U-turn Lane making it the slowest among all the lanes which made us choose this lane for installing the sensor. Also, if there is less traffic on this lane, the ultrasonic sensors have a good range and can detect the cars in the second or third lane. These sensors provide real-time data to the traffic signal controller, allowing it to adapt signal timings based on traffic flow.

Four congestion level L_0-L_3 by using three sensor and this is achieved by installing the UL_1 some distance before the stop level. Each signal is allocated a green time even if no congestion is detected by UL_1. Various traffic congestion levels on road segments R_2 are depicted in Figure 1, spanning from no traffic to heavy congestion conditions. As an example, Figure 1(a) illustrates a high congestion scenario, characterized by a lengthy queue, where all three ultrasonic sensors ($R_2\_UL_1$, $R_2\_UL_2$, and $R_2\_UL_3$) simultaneously detected vehicles. In contrast, Figure 1(b) depicts a moderate congestion scenario with a shorter queue, where vehicles are detected by two sensors, $R_2\_UL_1$ and $R_2\_UL_2$. Figure 1(c) showcases a low congestion scenario, featuring a smaller queue length, with vehicles detected by $R_2\_UL_1$ only. The last scenario in Figure 1(d) illustrates a situation where none of the sensors detects any vehicles, indicating an almost traffic-free scenario.

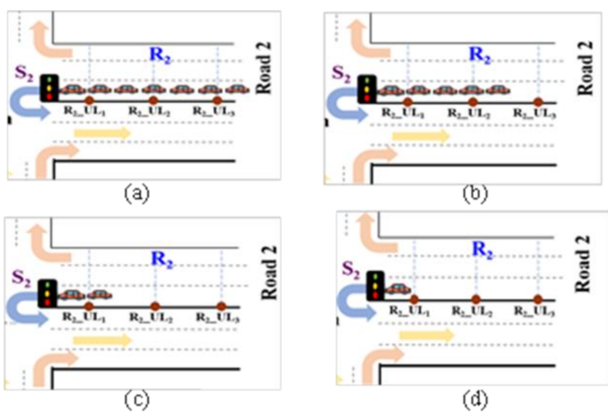

Figure 1: A road intersection scenario

IV. System Architecture

The architecture depicted in Figure 2 provides a comprehensive overview of the structure of the adaptive traffic signal control system. The fundamental components of this system encompass sensors responsible for data collection, data acquisition mechanisms, connectivity elements, cloud-based data storage, a user interface for interaction, and a dedicated component for data analysis. The four overhead signals are connected to digital pins of an Arduino Mega based controller with preprogrammed timings for turning red, green, and yellow on for each signal. Each intersection is installed with one an Arduino Mega which can communicate with each other over RS232 and the cloud through Wi-Fi. A total of twelve over-roadway ultrasonic sensors (HC-SRO$_4$) are installed on each intersection alongside the roadway, offset from the nearest traffic lane by small distance. There are three sensors on each road to measure the length of queue. The sensor sends out a signal that reflects upon detecting a vehicle. Subsequently, the sensor analyzes the reflected signal, comparing it with the initially emitted signal. If any disparity is detected between these signals, the sensor identifies the presence of a vehicle. This information provided is used to measure the congestion level on a particular road and adjust the traffic signal accordingly. Each ultrasonic sensor is represented by UL with prefix indicating the road where it is installed and subscript number indicating the level of congestion determined by the sensor. For example, sensor R1_UL2 is installed on road R_1 and determines the congestion level 2 of the road.

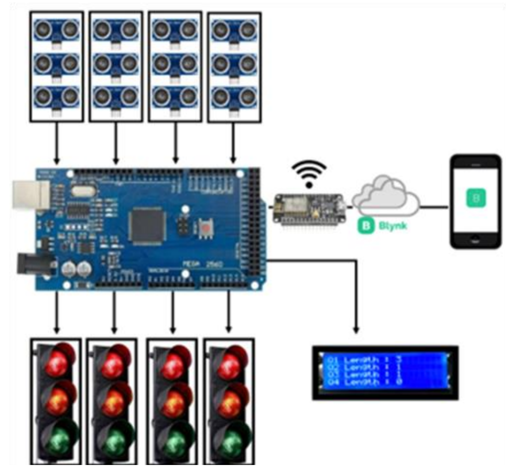

Figure 2: System Architecture

Ultrasonic sensors emit sound energy pressure waves at a frequency ranging surpasses 25 and 50 kHz (40 kHz in case of HC-SRO$_4$), which surpass the human audible range. Most ultrasonic sensors utilize pulse waveforms to furnish information on vehicle count, presence, and occupancy. The ultrasonic sensor can be placed in two ways to detect the car either from sideways or from the top. When installed on the top, the sensor employs pulse-shape waveforms to gauge distances to both the opposite wall (or road surface if installed on the top) and vehicle surface. They achieve this by detecting the reflected energy directed towards the sensor within the transmitter's beamwidth. If the measured distance deviates from that to the background surface, the sensor interprets it as the presence of a vehicle. Subsequently, the received ultrasonic energy undergoes conversion into electrical energy. The signal processing electronics, responsible for analyzing this energy, can be either collocated with the transducer or positioned in a roadside controller. Given that ultrasonic waves have the capability to bounce off a glass or liquid surface and then return to the sensor head, vehicles can be detected even if the waves are aiming at windscreen or the window glass of the vehicle.

The HC-SRO4 module initiates the ranging process by sending a brief 10 μS pulse to the trigger input. Subsequently, the module emits an 8-cycle burst of ultrasound at 40 kHz and raises its echo. The echo represents a distance object in pulse width, and the range is proportional to it. The range is calculated by determining the time interval between sending the trigger signal and receiving the echo signal. The Arduino Mega is a versatile microcontroller board built around the ATmega2560 that is utilized for collecting sensor data due to enough digital I/O pins required for this application. The information collected by sensors is sent to the controller which processes it, calculates new timings for signals S_1, S_2, S_3, and S_4.

The information about the congestion level is transmitted to Blynk cloud using built-in Wi-Fi. A local GUI is also provided using LCD which is connected to microcontroller using I2C protocol. This is a valuable tool for troubleshooting systems as it provides real-time visual feedback and information such as congestion level on each road validating the functionality of the sensor as well as the accuracy of the algorithm. This is also used to verify the timing of the signals during development and testing phase. Sudden changes or anomalies in these parameters can be quickly identified, aiding in the diagnosis of potential problems. The controller for intersection I_1 is connected to controller I_2 using RS232 serial port. This provides the local context of the I_2 allowing I_2 to make its controller aware of the conditions of neighboring intersections enabling it to make decision based on these decisions in future. The same information can also be fetched from the cloud.

The IoT platform employed in this study is Blynk [14], which enables the aggregation, visualization, and analysis of real-time data in the cloud. Three basic components in the Blynk are Application, Server, and Libraries. Server is in-charge of all the correspondence among application and the designs. Also, Libraries permits communication for equipment with the server utilizing directions. The data is transmitted from embedded devices to Blynk server. The Blynk Cloud provides seamless integration between the Cloud and connected devices. It also supports real-time data visualization through interactive graphs, charts, and gauges. This feature aids in monitoring and analyzing data generated by connected devices. The end user can interact with the Cloud through Blynk mobile app.

V. METHODOLOGY

Figure 3 outlines the entire sequence or flow of the system being discussed. This graphical depiction provides a comprehensive overview, allowing viewers to understand the workings of the system clearly and concisely. To start with, all the signals are pre-timed default values of 1 second and all signals are red. Starting with R_1, the system sets the green light on for 1 second (S_1_G_T=1s) while the red light is turned on all other lanes at the intersection. The green light for R_2 will be turned on next. While the red light of R_2 is red, its ultrasonic sensor nodes are monitored constantly, and, depending on their values, the period of green light for R_2 is specified. First R_2_UL_3 is checked and, if occupancy is detected (high level of congestion), the green light duration is configured for 9 seconds (R_2_G_T=9s). If no occupancy is detected, R_2_UL_2 is checked, if vehicle is detected (medium level congestion), then S_2_G_T is set for 6 seconds. If S_2_UL_3 and R_2_UL_2 are not set and R_2_UL_1 is set, then green light duration is configured for 3 seconds (R_2_G_T=3s). R2_G_T is set for default duration of 1 second if no vehicle is detected by any sensor. It should be noted that the red light of subsequent signal (S_3_R_T) is configured with same duration as that red light duration of the signal under consideration. The same procedure is iterated for setting green light duration for S_3, S_4, and S_1, in the same sequence. All the signal timings are scaled down by a factor of 10 for testing purposes.

VI. EXPERIMENTAL RESULTS

To validate our approach, we proceeded to develop a prototype, The final circuit realization of the suggested adaptive traffic light system for congestion management is illustrated in

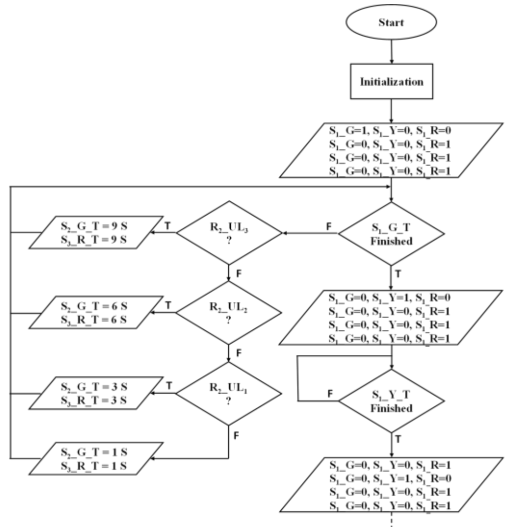

Figure 3: Traffic light control methodology

Figure 4. The construction of this prototype allowed us to practically implement and assess the effectiveness of our proposed approach. The system was developed for four intersections, I_1-I_4, and there is a separate controller for controlling the signal light duration for each section. Each controller is equipped with sixteen ultrasonic sensors. The queue length of each road is detected by the ultrasonic sensor as this information is displayed on the LCD.

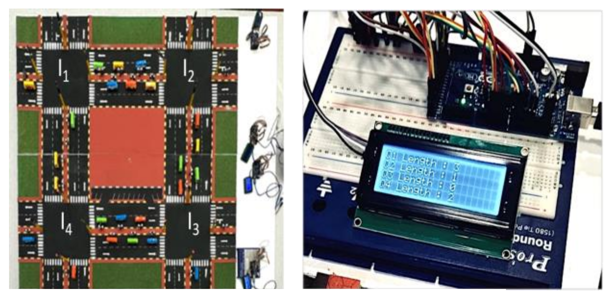

Figure 4: Final prototype

The smartphone application was implemented using Blynk application builder which provides a way to develop it without coding. This requires installing the application and creating a user account. The user is then required to create a project after which a unique authorization code is provided, vital for establishing the connection between the Arduino Mega and Blynk app. Therefore, the user needs to add Blynk library when developing sketch for the Arduino board and required to embed the Wi-Fi network name, password, and Blynk Auth Token into the Arduino program. This information allows the Arduino board to connect to the Blynk app. The congestion levels, determined by the queue length captured by the ultrasonic sensor, are displayed on the LCD, as shown in Figure 5. The first row displays the project ID and title. The second row provides information on the name and number of intersections (e.g., I1: Riqqah), followed by the road segment number "R_2." The green signal timings, calculated based on the congestion level information from the ultrasonic sensors, are displayed in the last row, indicating 9 seconds for high congestion.

Figure 5: Congestion levels and signal durations for different scenarios

For the user interface, the version of the Blynk app utilized, featuring a custom-designed layout and buttons to facilitate the monitoring of various connected components. Screenshots depicting the results of the designed system obtained on the Android application are presented in Figure 6. The gauges show the congestion levels at different road segments of an intersection. Mobile apps also include a template representing devices in the list of devices (tiles). The administrative staff can use the Blynk app to remotely manage traffic signal empowering them to engage with their devices from any location with an internet connection.

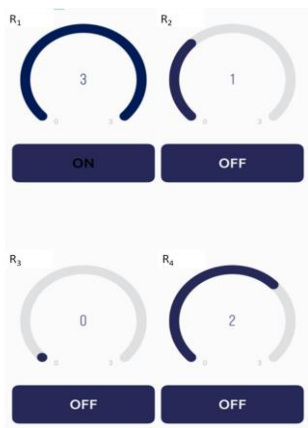

Figure 6: Screenshot of the Blynk app

VII. Conclusion

In this paper, we presented the design and development of ultrasonic sensor-based traffic light control system to deal alleviate the delays due to the congestion at road intersection. A comprehensive introduction to the system's architecture and data processing flow is also provided, delving into specifics such as the ultrasonic sensors utilized for gathering road vehicle driving information and the traffic congestion discrimination system, which assesses road congestion levels. A functional prototype was developed and tested mimicking actual road intersection yielding positive outcomes. In contrast to fixed traffic light control, the suggested road congestion alleviation system demonstrates its efficacy by significantly reducing the proportion of road congestion. In future work, we intend to enhance the system with the capability of detecting emergency vehicles and provide them with priority over the road.

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