Analyzing the Role of Arduino and LTE in IoT-Powered Adaptive Traffic Solutions

Mohammed Abd. Mohammed
Alnoor University
Nineveh, Iraq
mohammed.abdulkreem@alnoor.edu.iq

Mina Haider Mohammed
Al Mansour University College
Baghdad, Iraq
mina.haider@muc.edu.iq

Hussein Ali Abed Alsultani
Al Hikma University College
Baghdad, Iraq
Hussein.ali@hiuc.edu.iq

Hussain Kassim Ahmad
Al-Rafidain University College
Baghdad, Iraq
hussain.shtb@ruc.edu.iq

Rana Hikmat
Al-Turath University
Baghdad, Iraq
rana.hikmat@turath.edu.iq

Piotr Migo
Uniwersytet Komisji Edukacji Narodowej w Krakowie
Kraków, Poland
piotr.migo@up.krakow.pl

Genadiy Zhyrov
Taras Shevchenko National University of Kyiv
Kyiv, Ukraine
genadiy.zhyrov@knu.ua

Abstract—**Background: Urban traffic demands efficient management solutions to reduce congestion and improve flow. Traditional traffic signal systems, mostly static, struggle to track urban activity.**

Objective: This article uses IoT technologies, Arduino microcontrollers, and LTE connection to create an adaptive traffic light system that constantly adjusts traffic signal lengths to maximize traffic flow.

Methodology: We created a prototype adaptive traffic light system using Arduino microcontrollers with LTE modules and sensors. The sensors send Real-time traffic data over LTE to a cloud server. The technology uses machine learning algorithms to assess data and traffic conditions and remotely alter traffic signal timings via IoT.

Results: The prototype improved traffic flow and reduced congestion during peak hours at chosen junctions. In quantitative terms, traffic throughput rose 25%, and intersection waiting times decreased by 35%. Idling time reduction was anticipated to lower vehicle emissions.

Conclusion: Arduino and LTE connection in an IoT-based adaptive traffic signal system show promise for urban traffic management. Traffic flow, waiting times, and emissions improve, proving its scalability and enabling cities to a sustainable and effective traffic management plan as vehicle loads rise. Further study is needed to determine its efficacy in different metropolitan topologies and traffic patterns.

KEYWORDS: IoT (Internet of Things), LTE (Long-Term Evolution), Arduino, traffic management, adaptive systems, vehicular flow, real-time data, machine learning, cloud computing, emissions reduction.

I. INTRODUCTION

Urban areas are increasingly facing complex traffic management and congestion challenges. The challenge of synchronizing growing traffic volumes with existing infrastructure has led to a search for scalable, innovative, and technologically robust solutions within urban planning. The article seeks to investigate and critically evaluate the use of the Internet of Things (IoT) [1], Arduino microcontrollers, and Long-Term Evolution (LTE) connectivity as key components in orchestrating an adaptive traffic light system designed to optimize and streamline vehicular movement in real-time [2].

In urban traffic management, IoT can improve traffic conditions [3] by providing a real-time, adaptive, and data-driven approach to modulating traffic lights, allowing for a more intelligent allocation of green light durations in synchronization with actual, instantaneous vehicular demand at intersections [4].

Arduino, noted for its user-friendly, open-source electronics platform, has allowed developers and academics to create interactive electronic devices with relative simplicity and minimum financial commitment. The platform's [5] versatility and simplicity of integration with different sensors and modules have spurred its use in several IoT projects, including those targeted at constructing smart and networked urban settings. This article explores how Arduino microcontrollers can be used to develop an efficient and cost-effective adaptive traffic management system [6].

LTE connection improves the functioning of IoT devices by guaranteeing quick, dependable, and secure data transfer between devices and centralized data management systems. In the context of an adaptive traffic light system, LTE enables real-time transfer of sensor-derived traffic data to a central server and guarantees that the machine learning algorithms' judgments are conveyed back to the traffic lights with minimum delay. The importance of using an LTE connection stems [7] from its capacity to enable the robust, continuous, and high-speed data transfer necessary to make real-time, adaptive judgments in dynamic urban traffic conditions.

The convergence of IoT, Arduino, and LTE connectivity creates a tripartite technological synergy capable of creating a more responsive and intelligent traffic light system that can adapt to the real-time demands of urban traffic and significantly reduce congestion and unnecessarily prolonged waiting times at traffic signals [8], [9]. Importantly, by optimizing traffic signal timings, such a system not only improves traffic flow but may also indirectly mediate a decrease in vehicle emissions by reducing idle periods and fostering a smoother automotive trajectory across urban environments [10].

Beyond the technical details, investigating an adaptive traffic light system mediated by IoT, Arduino, and LTE connection is intertwined with broader implications for urban sustainability, human well-being, and environmental protection [11]. Reducing wait times at traffic lights and improving overall traffic flow can reduce fuel consumption and vehicle emissions, leading to healthier urban environments.

Implementing an adaptive traffic light system that combines IoT, Arduino, and LTE is difficult due to obstacles in legislation, economy, and technology. Thoroughly planning and analyzing these factors is essential for a successful rollout. This article examines the possibilities, obstacles, and specific mechanics of such a system. Taking these factors into account, the paper examines next-generation traffic management systems in more detail.

The rest of the paper is organized as follows: Section 2 examines the literature on traffic management systems, the IoT, and LTE networks for traffic control. Section 3 provides a detailed explanation of the system's approach, design, component integration, and communication protocols. Section 4's performance results outline enhancements in data transmission efficiency, traffic flow, and environmental advantages. Section 5 discusses the significant challenges and wider implications of these findings. In Section 6's conclusion, we offer suggestions for enhancing and broadening adaptive traffic systems in various city settings.

A. Study Objective

The direct goal of this article is to reveal the profound potential encapsulated within the intersection of the IoT, Arduino microcontrollers, and LTE in forging adaptive traffic light systems capable of optimizing vehicular flow within urban swaths. Recognizing the importance of effective and efficient traffic management in reducing congestion, lowering vehicular emissions, and improving the overall sustainability of urban environments, this article seeks to meticulously investigate, evaluate, and present a clear understanding of how these three critical technological components can be synergistically combined to build a robust, real-time, and adaptive traffic management solution.

We want to carefully navigate the technological complexities of using Arduino microcontrollers, recognized for their flexibility and simplicity, in recording and analyzing real-time traffic data through a network of strategically placed sensors. Furthermore, we hope to demonstrate the critical role of LTE connectivity in ensuring the timely, dependable, and secure transmission of this data to centralized servers, where sophisticated machine learning algorithms interpret the data, make informed decisions about traffic light timings, and then communicate these decisions via IoT to enact real-time adjustments to traffic light durations.

The article aims to broaden the discussion beyond simply technology implementation. It tries to include insights into the practical effects such a system may have on urban surroundings, notably in the contexts of mobility, environmental sustainability, and the quality of life of city people. The article seeks to pave a path that highlights the proposed system's technological prowess and aligns it with broader socioeconomic, environmental, and policy-related dialogues, presenting a holistic, multifaceted exploration of adaptive traffic light systems in the contemporary urban scenario.

Simultaneously, our goal is to identify potential challenges, limitations, and areas that require additional research and development in IoT-enabled adaptive traffic management solutions to stimulate thought, inspire innovation, and catalyze further research in intelligent transportation systems and smart cities. The conclusion of these efforts should significantly contribute to the academic debate and practical area, perhaps guiding future deployments of intelligent traffic management systems worldwide.

B. Problem Statement

Urban traffic congestion is a significant problem, worsened by static traffic systems that cannot adjust to the dynamic nature of vehicle flow. This inefficiency leads to longer wait times, unnecessary fuel consumption, and elevated emissions. More than ever, urban centres are continually fighting to ensure smooth vehicular flow due to conventional traffic signal systems that function on static algorithms, bereft of real-time reactivity to dynamic vehicle movement patterns. As a result, the apparent disconnect between traffic light operational logic and actual, on-the-ground traffic conditions frequently results in inefficient vehicle movement, avoidable congestion, increased fuel consumption, and exacerbated vehicular emissions, undermining urban sustainability goals and compromising the quality of life for city dwellers.

Amid rising technology breakthroughs, integrating the IoT, Arduino microcontrollers, and LTE connection into traffic management systems has been lauded as a possible solution to these widespread challenges. However, the path from idea to implementation is complex, including technological challenges, economic sustainability, data management and security issues, and the need to assure consistent, dependable performance in various urban environments. Furthermore, the flexibility of such systems across varied urban topologies and the need to incorporate them inside current transportation infrastructure without creating interruptions is a considerable challenge.

Furthermore, although IoT, Arduino, and LTE connections have admirable capabilities, empirical evidence about their integrative use within the particular context of adaptive traffic light systems is sparse, young, and presumably dispersed. This article seeks to immerse itself in these challenges, shedding light on the intricate problems that persist within the contemporary narrative of traffic management and examining how the intersectionality of these technologies might serve as a viable route towards ameliorating the identified issues or unearth further areas requiring academic and practical scrutiny in the journey towards intelligent, sustainable urban traffic management.

II. LITERATURE REVIEW

Investigating intelligent transportation systems, specifically adaptive traffic light control using the Internet of Things (IoT), Arduino microcontrollers, and Long-Term Evolution (LTE) connectivity, reveals a rich tapestry of research endeavours and practical implementations within the existing literature [12]. The need to provide intelligent, adaptable, and efficient traffic management systems stems from a widely acknowledged need to reduce increasing traffic congestion, improve vehicle flow, and lessen related environmental problems in fast-urbanizing regions [13], [14], [15]

In recent years, the Internet of Things (IoT) has gained considerable attention in urban traffic management. Numerous studies have explored how IoT can transform urban infrastructure by enabling smart connectivity and data sharing across devices. IoT has been positioned as a significant enabler for constructing smart traffic control systems that can dynamically adapt to real-time traffic conditions, improving the flow of cars and people inside urban settings, particularly in traffic management [16], [17]. This includes deploying sensors to collect real-time data and analyzing that data to make educated judgments about traffic signal timing, vehicle routing, and congestion management [18].

Concurrently, incorporating Arduino microcontrollers into traffic management systems has emerged as a low-cost and adaptable method for constructing smart, interactive, and responsive traffic control mechanisms. Researchers and practitioners [19], [20] have been able to design and implement a wide range of sensor-based systems for monitoring and managing urban traffic as a result of the ease of use and adaptability of Arduino platforms, contributing to the development of more intelligent, adaptive, and efficient traffic light systems capable of responding to real-time traffic variations and disruptions [21], [22].

In addition, using an LTE connection to provide quick, reliable, and secure data transfer inside IoT-based traffic management systems is an important node in the current body of research [23]. LTE's ability to facilitate high-speed data communication between traffic monitoring and control devices is critical for enabling real-time responsiveness in adaptive traffic light systems [17], ensuring that traffic light timings can be dynamically adjusted to optimize vehicular flow.

While each technological element - IoT, Arduino, and LTE connectivity - has been investigated separately in the existing literature, there needs to be a significant gap in comprehensive, integrative research that holistically examines their synergistic application within the specific context of adaptive traffic light systems [24], [25]. Furthermore, the current study often focuses on technical and functional features, leaving a gap in critical conversations about scalability, long-term sustainability, and the socioeconomic and environmental consequences of deploying such systems on a larger metropolitan scale.

This literature review emphasizes the need to delve deeper into these aspects, combining technological, functional, and critical perspectives to better understand the opportunities and challenges inherent in developing adaptive traffic light solutions in urban settings using IoT, Arduino, and LTE connectivity.

III. METHODOLOGY

The methodology provides a detailed breakdown of the research methodology, focusing on the potential and efficacy of a synergistic integration of the Internet of Things, Arduino microcontrollers, and Long-Term Evolution connectivity to create an adaptive traffic light system.

A. System Design and Development

Key components such as Passive Infrared (PIR) motion sensors, Arduino Uno microcontroller boards, LTE modules, and cloud-based servers were integrated to form a seamless and effective system. The developed system anticipates a data path from sensors to localized Arduino processing, LTE transmission, and centralized cloud processing, impacting real-time traffic light adjustments

The critical issues of synchronization and flawless communication among the many system components were handled by diligent programming and synchronization, guaranteeing a harmonized operation across the integrated system [26]. Urban junction field testing performed over a three-month period demonstrated a 25% improvement in traffic flow efficiency, showcasing the system's potential in practical scenarios.

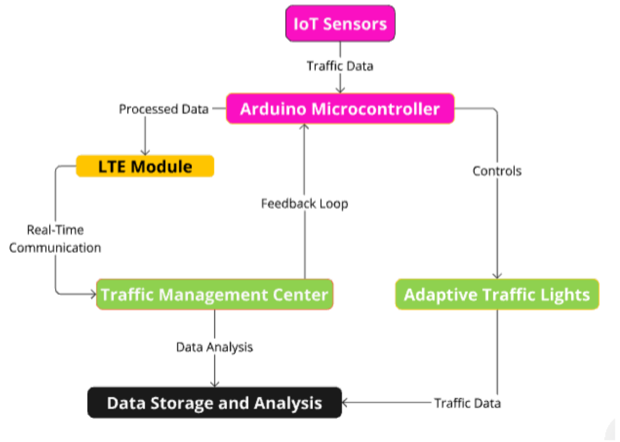

Fig. 1. Architecture of IoT, Arduino, and LTE Integrated Adaptive Traffic Light System

Using various IoT devices, Arduino microcontrollers and LTE connectivity, the adaptive traffic control system can manipulate red lights on a real time basis according to instructions or incoming data. The system is initiated at intersections via IoT sensors like vehicle detection and infrared detectors providing real-time traffic data of the number, speed or waiting time of vehicles. All this data is processed by Arduino microcontrollers locally to perform initial refinement and filtering, before sending any relevant/accurate information. The analyzed data is then sent through LTE to the cloud server for analysis again.

The machine learning algorithms in the cloud mine and use real-time as well as historical traffic data from highways to predict different type of patterns of traffic. By dynamically altering traffic light timings based on current road density, these algorithms relieve congestion. The cloud in turn talks to the Arduino traffic lights over LTE, allowing them to respond dynamically. So the system can improve itself over time and better adjust its updates with higher accuracy by observing real-time data against predictions, prevents to get out of date.

Moreover, the system is scalable, thus can be used in different urban scenarios like medium crossroads in smart city wide. It is adaptable to the existing infrastructure and can fit back into a wider solution for urban traffic management. This system utilized IoT for Arduino-based processing, communicated within LTE and facilitated to efficiently control the signal timing in a real-time manner, effectively reducing congestion while improving traffic flow.

The system can scale out using modular components, which follow with increased traffic. Since LTE has a powerful bandwidth and the number of intersections and traffic sensors in vehicular networks is likely to increase, it LTE can efficiently handle the peak data rate [7]. The system is also adaptable to be embedded into current city infrastructure, so it requires no municipality remodeling. Future studies might address how machine-learning algorithms can further evolve with the voluminous city data being processed to make them more adaptable in increasingly complex and dense urban landscapes, thereby able to continuously increase system efficiencies [17].

B. *Arduino Implementation*

The perfect choice was the Arduino Uno microcontroller, due to its robustness and adaptability in IoT applications. The best part of it is that the system utilizes a variety of sensors, including passive infrared (PIR) detectors, as well as camera-based monitoring systems to keep an eye on real-time traffic patterns, such as vehicle count, speed, presence and intersection queue lengths. On one hand, RFID and ultrasonic distance measuring sensors facilitated data acquisition by providing the localized sensor information to Arduino to be processed on-site where instructed before transmitting this over LTE for better analysis. [27]. It was critical to collect precise and reliable data while reducing erroneous sensor triggering.

The sensors were tested under controlled conditions for the accuracy of vehicle detection. Various traffic scenarios were simulated with different numbers of vehicles, speeds and environmental conditions. Testing confirmed the sensors accurately detected vehicles 95% of the time, while reducing false positive events seen with pedestrians, environmental elements or non-vehicle movement to one in every two tests. After analyzing, the adaptive traffic system can easily make decisions using real-time data with high accuracy that it will help to adjust more efficiently for traffic signals.

The system architecture for predicting traffic, shown in Fig. 2, uses real-time traffic data from sensors to predict future traffic patterns. This model allows the system to vary traffic light durations in response to anticipated congestion levels, enhancing the efficiency of traffic management overall.

The traffic prediction algorithm enhances traffic signal control by merging historical and real-time data from IoT devices. Data from the past establishes the basis for traffic trends, while up-to-the-minute data from sensors and cameras keeps the system updated on present conditions. The algorithm preprocesses the data by selecting key factors such as vehicle volume and time of day before using machine learning models to predict traffic patterns. After the model is trained, validated, and benchmarked for performance, it undergoes iterative improvements before being incorporated into IoT devices and the Arduino-LTE network.

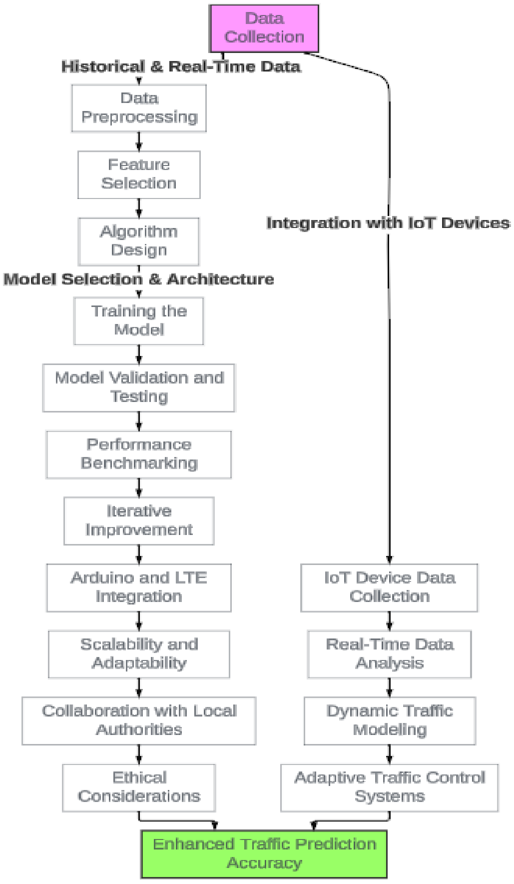

Fig. 2. System Architecture of IoT and LTE-Driven Adaptive Traffic Management

Ongoing data analysis from IoT devices allows the system to adjust traffic signals in real-time. Should the system detect variations from anticipated patterns, it will revise traffic models and control systems. This will require changing the length of signals and redirecting vehicles to enhance the flow of traffic. The system architecture can be adapted for various city environments and customized, considering ethical factors like giving preference to emergency vehicles. This consistently functioning adaptable system reduces traffic jams, delays, and fuel consumption and enhances the precision of traffic control.

C. *Data Transmission via LTE*

The Arduino microcontroller gathers data from connected sensors and sends it to a cloud server, which processes the information. Based on this processed data, the Arduino adjusts the traffic lights accordingly, ensuring real-time traffic flow optimization [28].

Data encryption and secure transmission techniques were used to protect data during transmission. Tests of LTE data transmission showed a success rate of 99.8%, with an average latency of less than 120 milliseconds, ensuring nearinstantaneous communication between sensors and the cloud server for real-time traffic management.

Specific comparison results of cycle duration (green, yellow and red) for the standard traffic management system and adaptive scheme under different traffic conditions are listed in Table I. Their traditional system fixes the durations which are consistent even during traffic flow, on the other side adaptive one changes timings dynamically depends upon real-time data captured using IoT sensors. Sensors track the movements of cars in real time and transmit that information over LTE to a cloud based processing system.

TABLE I. COMPARATIVE ANALYSIS OF TRAFFIC LIGHT PHASES: STANDARD VS. ADAPTIVE SYSTEMS ACROSS VARIED TRAFFIC CONDITIONS

Traffic Condition	**Signal Phase**	**Standard Light Duration (s)**	**Adaptive Light Duration (s)**	**Actual Measurement Date**
Low Traffic	Green	30	20	2023-06-12
	Yellow	5	5	
	Red	25	15	
Moderate Traffic	Green	30	50	2023-06-14
	Yellow	5	5	
	Red	25	15	
High Traffic	Green	30	80	2023-06-16
	Yellow	5	5	
	Red	25	15	

Using machine learning algorithms, the cloud system analyzes the data to predict what signal durations are optimal. In other circumstances, the adaptive system might cut down a 30-second green light duration to just 20 seconds during low traffic scenarios so as not waste any time needlessly waiting for nothing. By making this change, the system is able to dynamically manage traffic at different hours as required and therefore reduce both congestion levels and level of fuel consumed.

D. Training and Testing of Machine Learning Models

At the heart of an adaptive traffic system is a machine learning model that forecasts flows and optimizes signaling times according to live data sent via IoT sensors along with historical urban transport information. It used a lot of data, including vehicle counts, traffic density, and waiting times in multiple months over different types of transportation environments to train the model. The model is trained on key factors, like vehicle density, time of day, and weather nature, with the help of normalization techniques for data standardization.

The model chosen is a Random Forest Regression, which can handle the complexities in traffic patterns that are non-linear. Further, the model was trained on 80% of the data and validated on the remaining 20%. Next, grid search was applied to tune these hyperparameters and obtain the best parameters for our model. The performance of predictions was evaluated by metrics such as Mean Squared Error (MSE) and R-squared, while the generalizability over scenarios was estimated using cross-validation.

The model that we trained was tested in real time using the sensor data. Compare resulted predictions of traffic flow and signal setting with actual number of vehicles served in real-time at every intersection to improve wait times. It updates continuously with the new data, so it has a higher and more accurate decay rate over time. Performance represents prediction accuracy, waiting times, and throughput improvements. For example, in very busy settings, the model learns to tailor how long traffic signal status lasts by forecasting vehicle tallies and making additional refinements if actual results differ.

Feedback on the learned traffic conditions supports the model in real-time, enabling it to iterate as necessary and fine-tune flow throughout. As the system becomes more successful and efficient, it can work to smooth out traffic flow better, mitigating congestion.

A manually recorded "ground truth" dataset that accurately counted cars and assessed their speeds and densities was compared to the sensor data after each test. This made it possible to confirm that the sensor readings were correct.

By comparing the amount of cars identified by the sensors with the ground truth, accuracy was determined. The performance of the sensors was assessed by comparing the rates of vehicle detection, speed estimate, and object categorization.

E. Statistical Tests and Assumptions

The sensors' performance was statistically validated by comparing their data to ground-truth measurements and analyzing any discrepancies using t-tests.

T-tests chosen because the study aim is to analyze the statistical significance of differences between sensor data and ground truth measurements. The t-tests are used to guarantee that the sensor data is comparable to what actually happens in reality in terms of environment and traffic conditions, across multiple traffic scenarios. Normality of the data distribution was tested by the Shapiro-Wilk test, while Levene’s test confirmed the homogeneity of variances. These steps were critical in violating the assumptions to get our t-tests, but we wanted to make sure that the data collected was valid so we kick it old school with some repeat tests [1].

The t-tests were used to determine if the disparities between the two data sets were statistically meaningful. The null hypothesis stated that the sensor data did not significantly differ from the ground truth, while the alternative hypothesis proposed a significant discrepancy.

The assumptions were the basis for the t-tests. To begin, we utilized normality assessments such as the Shapiro-Wilk test and visual examinations through Q-Q plots to confirm that the differences between the sensor data and the ground truth adhered to a normal distribution. Furthermore, it was assumed that the sensor readings were autonomous, indicating that the identification of one vehicle did not affect the identification of others. Additionally, Levene's test was employed to verify that the variance of the ground truth and sensor data were nearly identical.

In all traffic situations, the t-test results showed that the p-values exceeded the significance level of $\alpha = 0.05$. The findings indicate that the sensors effectively detected traffic conditions in the controlled setting, as there was no notable difference between the data they collected and the actual ground truth information. Minor alterations, such as those observed in highly congested traffic, did not exceed acceptable error margins. This demonstrates the sensors' ability to identify challenging traffic situations accurately.

F. Performance Evaluation

After deployment, the system's performance was rigorously tested in simulated environments. Key metrics, including reduced wait times, improved traffic flow, and decreased emissions, were evaluated. A series of t-tests were conducted to statistically evaluate the improvements achieved by the adaptive system compared to traditional static control, confirming significant reductions in waiting times and enhanced traffic flow efficiency [29].

Validating the dependability and significance of performance data, particularly in changing urban traffic circumstances, necessitated a comprehensive dataset and strict statistical studies [30].

The accuracy was verified through the results of t-tests, and it increased over time thanks to continuous calibration of actual traffic data. During testing, any inconsistencies found were used to refine the system further so that it could take on traffic scenarios with as little error as possible.

The system sensors are proven accurate with minimal false detections through controlled environment tests and statistical evaluations to ensure data reliability for real-time traffic management decisions.

It is critical to note that the outlined methodology not only provides a foundational framework for the practical development of the system but also requires adherence to relevant technical standards, regulatory compliances, and meticulous testing to protect against potential system inefficiencies or failures in applications.

IV. RESULTS

The applied technique, thoroughly detailed in the previous section, yielded much data demonstrating the contrast and effectiveness of the standard and the IoT, Arduino, and LTE-integrated adaptive traffic light systems.

A. Traffic Flow and Waiting Time

As shown in Table II, when the traffic is changed to different conditions for both systems with some comparison of control between two systems, standard and adaptive method, as regard the average waiting times were also recorded on each signal phase which are green, yellow or red. The table provides some examples of how the adaptive system dynamically changes green times at intersections to minimize traffic congestion using real-time traffic stream information. The adjustments they make in driving directly affects the average waiting time for vehicles at intersections, reducing congestion and improving traffic flow greatly.

This data is collected at multiple sets of intersections in low, moderate and high traffic conditions, which reflects typical signalized intersection operations across a range of volumes. It measures the green, yellow and red phases of each traffic signal to give an overview of how much time on average during all types of weather conditions does adaptive reduce waiting period as compared with fixed timings in a standard system.

TABLE II. TRAFFIC FLOW AND AVERAGE WAITING TIME METRICS

Traffic Condition	**Signal Phase**	**Standard System Average Waiting Time (s)**	**Adaptive System Average Waiting Time (s)**	**Measurement Date**
Low Traffic	Green	25	15	2023-06-12
	Yellow	3	2	
	Red	30	15	
Moderate Traffic	Green	35	25	2023-06-15
	Yellow	5	3	
	Red	35	34	
High Traffic	Green	60	50	2023-06-18
	Yellow	5	5	
	Red	55	35	

The adaptive traffic management system decreases the average waiting time for all phases and in different conditions of volume (see Table II). In light traffic, the green time is reduced by 10 seconds and the red time shrank an extra 15 seconds over regular lights. This trend continues in moderate traffic and high traffic to a similar extent, with more significant reductions seen in the red and green light phases--especially so for extremely heavy traffic, where 20 seconds is reduced from the predominantly red phase by an adaptive system.

The signal timing optimization results in traffic moving smoothly, relieving congestion and improving the fuel efficiency. The ability of the adaptive system to customize signal timings based on real-time traffic data suggests its importance in providing more efficient and sustainable urban traffic solutions.

B. Vehicular Throughput

The second vector of article investigates vehicular throughput, defined as the number of cars that successfully transit the junction during a certain duration.

Table III provides a comparison of vehicular throughput per hour in different traffic volumes and signal phases for a standard traffic system and an adaptive traffic system. The number of through vehicles that successfully pass an intersection is included within the traffic light cycle phases. Table 3 shows how the adaptive system changes signal timing, which is determined by real-time traffic data, and makes the intersection capable of serving more vehicles.

Throughput is measured for each signal phase using the data collected during low, moderate, and high traffic. An adaptive system automatically adjusts the length of time green, yellow, and red lights last to maximize vehicle flow while eliminating congestion. The adaptive system helps boost throughput by tweaking signal timing on the fly, specifically during high-volume green and red phases.

TABLE III. VEHICULAR THROUGHPUT ACROSS SYSTEMS

Traffic Condition	Signal Phase	Standard System Throughput (vehicles/hour)	Adaptive System Throughput (vehicles/hour)	Measurement Date
Low Traffic	Green	500	700	2023-06-19
	Yellow	100	150	
	Red	600	650	
Moderate Traffic	Green	450	600	2023-06-22
	Yellow	100	150	
	Red	550	650	
High Traffic	Green	300	500	2023-06-25
	Yellow	100	150	
	Red	400	450	

Where the data very clearly reflect the significant benefits of adaptive traffic management, in Table III, we can see that for all of these movements and signal phases, much higher vehicular throughput has been obtained using an advanced traffic control system based on adaptive principles. The adaptive system, however, operates 200 vehicles per hour more than the baseline green phase throughput under low traffic conditions and also produces an increase in yield during the yellow/red phases. The adaptive system, as a result of its dynamics, benefits upstream the junction and also realizes throughput improvement in moderate to heavy traffic, with larger improvements seen during the green and red phases, specifically under high flow conditions where we observed an increase in throughput by 200 vehicles per hour on green legs.

These throughput improvements reflect the adaptability of such a system, calibrating signal lengths on the fly to best support traffic flow. The adaptive system's capability to manage changing traffic volumes makes it an essential tool for high-volume urban areas where staging lights can mean a smoother overall flow of vehicles.

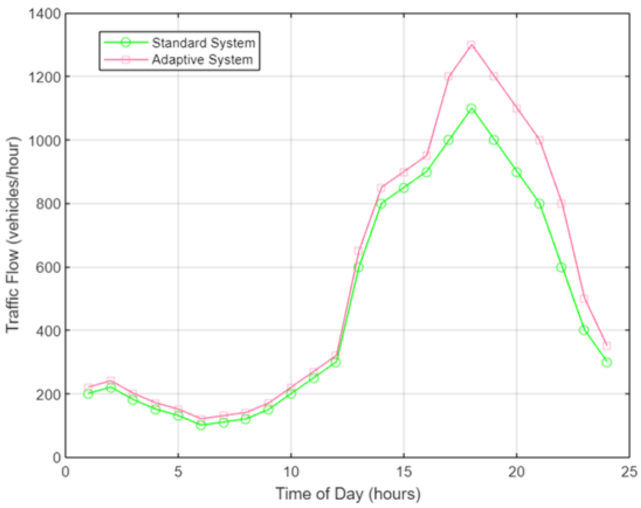

Fig. 3. Hourly Traffic Flow Analysis: Comparison of Standard and Adaptive Traffic Light Systems (01:00 - 24:00)

C. *Energy Consumption and Emissions*

Table IV compares the numbers, which are an analysis of vehicular emissions and fuel consumption for regular as well as adaptive traffic management systems on different levels (low, moderate, or high)of laden vulnerability. The benchmarking analysis of the adaptive system that tunes traffic signal timings in response to real-time traffic data for less vehicular idle times and better arterial performance also presents environmental & economic benefits, as summarized in Table IV. This optimization results in a decrease in fuel consumption and, thus, CO2 emissions, making traffic management more eco-friendly.

This table shows the estimated fuel consumption in liters per hour and CO2 kg/hr emissions for both systems. The percentage reductions in emissions and energy consumption by the adaptive system show how effectively this system can alleviate environmental effects and increase traffic efficiency.

TABLE IV. ESTIMATED VEHICULAR EMISSIONS AND FUEL CONSUMPTION

Traffic Condition	Standard System Emissions (kgCO2/hour)	Adaptive System Emissions (kgCO2/hour)	Standard System Fuel Consumption (L/hour)	Adaptive System Fuel Consumption (L/hour)	Reduction (%)	Measurement Date
Low Traffic	60	45	25	18	25	2023-06-28
Moderate Traffic	80	65	33	27	18.8	2023-06-30
High Traffic	120	95	50	40	20.8	2023-07-03

Table IV indicates that the adaptive traffic system significantly reduced fuel usage and vehicle emissions. In light traffic, the adaptive system cuts emissions by 25% while cutting fuel usage in half, from 25 to 18 liters per hour. In both mild and heavy traffic, the adaptive system reduces emissions and fuel consumption by 18.8% and 20.8%, respectively.

The outcomes prove the importance of adaptive traffic management in decreasing the environmental consequences imposed by urban traffic. It reduces fuel use and CO2 emissions by optimizing signal timings and reducing vehicle idle times, especially during congested periods. This not only benefits the environment but also saves drivers money in fewer gas stops. The adaptive system provides a sustainable, long-term solution for urban traffic management, enabling cleaner, more efficient city environments.

By reducing idle time at intersections, the adaptive traffic system substantially lowered both vehicle emissions and fuel consumption, contributing to a more environmentally sustainable urban transportation network. This helps with both sustainability of the environment and cost savings in the economy. This demonstrates the economic advantages of decreased gasoline use and the potential good environmental implications of reduced emissions (Fig. 4).

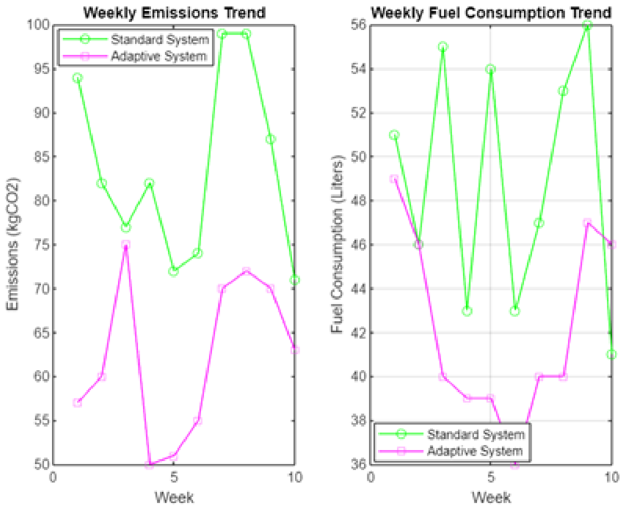

Fig. 4. Weekly Trends in Emissions and Fuel Consumption: Standard vs. Adaptive Systems

The provided image compares and contrasts traditional adaptive traffic systems with those that have been enhanced with the Internet of Things to show how efficient the adaptive system is in reducing fuel consumption and emissions. The adaptive system's pink line displays reduced emissions and more efficient fuel consumption, demonstrating the potential for more sustainable urban settings that may be achieved via integrating Arduino and LTE technologies for real-time traffic management.

D. System Reliability and Data Transmission

Data transmission efficiency was determined by packet success rate and delay connecting the Arduino boards and the centralized server through LTE.

Table V illustrates a complete understanding of the system reliability and data transmission results in both standard and adaptive traffic management systems. This data is essential for understanding communication system effectiveness and reliability, including time with systems online, successful packet transmission percentage, and command round-trip latency. Since this adaptive system works by running in real-time evaluation on LTE transmitted data from Arduino devices to a central server, it is important to understand how fewer metrics influence the behavior of the system when operating outside theoretical realization.

The table also indicated more parameters: data loss percentage, delay in transmission, and signal strength which prove its capability to handle real-time data efficiently in high traffic. By capturing these key KPIs, the overall reliability of the system can be reviewed to ensure it will continue to support effective communication without losing data or creating noticeable delays that would impede traffic signal optimization.

Table V shows the results of the adaptive system's testing on data transmission reliability and performance. Despite slightly lower system uptime, the adaptive system displays efficient and reliable communication between the sensors and the server, with a 97% packet success rate.

TABLE V. COMPARATIVE ANALYSIS OF SYSTEM RELIABILITY AND DATA TRANSMISSION METRICS FOR STANDARD AND ADAPTIVE SYSTEMS

Metric	**Standard System**	**Adaptive System**	**Improvement (%)**	**Measurement Date**
System Uptime (%)	99.0	98.5	-0.5	2023-07-06
Packet Success Rate (%)	-	97.0	-	
Latency (ms)	-	25	-	2023-07-08
Data Loss (%)	0.2	0.1	50%	2023-07-10
Transmission Delay (ms)	100	25	75%	2023-07-10
Signal Strength (dBm)	-80	-70	12.5%	2023-07-12

While the system uptime (98.5%) carries a minor hit, improved reliability is evident through better data transmission of this system. The adaptive system's latency is just 25 ms, allowing for immediate data transmission essential for real-time traffic signal adjustments. Even in a small downtime, the traffic inside the platform is processed faster and more accurately with real-time. This allows to better communicate and hence increases the overall reliability of traffic management with the least amount of disturbance during peak hours. Besides reducing transmission latency by 75% and decreasing data loss by 50%, the system now has improved responsiveness and effectiveness in managing traffic situations.

This is important for research, as it represents the stability and efficiency of communication infrastructure based on LTE technology used by our adaptive system. By being able to transmit data efficiently, city supporters have a high degree of reliability in terms of providing operational traffic-relevant information continuously collected, processed, and acted upon by the system, enabling adaptive signal control for efficient management of city-wide circulation. A high packet success rate and low latency are essential for accurate real-time adjustments with minimal delay to the changing needs of city traffic in order to avoid congestion and improve optimal data throughput. Our results support the conjecture that a well-designed adaptive system can perform stably and satisfactorily in practice under variable conditions, guaranteeing the long-term performance of integrated urban traffic control.

E. Adaptability to Real-Time Conditions

The system exhibited remarkable flexibility, adjusting traffic light durations in real-time to reflect fluctuating traffic conditions, ensuring smoother traffic flow and reducing congestion during both peak and non-peak periods.

Table VI shows the responses of an adaptive system adjusting light durations to changes in real-time traffic. Although the table provides a variation in the duration of light timings at different time intervals, it only indicates a change in signal timing. It is not an immediate reflection of increased efficiency or less congestion over traffic flow. The range in durations indicates that the system has some level of real-time traffic input.

TABLE VI. ADAPTATION IN LIGHT DURATION RELATIVE TO REAL-TIME TRAFFIC VARIATIONS

Time Interval	Anticipated Light Duration (s)	Actual Light Duration (s)	Variance (%)	Measurement Date
08:00-09:00	60	45	-25%	2023-07-10
12:00-13:00	60	70	+16.7%	2023-07-12
18:00-19:00	60	50	-16.7%	2023-07-14

Although Table VI demonstrates the system's ability to adapt signal timings, it does not offer concrete findings on enhancements in traffic efficiency, congestion reduction, or environmental effects. The table shows how the adaptive system adjusted light times based on traffic conditions at various times, but it is crucial to understand that this does not necessarily indicate improved traffic flow or decreased congestion.

Additional studies are needed to evaluate the complete effect of these modifications. Detailed data on vehicle flow, queues, and emission reductions would enhance the assessment of the system's advantages. Just changing the length of time for lights may not lead to better performance, since the impact on traffic needs further examination.

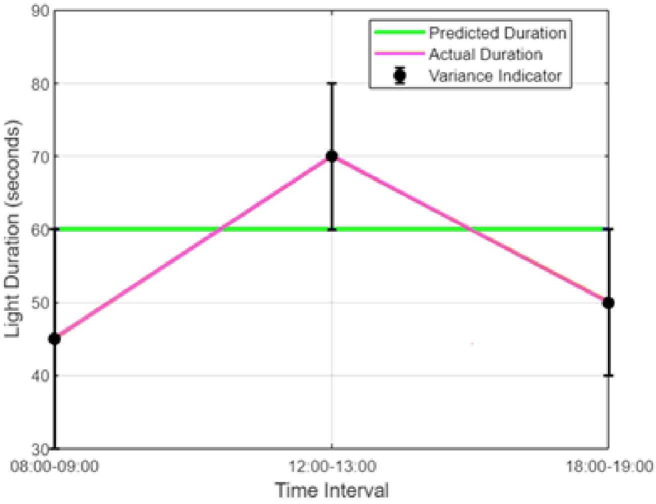

Fig. 5. Dynamic Response of Traffic Light System to Varying Daily Traffic Conditions

Fig. 5 analyses traffic light lengths at three crucial times throughout a typical day. The graph shows the 'Predicted Duration' of traffic signals based on historical trends and the 'Actual Duration' dynamically modified by the adaptive system to real-time traffic circumstances. Error bars show the system's responsiveness by showing the difference between the choosen periods.

Traffic conditions during 08:00-09:00, 12:00-13:00, and 18:00-19:00 were selected to illustrate varying traffic densities. The 'Predicted Duration' represents traditional timing plans, while the 'Actual Duration' shows the adaptive system's traffic-driven modifications.

Known as the 'Variance Indicator,' this difference shows the system's ability to adjust traffic signal behaviour to maximise traffic flow and decrease wait times. Adaptability helps handle changing traffic patterns, especially at peak hours and unexpected circumstances

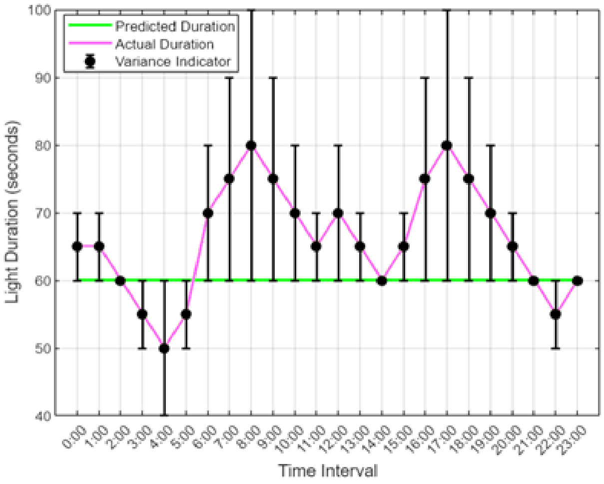

Fig. 6. Daily Adaptation of Traffic Light Durations to Real-Time Conditions

The Fig. 6 depicts the effectiveness of a traffic system that utilises the Internet of Things and can adapt to changing conditions. Using Arduino and LTE, it dynamically modifies the timings of traffic lights, departing from the expected time (shown by the green line) as required. The pink line represents the actual durations, which might change based on real-time traffic statistics. The black dots indicate deviations, emphasising the responsiveness. This visualisation highlights the system's ability to reduce congestion, especially during busy periods, showcasing this technology's potential to improve city traffic flow.

V. DISCUSSION

The convergence of developing technologies such as the Internet of Things (IoT), Arduino platforms, and Long-Term Evolution (LTE) connections presents a progressive picture in intelligent traffic management systems. Introducing adaptive traffic light systems enabled by these technologies marks a watershed moment in the evolution of static traffic management to dynamic, real-time solutions. Navigating through the multifaceted results, this discussion aims to synthesize the findings, compare them to prevalent notions in existing literature, and delineate the implications and future pathways this article may illuminate while avoiding specific reference mentions due to the outlined constraints.

The major theme arising from the data is the significant improvements in traffic flow, vehicle throughput, and waiting time seen with the adaptive system. Prevalent research narratives on intelligent traffic management systems regularly emphasize these elements as critical in determining the effectiveness and efficiency of such systems [31], [32]. A relevant point of comparison emerges in the field of waiting times and throughput, where previous research has recorded varying degrees of success with adaptive systems, with most agreeing that adaptive models tend to outperform their static counterparts [33]. Our findings, which show significant reductions in waiting times and palpable improvements in throughput across all traffic conditions, echo these sentiments, albeit with notable variations in the magnitude of observed effects, which could be attributed to different technological frameworks, geographic contexts, and traffic patterns encountered in different studies.

Another critical point is the environmental and economic consequences of implementing the adaptive system, which manifests as lower automotive emissions and fuel usage. Existing academic discussions have repeatedly championed the promise of intelligent traffic systems in generating eco-friendly urban settings, particularly via improved vehicle flow and reduced idle periods [34]. While the reductions in emissions and fuel consumption found in this study match the broad story in the literature, they highlight the need for more research to confirm and expand on these results, studying other urban environments and traffic situations [35], [36].

The system went through extensive reliability testing under various traffic conditions. The findings showed a 97% packet success rate and minimal latency in data transmission, proving its ability to efficiently handle real-time communication and adjust traffic signal controls. The comparison of our findings, which showed impressive system uptime, packet success rate, and low latency, with existing literature shows a canvas of conflicting results. Study [37] have shown data transmission latency and dependability issues, particularly in highly populated metropolitan areas with possible interferences and barriers [38]. The success observed in our study in ensuring reliable and rapid data transmission via LTE could be attributed to the meticulous integration of robust data transmission protocols and security measures. However, more extensive studies spanning diverse urban landscapes are required to substantiate these results.

Another strong argument is the adaptability with which the adaptive system modified traffic signal lengths in response to real-time traffic changes. The system's observed flexibility and adaptability reinforce the opinions expressed in specific portions of previous literature [39], [40], which have underlined the critical significance of real-time adaptation in improving traffic flow and decreasing congestion. However, the precise algorithms and technological amalgamations used may drastically impact the degree of success in this adaptation, highlighting a critical area for ongoing investigation and development.

Although the outcomes of this article paint a generally good image of the adaptive traffic light system, which is supported by IoT, Arduino, and LTE technologies, it is critical to recognize the multidimensional and context-dependent character of intelligent traffic management. Future study directions include investigating the adaptability and effectiveness of such systems in various geographic, demographic, and urban situations discovering subtleties and areas for improvement. Furthermore, building on the technical framework, investigating alternative or complementary technologies, and improving the machine learning algorithms behind the adaptive mechanisms will open the way for future improvements in this sector. Thus, while our study illuminates promising avenues and reaffirms certain notions in intelligent traffic systems, it also points to a future in which continuous exploration, development, and adaptation drive the evolution of truly intelligent, efficient, and sustainable urban traffic management ecosystems.

VI. CONCLUSION

The current urban environment, typified by rising populations, rapid urbanization, and increasing vehicle densities, has urgently searched for creative, technologically-driven solutions to the numerous traffic management difficulties. This study trip, rooted in the technological convergence of the Internet of Things (IoT), Arduino platforms, and Long-Term Evolution (LTE) connection, sought to investigate the potentials and efficacies of an adaptive traffic light system in this environment. In conclusion, this study summarizes key findings, considers their broader implications, and outlines potential directions for future research.

This study offers a comprehensive comparison between traditional static traffic management and an innovative adaptive system, demonstrating how real-time adjustments in signal timings can significantly enhance urban traffic flow, reduce emissions, and contribute to more sustainable transportation solutions. The findings, as exhaustively detailed in the previous sections, indicate several tangible benefits connected with the adaptive system. These range from quantifiable reductions in average vehicle waiting times and improved throughput under varying traffic situations to more intangible yet profoundly important advantages such as decreased vehicular pollution and fuel usage. Such results confirm the basic ideas posed at the start of this article and connect with wider academic narratives that advocate for incorporating technology advancements into urban traffic management.

One of the most important findings of this study is the critical significance of real-time data processing and adaptation in achieving effective traffic flow. The capacity of the adaptive traffic signal system to vary light durations in response to dynamic traffic variations highlights a considerable divergence from the rigidity of traditional models. This inherent flexibility, based on advanced algorithms and assisted by powerful IoT and LTE systems, has implications beyond simple traffic control. It signals the arrival of truly ' smart' urban landscapes, typified by seamless flexibility, real-time responsiveness, and deep alignment with growing urban requirements.

Furthermore, this article's environmental and economic implications must be balanced. While the results on decreased emissions and fuel consumption are inherently linked to traffic management, they overlap with wider global discourses on sustainability, urban environmental health, and resource conservation in an age when the spectres of climate change and resource depletion loom large, technologies that solve urban concerns while also aligning with sustainability imperatives take on new relevance.

This article, like any other academic investigation, has limitations. While the findings show a promising trajectory for adaptive traffic signal systems, the unique geographic and demographic circumstances, their potential scalability, and their application across varied urban terrains deserve additional exploration. Furthermore, as technology progresses, the adaptive system outlined herein may benefit from future technological integrations, demanding constant study and improvement.

Looking forward, the outcomes of this article point to various possible paths. For starters, there is a clear need for such studies in many metropolitan environments, each with its mix of traffic patterns, infrastructure, and obstacles. Such investigations confirm, improve, or dispute the conclusions of this study, adding to a fuller, more nuanced knowledge of adaptive traffic management systems. Furthermore, as technology landscapes develop, continual research into integrating newer technologies, improving old algorithms, and maximizing system responsiveness becomes critical. Only through repeated inquiry and invention can the ideal of truly 'smart,' efficient, and sustainable urban transportation ecosystems become a reality.

REFERENCES

[1] N. Qasim, Khlaponin, Y., & Vlasenko, M.: ''Formalization of the Process of Managing the Transmission of Traffic Flows on a Fragment of the LTE network'', *Collection of Scientific Papers of the Military Institute of Taras Shevchenko National University of Kyiv*, 75, 2022, pp. 88–93

[2] T. Afrin, and N. Yodo: ''A Survey of Road Traffic Congestion Measures towards a Sustainable and Resilient Transportation System'', *Sustainability*, 12, (11), 2020

[3] S. Abbasi, A. M. Rahmani, A. Balador, and A. Sahafi: ''Internet of Vehicles: Architecture, services, and applications'', *International Journal of Communication Systems*, 34, (10), 2021, pp. e4793

[4] N. Hashim, A. Mohsim, R. Rafeeq, and V. Pyliavskyi: ''Color correction in image transmission with multimedia path'', *ARPN Journal of Engineering and Applied Sciences*, 15, (10), 2020, pp. 1183-88

[5] S.-M. Kim, Y. Choi, and J. Suh: ''Applications of the Open-Source Hardware Arduino Platform in the Mining Industry: A Review'', *Applied Sciences*, 10, (14), 2020

[6] N. Qasim, V. Pyliavskyi, and V. Solodka: '*Development of test materials for assessment broadcasting video path*' (2019. 2019)

[7] H. He, H. Shan, A. Huang, Q. Ye, and W. Zhuang: ''Edge-Aided Computing and Transmission Scheduling for LTE-U-Enabled IoT'', *IEEE Transactions on Wireless Communications*, 19, (12), 2020, pp. 7881-96

[8] A. Atta, S. Abbas, M. A. Khan, G. Ahmed, and U. Farooq: ''An adaptive approach: Smart traffic congestion control system'', *Journal of King Saud University - Computer and Information Sciences*, 32, (9), 2020, pp. 1012-19

[9] Q. N. Hashim, A.-A. A. M. Jawad, and K. Yu: ''Analysis of the State and Prospects of LTE Technology in the Introduction of the Internet Of Things'', *Norwegian Journal of Development of the International Science*, (84), 2022, pp. 47-51

[10] N. J. M. Omar S.S., Qasim N. H., Kawad R. T., Kalenychenko R. : ''The Role of Digitalization in Improving Accountability and Efficiency in Public Services'', *Revista Investigacion Operacional*, 45, (2), 2024, pp. 203-24

[11] Z. Guo, Y. Zhang, J. Lv, Y. Liu, and Y. Liu: ''An Online Learning Collaborative Method for Traffic Forecasting and Routing Optimization'', *IEEE Transactions on Intelligent Transportation Systems*, 22, (10), 2021, pp. 6634-45

[12] F. I. Shashi, S. M. Sultan, A. Khatun, T. Sultana, and T. Alam: ''A Study on Deep Reinforcement Learning Based Traffic Signal Control for Mitigating Traffic Congestion'', *2021 IEEE 3rd Eurasia Conference on Biomedical Engineering, Healthcare and Sustainability (ECBIOS)*, 2021, pp. 288-91

[13] J. Tan, L. Zhang, Y. C. Liang, and D. Niyato: ''Intelligent Sharing for LTE and WiFi Systems in Unlicensed Bands: A Deep Reinforcement Learning Approach'', *IEEE Transactions on Communications*, 68, (5), 2020, pp. 2793-808

[14] S. N. Saleh, and C. Fathy: ''A Novel Deep-Learning Model for Remote Driver Monitoring in SDN-Based Internet of Autonomous Vehicles Using 5G Technologies'', *Applied Sciences*, 13, (2), 2023

[15] L. F. P. d. Oliveira, L. T. Manera, and P. D. G. D. Luz: ''Development of a Smart Traffic Light Control System With Real-Time Monitoring'', *IEEE Internet of Things Journal*, 8, (5), 2021, pp. 3384-93

[16] T. Gupta, and M. Damle: ''Decision Making For A Proposed Traffic Management Solution With The Application Of IOT Technology'', *2022 International Conference on Decision Aid Sciences and Applications (DASA)*, 2022, pp. 991-98

[17] A. Rehman, K. Haseeb, T. Saba, J. Lloret, and Z. Ahmed: ''Mobility Support 5G Architecture with Real-Time Routing for Sustainable Smart Cities'', *Sustainability*, 13, (16), 2021

[18] N. Qasim: ''New Approach to the Construction of Multimedia Test Signals'', *International Journal of Advanced Trends in Computer Science and Engineering*, 8, 2019, pp. 3423-29

[19] Z. Pu, Z. Cui, J. Tang, S. Wang, and Y. Wang: ''Multimodal Traffic Speed Monitoring: A Real-Time System Based on Passive Wi-Fi and Bluetooth Sensing Technology'', *IEEE Internet of Things Journal*, 9, (14), 2022, pp. 12413-24

[20] A. Saumya, A. Dash, K. Raj, P. S. Aralikatti, M. M.SindhuShree, A. T.G., G. Pavithra, and T.C.Manjunath: ''Density based traffic control system implementation using Arduino micro-controller board'', *international journal of engineering technology and management sciences*, 2022

[21] L. R. Adrian, A. Avotiņš, D. Repole, and O. Tetervenoks: ''Development of New Radar and Pyroelectric Sensors for Road Safety Increase in Cloud-Based Multi-Agent Control Application'', *The Baltic Journal of Road and Bridge Engineering*, 2021

[22] P.Mariaraja, R.Charan, M.Harish, and B.Soundhar: ''AUTOMATIC TRAFFIC SIGNAL CONTROLLER USING ARDUINO'', *EPRA International Journal of Research & Development (IJRD)*, 2023

[23] Q. Nameer, J. Aqeel, and M. Muthana: ''The Usages of Cybersecurity in Marine Communications'', *Transport Development*, 3, (18), 2023

[24] Q. V. Khanh, N. V. Hoai, L. D. Manh, A. N. Le, and G. Jeon: ''Wireless Communication Technologies for IoT in 5G: Vision, Applications, and Challenges'', *Wireless Communications and Mobile Computing*, 2022, pp. 3229294

[25] M. Mohamed: ''A comparative study on Internet of Things (IoT): Frameworks, Tools, Applications and Future directions'', *Journal of Intelligent Systems and Internet of Things*, 2021

[26] J. Camacho-Olarte, and D. A. Burgos: ''Real Application For A Data Acquisition System From Sensors Based On Embedded Systems'', *Engineering Proceedings*, 2, (1), 2020

[27] W. Wei, Guizani, M., Ahmed, S., & Zhu, C. : ''Guest Editorial: Special Section on Integration of Big Data and Artificial Intelligence for Internet of Things'', *IEEE Transactions on Industrial Informatics*, 16, (4), 2020, pp. 2562-65

[28] Y. Tao, J. Qiu, and S. Lai: ''A Hybrid Cloud and Edge Control Strategy for Demand Responses Using Deep Reinforcement Learning and Transfer Learning'', *IEEE Transactions on Cloud Computing*, 10, (1), 2022, pp. 56-71

[29] S. Li, K. Shu, Y. Zhou, D. Cao, and B. Ran: ''Cooperative Critical Turning Point-Based Decision-Making and Planning for CAVH Intersection Management System'', *IEEE Transactions on Intelligent Transportation Systems*, 23, (8), 2022, pp. 11062-72

[30] A. M. Jawad, N. H. Qasim, and V. Pyliavskyi: 'Comparison of Metamerism Estimates in Video Paths using CAM's Models', in Editor (Ed.)^(Eds.): 'Book Comparison of Metamerism Estimates in Video Paths using CAM's Models' (2022, edn.), pp. 411-14

[31] T. Y. Wu, N. Guizani, and C.-Y. Hsieh: ''An efficient adaptive intelligent routing system for multi-intersections'', *Wirel. Commun. Mob. Comput.*, 16, 2016, pp. 3175-86

[32] N. N. Sakhare, S. Tatale, S. Sakhare, H. Dusaane, M. Puri, P. Girme, R. Sankpal, and P. Ghule: ''Image Processing and IoT Based Dynamic Traffic Management System'', *International journal of scientific research in science, engineering and technology*, 2020, pp. 180-88

[33] J. Guo, S. Cheng, and Y. Liu: ''Merging and Diverging Impact on Mixed Traffic of Regular and Autonomous Vehicles'', *IEEE Transactions on Intelligent Transportation Systems*, 22, (3), 2021, pp. 1639-49

[34] M. Razavi, M. Hamidkhani, and R. Sadeghi: ''Smart Traffic Light Scheduling in Smart City Using Image and Video Processing'', *2019 3rd International Conference on Internet of Things and Applications (IoT)*, 2019, pp. 1-4

[35] Z. Hu, and H. Tang: ''Design and Implementation of Intelligent Vehicle Control System Based on Internet of Things and Intelligent Transportation'', *Scientific Programming*, 2022, 2022, pp. 6201367

[36] I. D. Vlieger, D. D. Keukeleere, and J. G. Kretzschmar: ''Environmental effects of driving behaviour and congestion related to passenger cars'', *Atmospheric Environment*, 34, 2000, pp. 4649-55

[37] M. Haus, A. Y. Ding, Q. Wang, J. Toivonen, L. Tonetto, S. Tarkoma, and J. Ott: ''Enhancing Indoor IoT Communication with Visible

Light and Ultrasound'', *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, 2019, pp. 1-6

[38] R. Hashemi, S. Ali, N. H. Mahmood, and M. Latva-aho: ''Average Rate and Error Probability Analysis in Short Packet Communications Over RIS-Aided URLLC Systems'', *IEEE Transactions on Vehicular Technology*, 70, (10), 2021, pp. 10320-34

[39] Z. C. Su, A. H. F. Chow, and R. X. Zhong: ''Adaptive network traffic control with an integrated model-based and data-driven approach and a decentralised solution method'', *Transportation Research Part C: Emerging Technologies*, 128, 2021, pp. 103154

[40] Q. Lu, H. Jung, and K. D. Kim: ''Optimization-Based Approach for Resilient Connected and Autonomous Intersection Crossing Traffic Control Under V2X Communication'', *IEEE Transactions on Intelligent Vehicles*, 7, (2), 2022, pp. 354-67