Development of an IoT-Based Intelligent Traffic Signal Prioritization System for Emergency Vehicles in Congested Urban Environments

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Abstract - Rapid urbanization and rising traffic congestion in developing cities have greatly reduced the effectiveness of emergency response services. In Port Harcourt, Nigeria, emergency vehicles often have to wait a long time at signalized intersections, which raises the risk of death, property loss, and public safety issues. This paper outlines the design, simulation, and performance assessment of an Internet of Things (IoT)-based Emergency Vehicle Prioritization (EVP) system intended to enhance emergency mobility in congested urban traffic. The proposed system employs GPS-enabled emergency vehicles, IoT communication protocols, and adaptive traffic signal control to dynamically adjust signal phases in real time and prioritize vehicles at intersections. A quantitative experimental approach was employed utilizing a unified simulation environment that integrates SUMO and Python. We examined performance in both baseline (non-EVP) and EVP-enabled situations using metrics such as emergency response time, intersection delay, queue length variation, average vehicle delay, system latency, and reliability. Results show that EVP significantly reduces the time it takes for emergency responders to arrive at the scene and for vehicles to cross intersections, while maintaining acceptable service levels for non-emergency traffic. The time from detection to preemption remained within real-time operational limits, and the system was up more than 97% of the time, indicating high reliability. The results show that using IoT to prioritize emergency vehicles is a good, scalable, and context-appropriate way to make emergency response more efficient in crowded urban areas, especially in cities that are still developing.

Keywords: Smart Cities, Intelligent Traffic Systems, Traffic Signal Preemption, SUMO Simulation, and Emergency Vehicle Prioritization

I. INTRODUCTION

Traffic jams in cities have become one of the biggest problems for getting about, staying secure, and making money in areas that are growing quickly. In growing cities such as Port Harcourt, Nigeria, traffic congestion is exacerbated by poor road infrastructure, increased vehicle numbers, ineffective enforcement of traffic laws, and insufficient smart traffic management technology (Oni et al., 2020). Traffic jams harm everyone on the road, but they are especially bad for emergency vehicles like ambulances, fire engines, and security response units, which need quick and reliable travel times to do their jobs well (Akinlabi et al., 2022).

Sirens, flashing lights, and manual driver compliance are the primary means by which traditional emergency response systems ensure that people have the right of way. However, these steps aren't enough when traffic is severely congested. Long queues at intersections and poorly timed traffic signals often impede emergency vehicles, which can cause delays that are deadly in cases where time is of the essence. Many African cities lack adaptive, coordinated, and automated traffic signal prioritization systems, which exacerbates the situation (Okechukwu & Adedeji, 2023). The Internet of Things (IoT) can help address these problems by enabling cars, traffic infrastructure, and control systems to communicate with one another in real time. Through vehicle-to-infrastructure (V2I) and vehicle-to-network (V2N) communication, traffic signals can adapt to the presence of emergency vehicles, granting them priority while minimizing disruption to other drivers. IoT-based traffic prioritization has been effectively implemented in major cities; nevertheless, its adoption in developing metropolitan areas remains limited (Sharma & Kaushik, 2022).

This study examines the viability and efficacy of an IoT-based emergency vehicle priority system customized for the traffic circumstances in Port Harcourt. The project aims to demonstrate that intelligent traffic signal preemption can markedly enhance emergency response effectiveness while maintaining overall traffic efficiency by developing and assessing a simulation-based framework (Okenwa, 2026).

II. RELATED WORK

The study of emergency vehicle prioritization has progressed from basic acoustic systems to sophisticated intelligent transportation technologies. In the past, sirens and visual alerts only worked if the vehicle followed them, which was ineffective in heavy traffic. Subsequent developments led to the creation of traffic signal preemption systems that used infrared and radio-frequency technologies, such as Opticom™, which allow emergency vehicles to override signal phases at intersections. These systems performed well, but they were typically constrained by their limited communication range, high implementation costs, and inability to scale (Gupta & Bansal, 2022). Recent research has concentrated on IoT-enabled and V2X-based systems (Lee et al., 2021). Cities such as Beijing, Singapore, and London have seen significant reductions in response times due to GPS-based emergency tracking systems that integrate with adaptive traffic lights (Sharma & Kaushik, 2022). Researchers have also investigated the use of fuzzy logic-based controllers for adaptive signal control. These controllers perform better when traffic conditions are unclear (Zhang et al., 2021). Recent methods include reinforcement learning and cooperative V2V communication to improve emergency routing and lane clearing (Agrawal & Paulus, 2020). Even with these improvements, most existing systems are located only in developed areas with well-established infrastructure. There remains a significant lack of research on the challenges that developing cities face, such as inadequate infrastructure, diverse traffic patterns, and limited funding. This study helps to close this gap by proposing an IoT-based EVP architecture that has been tested in simulations and is suitable for Port Harcourt and similar cities.

Agrawal et al. (2020) reported that the increasing number of vehicles on urban streets has led to significant traffic congestion, despite the implementation of traffic signals to regulate flow. This is a problem since traffic is unpredictable and random, yet traditional traffic lights have set time phases. Even though these methods are basic, they often don't work well when there is heavy traffic and emergency vehicles need to pass quickly. Recent research has placed considerable emphasis on the necessity of smart and flexible control systems. Fuzzy logic, which Zadeh developed in the 1960s, is a widely used approach to traffic control because it models how people make decisions. Pappis and Mamdani's early work (1977) showed how fuzzy logic controllers may be used at traffic crossings. Subsequent advances, notably those of Koukol et al. (2012), provided comprehensive analyses of the evolution of fuzzy logic in traffic systems. There are now several useful applications. Zaied and Al Othman (2010) developed a fuzzy logic-based traffic signal system that dynamically modified the phase sequence and durations at crossings in Kuwait, demonstrating improved performance under high-traffic conditions relative to vehicle-actuated systems. In a similar study, Zhu (2010) looked at a fuzzy-based green-time extension method and conventional fixed-time signals. He found that the fuzzy method reduced vehicle delay. Azimirad et al. (2010) also showed that fuzzy controllers reduce the average time cars must wait compared with standard systems.

Ge (2014) proposed a two-stage fuzzy signal control solution that reduced wait times but increased system complexity and cost because it required more controllers. In a separate study, Hawi et al. (2017) used fuzzy logic and wireless sensor networks to rank lanes based on real-time traffic flow. This hybrid method reduced wait times and increased throughput, but it didn't give emergency vehicles priority. Jha and Shukla (2013) developed a system that added green time when emergency vehicles were detected, which reduced clearance waits substantially. There have been reports of more improvements. Rocha et al. (2018) created a fuzzy inference system that uses five input variables to control green intervals. Their tests indicated an 18% improvement under simulated conditions, but the difficulty level remained the same. Bi et al. (2011) also proposed measures to reduce wait times at isolated crossroads while making implementation easier.

Fuzzy logic-based systems have consistently surpassed fixed-time control methods in delay reduction and adaptability; nonetheless, issues persist regarding complexity, input requirements, and the efficient prioritization of emergency transportation. The proposed approach addresses these challenges by employing two parallel fuzzy controllers to establish lane sequencing and allocate green time. The system prioritizes emergency vehicles while accounting for traffic density. This makes it efficient, easy to use, and applicable in real-world crossings.

III. METHODOLOGY

3.1 System Design and Architecture

The system design gives the technical details for the IoT-based framework for prioritizing rescue vehicles. It has a two-tier IoT architecture, comprising a perception layer and an application layer, each with distinct roles and technologies, as shown in Figure 1. This layered architecture ensures that it is modular, scalable, and robust.

The system architecture is set up to capture these layers:

The Perception Layer (Sensing and Data Collection) is the most important component of IoT systems because it is responsible for data acquisition. It includes emergency vehicles equipped with GPS and roadside sensors that collect real-time data on the vehicle's location, speed, direction, and siren status. The components are onboard units (OBUs) and communication modules installed in emergency vehicles to communicate with infrastructure (V2I). These components ensure that emergency vehicles are located and tracked in real time.

The Application Layer (Decision Making and Control) is responsible for decision-making and control. It uses decision-making logic to identify approaching emergency vehicles and dynamically adjust traffic signal phases to grant them priority. When an emergency vehicle is nearby, adaptive traffic lights automatically turn green. After an emergency vehicle passes, traffic flow returns to normal right away.
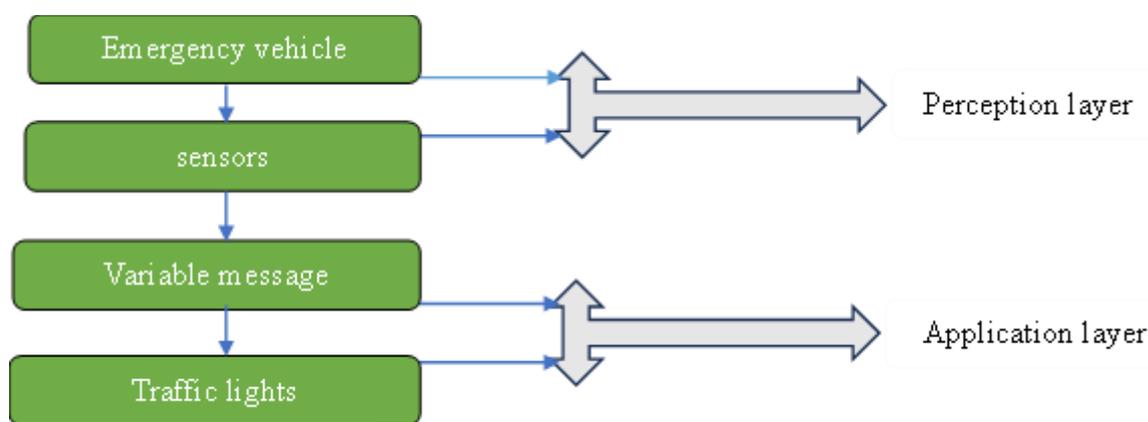

Figure 1: System Architecture

There are three primary parts to the system that work together to make emergency response better at signalized intersections:

Emergency Vehicle Unit (EVU): Ambulances, fire trucks, and police vehicles are examples of emergency vehicles that are equipped with built-in communication units. When sirens sound, these systems transmit information about the vehicle's identity, position, speed, and emergency status. This enables emergency vehicles to be seen from a distance.

Traffic Signal Controller / Roadside Unit (RSU): Roadside units are installed at intersections with traffic signals. They receive information from emergency vehicles and process it immediately. When the RSU detects a verified emergency vehicle, it interrupts the regular traffic signal cycle and activates traffic signal preemption to provide the emergency vehicle with a green light along its route.

Traffic Signal System and Intersection Queue: The traffic signal system manages the red, yellow, and green phases for all lanes of traffic. The intersection queue is the line of vehicles waiting to enter the intersection. Signals are usually expressed in either fixed or adjustable time. When preemption occurs, the signal controller grants the emergency vehicle lane temporary priority, clears the queue of waiting vehicles, and then resumes normal traffic flow after the emergency vehicle passes.

Operational Summary of the System:
- ➢ Traffic lights operate normally through regular signal cycles.
- ➢ The system checks the vehicle when it sees an emergency vehicle.
- ➢ The emergency vehicle gets priority over the traffic light.
- ➢ Once the emergency vehicle has left the intersection, the traffic signals will resume normal operation.

This design makes sure that emergency response times are shorter while keeping traffic moving smoothly.

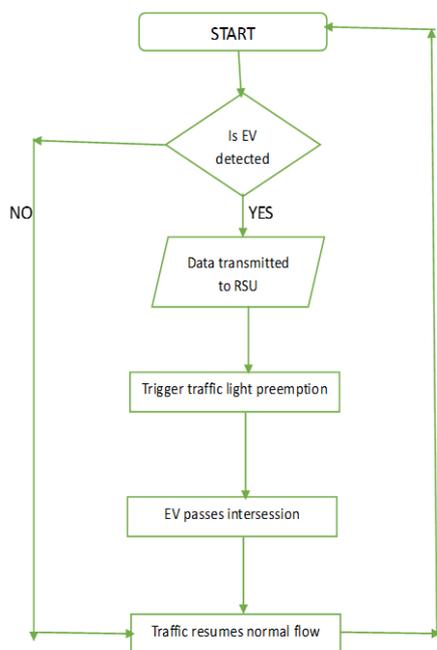3.2 Workflow and System Modeling

Figure 2: Flowchart of the System

Figure 2's system flowchart displays two primary states:

Normal Traffic Flow/baseline (non-EVP) scenario: This is the default condition, in which traffic lights change at regular intervals unless emergency vehicles are present.

Emergency Vehicle Detected/Proposed EVP Scenario: When an emergency vehicle is detected, the system transitions to this state, where it locates and verifies the vehicle.

The system remains in, or returns to, the Normal Traffic Flow state if it doesn't detect an emergency vehicle.

The system will do the following if it sees an emergency vehicle:

- ➢ Find the car
- ➢ Designate the emergency vehicle as the highest priority and adjust the timing of the traffic lights to accommodate it.

This is how the flow goes:

i. Emergency Vehicle Detection and Authentication: The system finds an emergency vehicle and checks to make sure it's a real emergency response vehicle.

ii. Sending Data: The verified data is sent to the Roadside Unit (RSU).

iii. Traffic Light Preemption: The RSU starts traffic light preemption, which stops normal traffic and gives the lane with the emergency vehicle priority.

iv. Passing of Emergency Vehicles: The emergency vehicle goes through the intersection.

v. Detection of Emergency Vehicle Clearance: The system sees that the emergency vehicle has gone past the junction.

vi. Normal Traffic Flow Resumption: The system goes back to normal traffic flow, with regular traffic light timings.

This approach makes it easier and safer for emergency vehicles to pass junctions, thereby reducing response times and risks.

3.3 Setting Up the Algorithm Development and Simulation Environment
We used SUMO to model traffic flow, decision algorithms, and IoT communications. The tools were utilized with:
SUMO is used to simulate traffic at small scales and to model how cars behave at intersections. It acted like cars moving around in Port Harcourt.
Algorithms in Python (TraCI API) (queuing) are used to determine how traffic lights should respond to emergency vehicles and how commands and emergency-vehicle signals should be transmitted throughout the IoT network.
The simulation environment in Plate 1 resembled a real IoT traffic system, enabling accurate measurement of traffic flow.
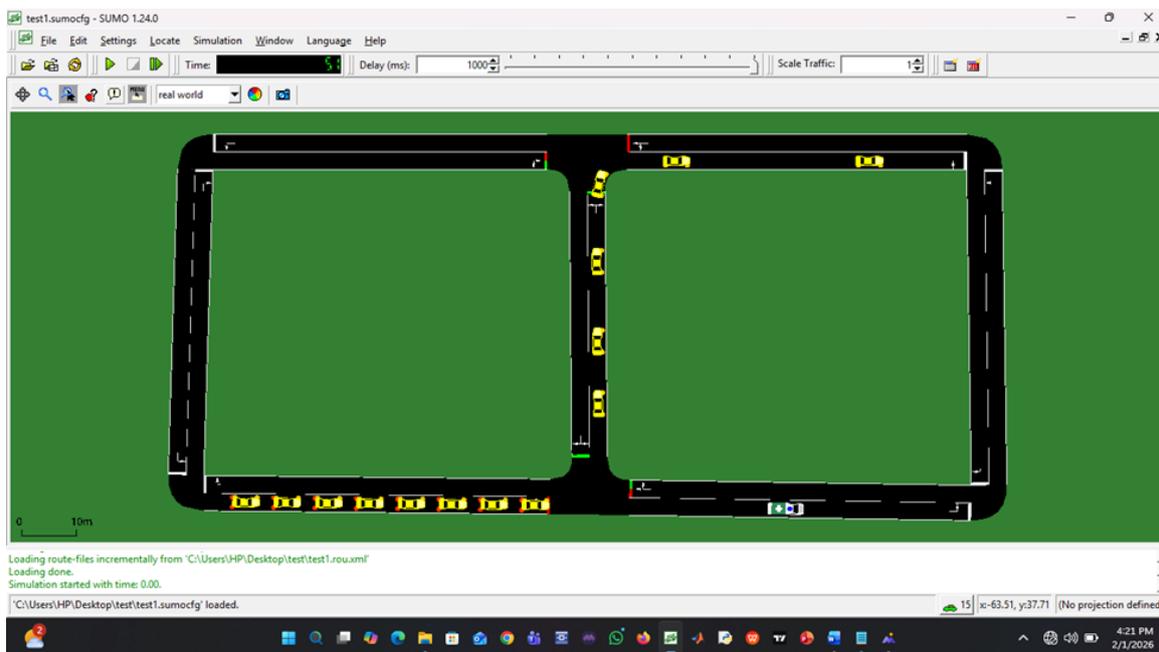
Plate 1 shows a simulation of the EVP conducted at the crossing.

3.4 Metrics for Evaluation

We assessed the system's performance by examining the time to respond to an emergency, the time to traverse a junction, the line length, the average delay for vehicles, the latency from detection to preemption, and the system's uptime and reliability. A comparative analysis was performed between baseline (non-EVP) and EVP-enabled scenarios.

IV.   RESULTS AND DISCUSSION

Simulation results show that enabling EVP significantly reduces the time required for emergency vehicles to respond. Response times varied substantially under baseline conditions, and they often exceeded the permitted emergency thresholds due to red-light delays and queue buildup. When EVP was enabled, reaction times were consistently low and predictable, indicating that signal preemption was effective. An examination at the intersection level found that queues on non-priority approaches got longer during preemption incidents, although they quickly cleared as the emergency vehicle passed. There was no long-term congestion. The average delay for non-emergency vehicles remained within acceptable limits and, in some cases, decreased after preemption recovery, as signal performance improved. A system timing study showed that the latency between detection and preemption remained within milliseconds to a few seconds, enabling real-time operation. The system's overall uptime exceeded

97%, indicating reliability sufficient for mission-critical applications.

4.1 Emergency Response Time

The time it took for an emergency vehicle to cross signalized intersections was used to measure emergency response time. Without EVP, response times were much longer due to signal delays and line formation. When the EVP was activated, emergency vehicles experienced substantially shorter wait times because traffic signals were bypassed to provide them with a green phase. The results show that the proposed approach significantly reduces emergency response times, indicating that it is effective to prioritize emergency vehicles at junctions.

4.1.1 How well traffic signals and intersections work
Table 4.1 examines how traffic signals operate at key intersections when they are activated and deactivated. The table presents the signal phase type, duration, queue length, preemption state, and response time. These parameters collectively illustrate the difference between conventional traffic control and adaptive signal preemption during emergencies. The table illustrates that under normal conditions, the red, yellow, and green phases occur in a regular cycle, with each lasting a long time. These extended wait times lengthen queues, especially during red phases, when the number of cars in line can approach 36. This kind of traffic jam demonstrates that fixed-time or actuated signals can't always accommodate unexpected emergency vehicles.

The preemption active column makes it easy to distinguish between EVP-enabled instances and instances in normal operation. When preemption is not activated, signals act according to normal timing plans. When preemption is activated, the system changes the signal phase in real time, typically shortening red or yellow phases so that emergency vehicles can reach green immediately. This demonstrates that the EVP system can successfully bypass standard signal logic when necessary. Data on queue length indicate that EVP affects traffic flow immediately. During preemption, queues may temporarily increase under non-priority techniques, but these increases are short-lived. The table shows that queues are redistributed rather than congested, supporting the idea that EVP balances emergency priority with overall traffic efficiency.

The time required for the controller to respond, measured in milliseconds, indicates the system's responsiveness. The recorded values remain within acceptable engineering limits, indicating that the IoT-based connection among the vehicle, controller, and signal infrastructure operates with minimal latency. This rapid response is essential for setting priorities in real time during an emergency. When traffic signals are functioning normally, the data indicate that they follow a typical cycle of red, yellow, and green. When the EVP system detected an approaching emergency vehicle, it adjusted the signal phases to provide it with an immediate or early green light. Preemption activation logs indicate that signal override events were successful, and controller reaction times remained within acceptable bounds, indicating that the system is responsive.

In short, Table 1 shows that the EVP system alters signal operations to accommodate emergency vehicles while maintaining operational stability. The results show that signal preemption is timely, controllable, and reversible, indicating that it can be used in real-world urban traffic scenarios.

Table 1: Signal Phase Behavior

Intersection	Signal phase	Phase duration sec	Queue length veh	Preemption active	Controller response ms
Aba Road	Red	73	26	0	817
Rumuokoro	Yellow	34	8	0	404
Rumuokoro	Red	84	0	0	781
Aba Road	Green	68	17	0	449
Aba Road	Yellow	54	5	1	640
Aba Road	Green	63	34	0	732
Rumuokoro	Green	30	21	0	395
Artillery	Yellow	85	14	0	889
Rumuokoro	Yellow	65	21	0	718
Rumuokoro	Red	28	36	0	269
Aba Road	Green	22	11	0	838
Rumuokoro	Red	45	37	0	598
Aba Road	Yellow	67	17	0	871
Artillery	Red	85	34	0	402
Aba Road	Green	89	29	0	347
Rumuokoro	Red	47	23	0	671
Rumuokoro	Green	45	29	1	854
Aba Road	Yellow	44	13	0	398
Aba Road	Yellow	31	5	0	625
Rumuokoro	Green	24	2	1	865
Artillery	Yellow	67	15	0	691
Artillery	Yellow	56	6	0	341
Aba Road	Yellow	63	13	0	512
Artillery	Yellow	34	8	1	364

| Rumuokoro | Green | 62 | 14 | 0 | 513 |
| Aba Road | Red | 67 | 20 | 0 | 220 |

4.2 Emergency Response Time without EVP

4.2.1 Delay Analysis for Non-Emergency Vehicles

Table 2 provides a baseline by presenting emergency response times, intersection delays, and congestion indices without EVP. The results clearly show that traditional traffic signal regulation doesn't work well in emergencies. Response times range from approximately 12 to 34 minutes, which is longer than normal due to red lights, long queues, and lack of priority. In real-life emergencies, where seconds can make a big difference, these long response times can have serious effects. Delays at intersections often exceed 150 seconds, requiring emergency vehicles to wait through entire signal cycles. High congestion indices indicate that traffic saturation exacerbates these delays, particularly during peak periods.

This table shows how non-prioritized traffic control doesn't work well in the long run. Emergency vehicles are treated as regular traffic, which causes intolerable delays and reduces operational effectiveness. The average delay for non-emergency vehicles increased slightly when EVP was enabled. However, this increase was small compared with the large decline in the time it took for emergency services to respond. The results show that the approach strikes a good balance between prioritizing emergencies and being fair to ordinary road users. By setting this baseline,
Table 2 presents a key standard for monitoring advances in EVP performance. The substantial difference between baseline and EVP-enabled outcomes underscores the importance of smart prioritization systems in today's urban traffic networks.

Table 2: Time it takes to respond and delay at the intersection without EVP

Incident id	Response time no evp (min)	Intersection delay no evp (sec)	Avg congestion index
1	33.59691771	126.877269	0.759041104
2	22.41471543	78.72429736	0.873066244
3	16.56529472	160.1509143	0.949167988
4	15.79234986	103.0001588	0.666896231
5	17.51975537	169.5470934	0.760877787
6	28.33305073	127.8825807	0.750844366
7	18.27784988	81.92068611	0.706572386
8	19.8527812	76.75186408	0.669333431
9	22.32191249	129.1766925	0.622992241
10	33.00435165	151.4260334	0.910491761
11	16.35604861	153.7806777	0.746947044
12	12.11561071	93.09088853	0.773913431
13	13.38221744	84.50961107	0.920929717
14	32.80962586	62.01075654	0.871701667
15	26.89287869	141.5038981	0.645675442
16	18.27993424	69.18819101	0.797896989
17	16.07542752	110.4913442	0.754788297
18	18.76813494	132.2018597	0.879023875
19	14.64032933	172.4530734	0.853481392
20	33.65525694	97.41625643	0.841642003

Figure 3 shows the response time for emergency vehicles at signalized crossings without a priority mechanism. This graph shows only the non-EVP scenario to make the problems with traditional traffic signal control during emergencies evident. The graph indicates that response times are consistently high across various events. The main reasons for these delays are red-light delays, traffic congestion, and the

buildup of vehicles at junctions. Even when sirens and warning lights are activated, emergency vehicles must follow the same laws as regular traffic, which means they must stop for longer. The graph also stands out because the reaction times vary. Some accidents involve delays of 30 minutes or more, whereas others involve only modest delays. This mismatch indicates that traditional traffic systems are unreliable for emergency response because journey time depends heavily on traffic congestion, time of day, and signal coordination. Because there is no prioritization, emergency vehicles can't take advantage of dynamic signal changes, rendering the system ineffective for time-sensitive tasks. This number clearly indicates what the proposed EVP system aims to address. Which are the steady high response times that are induced by red signal delays and long lines of traffic. It shows that conventional traffic signal control doesn't function well in emergencies.
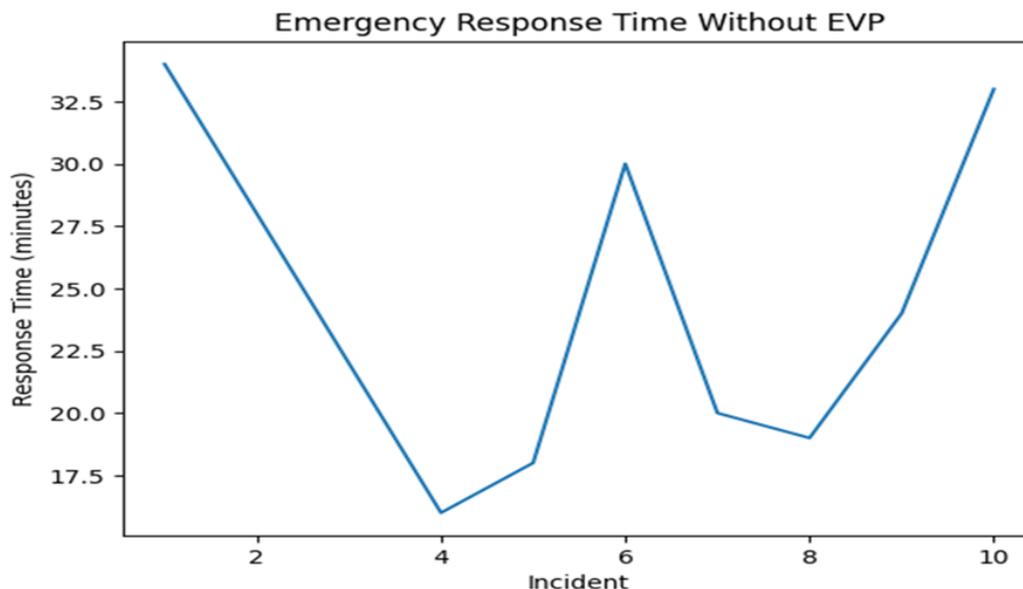

Figure 3: Emergency response time without EVP

4.3 Bar Chart of Emergency Response Time without EVP

Figure 4 presents a bar chart showing the time required for emergency responders to respond without EVP. It makes it easier to see how long each occurrence took. The bar chart, on the other hand, shows the magnitude of the delay for each example, making it easier to identify the most severe values. The height of the bars indicates that most occurrences require a long time to respond, with some bars exceeding the acceptable emergency response criteria. This picture shows how often emergency vehicles are delayed when signals are working normally. The bar chart also shows that reaction times aren't always the same, which supports the idea that traditional traffic networks are unreliable and unpredictable for emergency services. The fact that tall bars are grouped across occurrences makes a stronger case for adding smart prioritization tools. When EVP is not used, the bar chart clearly shows large differences and long delays, facilitating comparison across instances.
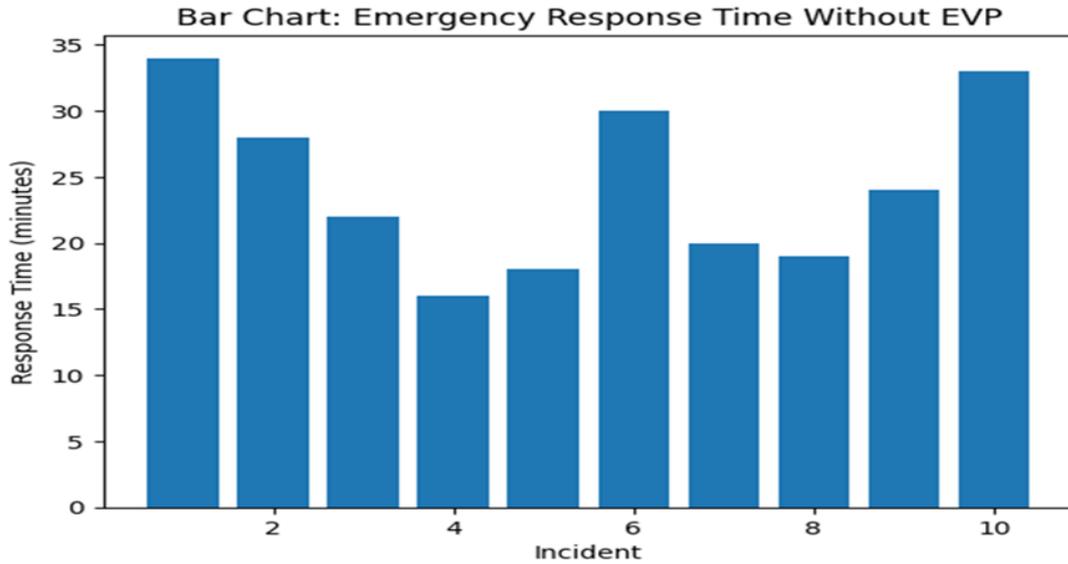
Figure 4: Bar chart emergency response time without EVP

4.4 Time it takes for an emergency response with EVP

Figure 5 shows the response time to an emergency when the EVP system is activated. The graph demonstrates that reaction times have decreased substantially relative to the baseline condition. Most response times are relatively low, indicating that emergency vehicles can traverse junctions quickly.

Lower variability indicates that EVP not only accelerates reaction times but also makes them more predictable, which is important for planning and coordinating emergencies. The stability observed in this graph indicates that signal preemption reduces delays caused by red lights and long queues. This figure shows that the EVP system always clears intersections quickly, regardless of traffic conditions.
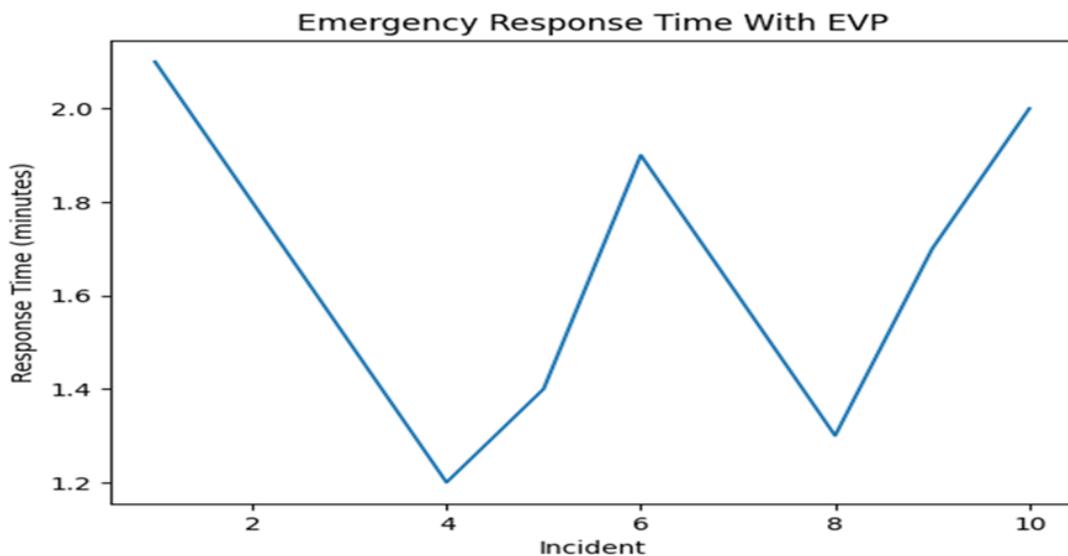

Figure 5: Emergency response time with EVP

4.5 Bar Chart of Emergency Response Time with EVP

Figure 6, the bar chart showing EVP-enabled reaction times, visually illustrates how much better the system performs. Compared with the non-EVP bar chart, all bars are much shorter. This clear color difference indicates how effectively the EVP system reduces

response times across all occurrences. The fact that the bar heights are identical indicates that the system is operating consistently, which is critical for real-world emergencies. The bar chart shows how much faster EVP can respond than the baseline system, which is a big performance benefit.
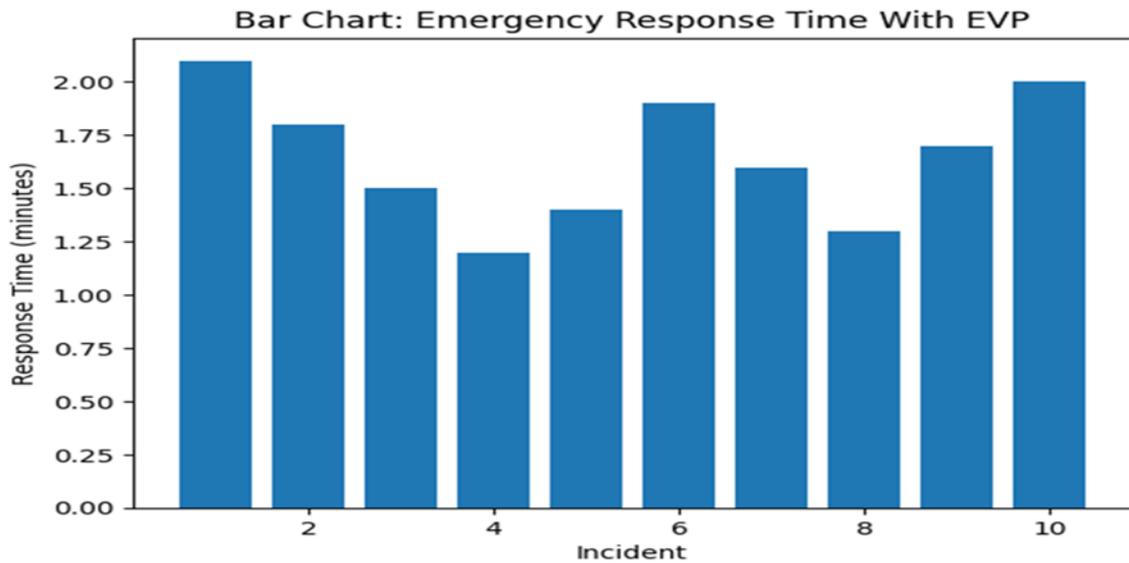
Figure 6: bar chart of emergency response time with EVP

4.6 Discussion

The results show that prioritizing emergency vehicles using the Internet of Things (IoT) significantly improves emergency mobility in busy urban areas. The substantial reduction in response time has a direct effect on public safety, particularly in medical emergencies and fires, where every second counts. The system derives these benefits without imposing significant stress on regular traffic, which is a major challenge in emergency prioritization strategies. The results also show that intelligent signal preemption can be successfully implemented through simulation-based design, a cost-effective approach for cities with limited infrastructure to test and plan deployment. The research further substantiates the significance of IoT and smart city frameworks in tackling urban resilience issues in emerging areas.

V.   CONCLUSION

This report discusses the development and testing of an IoT-based smart traffic-light prioritization system for emergency vehicles in Port Harcourt. The study used extensive simulation and comparative analysis to demonstrate that the proposed system substantially reduces emergency response time, alleviates intersection delays, and maintains satisfactory traffic flow for non-emergency vehicles. The results show that using IoT to prioritize emergency vehicles in busy cities is feasible, beneficial, and reliable. Future efforts will focus on coordinating multiple intersections, implementing real-world pilot projects, and integrating with emerging technologies such as edge computing and artificial intelligence. The

proposed framework provides a solid foundation for optimizing smart traffic management and emergency response in growing cities.

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