Smart Traffic Signal Management for Urban Efficiency and Safety: Leveraging Vehicle Density and Emergency Prioritization

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Abstract

Traffic congestion is a prevalent problem in urban areas, that leads to increase in time of travel, consumes more fuel, and environmental pollution. Efficient traffic signal management and control systems are crucial for mitigating congestion and improving road safety. This paper introduces a comprehensive solution, a Traffic Signal Management and Control System (TSMCS), leveraging advanced technologies and data-driven approaches. The system integrates ultrasonic and Light Detection and Ranging (LiDAR) sensors for accurate vehicle counting, adaptive signal control algorithms, and cloud-based servers for real-time traffic predictions. A key innovation is the prioritization of emergency vehicles, enhancing public safety. Real-world case studies in Mumbai and Bangalore highlight the urgency for advanced traffic management. The proposed system's novelty lies in its dynamic signal control, hybrid sensor integration, and cloud-based predictive capabilities. Contributions include multi-agent reinforcement learning, practical case studies, and a vision for smart city integration. The results demonstrate improved traffic flow and emergency response times, making TSMCS a promising advancement in intelligent transportation systems.

Keywords

Traffic Congestion, Traffic Signal Management, IoT, road safety, emergency vehicles

1. Introduction

Traffic control poses a significant infrastructure challenge for developing nations in the present day. Advanced nations and intelligent urban centers have effectively utilized the capabilities of the Internet of Things (IoT) to address issues associated with traffic. The widespread adoption of personal vehicles has quickly taken root in various countries, with people in most cities favoring their own automobiles, regardless of the quality of public transportation or the time and cost associated with reaching their destinations. A smart traffic management system (STMS)

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involves incorporating sophisticated technologies and data-driven strategies to streamline traffic, boost transportation efficiency, and enhance overall road safety. It employs a range of sensors, communication networks, data analytics, and control mechanisms to actively observe and oversee real-time traffic conditions. Traffic congestion is a pressing concern in urban areas, with serious implications for daily life, public safety, and the environment. Inefficient traffic management not only leads to frustration among commuters but also delays emergency response vehicles, putting lives at risk. Let's examine the situations in Mumbai and Bangalore as a case study. In a survey covering 416 cities in 57 nations, Bangalore has been identified as the city experiencing the most challenging traffic conditions worldwide, with Mumbai closely trailing in the fourth position. In Bangalore, travel times are extended by 71% during peak hours, whereas in Mumbai, the increase is 65% [1]. There are currently three conventional methods for traffic control in use. The first is manual control, which relies on the presence of traffic police to manage traffic in specific areas. These traffic police officers use signboards, signal lights, and whistles to regulate traffic. The second method involves traditional traffic lights with fixed timers, where a predetermined numerical value is programmed into the timer, causing the lights to switch between red and green based on this fixed schedule. The third approach utilizes electronic sensors like loop detectors or proximity sensors placed on the road to collect data about traffic conditions, and the traffic signals are adjusted based on this sensor data. However, these traditional methods have their limitations. Manual traffic control is labor-intensive and often hindered by a shortage of traffic police, making it impractical to manually control traffic in all areas of a city or town. Static traffic control relies on fixed timers that do not adapt to real-time traffic conditions, while electronic sensors can be limited in accuracy and coverage due to their cost and sophistication, as well as the budget constraints that restrict the number of sensors that can be deployed [2]. Over the past few years, video monitoring [3] and surveillance systems [4] have gained extensive usage for managing traffic, encompassing security, ramp metering, and delivering up-to-the-minute information to commuters. These video systems are capable of gauging traffic density and categorizing vehicles, enabling the modification of traffic signal timings. This, in turn, enhances traffic flow efficiency and minimizes congestion. To address these issues, we propose a Traffic Signal Management and Control System that dynamically adjusts traffic signals based on the density of vehicles and alongside prioritize the movement of emergency vehicles. The proposed system integrates various technologies, including ultrasonic sensors, data fusion, and adaptive signal control algorithms. This integration addresses the limitations of existing traffic management systems and contributes to the research community by showcasing a comprehensive approach to traffic control. The system also introduces a novel aspect by prioritizing emergency vehicles based on real-time data. This feature not only enhances public safety by expediting emergency response times but also represents a significant advancement in the field of intelligent transportation systems. The case studies on traffic conditions in Mumbai and Bangalore add a practical dimension to the research. By applying the proposed system to real-world scenarios, the paper contributes valuable insights into the potential impact of the system on highly congested urban areas. The proposed system employs an adaptive signal control algorithm that dynamically adjusts signal timings based on real-time traffic density and patterns. This dynamic approach represents a departure from traditional fixed-time traffic signal control, offering a more responsive and efficient solution. The integration of cloud servers for traffic light timing predictions is a novel aspect. The system calculates optimal duration for each LED phase based on received car counts, contributing to the flexibility and adaptability of the traffic control system. The use of both ultrasonic distance sensors and LiDAR sensors for vehicle counting adds a layer of sophistication to the system. This hybrid sensor integration ensures precise and reliable data collection, addressing the accuracy concerns associated with single-sensor systems.

2. Literature Review

In the contemporary age, there has been a significant surge in the urban population, which has had a detrimental impact on various aspects of daily life, particularly in the realm of transportation. Many cities in developing countries, such as Delhi and Kolkata, continue to rely on conventional methods to handle the growing number of vehicles. According to a United Nations report from 2018, approximately 55% of the global population currently lives in urban areas, a figure projected to rise to 68%. Moreover, the urbanization rate in Asia and Africa is expected to approach 90% by 2050. The efficiency of traffic flow is significantly impacted by the role of traffic controllers, making it crucial to enhance traffic control methods to cope with the rising demand. In their study, Gandhi et. al. [2] put forward a system designed to make use of real-time images captured by traffic junction cameras. This system employs image processing and artificial intelligence for calculating traffic density. It also emphasizes the development of an algorithm for adjusting traffic signal timings based on vehicle density, ultimately reducing traffic congestion, improving travel speed, and mitigating pollution.

In the research conducted by Muhammad Masum et al. [5], they introduce a real-time traffic management system that utilizes the IoT [6] and data analytics. Ultrasonic sensors are employed in this system to measure traffic density. Upon analyzing the sensor data, the system controller adjusts traffic signal timings using a traffic management algorithm. Furthermore, it sends data to a cloud server through a Wi-Fi module. This innovative system possesses the ability to predict potential traffic congestion at intersections. Notably, in the presence of an emergency vehicle, the system grants priority by extending the signal duration for passage through the intersection. In cases of signal violations, the system can identify vehicles and collect fines, a process facilitated through the Traffic Wallet mobile app. Crucially, this system is cost-effective, easy to install, and requires minimal maintenance.

Back in 2014, more than half of the world's population, at 54%, was living in urban areas. Projections suggested an annual growth rate of approximately 2% until 2020, which put additional strain on urban transportation systems. Rather than merely expanding roadways or constructing more roads, it becomes essential for cities to implement smarter street management. This is where the system proposed by Rachana et al. [7] comes into play. Their solution involves the use of a Raspberry Pi and a camera to track vehicle counts, enabling time-based monitoring of the transportation system.

Jakarta is notorious for having one of the world's most congested traffic systems, and it confronts numerous challenges as a result. There is a pressing need for the development of a comprehensive and systematic transportation network, underpinned by a thorough analysis. To address these issues, it is crucial to establish firm and consistent planning and implementation standards, along with transportation regulations. The integration of a mass public transportation system is vital in combating these challenges, and this can be achieved through the implementation of the Internet of Things (IoT). The potential benefits of IoT are exceptional and offer significant opportunities for the community. This presents a promising and potentially lucrative market share for the DKI Jakarta Province. To realize these improvements, the involvement of all stakeholders is essential to support the advancement of intelligent transportation and address the dynamic challenges faced by Jakarta as it aspires to become a smart city. Consequently, Sriratnasari et al. [8] propose an IoT-based Integrated Smart Transportation system in Jakarta, and they also outline various challenges associated with its implementation.

In today's global issues, urban mobility poses a significant challenge, particularly in large metropolitan areas. Existing traffic management systems are proving inadequate to cope with the escalating traffic volume on road networks. The paper by Javaid et al. [9] aims to introduce a system that utilizes the IoT and a decentralized approach to enhance traffic optimization. It employs intelligent algorithms for more precise traffic management in various scenarios, addressing the limitations of previous systems. This innovative system operates by collecting traffic density data from cameras and sensors, which is derived through Digital Image Processing techniques. It then uses this data to manage traffic signals effectively. An algorithm is employed to forecast future traffic density, reducing the likelihood of traffic congestion. Additionally, Radio-Frequency Identification (RFID) technology is utilized to give priority to emergency vehicles like ambulances and fire brigades by equipping them with RFID tags. In cases of emergencies such as fires or hazardous situations, fire and smoke sensors are deployed on the road to detect and respond to these events. Furthermore, the system includes a mobile application linked to a centralized server, which can alert nearby rescue departments about fire emergencies and provide the exact location for prompt action. In addition, regular users can inquire about future traffic conditions at specific locations. The proposed system was validated through the creation of a prototype deployed in a city in Pakistan. A web application has also been developed to present valuable graphical information to the city's authorities, aiding in future road planning.

The study by Damadam et al. [10] addresses the practical situation in Shiraz City, where the existing traffic signal management relies on fixed schedules without employing intelligent methods. We have harnessed the potential of the IoT and AI to enhance the efficiency of traffic light control, a crucial component of Intelligent Transportation Systems (ITS). Specifically, we have incorporated sensors like surveillance cameras to gather real-time traffic data for an intelligent traffic signal control system. The approach involves the utilization of a distributed Multi-Agent Reinforcement Learning system that considers not only the traffic data at individual intersections but also information from neighboring junctions. By employing MARL, the objective was to enhance traffic flow at six signalized junctions in Shiraz City, Iran. The effectiveness of the proposed system was evaluated against the traditional fixed-time traffic signal control method currently employed in Shiraz. The simulation outcomes indicate that our approach surpasses the conventional fixed-time traffic signal scheduling implemented in Shiraz, resulting in decreased average vehicle queues and reduced waiting times at intersections.

3. Proposed System Architecture

The proposed system architecture comprises of the following components:

3.1. Data Collection:

This module consists of vehicle detection Sensors that utilizes a network of sensors such as cameras, radar, and loop detectors; the system continuously collects data on vehicle density and speed at intersections. It also consists of emergency vehicle detection which are special sensors are installed to detect the presence of approaching emergency vehicles equipped with transponders.

3.2. Data Processing:

This module comprises of data fusion that collects real-time data from various sensors and fused to generate a comprehensive view of traffic conditions at each intersection. The system identifies emergency vehicles based on unique signals from their transponders.

3.3. Traffic Signal Control:

This module constitutes adaptive signal control which describes that the system uses advanced traffic signal control algorithms that consider real-time traffic density and patterns to adjust signal timings. When an emergency vehicle is detected, nearby traffic signals are automatically adjusted to provide a green light, allowing the emergency vehicle to pass unhindered.

3.4. Communication:

The system is connected to a central traffic management center, where traffic engineers and emergency services personnel can monitor and control the traffic signals remotely. The proposed system design to perform the module tasks is depicted in Fig. 1.

There are several technologies and approaches to compute the quantity of vehicles, but one of the most common and practical approaches are using an Ultrasonic Distance Sensor or a LiDAR sensor. A distance is determined by an Ultrasonic Distance Sensor through the use of sound waves to assess the space between the sensor and an object, specifically the trailing vehicle on a straight road. The sensor releases ultrasonic pulses and gauges the duration it takes for these pulses to rebound upon encountering an object. Utilizing the time taken and the speed of sound in the medium, typically air, the distance can be computed. A LiDAR sensor works similarly to an ultrasonic sensor but uses light waves instead of sound waves. The device emits laser pulses and gauges the duration it requires for the light to bounce off an object and return to the sensor. With knowledge of the speed of light and the elapsed time, the distance can be precisely calculated. Both of these sensors can provide precise distance measurements and can be used to maintain a safe following distance between vehicles on a straight road. The sensor can be integrated into the vehicle's onboard computer system, and the distance information can be used for various purposes like adaptive cruise control, collision avoidance

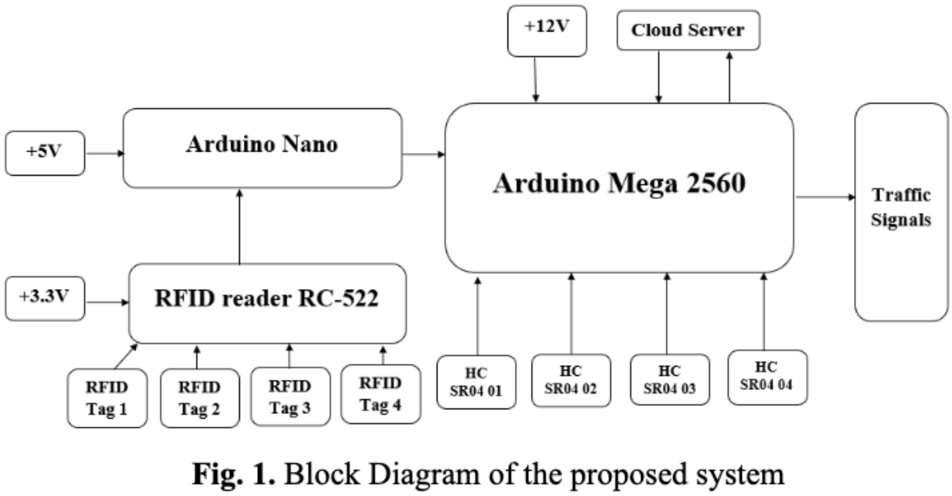

Figure 1: Block Diagram of the proposed system

systems, or for warning the driver if they are following too closely.

In this proposed system, LED traffic lights and an ultrasonic car counting sensor are interconnected with a microcontroller using physical wiring. The microcontroller serves as the traffic light controller, gathering data from the sensors and managing the traffic lights' transitions between green, yellow, and red phases. It calculates the number of cars on the intersection street by analyzing the distances measured by the ultrasonic sensor and the timing between these measurements. Subsequently, the microcontroller transmits the car count to a local server every minute via its serial port. The local server then shares this data with a cloud server to enhance traffic light timing predictions. This communication is carried out over a Wi-Fi connection. The cloud server employs a formula, utilizing the received car count as an input, to ascertain the ideal duration for each LED phase, aiming for efficient traffic flow. This computed duration is then compared to the existing LED timing details stored in a database on the cloud server. If the current green phase duration is found to be less than the calculated duration, the server suggests extending the green time; conversely, if it's greater, the server recommends reducing the green time [11].

Now, the working of the system in real world intersection of a 4-way crossing is shown in the Fig. 2.

In the depicted scenario, at Point 1, LANE 1 currently has an active green signal, while LANE 4 is displaying a yellow signal, indicating readiness to stop. However, LANE 2 and LANE 3 are both obstructed. In LANE 3, the quantity of vehicles has already exceeded a predefined threshold, resulting in the road leading to LANE 2 at Point 1 being blocked at Point 2. Consequently, these vehicles are rerouted through alternative lanes. (Assuming that Point 1 represents the current intersection, and Point 2 is the preceding intersection.)

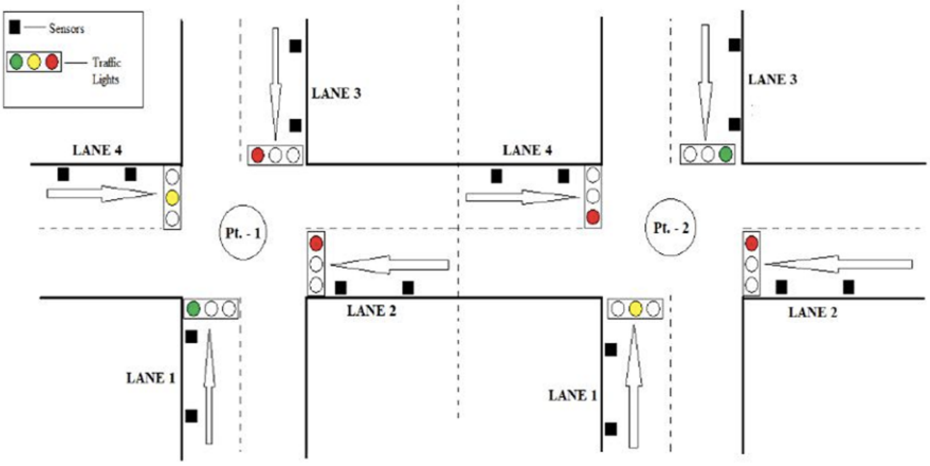

Figure 2: Control of previous Intersection

The proposed system utilizes a multi-module architecture, involving data collection through various sensors, data processing for real-time analysis, adaptive traffic signal control, and communication with a central traffic management center. The system incorporates ultrasonic distance sensors and LiDAR sensors for accurate vehicle counting, ensuring reliability in data collection. The adaptive signal control algorithm adapts signal timings in real-time, considering the current traffic density to optimize the flow of traffic. The inclusion of cloud servers enhances the system's predictive abilities, enabling immediate adjustments to traffic light timings. Emergency vehicle detection and prioritization further contribute to the efficiency of the system. The system's operation involves continuous data collection, real-time analysis, and responsive adjustments to signal timings. The proposed algorithms for emergency vehicle detection, vehicle counting, and traffic control strategy work in tandem to create a smart and adaptable traffic management system.

4. System Operation

The operation of the system is shown by the flow diagram in Fig 3.

The proposed system operates as follows:

Vehicle density and speed data are continuously collected at each intersection. Special sensors detect emergency vehicles approaching intersections. Real-time data are processed and analyzed to determine the current traffic density and congestion levels. When an emergency vehicle is detected, its location and route are determined. The control algorithms use the processed data to adjust signal timings, favoring routes with higher vehicle density. If an emergency vehicle is approaching an intersection, the system prioritizes its movement by providing a green light. Traffic engineers and emergency services personnel can monitor and control the system from a central control center. Emergency services can request traffic signal

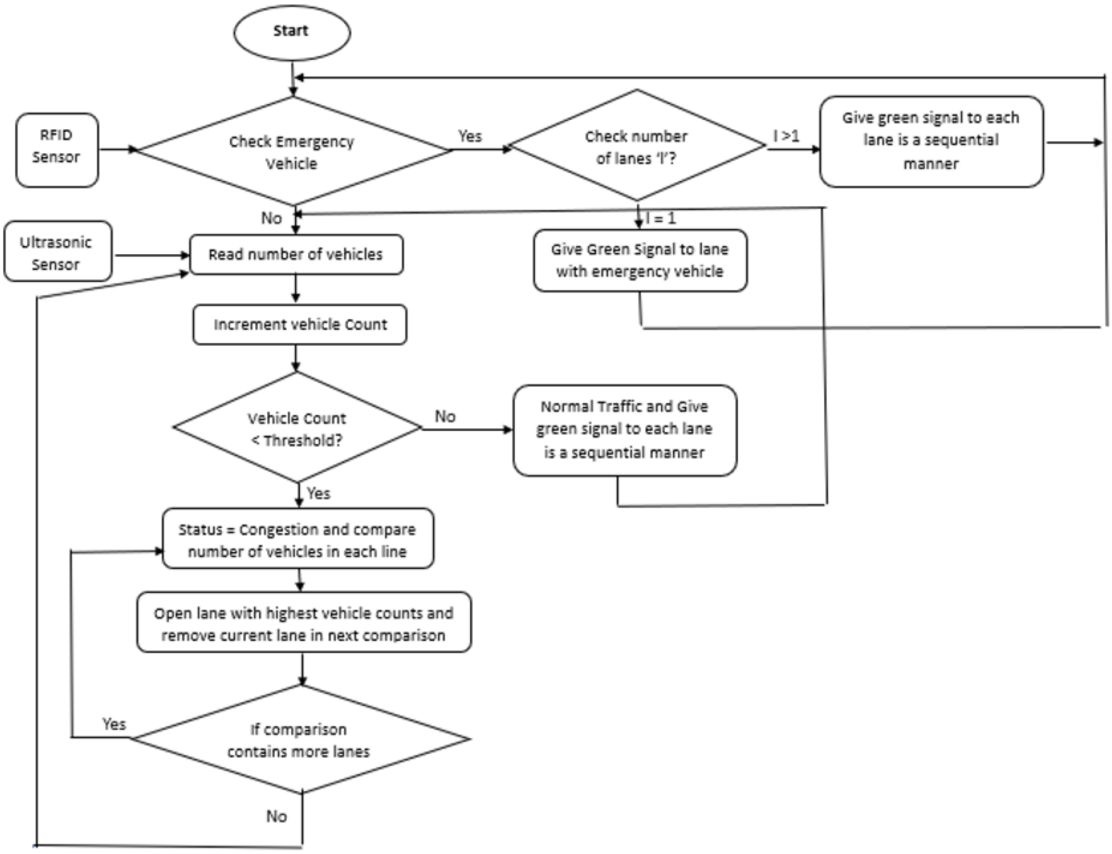

Figure 3: Flowchart of the proposed system

prioritization when necessary [12].

There are two algorithms that operate within the proposed system.

Algorithm 1. Emergency Vehicle Detection
Number of sensors = 4, represented through RF1, RF2, RF3, RF4
Step 1: Check if RF1, RF2, RF3 and RF4 are activated or not,
Step 2: If single RF Sensor is activated,
Turn on Green signal for Lane where RF is activated
Turn on Red signal for Remaining Lanes
Step 3: If RF1, RF2, RF3 and RF4 are activated at same time,
Turn on Green signal for Lane 1
Turn on Green signal for Lane 2
Turn on Green signal for Lane 3
Turn on Green signal for Lane 4

Step 4: If two or three RF Sensor is activated,
Follow Sequence as per increasing Lane number.
Step 5: If no RF Sensor is Activated,
Go to Algorithm 2

Algorithm 2. Vehicle Counting
Initialize a counter variable to zero and a boolean variable hitObject to false.
Step 1: Involves retrieving the sensor reading, referred to as 'val,' where the sensor outputs 0 when a car is detected and 1 when no car is present.
Step 2: If 'val' equals 0 and 'hitObject' is not true, increment the counter by one and set 'hitObject' to true. If 'val' is 1, set 'hitObject' to false.
Step 3: Return to Step 1 and repeat the procedure.
This algorithm essentially counts vehicles by checking the sensor's output. When a car is detected, it increments the counter and ensures that it doesn't count the same car multiple times by tracking whether it has already "hit" an object (vehicle) or not.

Algorithm 3. Traffic Control Strategy
Begin with 8 sensors considered as S1, S2, S3, S4, S5, S6, S7, and S8. Four lanes are defined: Lane 1 (L1), Lane 2 (L2), Lane 3 (L3), and Lane 4 (L4). Corresponding to each lane, we have the number of cars N1, N2, N3, and N4, and the duration for which each lane has a green signal, denoted as T1, T2, T3, and T4.

Step 1: Initiate the algorithm.
Step 2: The sensors monitor the vehicle count in each lane (L1, L2, L3, L4).
Step 3: If the overall vehicle count is below a designated threshold, categorize the traffic status as "Normal." In this scenario, activate the green signal for each lane se-quentially (L1-L2-L3-L4). While a lane displays a green signal, the signals for the remaining lanes are set to red.
Step 4: If the total vehicle count exceeds the threshold, the traffic status is labeled as "Congestion."
Step 5: Compare the number of cars in each lane (N1, N2, N3, N4) and select the lane (Ni) with the highest vehicle count. Activate the green signal for this lane (Li) for a specified duration (Ti). After the time Ti elapses, switch the signal to red.
Step 6: Next, compare the number of cars in lanes 2, 3, and 4 (N2, N3, N4), and select the lane (Ni) with the highest vehicle count. Activate the green signal for the specified lane (Li) for a duration of time (Ti), followed by a transition to red.
Step 7: Repeat the comparison and green signal activation process for lanes 3 and 4, selecting the lane (Li) with the highest vehicle count for duration of time (Ti) until all lanes have had their turn.
Step 8: The final remaining lane is automatically granted the green signal for the designated duration Ti.
Step 9: Return to Step 3 to continue the traffic control process.

This algorithm efficiently manages traffic by dynamically adjusting the signal timing based on the congestion level and vehicle count in each lane [13, 14, 15].

5. Benefits of the Proposed System

The proposed Traffic Signal Management and Control System offers several benefits and advantages that includes,

- Reduced Traffic Congestion: Through the dynamic adaptation of signal timings according to vehicle density, the system has the potential to notably decrease traffic congestion, leading to shorter commute times and decreased fuel consumption.
- Improved Safety: Emergency vehicle prioritization ensures faster response times, potentially saving lives in critical situations.
- Environmental Benefits: Reduced traffic congestion and smoother traffic flow contribute to decreased air pollution and greenhouse gas emissions.
- Data-Driven Decision Making: The system provides valuable real-time data that can be used for traffic planning, optimization, and future infrastructure development.

6. Results and Analysis

The proposed system was implemented in traffic simulation software VISSIM for a road network of Mumbai. The performance of the system was analyzed using the performance parameters that include:

- Average Queue Length represents the average number of vehicles waiting in a queue at a particular location (e.g., an intersection or a specific lane) during a specified period. Monitoring the average queue length helps assess the level of congestion and can be used to optimize signal timings to reduce queues and enhance traffic flow.
- The maximum queue length is the highest number of vehicles observed in a queue at a specific location during a given timeframe. Identifying the maximum queue length is crucial for understanding the peak congestion levels. This information can guide traffic signal adjustments to prevent excessive queues and improve overall system performance.
- Average Delay refers to the average amount of time that each vehicle is delayed in the traffic system. It is the additional time spent by a vehicle beyond what it would have taken in an uncongested or free-flowing traffic scenario. Minimizing average delay is a key objective of traffic management systems. By dynamically adjusting signal timings and prioritizing certain vehicle movements, the system aims to reduce delays and improve overall travel time for commuters.
- Weighted average travel time is the average time it takes for vehicles to travel through a specific route or network, considering the weight assigned to each route based on factors such as distance or importance. This metric provides a comprehensive view of the overall travel time experienced by vehicles, considering different routes and their significance.

Fig. 4 demonstrates that Lane L1 has the highest average queue length (510), indicating that, on average, there are 510 vehicles waiting in the queue at any given time. This lane experiences relatively high congestion compared to the other lanes. Lane L1 also has the highest maximum queue length (620), representing the peak congestion observed in this lane during the analyzed

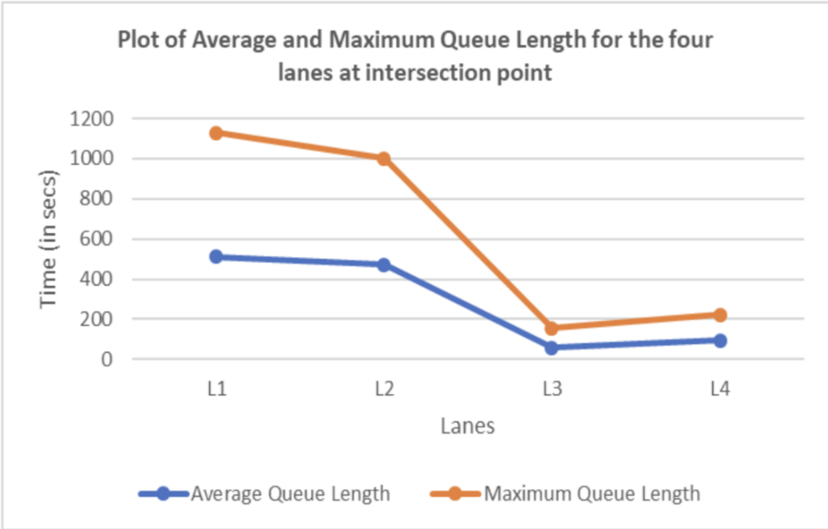

Figure 4: Average and Maximum Queue Length for the four Lanes at an Intersection Point.

period. Lane L3 has the lowest average queue length (57), indicating lower congestion on average compared to the other lanes. Lane L3 also has the lowest maximum queue length (98), representing the least congested state observed in this lane during the analyzed period. This analysis provides insights into the congestion levels in different lanes, helping traffic management authorities make informed decisions to optimize traffic flow and reduce delays in the identified lanes.

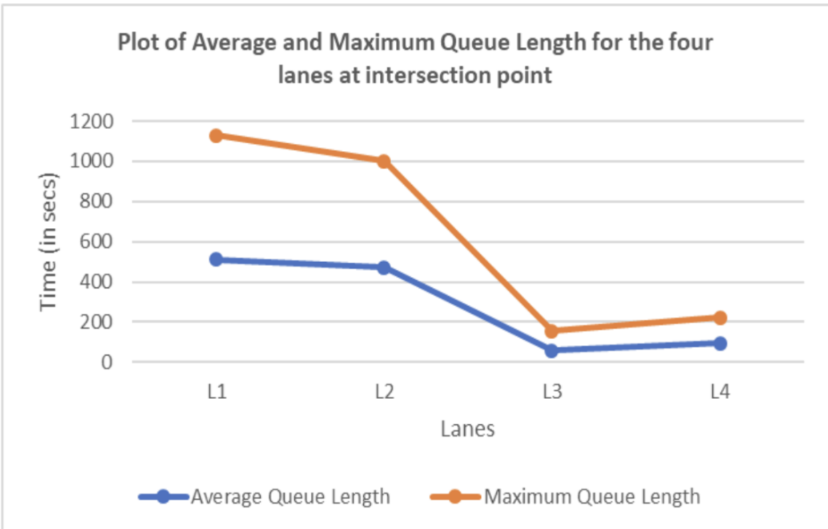

Figure 5: Average Delay and Weighted Average Travel Time for the vehicles.

Fig. 5 illustrates that, Lane L1 has the highest average delay (170), indicating that, on average, vehicles in this lane experience a delay of 170 units of time. Lane L1 also has the highest weighted average travel time (185), representing the average time it takes for vehicles to travel through this lane, considering different factors such as distance or importance. Lane L3 has the lowest average delay (120), indicating lower delays on average compared to the other lanes. Lane L3 also has the lowest weighted average travel time (116), representing the shortest average travel time for vehicles in this lane, considering different factors. This analysis provides insights into the delays and travel times in different lanes, guiding traffic management authorities in making informed decisions to optimize traffic flow and improve the overall travel experience for commuters in the identified lanes. The algorithm efficiently manages traffic by dynamically adjusting signal timings, responding to congestion levels, and prioritizing lanes based on vehicle counts. The proposed Traffic Signal Management and Control System not only demonstrates promising results in simulations but also addresses real-world traffic challenges, making it a valuable contribution to the field of intelligent transportation systems.

7. Conclusion

The Traffic Signal Management and Control System based on vehicle density and emergency vehicle prioritization represents a promising solution to alleviate traffic congestion and improve emergency response times. By utilizing advanced technology and data-driven algorithms, this system has the potential to transform urban traffic management, making cities more efficient, safer, and environmentally friendly. Proper planning, investment, and public engagement are essential for the successful implementation of such a system, ultimately benefiting urban communities and their residents. Looking ahead, it's worth exploring the idea of assigning various priority levels to multiple incidents and situations. When it comes to IoT (Internet of Things), a critical concern is ensuring the security of the entire system rather than focusing on individual IoT layers, devices, or software components. The proposed system lays the groundwork for integration into broader smart city initiatives. Future research could explore how this traffic control system aligns with and complements other smart city components, such as energy management, waste disposal, and public services. Further research could focus on incorporating machine learning techniques for more advanced traffic prediction and adaptive signal control. Machine learning models could learn from historical data to make more accurate predictions and improve overall system efficiency. As smart systems become more prevalent, ensuring the cybersecurity of such traffic management systems is crucial. Future work could delve into securing communication channels, protecting data integrity, and safeguarding against potential cyber threats. Investigating the scalability of the proposed system and its adaptability to different urban landscapes worldwide is essential. Future research could explore how the system performs in diverse environments and under varying traffic conditions.

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