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GPU-based video-processing traffic signals for high-density vehicle areas

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Abstract: This work focuses on developing a traffic management system that utilises video camera inputs and real-time analysis to improve signal control and enhance traffic conditions. The system captures live video feeds from cameras installed at traffic junctions and employs graphics processing unit-based image processing techniques to calculate the real-time vehicle density on each side of the road. An algorithm dynamically adjusts the timing of traffic lights based on the congestion levels of different roads to optimise traffic flow, reduce congestion, and enhance road safety. Real-time decision-making capabilities for traffic control improve transportation efficiency, reduce fuel consumption, and minimise waiting time. The system provides valuable data for future road planning and research. The system further improves traffic flow and minimises traffic jams by synchronising multiple traffic lights using video and image processing technologies in traffic management systems to enhance overall traffic conditions and promote safer and more efficient transportation.

Keywords: congestion levels; fuel consumption; GPU; graphics processing unit; image processing technologies; intelligent traffic system; real-time analysis; traffic jams; traffic lights; traffic management system; video processing.

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1 Introduction

The exponential development of traffic congestion is among the most critical challenges in the modern world. In order to illustrate this point, we will use Mumbai, one of India's most populated cities, as a case study. Vehicle density in Mumbai is among the highest in all of India. The total vehicular population in Mumbai is now over 42 lakh, with a density of 2,100 vehicles per km of road, as reported in the Times of India (TOI) dated April 5, 2022, as shown in Figure 1. The city's infrastructure cannot keep up with the rapidly growing number of cars and trucks.

Figure 1 Mumbai traffic day on 21 August, 2021 (see online version for colours)

Source: Article by Chittaranjan Thembekar in TOI dated 10 February, 2022)

Growing demand for increased traffic leads to an urgent need to model and improve existing traffic control systems. In recent years, there has been a rise in video monitoring and surveillance systems for traffic management. These systems are used for traveller information, ramp metering, and real-time updates. An additional two metrics, namely the estimation of traffic volumes and the classification of various vehicles, can be gleaned from a video surveillance system.

As the population increases, vehicles on the road also increase. Hence, reaching the desired place in a given duration becomes a big problem. Emergency vehicles such as Ambulances get stuck in traffic jams and cause delays. In the present traffic control system, traffic congestion is monitored manually like traffic police. However, traffic cops are unable to control traffic effectively. The city's infrastructure cannot keep up with the rapidly growing number of vehicles. Worst of all, vast lines of stalled vehicles are becoming the norm during rush hour on the inner ring roads. Estimating traffic density and vehicle classification are metrics that can be gathered from graphics processing unit (GPU) based video surveillance systems.

This study introduces a real-time method for calculating traffic density by analysing video and images captured by cameras at intersections. The paper also investigates the algorithm used to switch traffic lights based on the number of vehicles on the road to achieve its goal of reducing traffic congestion on roadways.

2 A survey of intelligent traffic control systems

Various traffic control methods, including human control, static timers on traditional traffic lights, and electronic sensors, are currently used. However, each method has its advantages and limitations. Human control requires significant human resources and may not be an efficient strategy for dealing with traffic congestion. Static traffic control using predetermined countdowns does not adapt to changing traffic conditions. Obtaining high-quality traffic data can be challenging due to the deployment of expensive technology, which may compromise accuracy and coverage.

Additionally, using many sensors is often required to provide complete coverage. Therefore, there is a need for an improved method of managing traffic. The following work presents a survey of several intelligent traffic control systems.

The system mentioned in Patan et al. (2016) involves the deployment of various sensors and cameras at traffic intersections to capture real-time traffic data. The collected data is then processed and analysed in real-time using big data analytics techniques to derive insights into traffic patterns and identify potential congestion points. Based on this information, the system dynamically adjusts the traffic signal timings to optimise the traffic flow and reduce congestion. The authors evaluated the performance of the proposed system through simulation experiments, and the results showed significant improvements in traffic flow and a reduction in travel time. The study highlights the potential of Internet of Things (IoT) and big data technologies in developing smart traffic management systems for smart cities. While the proposed system of a real-time smart traffic management system using IoT and big data has many potential advantages, there are also some potential disadvantages to consider, including:

High implementation costs: Implementing such a system can be expensive due to installing sensors and cameras at various traffic intersections and deploying the necessary big data infrastructure to process and analyse the collected data.

Dependence on technology: The system heavily relies on the technology functioning optimally, which may not always be the case due to technical glitches, malfunctions, or cyber-attacks, leading to system failures and disruptions in traffic flow.

Privacy and security concerns: Collecting and processing large amounts of data from sensors and cameras raises privacy and security concerns for the public. There may be risks of sensitive data being exposed to unauthorised parties or used for malicious purposes.

Need for maintenance and upgrades: The system requires regular maintenance and upgrades to ensure that the sensors and cameras are functioning correctly and that the data processing and analysis infrastructure is up to date.

Limited applicability: The system may not apply to all traffic scenarios or cities, and the effectiveness of the system may depend on various factors such as traffic density, road infrastructure, and weather conditions.

A camera captures traffic data, which is processed using an image processing algorithm (Zaid et al., 2017). The system's advantages are its cost-effectiveness, efficient algorithm, and low maintenance. However, the system is highly dependent on accurate traffic data, may not apply to all traffic scenarios, and does not address other factors that may impact traffic flow.

The system uses real-time traffic data and machine learning algorithms to predict traffic flow and adjust signal timings accordingly (Gandhi et al., 2020). The system's advantages are its ability to adapt to changing traffic conditions and its effectiveness in reducing traffic congestion. The system can also reduce energy consumption and decrease the waiting time for drivers. However, the quality of the traffic data and the availability of computing resources may affect the system's accuracy.

Furthermore, the implementation of the system may require significant upfront costs. As the number of vehicles on the road increases in major cities, difficulties such as capacity drop-offs and the resulting Level of Service increase. Many traffic problems emerge at intersections as a result of fixed signal timers. As the road capacity demand grows, so does the need for improved traffic control technologies. According to a survey analysing the 416 cities in 57 countries affected by traffic congestion, Bangalore has the worst traffic congestion globally, but Mumbai is close to fourth place. A journey in Bangalore takes 70% longer during rush hour. It is 65% longer in Mumbai (Gandhi et al., 2020).

Data from various sources, including cameras and sensors, to analyse traffic conditions and optimise traffic flow in real-time. The system uses a cloud-based platform for data storage and processing and big data mining techniques to extract valuable insights from the data (Shengdong et al., 2019). The proposed system includes the ability to process and analyse large volumes of traffic data, improving the accuracy of traffic predictions and enabling better decision-making. Additionally, cloud computing allows for scalability and flexibility, as the system can quickly adapt to changing traffic conditions and user demands. The system also has the potential to reduce traffic congestion and improve safety on the roads. However, the paper does not mention the potential disadvantages of the proposed system, such as the potential cost of implementing and maintaining such a system and the need for extensive data collection infrastructure. Additionally, the system may face data privacy and security challenges, as collecting and storing sensitive traffic data may raise privacy concerns.

Ensemble learning and transfer learning techniques to improve the accuracy of models are developed by Nallaperuma et al. (2019). The advantages of their system include real-time monitoring and decision-making, adaptability to changing traffic conditions, and scalability for use in larger cities. However, the system requires a large amount of training data, and privacy concerns may be related to data collected from drivers.

The system developed by Lin and Jhang (2022) can accurately detect vehicles and estimate traffic flow in real-time. The advantages of their system include high accuracy and low computational complexity, making it suitable for use in resource-constrained environments. However, the system may be sensitive to changes in lighting and weather conditions. The system developed by Ning et al. (2020) can dynamically adjust the routing of traffic flows to optimise network performance. The advantages of their system include adaptability to changing traffic conditions, scalability, and improved network efficiency. However, the system requires much training data and may be computationally intensive.

The system uses sensors and cameras to detect and monitor traffic flow and a dashboard for real-time monitoring and analysis (Putra and Warnars, 2018). The advantages of their system include high accuracy and real-time monitoring, making it suitable for use in large cities. However, the system may be expensive and require significant infrastructure investment. The use of deep neural networks for traffic prediction, classification, and optimisation is discussed in Fadlullah et al. (2017). The advantages of their system include high accuracy and adaptability to changing traffic conditions. However, the system may require large training data and be computationally intensive. The review (Avatefipour and Sadry, 2018) discusses using sensors, cameras, and other devices for monitoring traffic flow and optimising traffic control. The advantages of their system include real-time monitoring and analysis, improved traffic flow, and reduced congestion. However, the system may be expensive and require significant infrastructure investment.

The system optimises traffic flow by adjusting traffic signal timings based on real-time traffic conditions (Tang et al., 2019). The advantages of their system include adaptability to changing traffic conditions, reduced congestion, and improved traffic flow. However, the system may require significant infrastructure investment and may be sensitive to changes in weather and lighting conditions. The system (Kumar et al., 2018) uses a combination of ant colony optimisation and IoT technology to optimise traffic flow. The advantages of their system include adaptability to changing traffic conditions, reduced congestion, and improved traffic flow. However, the system may require significant infrastructure investment and be computationally intensive. The system uses video processing techniques to detect and classify vehicles and adjusts traffic signal timings accordingly (Sarath and Deepthi, 2018). The advantages of their system include real-time monitoring and analysis, improved traffic flow, and reduced congestion. However, the system has limited evaluation of real-world data and may not handle highly dynamic traffic situations well and can improve testing on more complex traffic situations.

Several related works have explored the application of IoT technology in intelligent traffic management systems. Samir and AlShalfan (2021) developed a system based on the Internet of Vehicles (IoV) to optimise traffic flow and enhance road safety. Their system demonstrated improved traffic efficiency, reduced congestion, and enhanced safety. However, infrastructure requirements and data privacy challenges must be addressed to refine the system further. Another study by Javaid et al. (2018). proposed a smart traffic management system using IoT devices and sensors. The system aimed to monitor and control real-time traffic, improving traffic flow and reducing congestion. However, factors like network connectivity and scalability may impact its effectiveness. Sharif et al. (2018) presented an IoT-based smart traffic management system for smart cities, incorporating big data analytics. This system offered advantages such as real-time monitoring, optimised traffic flow, and improved decision-making. Challenges regarding data privacy and security must be addressed. An IoT-based real-time traffic monitoring system for city governance is developed by Sarrab et al. (2020). Their system utilised IoT devices and sensors to collect traffic data and provided real-time monitoring and analysis. It showcased benefits such as enhanced traffic management, reduced congestion, and improved resource allocation. However, challenges related to data processing and integration with existing infrastructure remain. Roopa et al. (2020) proposed a dynamic traffic signal management system using Social IoT, which combined IoT devices, social networks, and data analytics. This system demonstrated advantages like improved traffic flow, reduced waiting times, and energy efficiency. Challenges included network reliability and scalability. Future research may involve refining algorithms and integrating the system with emerging technologies. Another study (Sahu et al., 2021) introduced a traffic management system that utilised IoT devices and sensors for real-time traffic data collection and analysis. This system showcased improved traffic flow, reduced congestion, and enhanced road safety. However, infrastructure requirements and data privacy concerns should be addressed. Future research could explore innovative IoT applications and integration with smart city frameworks.

Several traffic management systems have been developed. The system proposed by Natafgi et al. (2018) relies on accurate and extensive data for training but faces computational complexity for real-time control and is susceptible to adversarial attacks. Qadri et al. (2020) presented a system that requires complex infrastructure and communication networks, raising privacy concerns. Wong et al. (2022) highlighted the challenges of coordinating timings and adapting to dynamic conditions in their system. Mandhare et al. (2018) Identified wireless communication and scalability challenges and the need for comprehensive traffic data and integration with existing infrastructure. Miyim and Mansur (2019), Lanke and Sheetal (2013) developed a system that relies on real-time data, integration, and robust communication.

Traffic management systems generally face complexity, integration challenges, and the need to adapt to evolving technologies (de Souza et al., 2017). Computer vision-based systems for traffic control require real-time processing, handling complex scenarios, and high-quality video feeds (Trivedi et al., 2017). On the other hand, Zamri and Hamzah (2022), Humayun et al. (2022), Rachana et al. (2021) and Patil et al. (2021) have made significant contributions to addressing traffic congestion. However, there is still scope for improvement. Future research should focus on implementing and evaluating these systems in real-world scenarios to assess their performance with continuous refinement and integration of user feedback for more efficient and advanced traffic management solutions. The proposed work intends to tackle these challenges by incorporating real-world implementation and evaluation to assess the performance of the developed systems.

3 Methodology

The approach that is being proposed alters the time duration of green based on the traffic density of the signal, which ensures the direction with the most significant traffic is given a green signal for longer than the minor traffic and will prevent unwanted delays, congestion, and waiting times, reducing fuel consumption and pollution levels.

The system comprises cameras installed at crossroads, one on each side, as if the intersection were a four-way stop. Because of this, four security cameras will be installed above the traffic signals, each pointing toward the road. Cameras would record the road using video and image processing technologies and then communicate the data to computers. An algorithm would assess the traffic density on either side of the road, and the lights would be controlled accordingly. In order to receive live video from the cameras, a server with adequate computational capability must be linked to the cameras before the hardware setup can be considered complete.

3.1 Block diagram

Present traffic signal system

Traffic management authorities employ manual measures to manage the traffic on the road. The current method of controlling traffic involves manually monitoring various aspects of it, such as congestion on the roads. However, traffic cops cannot effectively manage traffic flow in their areas. The manual approaches are not only time-consuming but also not very accurate. Because of this, it might be challenging to clear traffic congestion in big cities like Delhi, Mumbai, and Bangalore.

Proposed traffic signal system

Figure 2 illustrates the integration of cameras as input devices for the server in the traffic management system. A live feed is transmitted from the cameras to the server for analysis. The cameras capture video frames at specific intervals, which are then sent to the processor for detection and comparison. The processor plays a vital role as the central processing component of the system. It analyses the input feed received from the cameras and determines the appropriate modification of the signal ON time for the side with higher traffic density. This adjustment of the traffic light timings is based on the vehicle count obtained from the server/processor, considering preset limits. The power supply ensures that all components receive the necessary power, with the camera module requiring 7V DC and the processor operating on 5V DC. Installing cameras at the signal junctions enables live video feeds to be transmitted to the server/processor. The server/processor's primary function is to calculate vehicle density using an image processing algorithm. The traffic signals' ON and OFF times are adjusted based on the calculated vehicle density on the road. This system comprises video cameras positioned at each side of the traffic junction, typically in a four-way configuration. The cameras capture video, which is processed using video and image processing techniques. Vehicle density on each side of the road is calculated, and an algorithm is employed to regulate the traffic light timings accordingly. The hardware setup involves establishing a connection between the cameras and the server to facilitate the transmission of live feeds, and the server must possess sufficient processing capabilities to handle the system's requirements. This traffic management system is designed to enable the monitoring of traffic in specific areas and relay this data to the traffic control cabinet. The cabinet then utilises an algorithm based on the relative weight of each road, derived from traffic sensor readings, to control the traffic lights. The system optimises traffic flow by allocating longer green times to more congested roads and making real-time decisions based on the relative weights. The system's ability to make these decisions in real-time is a prominent feature, contributing to its overall effectiveness.

The suggested system would calculate the traffic density in the area based on real-time video collected from cameras installed at intersections. The algorithm that calculates the appropriate time to change the lights based on the traffic volume on the road is the primary focus of this discussion.

As shown in Figure 3, in this system, the vehicle density of the following two signal lanes is compared, and the ON time of the green signal is modified based on the comparison of vehicle density. Similarly, this loop repeats itself, but the ON time of the traffic light is altered. We will have shorter wait times, and there will be less congestion.

Figure 2 Block diagram of vehicle density-based traffic signal using video processing (see online version for colours)

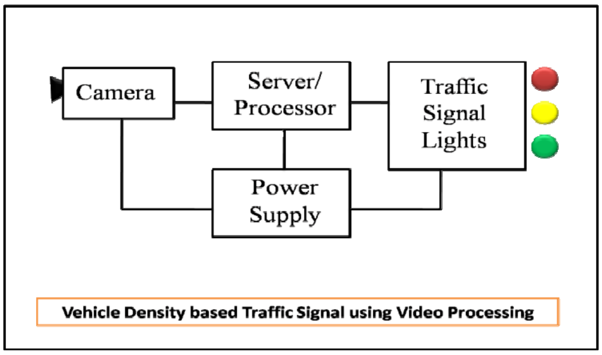
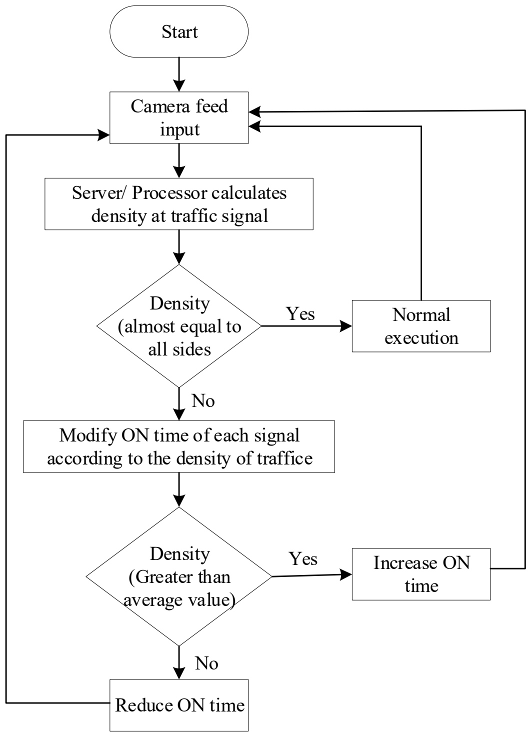


Figure 3 Flowchart of proposed traffic signal system



The proposed traffic management system incorporates the following steps for analysing vehicle density and controlling traffic lights. One suitable algorithm for this purpose involves the following stages:

Image/video acquisition: Live video feeds are captured from cameras installed at traffic junctions.

Pre-processing: The captured video frames undergo pre-processing techniques to enhance image quality, eliminate noise, and normalise lighting conditions.

Object detection: An object detection algorithm, such as Haar cascades or deep learning-based models like YOLO, is applied to identify and locate vehicles within the video frames.

Vehicle counting: The system counts the number of vehicles detected in each frame or accumulates counts over a specific period to estimate the vehicle density on each road segment.

Congestion analysis: The system uses vehicle counts to perform congestion analysis to assess the relative traffic density on different roads.

Traffic light control: Based on the congestion analysis, an algorithm is employed to adjust the timing of traffic lights dynamically. Factors considered may include the relative weight of each road, historical traffic patterns, and predefined thresholds for congestion levels.

Traffic light timing adjustment: The algorithm modifies traffic lights' ON/OFF timings, prioritising roads with higher congestion and adjusting timings for other roads accordingly.

Real-time decision-making: The system continuously monitors traffic conditions, updates vehicle counts, and makes real-time decisions on traffic light timings to optimise traffic flow and alleviate congestion.

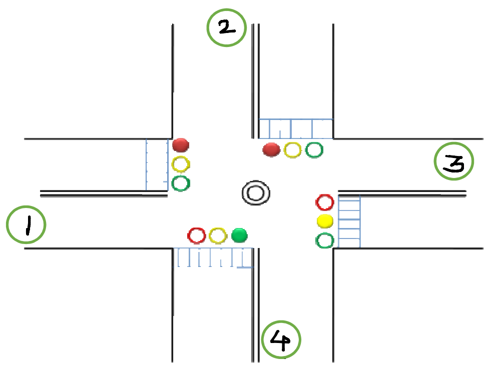
The proposed traffic management system effectively analyses vehicle density and optimises traffic light control based on real-time conditions, improving traffic management and enhancing road efficiency.

Figure 3 shows the flowchart of the proposed traffic signal system in detail.

4 System execution and results

Figure 4 shows the prototype of the 4-lane road and the existing traffic light system. In the proposed prototype, lanes 1, 2, 3, and 4 are designated for traffic flow. A working model of the system has already been developed, and its functionality can be observed in Figure 2. The facility has installed a camera and processing system specifically in the first lane.

Figure 4 System prototype (see online version for colours)



When the traffic light for lane one switch to red, the system compares the traffic volumes in lanes two and three. This comparison aims to determine which of the two lanes has a higher density of vehicles. Based on the results of this comparison, the system adjusts the duration of the green signal for lanes 2 and 3. The lane with a higher vehicle density will receive additional green time, allowing for smoother traffic flow and reduced congestion.

Once the second lane completes its turn, a similar comparison process occurs between lanes three and four. The system evaluates the traffic volumes in these lanes and adjusts the green signal duration accordingly.

It is important to note that this comparison and adjustment process operates in a loop, continuously monitoring the traffic conditions and dynamically allocating green time based on the current density of vehicles in each |lane. This adaptive approach ensures the traffic signal system responds to changing traffic patterns in real-time, optimising traffic flow and minimising delays.

5 System specifications

The specifications for a smart traffic control system will depend on the specific requirements of the system, but here are some general specifications that may be included:

Sensors: The system should include a camera as a sensor.

Communication: The system communicates with the traffic lights system. Further modifications in the system can be done for communication with emergency services and other vehicles on the road.

Data processing: The system has powerful processing capabilities to handle large amounts of real-time data.

Artificial intelligence: The system does not involve direct Artificial intelligence algorithms but uses the Raspberry Pi platform for implementing AI algorithms that help analyse the data collected from the camera and make decisions about traffic flow and safety.

Integration: The system integrates with existing traffic management systems and infrastructure.

Security: The system is secure and resistant to hacking and other cyber-attacks.

User interface: The system is user-friendly for traffic managers to monitor and control traffic flow.

Power supply: The system has a reliable power supply to ensure uninterrupted operation.

Maintenance: The system is designed for easy maintenance and repair, with components that can be easily replaced.

Scalability: The system should be scalable to accommodate future growth and changes in traffic patterns.

6 Results

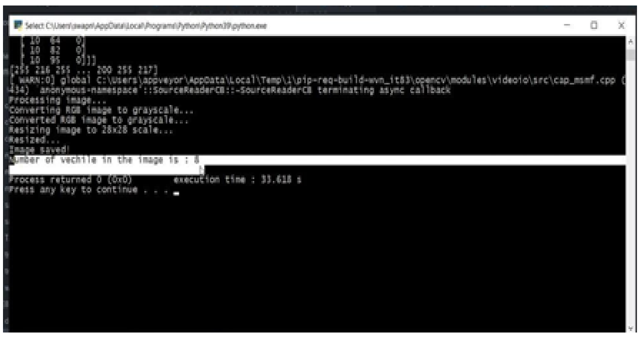
The research proposes the inclusion of a primary circuit diagram simulation as part of the system to validate the efficacy of the compiled code in accurately determining the density of vehicles in traffic. This simulation process involves several crucial steps visually depicted in the accompanying figures. Figure 5 illustrates the initial phase of the simulation, where a captured image is converted into greyscale, enabling real-time analysis of the traffic scenario. This step is essential for extracting relevant features and preparing the image for further processing.

In Figure 6, the processed image is presented, showcasing the results of the algorithm developed for vehicle detection. This algorithm analyses the image to identify vehicles within the frame using specific criteria such as shape, size, and motion patterns.

Figure 5 Captured image for actual results

Figure 6 Processed image (see online version for colours)

Figure 7 Console output



The console output, depicted in Figure 7, displays the actual count of vehicles detected on the road. In this particular example, the output reveals a count of 8 vehicles. This information accurately estimates the vehicle density based on the algorithm's image data analysis.

To further validate the system's performance, Figures 8–10 present additional examples demonstrating its ability to accurately count vehicles on the road. These examples prove the algorithm's consistent and reliable performance across traffic scenarios. These outcomes obtained from the simulation process confirm the successful implementation of the proposed algorithm within the system. The algorithm's ability to accurately estimate traffic density based on vehicle detection validates its potential for practical application in effectively monitoring and managing traffic flow.

Figure 8 Captured image for actual results

Figure 9 Processed image (see online version for colours)

Figure 10 Console output

Figures 8–10 display the number of nine vehicles with an accuracy greater than 90%.

Figure 11 depicts the real-time image the camera took for simulation purposes in vehicle classification. This system classifies car and bus types and can be adapted to identify additional vehicle categories, such as emergency vehicles and ambulances. If any lane is detected with an emergency vehicle, the green light will be activated for that lane, and vehicles will be permitted to proceed first.

Figure 12 shows the vehicles detected by the program feed in the system for vehicle count and density calculation in real-time.

Figure 11 Image captured by the camera (see online version for colours)

Figure 12 Vehicle detected by the program feed in the system (see online version for colours)

7 Conclusion

In Google Colab, the system utilises a powerful GPU, the NVIDIA Tesla V100. Python 3 code is executed on the GPU V100 by selecting the appropriate runtime type and enabling GPU acceleration. The proposed system is an intelligent traffic light control and monitoring solution that adjusts the green signal's duration based on traffic density. This approach ensures that the direction with the highest traffic flow receives a longer green signal time than the one with lower traffic. The proposed work significantly reduce delays, congestion, and waiting times, lowering fuel consumption and emissions.

The technology requires minimal investment, as it utilises live feeds from existing surveillance cameras installed at major intersections with heavy traffic in most cities. Therefore, there is no need for expensive hardware. Some cameras may require relocation or modification, but this is a minor issue. The system requires little maintenance compared to conventional traffic monitoring systems that rely on pressure mats, which are vulnerable to damage because they are placed on the road surface.

By managing traffic signals based on vehicle density, the suggested system reduces waiting times and traffic congestion, which can help manage traffic efficiently during peak hours.

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