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Smart Traffic Signal Management System: An AI-Powered Real-Time Traffic Monitoring and Adaptive Signal Control System

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Abstract - Traffic congestion is a major challenge in urban areas, particularly at road intersections where a large number of vehicles compete for limited road space. Conventional traffic signal systems generally operate using predefined time intervals, which do not always reflect the actual traffic conditions on the road. As a result, vehicles may wait unnecessarily on less congested roads while heavily congested roads continue to face long queues. To address this issue, this paper presents a Smart Traffic Signal Management System that uses artificial intelligence and computer vision techniques for real-time traffic monitoring and adaptive signal control. The proposed system uses camera-based video input to continuously observe traffic at a four-way intersection. A YOLO-based object detection model is used to identify and count vehicles from the captured video, while the detected vehicle information is analyzed to estimate the traffic density and queue level on each road. Based on the calculated traffic condition, the system dynamically determines the priority and duration of the green signal for different directions. This approach allows the signal timing to respond to changing traffic conditions instead of relying only on fixed schedules. The system also includes a monitoring interface through which authorized traffic personnel can observe vehicle counts, traffic density, signal status, and other relevant information. A manual override facility is provided to allow human intervention in situations where the automated detection system is affected by poor visibility, unusual traffic conditions, or other operational issues. The collected traffic information can be stored in a centralized database and used for generating periodic reports and analyzing traffic patterns. The proposed system was developed and tested in a controlled environment using traffic video data to evaluate its ability to detect vehicles and determine traffic density. The results demonstrate that an AI-assisted adaptive signal system can provide more responsive traffic management compared with conventional fixed-time signal operation. The system can potentially reduce unnecessary vehicle waiting time, improve the utilization of green signal periods, and provide traffic authorities with useful real-time information for intersection management.

Index Terms - Smart Traffic Signal Management, Artificial Intelligence, Computer Vision, YOLO, Vehicle Detection, Traffic Density Estimation, Adaptive Traffic Signals, Real-Time Traffic Monitoring, Intelligent Transportation System.

I. INTRODUCTION

The rapid growth of urban areas has resulted in a significant increase in the number of vehicles on roads. As the number of vehicles increases, traffic congestion has become a common problem, especially at busy road intersections. Long vehicle queues, unnecessary waiting time, and inefficient use of signal timings can lead to delays, increased fuel consumption, and additional air pollution. Managing traffic effectively therefore requires a system that can understand the actual traffic situation and respond accordingly. [8]

Traditional traffic signal systems generally work with fixed timing schedules. In such systems, the green, yellow, and red signal durations are usually decided in advance and remain the same even when the traffic density changes. For example, a road with only a few vehicles may continue to receive the same green-light duration as a road with a long queue of vehicles. This results in inefficient utilization of signal time and increases the waiting time of road users. Manual traffic monitoring can help in some situations, but continuously observing multiple roads and making timely decisions is difficult and requires significant human effort.

Recent developments in Artificial Intelligence (AI) and Computer Vision provide an opportunity to improve the way traffic is monitored and managed. Camera-based systems can capture real-time traffic conditions, while object detection algorithms can identify and count vehicles from video streams.

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By analyzing the number of vehicles and the traffic density on each side of an intersection, signal timings can be adjusted according to the current traffic conditions. This makes the traffic signal more responsive than a conventional fixed-time system. [1]

The proposed Smart Traffic Signal Management System is designed to monitor traffic conditions at a four-way road intersection using camera-based video input. A YOLO-based object detection model is used to detect vehicles and calculate the number of vehicles present on each road. The detected information is processed to estimate traffic density and determine which direction requires greater signal priority. Based on this analysis, the system can dynamically allocate green-light time to reduce unnecessary waiting and improve the movement of vehicles through the intersection. [7]

In addition to automatic signal management, the system provides a monitoring interface for authorized traffic personnel. The interface can display vehicle counts, traffic density, signal status, and other relevant traffic information. A manual override option is also included so that traffic personnel can take control when the automated system is unable to make an appropriate decision or when special traffic conditions occur. This combination of automated analysis and human control provides greater flexibility in practical traffic management.

The system can also maintain traffic-related information in a centralized database. This information can be used for monitoring, record maintenance, and generating periodic reports for further analysis. By combining real-time vehicle detection, traffic-density estimation, adaptive signal control, and centralized monitoring, the proposed system aims to provide a practical approach to intelligent traffic management.

The main objective of this work is not simply to replace existing traffic signals, but to make signal control more responsive to actual road conditions. The proposed approach can help reduce unnecessary waiting time, improve the utilization of available green-light periods, and provide traffic authorities with useful information for making better traffic management decisions. The system demonstrates how AI and computer vision can be applied to address a practical transportation problem and contribute toward the development of smarter and more efficient urban traffic management systems.

II. PROBLEM STATEMENT

The increasing number of vehicles on urban roads has made traffic congestion a major issue, particularly at busy intersections. Most conventional traffic signal systems operate using fixed time intervals, where the signal duration is decided in advance without considering the actual number of vehicles waiting on each road. This approach may work under normal traffic conditions, but it becomes inefficient when traffic volume changes frequently throughout the day. [9]

At a four-way intersection, one road may have a long queue of vehicles while another road may have only a few vehicles. However, with a fixed-time signal system, both roads may receive similar green-light durations. As a result, vehicles on the heavily congested road have to wait longer, while the green signal on a less busy road may remain active even when there are very few vehicles. This leads to unnecessary waiting time, longer queues, fuel consumption, and increased traffic congestion. [15]

Another major problem is the difficulty of continuously monitoring traffic manually. Traffic personnel cannot always accurately observe and count vehicles on all roads at the same time, especially during peak hours or in busy intersections. Manual monitoring also makes it difficult to collect consistent traffic data for later analysis and reporting. [6]

Therefore, there is a need for a traffic signal management system that can automatically observe the current traffic condition, detect and count vehicles, estimate the traffic density on each road, and adjust signal timings according to the actual traffic situation. The system should also provide traffic authorities with real-time information and allow manual intervention when required. [5],

The proposed Smart Traffic Signal Management System addresses these issues by using artificial intelligence and computer vision to analyze traffic video, detect vehicles, calculate traffic density, and support dynamic signal control. The system aims to make signal timing more responsive to real-time traffic conditions rather than depending entirely on predefined timings. This can help improve traffic flow, reduce unnecessary waiting, and provide a more efficient method for managing vehicles at road intersections.

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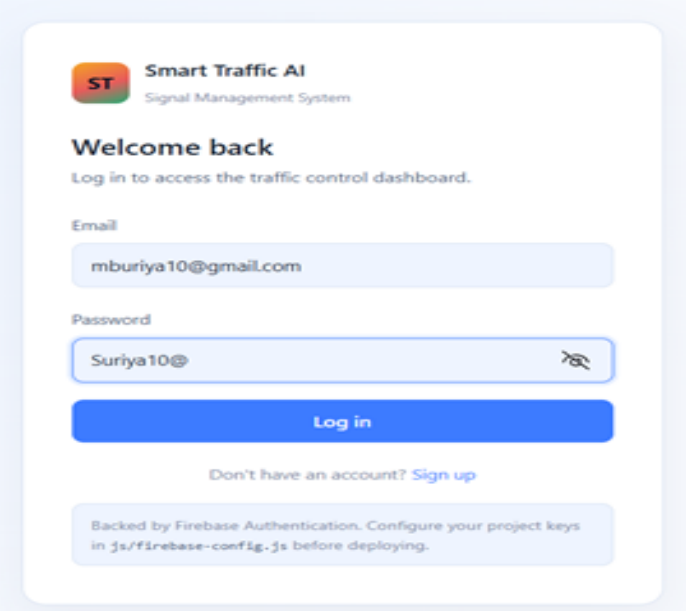


Fig 1: login Page

III. PROPOSED SYSTEM

The proposed Smart Traffic Signal Management System is designed to overcome the limitations of conventional fixed-time traffic signals by using artificial intelligence and computer vision to monitor traffic conditions in real time. Instead of providing the same signal duration regardless of the number of vehicles present, the proposed system analyzes the traffic on each road and adjusts the signal timing based on the current traffic situation. [10]

The system uses cameras to capture live or recorded video of a four-way road intersection. The captured video is processed using a YOLO-based object detection model to identify vehicles such as cars, buses, trucks, motorcycles, and other road vehicles. The detected vehicles are counted for each direction, and the vehicle count is used to estimate the traffic density. This allows the system to identify which road has a higher traffic load and requires a longer green signal. [1],

Based on the calculated traffic density, the system determines the priority of each direction and assigns an appropriate green-light duration. Roads with higher traffic density can receive more green time, while roads with lower traffic density can receive a shorter duration. After the green phase is completed, the system follows the required yellow and red signal phases before moving to the next direction. This process continues according to the changing traffic conditions. [4]

The proposed system also provides a real-time monitoring interface for authorized traffic personnel. The interface can display the number of detected vehicles, traffic density, current signal status, and the direction currently receiving the green signal. This gives traffic authorities a clear view of the intersection without depending completely on manual vehicle counting.

A manual override facility is included as an additional safety and control feature. If the camera fails to detect vehicles correctly, unusual traffic conditions occur, or an emergency requires direct control, authorized personnel can manually control the traffic signal. This ensures that the system does not depend entirely on automated decision-making.

The system can maintain important traffic information in a centralized database. Vehicle counts, traffic-density information, signal activities, and other relevant records can be stored for monitoring and future analysis. Periodic reports can also be generated to help authorities understand traffic patterns and identify frequently congested directions. [17]

The overall proposed system consists of traffic video acquisition, vehicle detection, vehicle counting, traffic-density estimation, signal timing calculation, adaptive signal control, real-time monitoring, manual override, and data storage. By combining these components, the system provides a practical and flexible approach to traffic signal management. The main purpose of the proposed system is to make traffic signals respond to actual road conditions, thereby improving traffic movement and reducing unnecessary vehicle waiting at intersections. [2],

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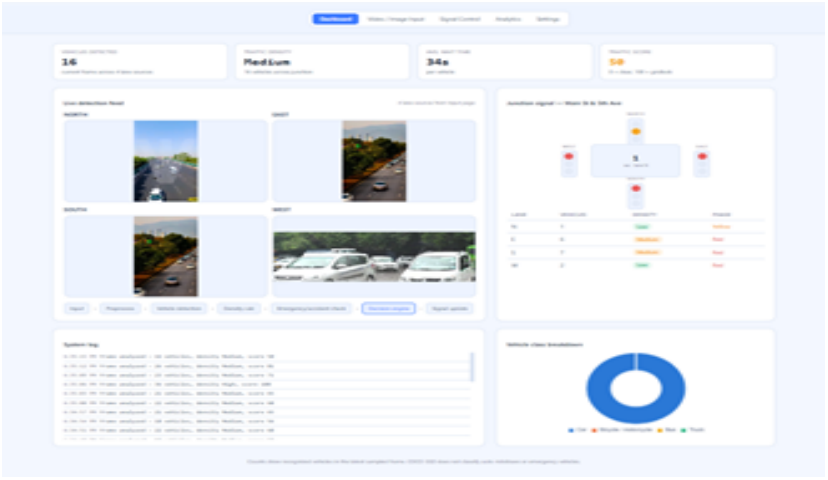


Fig 2 : Dashboard

IV. ADMINISTRATIVE STRUCTURE

The proposed Smart Traffic Signal Management System includes an administrative structure to ensure that the system can be monitored, controlled, and maintained properly. Since traffic signal management involves both automated decision-making and human supervision, the system provides different levels of access for different types of users.

The System Administrator is responsible for managing the overall application and its configuration. The administrator can manage authorized users, maintain system settings, monitor the operation of the traffic detection system, and access stored traffic information. This level of access helps ensure that only authorized personnel can make important changes to the system.

The Traffic Police or Traffic Control Officer is responsible for monitoring the traffic conditions at the intersection. Through the monitoring interface, the officer can view vehicle counts, traffic density, current signal status, and the direction receiving the green signal. The officer can also use the manual override option when required, particularly during emergencies, unusual traffic conditions, roadblocks, or situations where automatic vehicle detection does not provide reliable results.

The system can also provide access to Higher-Level Officials, such as department heads or authorized supervisory personnel, for reviewing traffic records and generated reports. These users can analyze stored traffic information, observe traffic patterns, and review periodic reports without directly modifying the operational settings of the traffic signal system.

The administrative structure can therefore be organized into three main levels:

1) System Administrator – Manages users, system configuration, database records, and overall system operation.

2) Traffic Control Officer – Monitors real-time traffic conditions and operates the manual signal control when necessary.

3) Higher-Level Officials – Review traffic data, reports, and system performance for administrative and planning purposes.

This role-based structure helps maintain proper access control and prevents unauthorized users from changing critical traffic signal settings. It also ensures that automated traffic management remains under human supervision, providing a balance between AI-based decision-making and practical traffic control requirements.



Fig 3 : Signal Output

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V. SYSTEM ARCHITECTURE

The Smart Traffic Signal Management System follows a modular architecture in which traffic information is collected from cameras, processed using artificial intelligence, and used to support adaptive traffic signal control. The architecture is designed to allow continuous monitoring of a four-way intersection while also providing traffic authorities with access to real-time information and manual control when required. [17]

The first layer of the system is the Traffic Data Acquisition Layer. Cameras are positioned to monitor the different directions of the intersection. The cameras provide live or recorded video containing the vehicles moving through each road. The captured video acts as the primary input for the vehicle detection process. [11]

The second layer is the Vehicle Detection and Processing Layer. The video frames are processed using a YOLO-based object detection model. The model identifies vehicles present in each frame and provides the required detection information. The system then counts the detected vehicles for each direction. This information is continuously updated as new video frames are processed. [7]

The third layer is the Traffic Density Analysis Layer. The detected vehicle counts are analyzed to determine the traffic condition of each road. Based on the number of vehicles and the estimated queue or density level, the system identifies roads with low, medium, or high traffic conditions. This analysis forms the basis for deciding the priority of the traffic signals. [16]

The fourth layer is the Adaptive Signal Control Layer. The traffic-density information is provided to the signal-control module, which determines the appropriate green-light duration for each direction. A road with higher traffic density can be assigned a longer green duration, while a road with lower traffic density can receive a shorter duration. The system continues to repeat this process as traffic conditions change. [2], [3], [4], [8], [10]

The fifth layer is the Monitoring and Administrative Layer. A monitoring interface allows authorized users to observe vehicle counts, traffic density, signal status, and other system information. Traffic officers can monitor the intersection in real time and use the manual override facility when automatic control is not suitable. Different levels of administrative access can be provided to ensure that critical system functions are available only to authorized personnel.

The final layer is the Database and Reporting Layer. Important information such as vehicle counts, traffic-density values, signal activities, user details, and system records can be stored in a centralized database. The stored information can be used to generate periodic reports and analyze traffic conditions over time. [14], [17]

The overall architecture can be represented as:

Camera / Video Input → Vehicle Detection (YOLO) → Vehicle Counting → Traffic Density Analysis → Signal Timing Decision → Adaptive Traffic Signal → Real-Time Monitoring → Database & Reports

This architecture allows the proposed system to combine AI-based vehicle detection, real-time traffic analysis, adaptive signal control, database management, and human supervision within a single traffic management platform. [7]

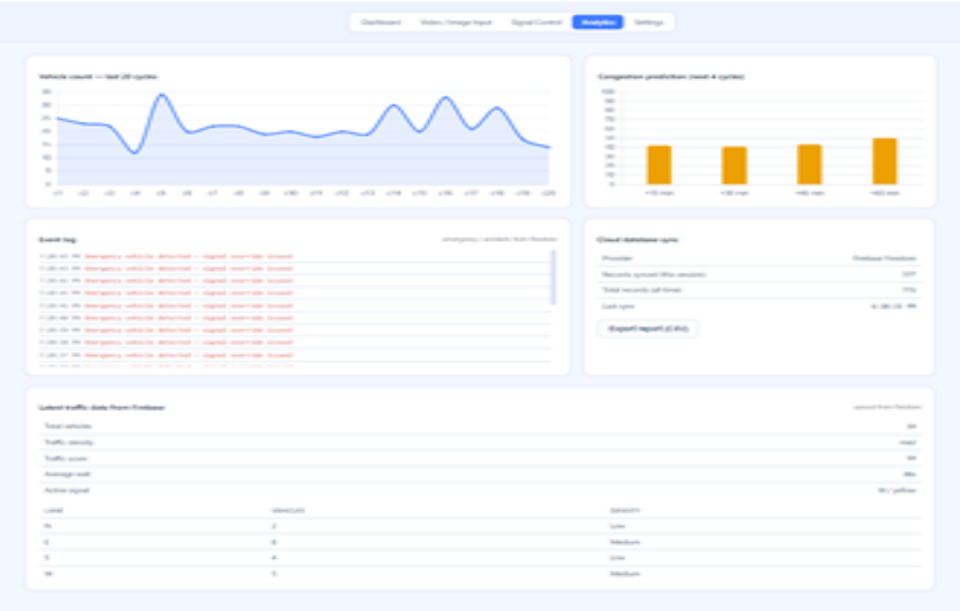


Fig 4 : Analytics Page

VI. AI-ASSISTED FEATURES

The Smart Traffic Signal Management System uses artificial intelligence and computer vision to improve the monitoring and management of traffic at road intersections. Instead of depending completely on manual vehicle counting, the system automatically analyzes traffic video and provides useful information for signal control. The AI-assisted features are mainly focused on vehicle detection, vehicle counting, traffic-density estimation, and adaptive signal decision-making. [13]

1) AI-Based Vehicle Detection

The system uses a YOLO (You Only Look Once) based object detection model to identify vehicles from camera footage. The model processes the video frames and detects vehicles present on each road. Bounding boxes are generated around the detected vehicles, allowing the system to identify and count them automatically. [7]

2) Automatic Vehicle Counting

After detecting vehicles, the system calculates the number of vehicles present in each direction of the intersection. This removes the need for traffic personnel to manually count vehicles. The vehicle count is continuously updated as new frames are processed, providing a better representation of the current traffic situation. [11]

3) Traffic Density Estimation

The detected vehicle information is used to estimate the traffic density of each road. The system compares the number of vehicles in different directions and identifies roads experiencing relatively higher or lower traffic. This information helps the system understand where traffic congestion is developing. [15], [16]

4) Intelligent Signal Timing

The traffic-density information is used to support the selection of suitable signal timings. When one direction has considerably more vehicles than the others, the system can allocate a longer green-light duration to that direction. Similarly, roads with lower traffic can receive comparatively less green time. This allows the signal operation to respond to changing traffic conditions rather than following only fixed timings. [10]

5) Real-Time Traffic Analysis

The AI model can analyze traffic continuously from the available camera feed. As the number of vehicles changes, the traffic information is updated accordingly. This provides the system with a real-time view of the intersection and allows signal decisions to be adjusted when traffic conditions change. [14]

6) Congestion Identification

By analyzing vehicle counts and traffic density, the system can identify directions where vehicle queues are increasing. Such information can be used to recognize potentially congested areas and give appropriate priority during signal control. [15]

7) Human-Assisted Decision Making

The system is designed to support traffic personnel rather than completely replace human control. If vehicle detection is affected by poor camera visibility, unusual traffic situations, emergencies, or other unexpected conditions, an authorized traffic officer can use the manual override option. This provides a practical combination of automated analysis and human supervision.

8) AI-Based Traffic Data Support

The information generated by the AI module, including vehicle counts and traffic-density values, can be stored in the system database. These records can later be used for monitoring, report generation, and understanding traffic patterns at the intersection. [14]

Overall, the AI-assisted features allow the proposed system to observe traffic automatically, detect and count vehicles, estimate traffic density, and support adaptive signal control. The combination of artificial intelligence with human supervision makes the system more flexible than a conventional fixed-time traffic signal system.

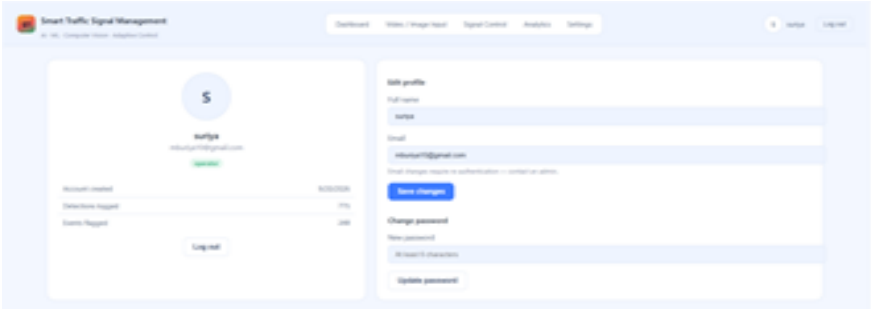


Fig 5 : Setting Page

VII. METHODOLOGY

The methodology of the proposed Smart Traffic Signal Management System is based on continuously monitoring traffic conditions, detecting vehicles using computer vision, estimating traffic density, and adjusting signal timings according to the observed traffic. The system combines automated AI-based processing with human supervision to provide a practical solution for managing traffic at a four-way intersection. [11]

1) Traffic Video Collection

The first step is to obtain traffic video from cameras positioned to cover the different directions of the intersection. The system can work with either live camera footage or previously recorded traffic videos. The video provides the input required for detecting and analyzing vehicles.

2) Video Frame Processing

The captured video is divided into individual frames for processing. Each frame is passed to the vehicle detection module. Basic image-processing operations may be applied when required to improve the quality of the input and provide suitable frames for detection.

3) Vehicle Detection Using YOLO

A YOLO-based object detection model is used to identify vehicles in the processed video frames. The model detects different vehicle classes and places bounding boxes around the detected objects. The detection results are then used to determine the number and location of vehicles on each side of the intersection.

4) Vehicle Counting

The detected vehicles are counted separately for each direction of the four-way intersection. The system continuously updates the vehicle count as new frames are analyzed. This provides a real-time estimate of the number of vehicles waiting or moving through each road.

5) Traffic Density Calculation

The vehicle counts obtained from the detection stage are analyzed to determine the traffic density of each direction. The system compares the traffic conditions between the four roads and identifies the direction with relatively higher traffic. The density information can be categorized into levels such as **low, medium, and high**, depending on the implementation.

6) Signal Timing Decision

After estimating the traffic density, the system determines the priority of the different directions. The direction with higher traffic can be assigned a longer green-light duration, while a direction with lower traffic can receive a shorter duration. The signal controller follows the required sequence of green, yellow, and red phases to maintain safe signal operation. [10]

7) Adaptive Signal Control

The calculated signal timings are applied to the traffic signal control process. Unlike a conventional fixed-time system, the proposed approach updates the signal decision according to the current traffic condition. When traffic conditions change, the system can recalculate the vehicle density and modify the subsequent signal timing accordingly. [4]

8) Real-Time Monitoring

A monitoring interface is provided for authorized traffic personnel. The interface can display the detected vehicle count, traffic density, current signal status, and the direction receiving the green signal. This allows the operator to understand the current condition of the intersection without manually counting vehicles.

9) Manual Override

Although the system performs automatic traffic analysis, human control is retained for situations where automated operation may not be appropriate. An authorized traffic officer can use the manual override facility during emergencies, unusual traffic conditions, camera problems, or incorrect detection. This provides an additional level of control and safety.

10) Data Storage and Reporting

The relevant traffic information generated by the system can be stored in a centralized database. Records such as vehicle counts, traffic-density levels, signal activities, and system events can be maintained for future reference. These records can also be used to generate periodic reports and study traffic patterns over a period of time. [14], [17]

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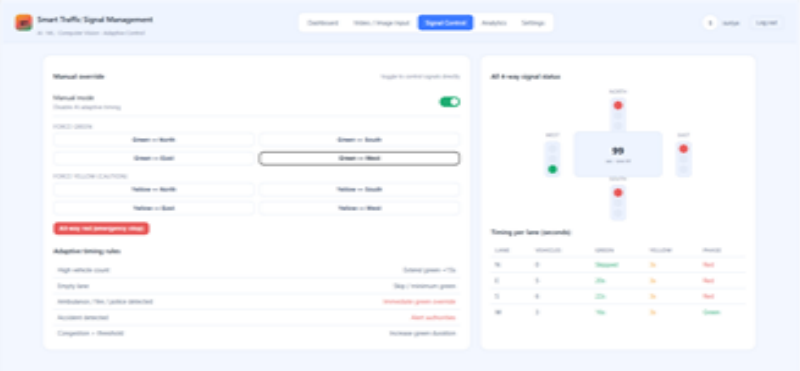


Fig 6 : Manual Control Of Traffic Signal

VIII. FLOW CHART

The process begins when the camera captures traffic video from the intersection. The video is divided into frames and processed by the YOLO-based vehicle detection model. The detected vehicles are counted separately for each direction of the four-way intersection. The system then uses these counts to estimate the traffic density and compare the traffic conditions between the different roads. [11]

If one direction has a higher traffic density, the system gives that direction greater priority and calculates a suitable green-light duration. After the green phase, the signal changes to yellow and then red before the next direction is considered. The traffic condition is continuously monitored because the number of vehicles can change at any time.

The system also checks whether manual intervention is required. If an authorized traffic officer needs to take control because of an emergency, unusual traffic condition, or detection problem, the manual override facility can be used. Otherwise, the system continues with automatic signal management.

Finally, relevant traffic information such as vehicle counts, traffic density, and signal activity can be stored in the database. The system then returns to the monitoring stage and repeats the process continuously. This makes the proposed system a **continuous, adaptive, and AI-assisted traffic signal management process**.



Fig 7 : Flowchart

IX. CONCLUSION AND FUTURE SCOPE

A. Conclusion

The proposed Smart Traffic Signal Management System provides an AI-based approach for monitoring and managing traffic at road intersections. The system uses camera-based video input and a YOLO-based object detection model to identify and count vehicles on different roads. The detected vehicle information is used to estimate traffic density and support the selection of suitable signal timings. [1]

Unlike conventional fixed-time traffic signals, the proposed system considers the current traffic condition while deciding signal priority. This can help reduce unnecessary waiting time on roads with higher vehicle density and make better use of the available green-light duration. The real-time monitoring interface also allows authorized traffic personnel to observe vehicle counts, traffic density, and signal status from a single platform. [10]

The inclusion of a manual override facility provides an important layer of human control when the automated system is affected by camera limitations, unusual traffic conditions, emergencies, or other unexpected situations. The ability to store traffic information in a centralized database also provides useful data for monitoring, reporting, and future traffic analysis.

Overall, the system demonstrates the practical use of Artificial Intelligence, Computer Vision, and adaptive signal control for improving traffic management. Although the system is primarily developed and evaluated in a controlled environment, the approach provides a foundation for developing more advanced intelligent traffic management solutions.

B. Future Scope

The proposed system can be further improved and expanded in several ways:

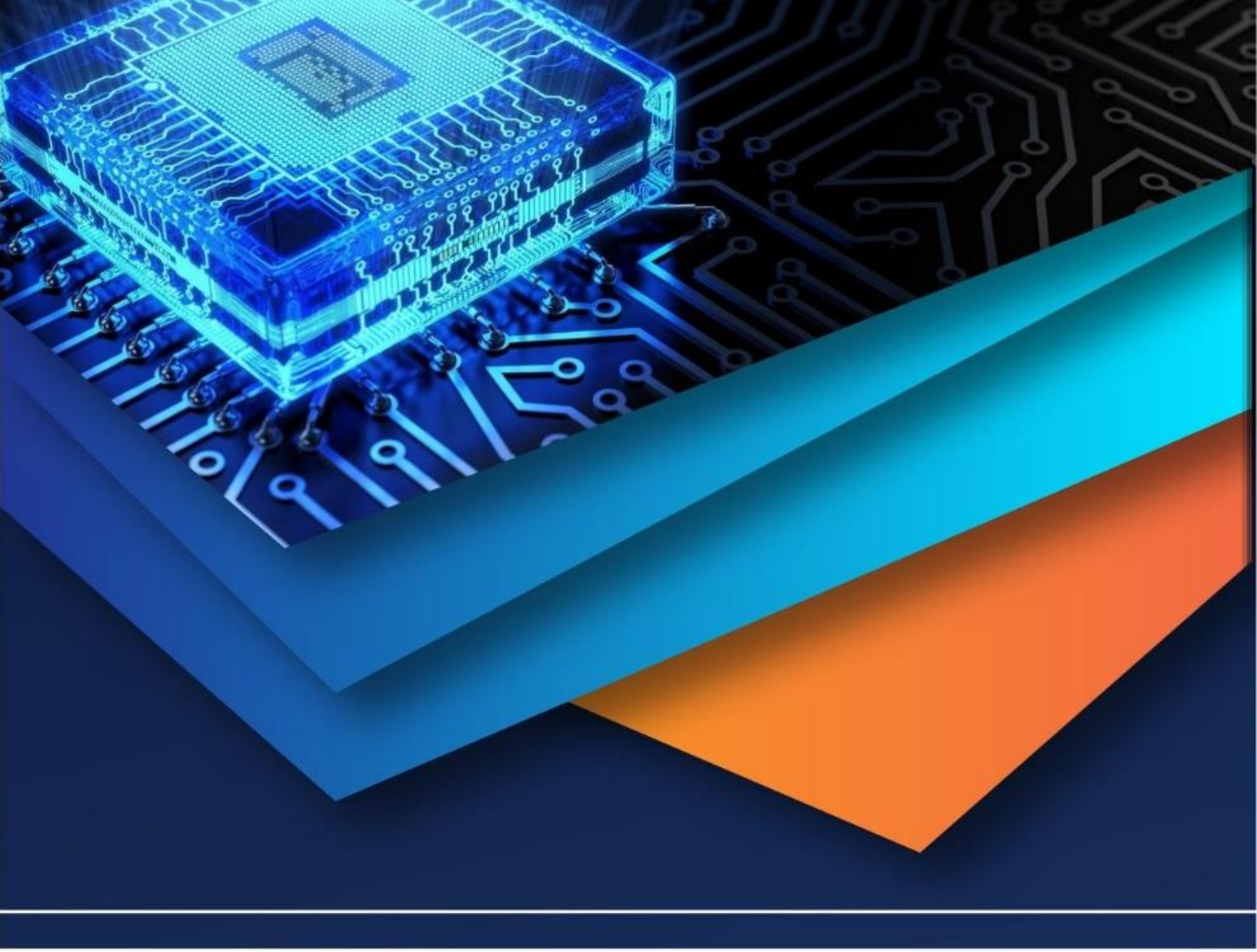
1) Live CCTV Integration: The system can be connected directly to existing traffic surveillance cameras for continuous real-time monitoring.
2) Advanced Vehicle Classification: Future versions can classify vehicles into cars, buses, trucks, motorcycles, and emergency vehicles to improve traffic analysis.
3) Emergency Vehicle Priority: Ambulances, fire engines, and police vehicles can be detected and given priority to reduce their travel delay during emergencies.
4) Improved Traffic Prediction: Machine learning models can be trained using historical traffic data to predict congestion before it becomes severe.
5) Multi-Junction Coordination: Multiple traffic signals can be connected so that signal timings are coordinated across several nearby intersections.
6) Automatic Incident Detection: The system can be extended to identify accidents, stalled vehicles, road blockages, or abnormal traffic conditions.
7) Weather and Visibility Analysis: Weather conditions such as heavy rain, fog, or poor visibility can be considered when making traffic-management decisions.
8) Mobile and Web-Based Alerts: Traffic authorities can receive notifications about unusual congestion, system failures, or emergencies through a mobile or web application.
9) Edge-Based Processing: AI processing can be performed closer to the camera using edge devices, reducing network dependency and improving response time.
10) Large-Scale Deployment: After further testing with real-world traffic data, the system can be adapted for deployment at busy intersections and integrated with existing intelligent transportation infrastructure.

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