



AI-DRIVEN ADAPTIVE TRAFFIC MANAGEMENT SYSTEM

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Abstract:

Traffic congestion has become a significant problem in urban areas as the number of vehicles continues to increase. Conventional traffic signals generally operate using predefined timing schedules and do not respond to the actual traffic conditions at an intersection. This can lead to unnecessary waiting, inefficient use of road infrastructure, increased fuel consumption, and congestion.

This paper presents an AI-Driven Adaptive Traffic Management System that adjusts traffic signal timing according to the number of vehicles detected in real time. A camera captures the traffic scene, and the video frames are processed using OpenCV and the YOLOv8 object detection model. Vehicles detected within predefined Regions of Interest (ROIs) are counted to estimate the traffic density in different directions. Based on these counts, an adaptive decision module determines the appropriate green signal duration for each traffic phase.

The generated control decisions are transmitted to ESP32 microcontrollers, which operate the physical miniature traffic signals. The proposed prototype combines computer vision, artificial intelligence, and embedded control to demonstrate a low-cost approach to adaptive traffic signal management. The system is intended to improve traffic flow by allocating signal time according to the observed traffic density.

Keywords: Artificial Intelligence, YOLOv8, OpenCV, ESP32, Computer Vision,.

**Introduction:**

The rapid growth of urban populations and the increasing use of private and commercial vehicles have made traffic congestion a major challenge for modern cities. Many conventional traffic signal systems operate using fixed timing plans, in which each direction receives a predetermined green signal duration. Since these timings remain unchanged regardless of the actual number of vehicles, the system may not efficiently handle continuously changing traffic conditions. During periods of uneven traffic distribution, one direction may experience long queues while another direction receives green time despite having fewer vehicles.

Advances in artificial intelligence, deep learning, and computer vision have created new possibilities for improving traffic monitoring and signal control. Object detection techniques can analyze video captured by cameras and identify vehicles present at an intersection. The YOLO family of object detection models is suitable for such applications because it can perform object detection with relatively fast inference. YOLOv8, when used together with OpenCV, can support the detection and counting of vehicles from video frames.

The proposed AI-Driven Adaptive Traffic Management System uses a vision-based approach to monitor a four-way miniature intersection. A USB webcam captures the traffic scene, while Python and OpenCV process the incoming video frames. The YOLOv8 model identifies vehicles, and four predefined Regions of Interest represent the North, South, East, and West approaches. The number of vehicles detected in these regions is used as an indicator of traffic density.

The system combines the North and South directions into one traffic phase and the East and West directions into another phase. The phase with comparatively higher traffic density is allocated an appropriate green signal duration, while the other phase receives a shorter duration. The resulting control commands are sent through Wi-Fi to two ESP32 DevKit V1 boards, which operate the corresponding traffic signal modules.

Unlike systems that depend on road-embedded sensing devices, the proposed prototype uses camera-based vehicle observation and embedded controllers. This approach demonstrates how AI-based vehicle detection and adaptive decision-making can be integrated into a traffic signal prototype.

The main objective of this work is to develop a cost-effective adaptive traffic management prototype that uses real-time vehicle detection to determine traffic signal timing. The project demonstrates the integration of computer vision, deep learning, and embedded systems for adaptive traffic control.

Literature Survey:

1. M. Lamrabet, M. A. Chentoufi, and R. Ellaia (2026) proposed an emergency-aware adaptive traffic signal control system using YOLO-based emergency vehicle detection and SUMO simulation. The study focused on providing signal priority based on detected emergency



conditions and demonstrated improvements in traffic signal efficiency and congestion management.

2. A. S. Alhazmi, A. Hamza, and A. Moubayed (2026) conducted a comparative study of different YOLO models for adaptive traffic signal control. The models were evaluated based on detection accuracy, inference speed, and computational efficiency. The study reported that YOLOv8 provided a good balance between these parameters for real-time traffic applications.
3. X. Han, Z. Qu, and S. Xia (2026) developed a Teacher–Student Adversarial YOLO model for traffic object detection under adverse environmental conditions. Their approach used domain adaptation techniques to improve vehicle detection performance in challenging conditions such as fog, rain, and low-light environments.
4. W. Song, J. Min, and J. Zhang (2026) proposed an adaptive multi-convolutional kernel fusion-based YOLO network for traffic object detection. The model used cross-scale feature fusion to improve the identification of small and distant vehicles while maintaining real-time detection capability.
5. N. L. Byenkya, N. Rose, and O. Nixson (2026) introduced a YOLOv11-based object detection system with continuous learning for dynamic road environments. The model was updated using newly collected road data, which improved its adaptability and robustness under changing traffic conditions.
6. L. Lyu, S. I. Guler, and V. V. Gayah (2026) proposed an adaptive action selection strategy based on reinforcement learning for intelligent traffic signal control. The system dynamically selected signal actions according to traffic conditions and achieved reductions in vehicle delay and queue length.
7. L. Li, Y. Zhao, Z. Zhou, and H. K. Lo (2026) developed an end-to-end traffic signal control approach based on fixed-location detector occupancy patterns. Deep learning techniques were used to optimize signal control under uncertain traffic demand, resulting in improved intersection performance.
8. H. Wang et al. (2026) presented an adaptive traffic signal control method based on Multi-Agent Soft Actor-Critic reinforcement learning. The approach enabled cooperation among multiple intersections and improved traffic throughput while reducing congestion.
9. M. Raza, M. Kazmi, H. M. Kidwai, H. R. Khan, S. A. Qazi, K. Arshad, and K. Assaleh (2025) developed a real-time adaptive traffic light control system using YOLO-based vehicle detection and Passenger Car Equivalent (PCE)-aware density estimation. Their approach dynamically adjusted traffic signal timings and helped reduce average traffic delay.
10. O. A. Ayegbusi, A. O. Akinwumi, O. L. Ogbeide, A. O. Akingbesote, J. R. Obafemi, O. D. Akinrolabu, and O. Rotiba (2025) proposed a deep learning-based traffic signal control system using the YOLO algorithm for vehicle detection. The detected traffic conditions were used to support adaptive signal operation, resulting in improved traffic flow and reduced vehicle



waiting time.

11. S. Shirulkar, R. Makode, and R. Khandelwal (2025) presented an adaptive traffic signal management system based on real-time vehicle detection and tracking. Computer vision techniques were used to estimate traffic density, and the signal timing was adjusted accordingly. The system improved intersection efficiency compared with conventional fixed-time signal systems.
12. M. Ravichandran, K. Laxmikant, and A. Muthu (2024) developed a smart traffic control system using YOLOv8 for real-time lane-wise vehicle detection. OpenCV was used along with the detection model to estimate traffic density and dynamically manage traffic signal timing.
13. S. Papanashi, M. Chadaga, R. Kshithi, S. S. Huddar, K. Sreelakshmi, and P. Ramakanth Kumar (2024) proposed an adaptive traffic signal timing approach using YOLOv10 and computer vision. The system analyzed traffic footage to estimate vehicle density and dynamically optimized the duration of traffic signals, improving traffic movement and reducing congestion.
14. R. Mahadshetti, J. Kim, and T.-W. Um (2024) developed Sign-YOLO, an attention-based YOLOv7 model for traffic sign detection. The proposed approach improved detection accuracy under varying weather, lighting, and occlusion conditions.
15. C.-Y. Wang, A. Bochkovski, and H.-Y. M. Liao (2023) introduced YOLOv7, an advanced real-time object detection model incorporating trainable bag-of-freebies techniques. The model achieved high detection accuracy while maintaining fast inference performance.
16. G. Jocher, A. Chaurasia, and J. Qiu (2023) presented the Ultralytics YOLO framework, which introduced efficient object detection capabilities including anchor-free detection and improved training strategies. The framework provided improved detection accuracy and faster inference, making it suitable for real-time applications.
17. K. F. L. Chu, A. Y. S. Lam, and V. O. K. Li (2022) proposed an end-to-end off-policy deep reinforcement learning approach for traffic signal control. Their method optimized traffic signal decisions dynamically and demonstrated improved signal performance with reduced traffic delay.
18. A. Haydari and Y. Yilmaz (2022) conducted a survey on deep reinforcement learning applications in intelligent transportation systems. The study identified reinforcement learning as a promising approach for traffic signal control, traffic prediction, and autonomous transportation applications.
19. S. Li, W. Deng, and Z. Liu (2020) proposed a deep adaptive traffic signal controller based on reinforcement learning. The system used spatial-temporal traffic state information and long-term planning to optimize signal control. The results showed reduced vehicle delay and improved traffic efficiency compared with conventional fixed-time traffic signal systems.

**Table 1 Comparative review of AI-Driven Adaptive Traffic Management System**

Sr.no	Authors	Year	Title	Journal/ Conference	Methodology	Findings
1	M. Lamrabet, M. A. Chentoufi, and R. Ellaia	2026	Emergency-Aware Adaptive Traffic Signal Control Using YOLO-Based Light-Bar Detection and SUMO System-Level Validation	IEEE Access	YOLO-based emergency vehicle detection integrated with SUMO traffic simulation for adaptive signal priority and intelligent traffic management.	Improved emergency vehicle response time, reduced traffic congestion, and enhanced traffic signal efficiency.
2	A. S. Alhazmi, A. Hamza, and A. Moubayed	2026	Edge-Enabled Detection for Adaptive Traffic Signal Control: A Comparative Study of YOLO-Based Models in Intelligent Transportation Networks	Transportation Research Procedia	Compared multiple YOLO models deployed on edge devices for real-time vehicle detection by evaluating accuracy, inference speed, and computational efficiency.	YOLOv8 demonstrated the best balance between detection accuracy, inference speed, and computational efficiency for edge deployment.
3	X. Han, Z. Qu, and S. Xia	2026	Teacher–Student Adversarial YOLO for Domain Adaptive Detection in Traffic Scenes Under Adverse Weather	Displays (Elsevier)	Proposed a Teacher–Student Adversarial YOLO with CycleGAN and domain adaptation for adverse-weather traffic detection.	Improved vehicle detection accuracy in fog, rain, and low-light traffic scenes.
4	W. Song, J. Min, and J. Zhang	2026	Adaptive Multi-Convolutional Kernel Fusion-Based YOLO Network via Hybrid Cross-Scale Head for Traffic Object Detection	Expert Systems with Applications	Developed AMKF-YOLO using hybrid cross-scale feature fusion and adaptive convolution kernels.	Improved detection of small and distant vehicles while maintaining real-time performance.
5	N. L. Byenkya, N. Rose, and O. Nixon	2026	Adaptive Object Detection in Dynamic Road Environments	Discover Artificial Intelligence (Springer)	Implemented YOLOv11 with continuous learning to update the detection	Increased robustness and detection accuracy in dynamic road environments.



			Using YOLOv11 with Continuous Learning for Real-Time Obstacle Detection		model using newly collected road data.	
6	L. Lyu, S. I. Guler, and V. V. Gayah	2026	Adaptive Action Selection Strategy of Reinforcement Learning Approach for Intelligent Traffic Light Control	IEEE Transactions on Intelligent Transportation Systems	Developed a reinforcement learning-based adaptive traffic signal controller using an adaptive action selection strategy to optimize signal timing dynamically.	Reduced average vehicle delay and queue length while improving overall traffic flow.
7	L. Li, Y. Zhao, Z. Zhou, and H. K. Lo	2026	An End-to-End Traffic Signal Control Approach Driven by Fixed-Location Detector Occupancy Patterns Under Demand Uncertainty	IEEE Transactions on Intelligent Transportation Systems	Used detector occupancy data and deep learning to perform end-to-end adaptive traffic signal optimization under uncertain traffic demand.	Achieved robust traffic signal control under uncertain traffic demand and improved intersection performance.
8	H. Wang <i>et al.</i>	2026	Adaptive Traffic Signal Control Based on Multi-Agent Soft Actor-Critic	IEEE Internet of Things Journal	Applied Multi-Agent Soft Actor-Critic deep reinforcement learning for cooperative adaptive signal control across multiple intersections.	Increased traffic throughput and reduced congestion across multiple intersections.
9	M. Raza, M. Kazmi, H.M. Kidwai, H. R. Khan, S. A. Qazi, K. Arshad, and K. Assaleh	2025	An Edge-Deployed Real-Time Adaptive Traffic Light Control System Using YOLO-Based Vehicle Detection and	IEEE Access	Used YOLO for vehicle detection, Passenger Car Equivalent (PCE) estimation, and edge computing to dynamically adjust traffic	Reduced average traffic delay and improved adaptive signal timing accuracy.



			PCE-Aware Density Estimation		signal timings.	
10	O.A. Ayegbusi, A. O. Akinwumi, O. L. Ogbeide, A. O. Akingbesote, J. R. Obafemi, O. D. Akinrolabu, and O. Rotiba	2025	A Deep Learning-Based Model for Traffic Signal Control Using the YOLO Algorithm	International Journal of Computer Applications	Applied YOLO for vehicle detection and adaptive traffic signal control.	Reported approximately 27% improvement in traffic flow and nearly 50% reduction in waiting time.
11	S. Shirulkar, R. Makode, and R. Khandelwal	2025	Adaptive Traffic Signal Management Using Real-Time Vehicle Detection and Tracking	IEEE IATMSI 2025	Vehicle detection and tracking using computer vision followed by adaptive traffic signal timing based on traffic density estimation.	Reduced waiting time and improved intersection traffic efficiency compared to fixed-time systems.
12	M. Ravichandran, K. Laxmikant, and A. Muthu	2024	Smart Traffic Control: Adaptive Signal Management Based on Real-Time Lane Detection Using YOLOv8	IEEE AUTOCOM 2024	Applied YOLOv8 and OpenCV for lane-wise vehicle detection and dynamic signal timing based on vehicle density.	Achieved accurate vehicle detection and efficient dynamic traffic signal management.
13	S. Papanashi, M. Chadaga, R. Kshithi, S. S. Huddar, K. Sreelakshmi, and P. Ramakanth Kumar	2024	Adaptive Traffic Signal Timing: Leveraging YOLOv10 and Computer Vision for Real-Time Optimization	IEEE CSITSS 2024	Used YOLOv10 with computer vision to estimate traffic duration in real time.	Improved traffic flow and reduced congestion through dynamic signal optimization.
14	R. Mahadshetti, J. Kim, and	2024	Sign-YOLO: Traffic Sign Detection Using	IEEE Access	Enhanced YOLOv7 with an attention	Improved detection accuracy under varying weather,



	T.-W. Um		Attention-Based YOLOv7		mechanism for robust traffic sign detection.	lighting, and occlusion conditions.
15	C.-Y. Wang, A. Bochkovskiy, and H.-Y. M. Liao	2023	YOLOv7: Trainable Bag-of-Freebies Sets New State-of-the-Art for Real-Time Object Detectors	IEEE/CVF CVPR 2023	Proposed an improved YOLO architecture using trainable bag-of-freebies for high-speed, high-accuracy real-time object detection.	Achieved state-of-the-art object detection accuracy while maintaining real-time performance.
16	G. Jocher, A. Chaurasia, and J. Qiu	2023	YOLO by Ultralytics	Ultralytics Documentation / GitHub	Introduced the YOLOv8 framework featuring anchor-free object detection, improved training strategies, and efficient real-time inference.	Improved detection accuracy, faster inference speed, and efficient deployment for real-time applications.
17	K. F. L. Chu, A. Y. S. Lam, and V. O. K. Li	2022	Traffic Signal Control Using End-to-End Off-Policy Deep Reinforcement Learning	IEEE Transactions on Intelligent Transportation Systems	Developed an end-to-end deep reinforcement learning model for adaptive traffic signal control.	Demonstrated better signal optimization and reduced traffic delay compared to traditional methods.
18	A. Haydari and Y. Yilmaz	2022	Deep Reinforcement Learning for Intelligent Transportation Systems: A Survey	IEEE Transactions on Intelligent Transportation Systems	Surveyed Deep Reinforcement Learning applications in Intelligent Transportation Systems.	Identified DRL as a promising solution for intelligent traffic control, autonomous driving, and traffic prediction.
19	S. Li, W. Deng, and Z. Liu	2020	A Deep Adaptive Traffic Signal Controller With Long-Term Planning Horizon and Spatial-Temporal State Definition Under Dynamic Traffic Fluctuations	IEEE Access	Proposed a deep reinforcement learning-based adaptive traffic signal controller using spatial-temporal traffic state representation.	Reduced vehicle delay, improved traffic efficiency, and outperformed conventional fixed-time traffic signal control methods.

Proposed Methodology:

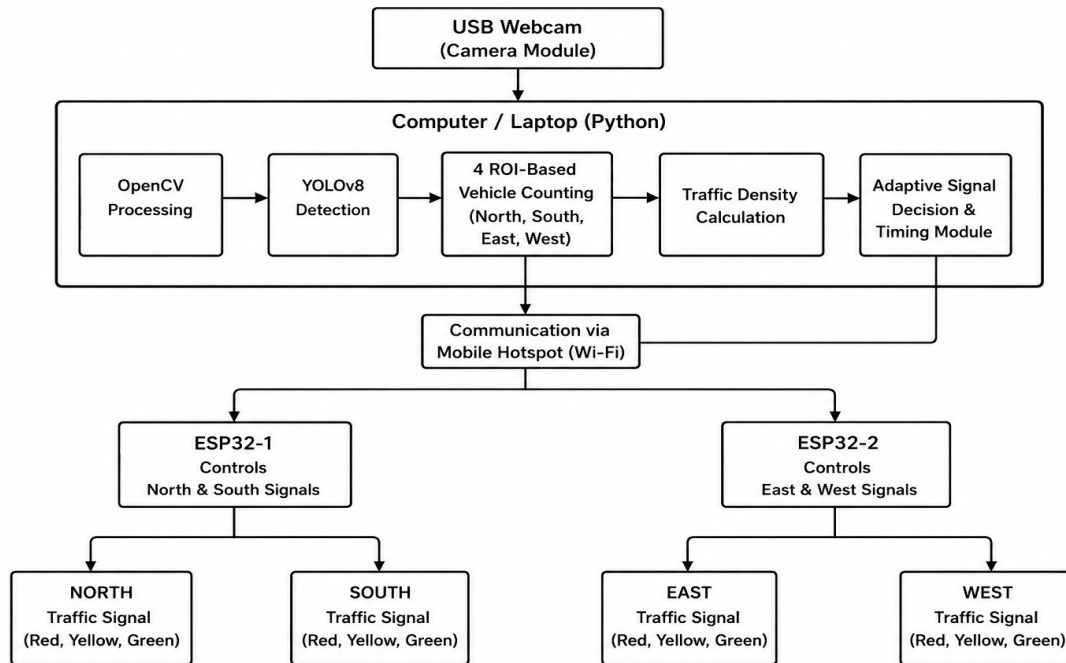


Figure 1 Block Diagram of AI-Driven Adaptive Traffic Management System

The proposed AI-Driven Adaptive Traffic Management System is designed to control traffic signals at a four-way intersection by considering the number of vehicles present in each direction. The overall operation consists of traffic video acquisition, vehicle detection, ROI-based counting, traffic density estimation, adaptive signal decision-making, and physical signal control.

1. Traffic Video Acquisition

A USB webcam is positioned above the miniature intersection to continuously observe the approaching vehicles. The live video stream is captured using Python and OpenCV. The captured video is divided into individual frames for further processing.

2. Vehicle Detection Using YOLOv8

Each selected video frame is processed using the YOLOv8 object detection model. The model identifies vehicles present within the camera view. The detection process provides the information required to estimate the number of vehicles approaching from different directions.

3. ROI-Based Vehicle Counting

Four Regions of Interest are defined within the camera frame to represent the following approaches: North, South, East and West



The detected vehicles located within each ROI are counted separately. These counts are used as an indication of the traffic density for the corresponding direction.

4. Traffic Density Calculation

The vehicle counts obtained from the ROIs are grouped into two traffic phases:

- a. North–South phase
- b. East–West phase

The total number of vehicles in each phase is determined by combining the counts of the corresponding directions. These values are then used by the adaptive control logic to compare the traffic conditions between the two phases.

5. Adaptive Signal Decision

The adaptive timing module analyzes the calculated vehicle density. The phase with a higher vehicle count is assigned a longer green signal duration, whereas the phase with lower traffic density receives a shorter green duration.

The signal transition follows the sequence:

Green → Yellow → All Red → Green

This sequence ensures an orderly transition between the North–South and East–West traffic phases.

6. Wireless Communication

The control decisions generated by the Python-based traffic controller are transmitted through Wi-Fi using a mobile hotspot. Two ESP32 DevKit V1 boards receive the commands.

- a. ESP32-1: Controls the North and South traffic signals.
- b. ESP32-2: Controls the East and West traffic signals.

7. Physical Traffic Signal Control

Each ESP32 activates the Red, Yellow, and Green LEDs of the connected miniature traffic signal modules according to the received command. The complete system continuously repeats the detection and control process, allowing the signal timing to respond to the observed traffic density.

Result:

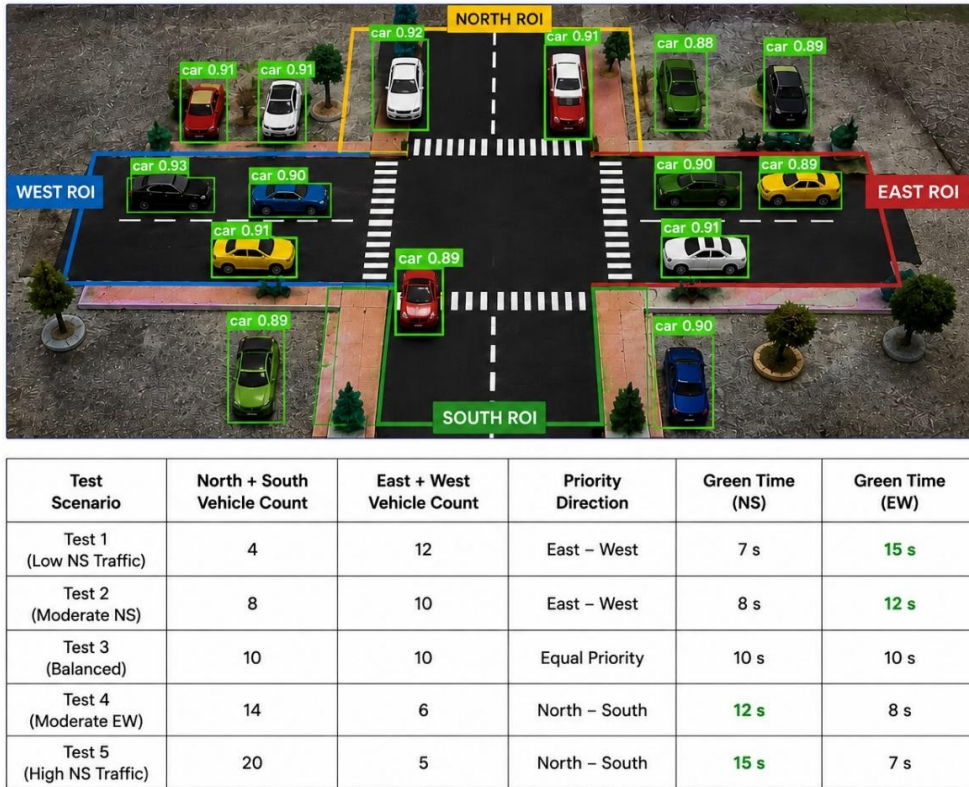


Figure 1 Project Setup

The developed prototype demonstrates the operation of an adaptive traffic signal system for a four-way miniature intersection. A USB webcam continuously captures the traffic scene, and the captured video frames are processed using OpenCV and the YOLOv8 model. Four predefined ROIs are used to identify the number of vehicles approaching from the North, South, East, and West directions.

The detected vehicle counts are used to estimate the traffic density of the two signal phases: North–South and East–West. Based on the calculated density, the adaptive control module determines the green signal duration. When a phase contains a comparatively higher number of vehicles, the system assigns it a longer green period. A phase with lower traffic density receives a shorter green duration.

The signal transition is implemented in the following order:

Green → Yellow → All Red → Green

This sequence provides a controlled transition between the two traffic phases. The generated control commands are transmitted through the mobile hotspot to the ESP32 controllers.

ESP32-1 operates the traffic signals for the North and South directions, while ESP32-2 controls the East and West directions. The miniature traffic lights respond by activating the appropriate Red, Yellow, and Green LEDs according to the commands received from the Python-based controller.



The prototype therefore demonstrates the complete flow from camera-based vehicle observation to AI-based detection, traffic density estimation, adaptive timing decisions, wireless communication, and physical traffic signal operation.

Conclusion:

This paper presented an AI-Driven Adaptive Traffic Management System for a four-way miniature intersection. The proposed system combines a USB webcam, OpenCV, YOLOv8-based vehicle detection, ROI-based vehicle counting, adaptive signal timing, Wi-Fi communication, and ESP32 microcontrollers.

The camera continuously monitors the intersection, while the YOLOv8 model detects vehicles within four predefined directional regions. The vehicle counts are used to estimate the traffic density of the North–South and East–West phases. Based on this information, the adaptive control logic determines the appropriate green signal duration, providing relatively longer green time to the phase with higher traffic density.

Two ESP32 DevKit V1 boards are used to control the physical miniature traffic signals. One controller operates the North–South signals, while the second controller operates the East–West signals. The system follows a controlled signal transition sequence of Green → Yellow → All Red → Green.

Overall, the developed prototype demonstrates the integration of artificial intelligence, computer vision, and embedded systems for adaptive traffic signal control. Compared with a fixed-time approach, the proposed system is designed to allocate signal time according to the observed vehicle density and provides a practical prototype for intelligent traffic management.

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