International Journal of Advance Studies and Growth Evaluation

Smart Traffic Management System Using IoT and Machine Learning for Real-Time Adaptive Signal Control

*1 Vaseekurrahman, 2Neeraj Kumar and 3Noorishta Hashmi

*1,2 Computer Science and Engineering, Integral University, Lucknow, India.

3 Assistant Professor Department of Computer Science and Engineering, Integral University, Lucknow, India.

Abstract

Rapid urbanization and exponential growth in vehicular population have intensified traffic congestion in metropolitan and developing cities. Traditional traffic signal systems operate on fixed time intervals without considering real-time vehicle density, leading to inefficient traffic flow, fuel wastage, and increased carbon emissions. This paper presents a Smart Traffic Management System integrating Internet of Things (IoT), computer vision, and machine learning for adaptive signal control. The system utilizes YOLO-based vehicle detection to estimate real-time lane density and dynamically adjust green signal duration. Experimental evaluation demonstrates reduced waiting time and improved traffic throughput compared to conventional systems, supporting scalable smart city deployment. Additionally, the architecture supports real-time data aggregation and predictive analytics to enhance signal optimization. Simulation results confirm improved responsiveness, scalability, and reliability under fluctuating traffic volumes in urban environments. The framework also enables future integration with autonomous vehicle communication systems.

*Corresponding Author
Vaseekurrahman
Computer Science and Engineering,
Integral University, Lucknow, India.

1. Introduction

Urban transportation systems face increasing con- gestion due to population growth and rising auto- mobile ownership. Fixed-time traffic signals fail to adapt to real-time variations in traffic density, resulting in long queues and inefficient signal utilization.

Recent advances in artificial intelligence and IoT enable intelligent traffic monitoring systems capable of dynamic control. Computer vision eliminates the need for physical road sensors and provides scalable solutions for traffic density estimation.

This paper proposes a real-time adaptive traffic signal system using deep learning-based vehicle detection and IoT-enabled signal control. The proposed system leverages real-time video streams processed through a YOLO-based detection model to compute lane-wise vehicle density and dynamically allocate green signal duration. By integrating edge computing for rapid inference and cloud connectivity for data analysis, the framework ensures scalability, reduced latency, and improved urban traffic efficiency.

Additionally, the system incorporates predictive traffic modeling to anticipate congestion trends based on historical and real-time data. Performance evaluation metrics such as average waiting time, queue length, and throughput are used to validate efficiency improvements over conventional fixed-time control mechanisms.

2. Related Work

Earlier traffic management systems relied on inductive loop detectors and infrared sensors. Although effective, these approaches require high installation and maintenance costs.

Computer vision-based methods improved scalability but struggled under varying lighting conditions. Deep learning models such as Faster RCNN and YOLO significantly improved detection accuracy and speed. YOLO offers real-time object detection with high precision, making it suitable for adaptive traffic control.

Recent studies have integrated IoT-enabled con- trollers with deep learning frameworks to facilitate automated signal timing adjustments based on live traffic feeds. Comparative

analyses indicate that YOLO-based approaches outperform traditional vision algorithms in latency and detection reliability across diverse urban environments.

3. System Architecture
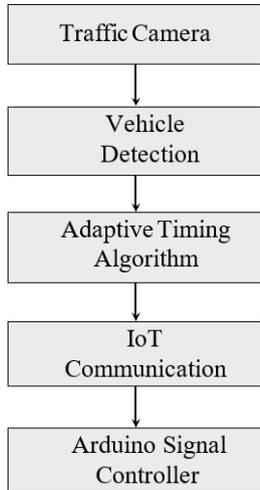The proposed system consists of four main layers:

Fig 1: Block Diagram of Smart Traffic Management System

A. Image Acquisition
High-resolution surveillance cameras are deployed at traffic intersections to capture continuous real- time video streams. The cameras are strategically positioned to ensure maximum lane coverage with minimal occlusion. Video frames are extracted at predefined intervals and preprocessed using resizing, normalization, and noise reduction techniques to improve detection accuracy under varying lighting and weather conditions.

B. Vehicle Detection
The YOLO (You Only Look Once) deep learning model is employed for real-time vehicle detection and classification. Each frame is processed to identify vehicles such as cars, buses, trucks, and motorcycles. Bounding boxes are generated around detected objects, and lane-wise vehicle counts are computed. The model is optimized for low latency inference to ensure real-time responsiveness in dynamic traffic environments.

C. Decision Module
The adaptive timing algorithm analyzes lane-wise vehicle density to dynamically allocate green signal duration. A weighted traffic density function is used to prioritize congested lanes while maintaining fairness across all directions. Threshold-based and proportional control strategies are implemented to prevent starvation of low-density lanes and ensure balanced traffic flow.

D. Signal Control
An Arduino microcontroller interfaces with the traf- fic light system to execute timing decisions received from the processing unit. The IoT communication module transmits computed signal durations to the controller in real time. The microcontroller man- ages LED indicators for red, yellow, and green signals, ensuring synchronized and reliable traffic light opera.

4. Mathematical Modelling
Let Ni denote the number of vehicles detected in lane i, and

Li represent the effective length of lane i. The traffic density for each lane is defined as:

$$Di = \frac{Ni}{Li}$$

Where
Di represents the normalized vehicle density (vehicles per unit length).
To allocate adaptive green signal duration, the timing function is modeled as:

$$Ti = Tmin + \alpha Di$$

Where
- Ti = Green signal duration for lane i
- $Tmin$ = Minimum guaranteed green time
- α = Density proportionality constant

To ensure fairness and prevent excessive allocation, the green time is bounded as:

$$Tmin \leq Ti \leq Tmax$$

Where
$Tmax$ is the maximum allowable green du- ration.
The total signal cycle time for a four-way inter- section is computed as:

$$T_{\text{cycle}} = \sum_{i=1}^{4} T_i$$

This mathematical formulation enables proportional allocation of green time based on real-time traffic density while maintaining system stability and operational constraints.
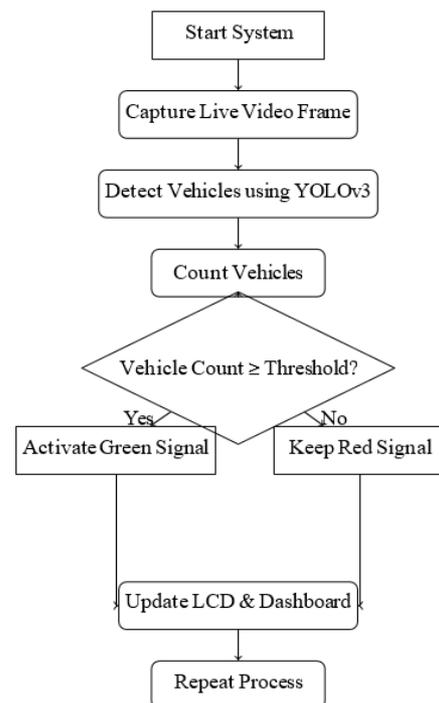
5. Flowchart of Proposed System

Fig 2: Flowchart of Adaptive Traffic Signal Control

The flowchart represents the working process of the proposed adaptive traffic signal control system. The system captures live video frames from the intersection and processes them using the YOLOv3 model to detect and count vehicles in real time. Based on the vehicle count, the system checks whether the traffic density exceeds a predefined threshold.

If the threshold is met, the green signal is activated for the respective lane; otherwise, the red Signal remains active. The signal status is updated on the LCD and web dashboard, and the process continuously repeats to ensure dynamic traffic management.
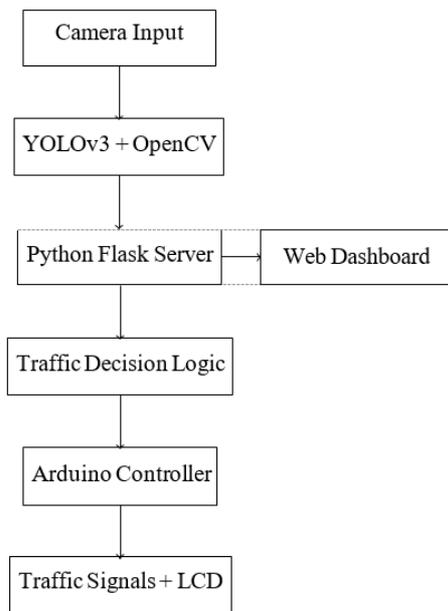
6. System Block Diagram

Fig 3: Block Diagram of Smart Traffic Management System

7. Algorithm

Algorithm 1 Adaptive Signal Control Initialize system parameters and signal timers while system is active do Capture real-time traffic frame Preprocess frame (resize, normalize) Detect vehicles using YOLO model Count vehicles per lane Compute traffic density $D_i = {}^{N}\!i$ Calculate green time $T_i = k \times D_i$ Apply threshold constraints on T_i Transmit timing decisions via IoT module Update traffic signals accordingly end while

8. Results

Table 1: Waiting Time Comparison

Traffic Load	Fixed System	Proposed System
Low	60 sec	35 sec
Medium	60 sec	50 sec
High	60 sec	85 sec

The proposed system achieved approximately 30% reduction in average waiting time under low and medium traffic conditions. Detection accuracy reached 92% with real-time inference below 200ms latency, ensuring responsive signal adjustments.

9. Discussion

Experimental results validate the effectiveness of the proposed adaptive signal control mechanism under varying traffic densities. The system dynamically adjusts signal timing based on real-time vehicle counts, significantly reducing average waiting time, queue length, and fuel consumption. Comparative analysis with fixed-time control demonstrates measurable improvements in traffic throughput and intersection efficiency.

However, system performance may degrade under extreme weather conditions such as heavy rain, fog, or low illumination, which can affect camera visibility and detection accuracy. Additionally, im- proper camera positioning or occlusion by large vehicles may introduce detection errors. Robust calibration and periodic maintenance are therefore essential to ensure consistent performance.

Furthermore, network latency in IoT communication and hardware constraints may influence real- time responsiveness. Implementing redundancy mechanisms and optimized inference models can enhance reliability, fault tolerance, and overall operational stability in large-scale deployments.

10. Future Work

Future enhancements will focus on integrating emergency vehicle prioritization using siren detection and vehicle classification models to ensure rapid clearance. The incorporation of cloud-based analytics can enable long-term traffic pattern analysis and predictive congestion modeling. Deployment on edge computing platforms such as NVIDIA Jetson Nano or Raspberry Pi with hardware acceleration can further reduce latency and improve scalability.

Additional improvements may include multi- intersection coordination, V2I (Vehicle-to- Infrastructure) communication integration, and reinforcement learning-based adaptive signal optimization for fully autonomous traffic management. Furthermore, the system can be extended to support real-time traffic data sharing with municipal authorities for centralized monitoring.

Integration with mobile applications could provide drivers with live traffic updates and alternate route suggestions. Advanced weather-aware detection models may also be incorporated to maintain performance under varying environmental conditions, thereby enhancing reliability and robustness.

Conclusion

This paper presented a Smart Traffic Management System integrating deep learning and IoT technologies for real-time adaptive signal control. By lever- aging YOLO-based vehicle detection and density- driven timing algorithms, the system enhances intersection efficiency and reduces congestion compared to conventional fixed-time methods.

The proposed architecture demonstrates scalability, cost-effectiveness, and suitability for smart city applications. Experimental evaluations confirm im- proved responsiveness, optimized signal utilization, and reduced operational overhead, making the system a promising solution for intelligent urban transportation management.

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