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AI-Based Real-Time Traffic Flow Analysis and Signal Optimization

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ABSTRACT

Traffic congestion has become one of the most critical challenges in modern urban environments due to rapid urbanization and a continuously increasing number of vehicles. Traditional fixed-time traffic signal systems operate using predetermined timing schedules without considering real-time traffic conditions. As a result, high-density lanes experience long waiting times, while low-density lanes may receive unnecessary green signal durations, leading to inefficient intersection management. This paper presents an AI-based real-time traffic flow analysis and signal optimization system that integrates vehicle detection, tracking, adaptive signal control, and congestion-aware route optimization. Vehicle detection is performed using the YOLOv9 deep learning model, and DeepSORT is applied for multi-object tracking and accurate vehicle counting. Based on computed lane-wise density, green signal time is dynamically allocated using proportional distribution while ensuring non-conflicting signal phases. Furthermore, the road network is modeled as a weighted graph, and Dijkstra's shortest path algorithm is applied to compute optimal aroutes considering congestion levels. Experimental evaluation demonstrates improved traffic throughput and reduced waiting time compared to conventional systems.

INTRODUCTION

Urban traffic congestion significantly affects economic productivity, fuel consumption, and environmental sustainability. As vehicle ownership increases, traditional traffic control mechanisms struggle to manage intersection efficiency. Most existing traffic signals operate on static timing cycles that do not adapt to real-time traffic variations. This often results in congestion during peak hours and inefficient road utilization during off-peak periods. Recent research highlights that deep learning-based object detection models such as YOLO [1] have significantly improved real-time vehicle detection accuracy in traffic monitoring applications. Multi-object tracking frameworks including SORT [2] and its enhanced version DeepSORT [3] enable reliable vehicle identity preservation and accurate counting across consecutive frames. Furthermore, reinforcement learning-based adaptive traffic signal control approaches have demonstrated improved intersection efficiency compared to fixed-time systems [4].

OBJECTIVE

The primary objective of the proposed system is to design and implement an intelligent traffic management framework capable of analyzing real-time traffic conditions and dynamically optimizing signal timing. The system aims to accurately detect and track vehicles, estimate lane-wise traffic density, allocate green signal time proportionally based on congestion levels, and compute optimal routes using graph algorithms. Ultimately, the goal is to minimize average waiting time, increase throughput, and support smart city infrastructure development.

LITERATURE SURVEY

[5] L. Chen, C. Wang, and X. Zhang,
"Deep Learning-Based Vehicle Detection for Traffic Monitoring," IEEE Access, vol. 7, 2019, describes the application of convolutional neural network-based object detection models for accurate vehicle identification in traffic surveillance systems. The study demonstrates improved detection accuracy under varying lighting and environmental conditions and highlights the effectiveness of deep learning frameworks in intelligent transportation systems. The work emphasizes real-time vehicle monitoring as a foundation for adaptive traffic control and congestion management.
[6] Y. Zhang, X. Wang, and L. Chen,
"Real-Time Traffic Flow Detection Using Computer Vision," IEEE Transactions on Intelligent Transportation Systems, vol. 21, no. 4, 2020, describes a vision-based traffic flow analysis framework that performs real-time vehicle counting and density estimation using advanced image processing techniques. The study focuses on accurate lane-wise vehicle detection and traffic parameter extraction to support dynamic traffic management systems. The proposed approach demonstrates improved traffic flow analysis compared to traditional sensor-based methods.
[7] K. Shaaban and I. Kim,
"Intelligent Transportation Systems: A Review," IEEE Access, 2020, describes a comprehensive survey of intelligent transportation technologies, including traffic monitoring, adaptive signal control, and smart mobility infrastructure. The paper discusses the integration of artificial intelligence, communication systems, and data analytics for sustainable urban transportation. It highlights the importance of centralized traffic management frameworks for smart city development.
[8] S. Chavhan and A. G. Bhalerao,
"Traffic Congestion Detection Using Computer Vision," Proc. IEEE International Conference on Intelligent Transportation Systems (ITSC), 2021, describes a computer vision-based congestion detection framework that analyzes vehicle density and traffic patterns using real-time surveillance footage. The study emphasizes automated traffic condition monitoring and demonstrates the potential of vision-based systems to support intelligent signal control mechanisms in urban road networks.
[9] Z. Chen, C. Jiang, and Y. Jia,
"Adaptive Traffic Signal Control Using Deep Reinforcement Learning," IEEE Access, 2022, describes a deep reinforcement learning-based traffic signal optimization model that dynamically adjusts signal phases according to real-time traffic states. The study demonstrates improved intersection efficiency and reduced waiting time compared to fixed-time signal systems. It highlights the growing role of AI-driven decision-making in modern traffic control systems.
[10] J. Jocher, A. Chaurasia, and G. Qiu,
"YOLOv5: Real-Time Object Detection," 2022, describes an advanced real-time object detection framework that improves detection speed and accuracy through optimized network architectures and training strategies. The model supports efficient inference on edge devices and has been widely adopted in traffic monitoring applications for vehicle detection and tracking tasks. Its lightweight architecture enables deployment in real-time intelligent transportation systems.

EXISTING SYSTEM

Conventional traffic management systems primarily rely on fixed-time signal controllers that operate using predefined timing schedules without adapting to real-time traffic variations. Even though modern smart transportation frameworks emphasize data-driven mobility management [11], many urban intersections still function without fully integrated AI-based control mechanisms.

Recent studies have explored AI-based traffic management solutions that combine detection and signal optimization [12]. However, several implementations focus on isolated components such as detection or signal timing without achieving complete integration within a centralized architecture. Multi-object tracking improvements for intelligent transportation systems have also been reported [13], yet their practical deployment in large-scale adaptive traffic control remains limited.

Similarly, congestion-aware routing approaches using real-time traffic data have been investigated [14], and vision-based adaptive traffic signal control methods have shown promising results [15]. Despite these advancements, existing systems often lack unified coordination between vehicle detection, tracking, density estimation, signal optimization, and route guidance within a single framework.

As a result, many intersections continue to operate without fully synchronized real-time density-based optimization. The absence of integrated traffic density analysis and coordinated route optimization leads to increased waiting time, higher congestion levels during peak hours, inefficient traffic movement, and limited responsiveness to emergency vehicle prioritization.

PROPOSED SYSTEM

The proposed system is an AI-based real-time traffic management framework that integrates vehicle detection, tracking, adaptive signal control, and congestion-aware route optimization into a centralized architecture. This design aligns with modern smart transportation system models proposed for smart city infrastructure [11].

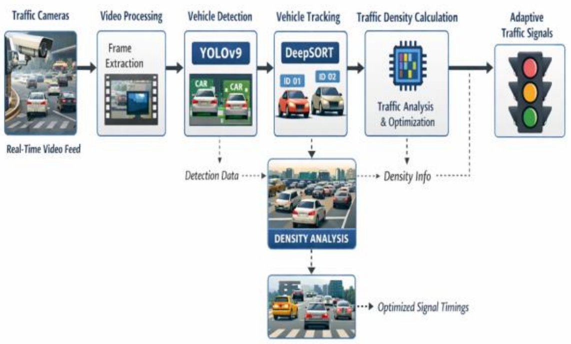
Building upon integrated AI-driven traffic management approaches [12], the system combines real-time object detection and multi-object tracking to accurately estimate lane-wise vehicle density. Improvements in tracking methodologies for intelligent transportation systems [13] further support reliable vehicle identity preservation and trajectory analysis.

Based on the computed density values, green signal time is dynamically allocated using proportional distribution rather than fixed timing cycles. This approach extends vision-based adaptive traffic signal control strategies [15] by incorporating centralized density estimation and decision-making mechanisms.

Furthermore, the road network is modeled as a weighted graph, incorporating congestion-aware routing principles based on real-time traffic data [14]. By combining adaptive signal optimization with dynamic route guidance, the proposed system ensures balanced traffic distribution and improved intersection efficiency.

This integrated framework enables intelligent, scalable, and real-time traffic management suitable for next-generation smart city environments.

SYSTEM ARCHITECTURE



Camera Acquisition Module

The Camera Acquisition Module is responsible for capturing real-time traffic video from surveillance cameras deployed at road intersections. Cameras are strategically positioned at an elevated height to ensure maximum lane coverage and minimal occlusion. The system supports both live video streams and recorded traffic footage for testing and simulation purposes.

The captured video is processed frame-by-frame at a predefined frame rate. Each frame is converted into a standardized format suitable for deep learning inference. Preprocessing steps such as resizing, normalization, and noise reduction may be applied to improve detection accuracy. The spatial resolution and placement angle of the cameras significantly influence detection performance and coverage range.

The processed frames are transmitted to the centralized processing server, where they serve as input to the vehicle detection module. This module acts as the primary data acquisition source for the entire traffic management framework.

Vehicle Detection Module

The Vehicle Detection Module performs real-time vehicle identification using the YOLOv9 deep learning architecture. YOLO (You Only Look Once) is a single-stage object detection model that performs object localization and classification in a single forward pass, making it suitable for real-time traffic applications.

For each input frame, the model predicts:

- Bounding box coordinates (x, y, width, height)
- Class probabilities (car, bus, truck, motorcycle, etc.)
- Confidence score

The detection confidence is computed as:

$$Confidence = P(Object) \times IoU$$

where $P(Object)$ represents the probability of object presence within a bounding box, and IoU (Intersection over Union) measures the overlap between predicted and ground-truth bounding boxes during training.

Non-Maximum Suppression (NMS) is applied to remove redundant overlapping detections, ensuring that each vehicle is detected only once per frame. The detection model is optimized to balance accuracy and inference speed, enabling real-time deployment in traffic monitoring scenarios

Vehicle Tracking Module

The Vehicle Tracking Module utilizes the DeepSORT algorithm to maintain consistent identities for vehicles across consecutive frames. While the detection module identifies vehicles independently in each frame, tracking ensures temporal consistency and prevents duplicate counting.

DeepSORT integrates:

- A Kalman Filter for motion prediction
- The Hungarian Algorithm for data association
- Deep appearance feature extraction for identity matching

The Kalman Filter predicts the next position of each detected vehicle based on its motion trajectory. The Hungarian Algorithm associates newly detected objects with existing tracks using a cost matrix. Appearance features extracted from deep neural networks enhance robustness against occlusion and overlapping vehicles.

Each vehicle is assigned a unique tracking ID that persists across frames. This enables accurate vehicle counting, lane-wise movement analysis, and trajectory estimation, which are essential for traffic density computation.

Traffic Density Estimstion Module

The Traffic Density Estimation (TDE) Module computes lane-wise congestion levels using tracked vehicle data. The system first assigns detected vehicles to specific lanes based on spatial coordinates and predefined lane boundaries.

Traffic density is calculated as:

$$Density_i = \frac{N_i}{L_i}$$

Where:

- N_i= Number of vehicles in lane i
- L_i= Effective length of lane i

This metric represents the concentration of vehicles per unit lane length and provides a quantitative measure of congestion. Higher density values indicate heavier traffic load.

The module continuously updates density values at regular time intervals to reflect real-time traffic variations. These density measurements are forwarded to the Adaptive Signal Control Module for dynamic signal timing adjustment.

Adaptive Signal Control Module

The Adaptive Signal Control Module dynamically adjusts green signal duration based on real-time traffic density information. Unlike conventional fixed-time systems, this module allocates signal timing proportionally according to congestion levels.

Green signal duration is computed as:

$$GreenTime_i = \frac{Density_i}{TotalDensity} \times CycleTime$$

Where:

- $TotalDensity = \sum Density_i$
- $CycleTime$= Total signal cycle duration

To ensure operational safety and fairness, the module enforces:

- Minimum green time threshold
- Maximum green time limit

- Non-conflicting signal phase constraints

The system prevents lane starvation by guaranteeing baseline green time allocation for all lanes. Signal timing updates are performed periodically to adapt to changing traffic conditions.

By dynamically redistributing green time based on density, the module reduces average waiting time, improves intersection throughput, and balances lane utilization.

RESULT ANALYSIS

The proposed AI-based traffic management system was evaluated using recorded traffic video data simulating real-time intersection conditions. The system performance was analyzed in terms of vehicle detection accuracy, tracking reliability, traffic density estimation, and signal optimization effectiveness.

The YOLOv9-based detection module demonstrated reliable vehicle identification under varying lighting and traffic density conditions. Non-Maximum Suppression effectively eliminated redundant detections, ensuring accurate object localization. The DeepSORT tracking module successfully maintained consistent vehicle identities across consecutive frames, preventing duplicate counting and improving lane-wise density estimation.

Traffic density values were dynamically computed for each lane and updated at regular intervals. Compared to conventional fixed-time signal systems, the adaptive signal control mechanism showed improved responsiveness to congestion variations. High-density lanes received proportionally increased green signal duration, while low-density lanes were allocated reduced timing, resulting in balanced traffic flow.

The integration of congestion-aware routing using Dijkstra's algorithm enabled optimal path computation based on real-time congestion cost. This reduced unnecessary accumulation of vehicles on heavily congested routes.

Experimental observations indicate:

- Reduction in average vehicle waiting time
- Improved traffic throughput at intersections
- Balanced lane utilization
- Enhanced responsiveness during peak traffic conditions

Overall, the proposed framework demonstrates improved efficiency compared to traditional static traffic signal systems.

CONCLUSION

This paper presented an AI-based real-time traffic flow analysis and signal optimization system designed to overcome the limitations of conventional fixed-time traffic control mechanisms. The proposed framework integrates deep learning-based vehicle detection, multi-object tracking, traffic density estimation, adaptive signal allocation, and congestion-aware route optimization within a centralized architecture.

The use of YOLOv9 ensures accurate real-time vehicle detection, while DeepSORT provides reliable multi-object tracking for precise density estimation. The proportional green time allocation strategy dynamically adjusts signal timing according to lane congestion levels, reducing waiting time and improving intersection efficiency. Additionally, graph-based route optimization enhances overall traffic distribution across the road network.

The proposed system offers a scalable and intelligent solution for smart city traffic management and demonstrates the practical applicability of artificial intelligence in intelligent transportation systems

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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