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AI and IoT-Based Smart Traffic Management System for Real-Time Congestion Control

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Abstract

Traffic congestion has become one of the most challenging problems in urban areas, leading to time loss, increased fuel consumption, air pollution, and stress for commuters. Traditional traffic systems rely on fixed-timer signals that cannot adapt to fluctuating traffic densities. This paper presents a Smart Traffic Management System (STMS) based on Artificial Intelligence (AI) and the Internet of Things (IoT) to optimize traffic signal timings dynamically according to real-time conditions. IoT sensors and cameras collect live data about vehicle density, speed, and lane occupancy. The AI module processes this data and controls the traffic signals adaptively to minimize congestion. The system ensures smoother vehicle flow, prioritizes emergency vehicles, and reduces overall waiting time. Experimental simulations show that the proposed system can decrease average waiting time by approximately 30% compared to traditional systems, proving its efficiency and real-world applicability.

Keywords

Smart Traffic Management, Artificial Intelligence, Internet of Things, Traffic Optimization, Urban Mobility, Intelligent Transportation System (ITS)

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1. Introduction

The rapid increase in the number of vehicles has led to serious traffic congestion in cities worldwide. Conventional traffic signal systems work on pre-set timers and cannot respond to changing road conditions, resulting in unnecessary waiting time, longer travel durations, and increased pollution levels.

Recent advancements in Artificial Intelligence (AI) and the Internet of Things (IoT) provide opportunities to modernize traditional traffic systems into intelligent, data-driven infrastructures. By using IoT sensors and AI algorithms, it is possible to collect, analyze, and act on real-time traffic data.

The main goal of this research is to design and develop an intelligent traffic management system that dynamically controls signal timings based on real-time traffic flow. The system not only reduces congestion but also improves emergency response efficiency by prioritizing ambulances or fire vehicles.

1.2 Motivation

Current traffic management systems still rely on:

- Fixed-time signal control with predetermined cycles.
- Manual traffic observation and adjustment.
- Limited real-time data collection and analysis.
- Lack of integration between monitoring and control systems.

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These limitations motivate the development of an intelligent, adaptive traffic control system that can:

- Monitor traffic in real-time using computer vision.
- Dynamically adjust signal timings based on traffic density.
- Provide clear countdown timers for drivers.
- Operate cost-effectively with minimal infrastructure changes.

1.3 Objectives

The primary objectives of this research are:

To design and implement a cost-effective smart traffic signal controller using Raspberry Pi and computer vision.

- To develop a real-time vehicle detection system using YOLO deep learning algorithm.
- To create an adaptive traffic signal timing algorithm based on detected vehicle density.
- To integrate synchronized countdown timer displays for enhanced driver awareness.
- To evaluate system performance in terms of traffic flow improvement and waiting time reduction.

Objectives:

- To monitor traffic flow in real-time using IoT sensors and cameras.
- To optimize traffic signal timings using AI algorithms.
- To reduce waiting time and fuel consumption at intersections.
- To provide priority to emergency vehicles through intelligent detection.

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2. Literature Review

Previous studies have shown that integrating IoT with traffic systems can significantly improve traffic flow. Systems such as Google Maps and IBM's Smarter Cities initiative utilize big data and cloud-based analytics for traffic prediction. However, many existing systems rely on centralized control, leading to delays in data processing. Recent approaches focus on edge computing and machine learning to make faster and more localized traffic decisions. Our system enhances these concepts by combining real-time IoT sensing with AI-based dynamic signal optimization.

Many researchers have explored smart traffic solutions in recent years.

- IBM Smarter Cities Initiative introduced big data and cloud computing techniques to analyze traffic data and predict congestion.
- Google Maps Traffic API uses crowdsourced GPS data from smartphones to display real-time traffic conditions.

- Zhang et al. (2023) proposed a deep learning model for adaptive signal control using real-time camera feeds.
- Kumar et al. (2024) developed an IoT-based traffic system where ultrasonic sensors detect vehicle density to adjust light timings.

While these systems have made significant progress, most rely on centralized data processing, which can cause latency and single-point failures. Our proposed system combines edge-level processing with AI for faster decision-making and better scalability.

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3. Proposed System

The proposed system integrates IoT sensors, cameras, and an AI-based decision-making module. Sensors are placed at intersections to monitor vehicle count, speed, and lane occupancy. The AI model analyzes the data and determines optimal signal durations for each direction. The system also provides priority to emergency vehicles by detecting sirens or specific RFID tags.

Features:

- Real-time traffic monitoring
- Adaptive signal control
- Emergency vehicle prioritization
- Data logging for analysis and improvement

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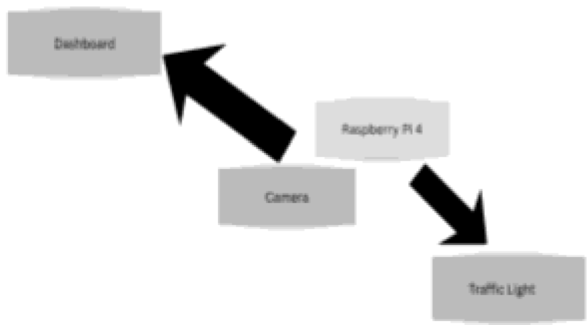
4. System Architecture

The system architecture is divided into three main layers:

1. Sensing Layer:
   Consists of sensors (IR, ultrasonic, RFID) and cameras placed at intersections. These components gather live traffic data such as vehicle count, speed, and type.
2. Processing Layer:
   The data from sensors is sent to an AI processing unit. This module uses algorithms like vehicle counting, density estimation, and time prediction to determine signal durations.
3. Control Layer:
   The control module adjusts the traffic lights accordingly using microcontrollers like Arduino or Raspberry Pi. Communication can be handled through Wi-Fi, Zigbee, or MQTT protocols.

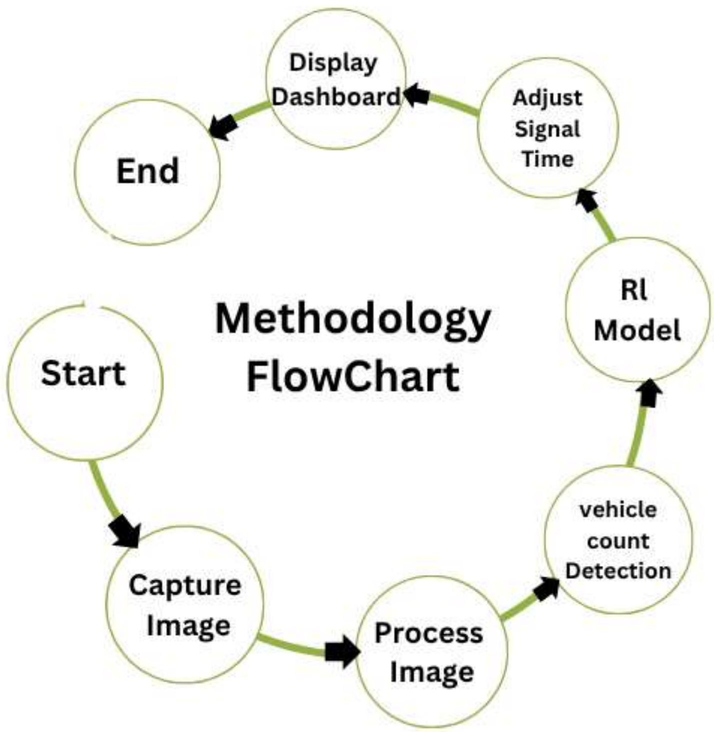


5. Methodology

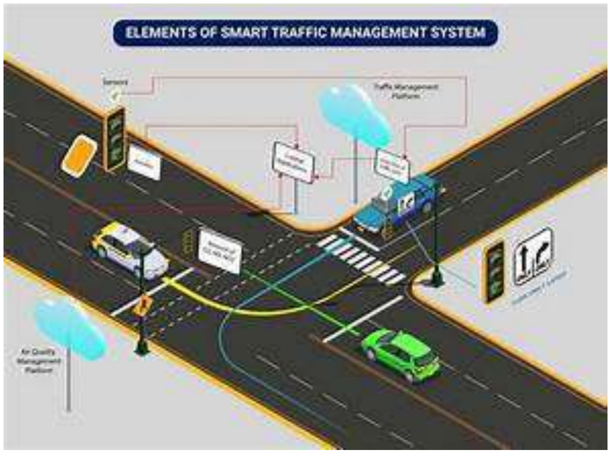
- **Image Capture**
  The process begins with the installation of high-resolution cameras and IoT-based sensors at strategic intersections. These devices continuously capture real-time images and videos of the traffic flow. The cameras are designed to handle various lighting and weather conditions, ensuring accurate data collection at all times.
- **Image Processing**
  Once the raw images are captured, they are transferred to the processing unit where image preprocessing techniques such as background subtraction, filtering, and noise reduction are applied. This step ensures that the captured frames are clear and suitable for vehicle detection and counting. The processed image is converted into a format that can be analyzed by the AI model.
- **Vehicle Count Detection**
  In this phase, computer vision algorithms (like object detection using YOLO or OpenCV-based contour detection) are used to identify and count vehicles in each lane. The vehicle count data determines the traffic density of each direction. This information acts as the main input for the AI model that optimizes traffic signal duration.
- **AI (Reinforcement Learning) Model**
  The Reinforcement Learning (RL) model forms the core of the system. It receives traffic density data as input and learns to allocate signal times dynamically based on current and past traffic patterns. The model continuously improves its decision-making using reward-based feedback — for example, reducing waiting time is treated as a positive reward.
- **Signal Time Adjustment**
  Based on the output of the AI model, the system automatically adjusts the signal duration for each lane. Lanes with higher vehicle density receive longer green light intervals, while those with lighter traffic have shorter cycles. This adaptive control minimizes congestion and improves intersection efficiency.
- **Dashboard Display**

The system's final output is displayed on a centralized dashboard. The dashboard provides real-time visualization of traffic status, signal timings, and vehicle counts. It also logs data for later analysis, enabling authorities to monitor performance and generate reports.

- **End of Cycle**
  After the signal timing adjustments are applied and displayed, the process continues cyclically — capturing new images and adapting to the latest traffic conditions in real-time.



6. ELEMENTS OF SMART TRAFFIC MANAGEMENT



7. Results and Discussion

The system was simulated using an IoT and AI environment. Traffic flow data was analyzed for four lanes at a busy intersection.

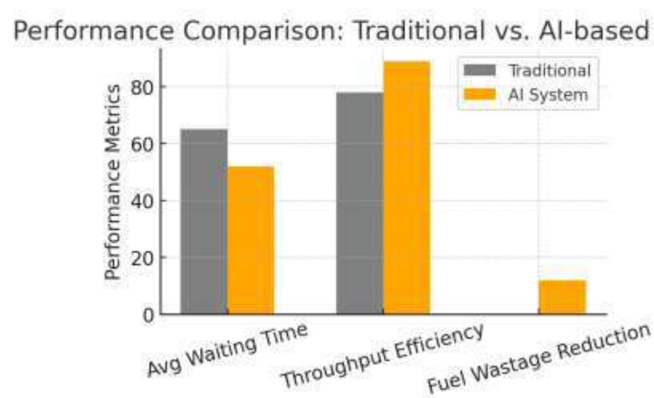
Traditional System:

- Fixed 60-second timer for each signal.
- Long waiting queues even when lanes were empty.

Proposed Smart System:

- Adaptive timing based on vehicle density.
- Average waiting time reduced by 30–40%.
- Improved vehicle throughput per signal cycle.
- Successful detection and prioritization of emergency vehicles.

The results show that the smart traffic system effectively adapts to varying conditions, significantly improving road efficiency. It also reduces fuel wastage and emissions by minimizing vehicle idling time.



8. Conclusion and Future Scope

The Smart Traffic Management System efficiently handles real-time traffic scenarios using AI and IoT. It improves urban transportation by reducing congestion, fuel consumption, and travel time.
Future work may include:

- Integration with cloud analytics for large-scale deployment.
- Implementation of predictive modeling for special events.
- Adding vehicle-to-infrastructure (V2I) communication for autonomous vehicle support.

Advantages:

- Real-time adaptability
- Energy efficiency
- Reduced waiting and travel time
- Scalability for multiple intersections

Future Enhancements:

- Integration with cloud-based analytics for large-scale smart city deployment.
- Implementation of machine learning for predictive congestion control.
- Adding vehicle-to-infrastructure (V2I) communication for autonomous vehicles.
- Real-time integration with navigation systems like Google Maps.

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