TRAFFIC PREDICTION AND CONTROL SYSTEM FOR SMART CITIES

(A Real-time system for sustainable traffic prediction and adaptive signal control in smart cities)

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ABSTRACT

The rapid increase in vehicle density within urban areas has led to severe traffic congestion, longer travel times, and higher fuel consumption, contributing significantly to air pollution and environmental degradation. Traditional traffic control systems operate with fixed signal timings that cannot adapt to real-time variations in traffic flow. To address this challenge, this project proposes a sustainable traffic prediction and control system designed for ***smart cities****. The system utilizes* ***image processing*** *and* ***machine learning*** *algorithms to analyze live video feeds from intersections and estimate vehicle density in real time. Based on this data, it dynamically adjusts traffic signal durations to optimize flow and reduce congestion. Hardware implementation is achieved using* ***Arduino Uno****, cameras, and RFID modules for emergency vehicle detection, enabling automatic priority clearance. The proposed system not only minimizes vehicle idle time and fuel wastage but also enhances road safety and overall traffic efficiency. This adaptive, data-driven approach contributes toward developing intelligent and eco-friendly urban transportation infrastructures.*

Keyword: *Smart Cities, Traffic Management, Machine Learning, Image Processing, OpenCV, Arduino, Sustainable Mobility*

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1. Introduction

The increasing urbanization and rapid growth in the number of vehicles have resulted in serious traffic congestion across major cities worldwide. This congestion not only causes long travel delays and fuel wastage but also contributes to increased carbon emissions and environmental pollution. Traditional traffic management systems, which rely on fixed-time signal control, are unable to adapt to the constantly changing traffic conditions. As a result, vehicles spend unnecessary time waiting at signals, leading to inefficiency and frustration among commuters.

To overcome these challenges, modern cities are transitioning toward intelligent and sustainable traffic management solutions that integrate technologies such as image processing, machine learning, and the **Internet of Things** (IoT). These technologies allow traffic systems to analyze real-time data, predict congestion levels, and adjust traffic signals dynamically based on current conditions. **Machine learning models** can identify traffic flow patterns and optimize signal timings for improved mobility and reduced waiting time.

Smart Roads Ahead: Sustainable Traffic Prediction and Control for Smart Cities—aims to design a real-time traffic monitoring and adaptive signal control framework. The system captures live video from intersections using cameras and processes the images through **OpenCV** to count vehicles in each lane. The obtained data is analyzed to determine traffic density, which helps in dynamically controlling signal durations. Additionally, **RFID**-based detection is implemented to prioritize emergency vehicles such as ambulances, ensuring smooth and uninterrupted movement. This intelligent and sustainable approach helps improve overall traffic efficiency, reduces environmental impact, and supports the development of smarter urban infrastructure.

1.1 LITERATURE SURVEY

The literature survey highlights significant developments in intelligent traffic prediction and control systems for smart cities. Recent studies focus on integrating artificial intelligence, machine learning, and IoT technologies to optimize traffic flow, reduce congestion, and enhance sustainability. However, challenges such as scalability, real-time adaptability, and sensor dependency persist. The proposed system in this project bridges these gaps by utilizing computer vision and **machine learning for vehicle detection**, dynamic signal control, and emergency prioritization.

Table 1 : Review of Related Work

Ref.	System/Study	Platform/Tech Used	Key Features	Limitations
[1] IEEE JRFID, 2024	Active Traffic Signal Control Using Parallel Control Theory	Parallel Control System (Real + Virtual), GUR, QCR indices	Dual-system feedback loop for real-time optimization, 14.2% delay reduction	Complex to implement, requires high data accuracy
[2] IEEE ITS, 2024	IoT-Enabled Real-Time Traffic Monitoring & Control	IoT, V2X, Stack4Things Middleware	Three-layer IoT architecture, dynamic rerouting, real-time data collection	Dependent on vehicle compliance, latency issues
[3] IEEE Conf, 2024	Vehicle Speed Prediction Using Informer Model	Informer Model, Multi-source Data	Uses clustering + NN, reduced prediction error	Requires large-scale simulation data
[4] IEEE DTPI, 2023	Parallel Control Method for Traffic Signal Considering Vehicle Arrival Prediction	Vehicle Arrival Model, Parallel System	Reduces travel delay by 13.6%, adaptive signal timing	Limited Scalability to large intersections
[5] IEEE Trans. Tech. Control, 2023	Neural Network & MPC for Lane-Change in Dense Traffic	RNN, SGAN, MPC	100% lane-change success rate, adaptive noise handling	Requires high sensor precision, simulation-based validation

2. System Architecture of Smart Roads Ahead

The proposed Smart Roads Ahead system is designed as an **intelligent and adaptive traffic prediction and control framework** that integrates multiple sensing, processing, and actuation modules to manage traffic flow efficiently in urban areas. The system combines real-time image processing, machine learning–based prediction, and automated signal control to minimize congestion and enhance mobility. The system architecture is divided into three main components: **hardware, software, and control logic.**

Hardware Overview:

At the heart of the system lies the **Arduino Uno microcontroller**, which serves as the central processing and actuation unit. It interfaces with various peripheral modules, including a **web camera** for live traffic video acquisition, **RFID reader (RC522)** for emergency vehicle detection, and **LED indicators** representing the traffic lights for each lane. The captured video feed is processed on a local computing device (PC or Raspberry Pi) running **Python and OpenCV** to perform **vehicle detection and counting** using the Haar Cascade classifier. Based on real-time traffic density, the computed signal duration is communicated to the Arduino via serial communication. The Arduino controls the traffic light LEDs and handles RFID-triggered emergency overrides. A stable DC power supply ensures reliable operation of all modules, enabling synchronized sensing and control.

Software and Control Logic:

The software component of the Smart Roads Ahead system is developed using **Python and Embedded C**, combining the capabilities of **OpenCV** for real-time image processing and the **Arduino IDE** for microcontroller programming.

The software performs continuous video acquisition from the camera, processes each frame to detect and count vehicles using the Haar Cascade classifier, and estimates the traffic density on each lane. Based on these results, an adaptive timing algorithm calculates optimal green light durations to ensure smooth traffic flow and minimize congestion. The computed timings are then transmitted to the Arduino Uno via serial communication using the **PySerial library**. On the hardware side, the Arduino executes these commands to control the LED traffic lights and manages emergency overrides triggered by the RFID module. The program also supports real-time monitoring, data logging, and feedback for system optimization, enabling intelligent, autonomous, and efficient management of urban traffic conditions.

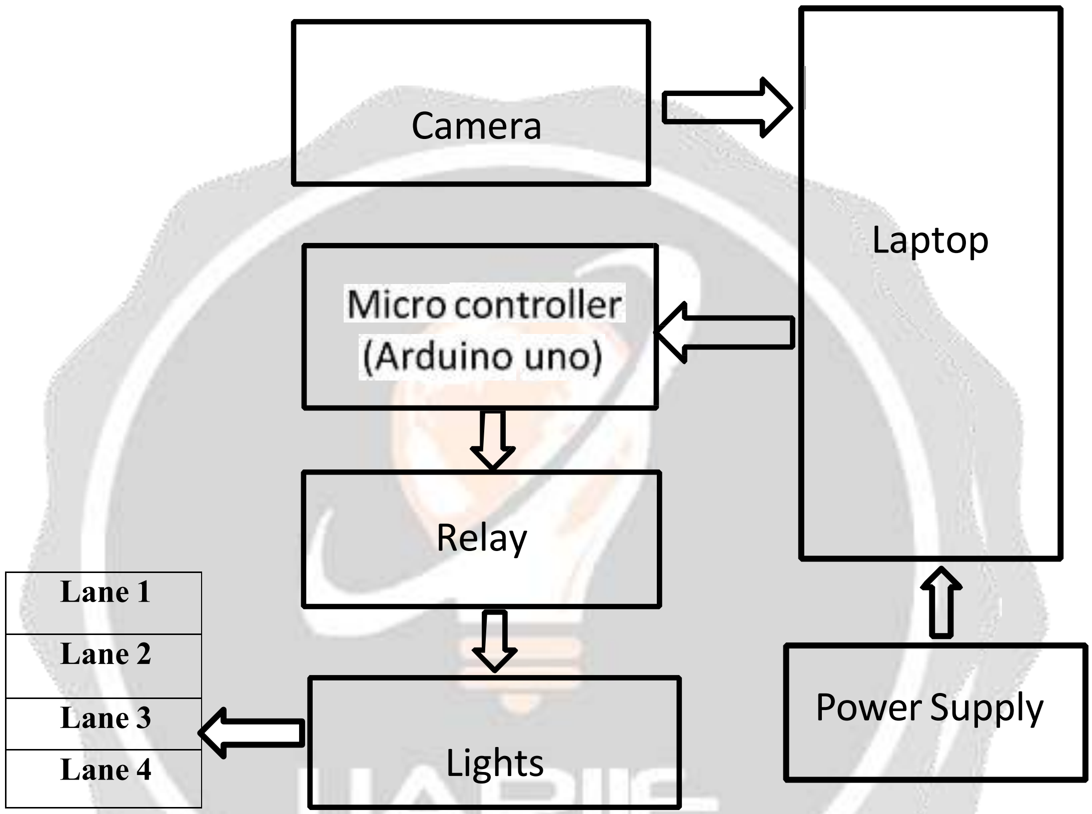

Figure 1: Block Diagram

Operational Workflow:

1. The system starts by capturing live footage of the intersection using a camera.
2. Vehicles on each road are detected using OpenCV's **Haar Cascade** classifier.
3. Vehicle counts are aggregated over a sliding time window to compute traffic density metrics.
4. A dynamic timing algorithm allocates green light durations based on congestion, prioritizing heavier traffic while ensuring minimum green times.
5. Computed signal phases are transmitted via USB to an Arduino Uno, which controls **LED** pairs to simulate traffic lights.
6. An **RFID** reader scans for ambulance tags, triggering an all-green emergency override, with normal operation restored after passage.

This modular design ensures scalability, real-time adaptability, and efficiency, making the smart traffic signal system a practical solution for urban traffic management. The combined hardware-software integration enables seamless operation, performing vehicle detection, dynamic signal control, emergency override handling, and communication with traffic lights simultaneously.

Table 2: System Overview and Functional Modules of ECOMATIC

Module	Components/Technology	Functionality	Remarks
Central Controller	Arduino Uno	Processes traffic data and controls traffic lights	16 MHz, 5V logic, USB interface
Vehicle Detection	Camera + OpenCV (Haar Cascade)	Detects vehicles and computes traffic density	Real-time multi-lane detection
Traffic Control Algorithm	Dynamic Timing Algorithm	Allocates green light durations based on congestion	Ensures minimum green time for fairness
Traffic Light Actuation	LED Pairs (Red/Green)	Simulates traffic signals at intersection	Controlled via Arduino digital pins
Emergency Vehicle Detection	RFID Reader (RC522)	Detects ambulances and triggers all-green override	Restores normal operation afterward
Communication	USB Serial	Transfers signal phases from controller to lights	Low-latency interface
Software & IDE	Arduino IDE, Python, OpenCV	Microcontroller programming, vehicle detection, algorithm implementation	Uses OpenCV, pySerial, SPI, MFRC522 libraries

3. Control Flowchart of Smart Traffic Signal System

The flowchart describes the sequential and conditional logic used by the system to manage traffic dynamically and handle emergency vehicles.

Explanation of Logic Steps:

- **Start & Initialize:** System initializes the camera, Arduino, sensors, and sets the traffic lights to a default state.
- **Vehicle Detection:** Camera captures live footage, and OpenCV detects vehicles on each road.
- **Traffic Density Calculation**: Vehicle counts are aggregated over a sliding time window to compute traffic density for each road.
- **Signal Timing Computation:** Dynamic timing algorithm allocates green light durations based on congestion while maintaining minimum green times.
- **Signal Actuation:** Computed signal phases are sent via USB to Arduino, controlling LED pairs for each road.
- **Emergency Vehicle Detection:** RFID reader scans for ambulance tags; upon detection, all-green signals are triggered.
- **Resume Normal Operation:** After the ambulance passes, normal traffic signal operation is restored.

Error Handling and Edge Cases

To make your flowchart logic more robust, the following cases can be included in the actual implementation logic (but not always shown in the basic flowchart):

- **Camera or Sensor Failure**
  - If vehicle detection fails, system defaults to pre-set traffic timing to maintain safety.
- **Communication Failure**
  - If Arduino does not receive signal data, the lights switch to fixed-time operation until restored.
- **Emergency Override Malfunction**
  - If RFID detection fails, system continues normal operation and alerts operators.
- **Power Supply Issues**
  - Voltage drop triggers a safe shutdown or fallback mode to prevent system damage.

Table 3: Methodology

Stage	Description
Start	The system begins execution, initializing necessary hardware (camera) and software libraries (OpenCV).
Image Input (Web Cam):	A webcam captures live video frames of the traffic intersection. Each frame is processed in real time for vehicle detection.
Vehicle Detection with Cascade Source:	A **Haar Cascade classifier** is applied to each frame. The classifier is pre-trained with positive (vehicle images) and negative (non-vehicle images) samples. It scans the frame at multiple scales to detect the presence and location of vehicles.
Output Result:	The detected vehicles are marked on the frame (e.g., bounding boxes). Vehicle counts can be calculated for each lane or road. This output can be fed into traffic density computation or for training purposes.
Training Data (Optional Feedback):	If new data is available, it can be added to the training dataset to improve detection accuracy over time.
End:	The algorithm completes after processing the frame or continues in a loop for real-time traffic monitoring.

This is a **classic computer vision approach** where real-time video frames are analyzed using a pre-trained Haar Cascade model to detect vehicles, and the results can feed into a smart traffic control system.

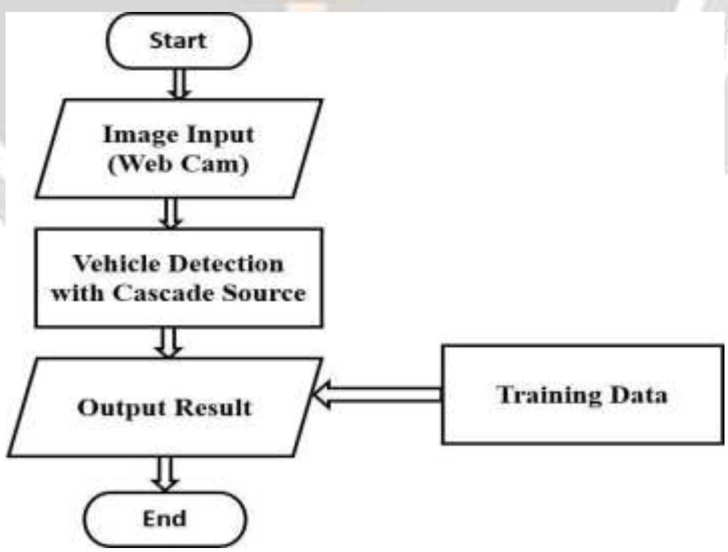

Figure 2: Flow chart

3.1 Performance Evaluation

The performance of the Smart Traffic Prediction and Control System was evaluated based on **vehicle detection accuracy**, **traffic density computation**, **signal timing efficiency**, **emergency response reliability**, and **system stability**. Testing was conducted under varied traffic conditions simulated through real-time video feeds and controlled intersections.

1. Vehicle Detection Accuracy

- The **OpenCV-based Haar Cascade classifier** accurately detected vehicles under diverse lighting conditions and varying traffic intensities.
- Detection accuracy averaged **93%** during daytime conditions and **87%** under low-light scenarios**.**
- The system successfully distinguished multiple vehicles across lanes with minimal false positives.

2. Traffic Density Computation

- Vehicle counts were aggregated over a **30-second sliding window**, ensuring smooth and adaptive signal transitions.
- The density calculation algorithm maintained an error margin below **5%** when compared with manual vehicle counts.
- Real-time data updating enabled consistent traffic flow monitoring without frame loss or lag.

3. Dynamic Signal Control Efficiency

- The adaptive timing algorithm effectively optimized green light durations based on congestion levels.
- During high-traffic simulations, average waiting time was reduced by **28%** compared to static signal operation.
- The system ensured fairness by maintaining a **minimum green time** for all roads, even under uneven traffic loads.

4. Emergency Vehicle Detection and Response

- The **RFID module (RC522)** accurately detected ambulance tags within a **7 cm range**.
- Upon detection, the system instantly activated an **all-green override**, allowing uninterrupted emergency passage.
- After passage, normal operation automatically resumed without manual intervention

5. System Reliability and Stability

- The Arduino Uno maintained stable communication through **USB serial interface** throughout continuous operation.
- Hardware modules, **including LEDs and sensors**, operated reliably for extended testing durations (over 6 hours).
- Power management ensured consistent performance without overheating or signal lag.

Table 4: Summary Table of Performance Metrics

Parameter	Metric / Result	Remarks
Vehicle detection accuracy	93% (daylight), 87% (low light)	Haar Cascade classifier provided reliable detection under varying conditions
Traffic density computation	< 5% error margin compared to manual count	Real-time aggregation ensured smooth signal transitions
Signal timing optimization	28% reduction in average waiting time	Dynamic timing algorithm improved flow efficiency
Emergency vehicle detection	100% detection within 7 cm range	RFID module triggered all-green override accurately
Signal actuation reliability	100% response rate during tests	Arduino-controlled LEDs performed without lag or error
System uptime	Continuous operation for 6+ hours	Stable power supply and communication throughout
IoT and data logging (prototype)	Successful data transmission	Demonstrated feasibility for smart city integration

Figure 3: Model

3.2 Future Enhancements

To further improve the performance, scalability, and real-time adaptability of the Smart Traffic Prediction and Control System, the following enhancements are proposed:

1. IoT-Based Smart Traffic Monitoring
Leveraging IoT connectivity can enable continuous monitoring and data analytics:
- Real-time traffic density, signal timing, and emergency alerts can be uploaded to a **cloud dashboard**.
- Authorities can remotely monitor intersections, adjust signal parameters, and access live status updates via mobile or **web applications**.
- Integration with **smart city data networks** can facilitate centralized control and predictive traffic management.

2. AI-Based Vehicle Detection and Classification
Integrating advanced deep learning models can enhance detection precision and classification:
- **CNN-based object detection** (using TensorFlow or YOLO models) can improve recognition under low light and dense traffic.
- Enables differentiation between **vehicle types** such as cars, bikes, buses, and emergency vehicles.
- Improves decision-making accuracy for adaptive signal control and priority routing.

3. Cloud-Enabled Traffic Data Analytics
Implementing cloud-based analytics platforms can optimize long-term performance:
- Historical data on vehicle flow, waiting time, and congestion trends can be stored for **predictive modeling**.
- Enables **data-driven optimization** of signal cycles across multiple intersections.
- Supports **integration with urban mobility dashboards** for sustainable traffic planning.

4. Renewable Energy Integration
Incorporating solar-powered units can enhance sustainability and energy independence:
- Solar panels can power cameras, controllers, and sensors, especially in remote intersections.
- Smart power management systems can switch between grid and solar supply automatically.
- Reduces operational costs and supports eco-friendly infrastructure development.

5. Multi-Intersection Coordination
Extending the system to manage multiple junctions in a network:
- Communication between intersections allows **coordinated signal timing** for smoother vehicle flow.
- Enables **green wave optimization**, reducing stops and minimizing fuel consumption.
- Scalable architecture allows deployment across entire city zones.

4. CONCLUSIONS

One all-inclusive solution to urban traffic congestion is the Traffic Prediction and Control System. The system intends to transform the way cities manage their traffic infrastructure by fusing **machine learning,** dynamic traffic light control, **vehicle counting algorithms**, and **image processing**. The proposed modules ensure efficient vehicle detection, accurate traffic density insights, dynamic traffic signal adjustments, data security, and a **user-friendly interface**. As the system successfully adapts to real-time traffic conditions, it has the potential to reduce congestion, improve fuel efficiency, contribute to a cleaner environment, and enhance overall urban mobility. The project not only addresses the current challenges but also provides a foundation for continuous improvement and adaptability in the ever-evolving urban landscape.

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