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Adaptive Traffic Light Control System

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BACHELOR OF TECHNOLOGY

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Introduction

1.1 Basic Idea

Controlling and managing traffic signals to ensure vehicular safety and maintain a continuous traffic flow is challenging in dense urban areas. The rapid growth in vehicle numbers and the lack of coordinated flow management often disrupt smooth movement, causing congestion and inefficient control [1]. According to [2], fixed traffic signal (FTS) delays contribute to nearly 10% of global traffic slowdowns. Early in urbanization, governments introduced manual Traffic Signal Control (TSC) systems, where officers adjusted green, yellow, and red durations based on real-time traffic volumes. Today, many intersections still rely on synchronized FTS, which provide equal green time to all directions within each cycle. However, studies [3,4] show that developed countries lose over 295 million hours annually due to these fixed systems, emphasizing the need for more accurate, time-dependent delay estimations. Congestion largely stems from the system's inability to adapt signal timings to dynamic traffic patterns that change with time of day and season. Research trends (2015–2024) show a strong rise in traffic signal control studies after 2018, peaking in 2022–2023, with growing interest in optimization and adaptive control systems.

1.2 Main Idea

The main idea of our Adaptive Traffic Light Control System (ATLCS) is to synchronize traffic lights across consecutive junctions by introducing a dynamic delay between the times each signal turns green in a particular direction. This delay is continuously updated based on the number of vehicles waiting at each junction, enabling vehicles leaving the city centre to move longer distances without stopping and reducing the frequency of the "stop-and-go" phenomenon. Performance evaluations show that ATLCS reduces the average travel time for vehicles in the synchronized direction by up to 39% compared to fixed-time systems, and achieves an overall improvement of 17% across the simulated network [5]. This aligns with the broader Smart City vision, where sustainable, efficient cities leverage advanced information and communication technologies (ICTs) to monitor and manage critical assets such as transportation, energy, and water. Smart Cities rely on technologies like IoT, sensors, 5G, cloud computing, AI, and connected vehicles, supported through collaboration between government, industry, academia, and society, to enable smart buildings, smart energy systems, and intelligent green transportation.

Brief Literature survey

2.1 Traffic Data Collection in Urban Cities

Many researchers have worked on traffic management to reduce congestion and delays in urban areas. Traffic congestion has become one of the biggest challenges in almost all major Indian cities. With rapid urbanization, increasing population, and rising vehicle ownership, city roads are unable to cope with the growing demand. Daily commuting has become not only time-consuming but also stressful, leading to loss of productivity, increased fuel consumption, and higher levels of pollution. Several national and international surveys, including reports from reveal the severity of this issue. They provide valuable insights into how long it takes to travel short distances during peak hours, the number of hours wasted annually in traffic, and the percentage of congestion compared to free-flowing conditions. These statistics give a clear picture of how much urban life and economic activity are affected by inefficient traffic flow. The table below summarizes key facts and figures for some of India's most congested cities.

During peak hours, major Indian cities experience heavy traffic congestion, with travel times for 10 km ranging from about 21 to 34 minutes. Kolkata records one of the slowest movements, taking 34 minutes 33 seconds and causing around 110 hours of annual delay, while Bengaluru is similarly congested with 34 minutes 10 seconds and nearly 117 hours lost each year. Pune also shows high congestion, taking 33 minutes 22 seconds and leading to roughly 108 annual hours wasted, whereas Chennai's traffic requires around 30 minutes 20 seconds, resulting in about 94 lost hours. In Mumbai, the average time to cover 10 km is 29 minutes 26 seconds, with congestion levels ranging between 35–54%, contributing to nearly 103 hours of yearly delay. Delhi performs slightly better in terms of speed, with about 21 minutes 40 seconds needed for 10 km in the city center, though peak-hour driving still consumes around 191 hours annually, reflecting significant slowdowns during rush hours [6].

2.2 Traffic Control System

Conventional traffic control systems rely on fixed-time signal cycles or basic proximity-sensor responses, where signal timings follow preset patterns with limited variation [7]. Because these systems cannot adapt to real-time traffic conditions, they often cause unnecessary waiting, higher fuel consumption, increased emissions, and frequent stop-and-go movement across the network. In rapidly growing urban cities, such rigid systems struggle to handle fluctuating traffic volumes during peak hours, special events, or unexpected road disturbances. To overcome these limitations, modern Adaptive Traffic Control Systems (ATCS) use real-time data from advanced sensors such as cameras and radar to collect detailed information on vehicle count, speed, and waiting time. By processing this diverse data, adaptive systems dynamically adjust signal timings at multiple intersections, reducing delays, improving traffic flow, and increasing overall energy efficiency. Simulation studies consistently show significant improvements over fixed-time methods, with further gains achieved by incorporating vehicle-type information for better fuel optimization. Real-world deployments reinforce these results—for example, Bengaluru's ATCS (BATCS) reported up to 33% travel-time reduction, while the Surtrac system in Pittsburgh achieved a 25% decrease in travel time and a 21% drop in emissions [8]. As cities move toward smart and sustainable transportation, adaptive, data-driven signal control provides a practical and scalable approach to managing congestion.

Problem Formulation

Traffic congestion is a long-standing issue that urban planners and engineers have attempted to mitigate using various technologies. Urban traffic congestion has become a critical issue in cities worldwide, especially in India, where rapid urbanisation and an ever-increasing number of vehicles have overwhelmed existing road infrastructure. Traditional traffic signal systems typically operate on fixed-time schedules, which are unable to adapt to real-time traffic conditions. As a result, vehicles often experience unnecessary waiting times at intersections, leading to longer commute durations, increased fuel consumption, higher vehicular emissions, and greater frustration among commuters. Semi-actuated or manually controlled traffic signals offer only limited relief, as they cannot efficiently optimise traffic flow across multiple intersections simultaneously.

According to the TomTom Traffic Index 2024**,** Indian cities such as Bengaluru, Mumbai, and Kolkata are among the most congested globally, with average commute times increasing by 30–35% during peak hours. This highlights the urgent need for smarter traffic management solutions capable of responding dynamically to changing traffic conditions. Fixed-time traffic systems are not only inefficient in reducing congestion but also fail to prioritise emergency vehicles or adapt to special events, accidents, or weather-related disruptions.

Therefore, our core problem is to design an Adaptive Traffic Light Control System that can continuously monitor real-time traffic conditions, dynamically adjust signal timings, and reduce congestion, waiting times, and environmental impact at urban intersections.

Objectives

The primary objective of this project is to design and implement an Adaptive Traffic Control System (ATCS) that optimises traffic signal operations based on real-time traffic conditions, thereby reducing congestion, waiting time, and environmental impact at urban intersections. Unlike traditional fixed-time or semi-actuated traffic signals, the proposed system aims to respond dynamically to fluctuating traffic patterns, ensuring smoother traffic flow and more efficient use of road infrastructure.

The specific objectives of this project include:

1. **Real-time Traffic Monitoring:** To gather and process traffic data from sensors, cameras, or publicly available datasets, including vehicle density, queue lengths, and flow patterns at multiple intersections. To implement algorithms that continuously monitor traffic conditions and detect peak and off-peak periods.
2. **Dynamic Signal Timing:** To develop a system that can adjust green, yellow, and red signal durations dynamically based on real-time traffic conditions. To optimise signal sequences for multiple intersections in coordination, preventing unnecessary waiting times and bottlenecks.
3. **Reduction of Travel Time and Congestion:** To minimise vehicle waiting times at intersections by applying adaptive algorithms that respond to changing traffic loads.
4. **Environmental and Economic Benefits:** To reduce vehicular emissions by decreasing idle time at red lights, contributing to cleaner urban air, lower fuel consumption and operating costs for commuters and transport operators.
5. **Future Scalability and Smart City Integration:** To ensure that the system is scalable and can be integrated with IoT devices, GPS-based vehicle tracking, provide a foundation for further enhancements such as emergency vehicle prioritisation, pedestrian-friendly adaptive signals, and predictive traffic modelling.

Methodology/ Planning of work

The proposed system aims to develop an intelligent traffic monitoring and management system using deep learning and IoT-based approaches. The methodology involves a combination of real-time object detection, data analytics, and AI-driven decision-making to enhance traffic flow, improve safety, and reduce congestion in urban environments [12]. The system architecture integrates computer vision, edge computing, and cloud-based analytics for efficient data processing.

1. **Data Collection and Preprocessing:**
   IoT-enabled sensors, cameras, and GPS trackers are deployed at intersections to collect traffic data. Data attributes include vehicle count, speed, congestion levels, and weather conditions. The raw data undergoes preprocessing techniques such as cleaning, normalization, and feature selection for model training.
2. **Machine Learning-Based Traffic Prediction:**
   Supervised learning models (Random Forest, Support Vector Machines, and Deep Learning techniques like CNNs and LSTMs) are trained on historical and real-time traffic data. Traffic signal timings dynamically adjust based on real-time congestion data Anomaly detection is implemented for incident detection and emergency response.
3. **IoT and Cloud-Based Integration:**
   Cloud computing is used for real-time traffic data processing and model updates. IoT-enabled traffic control units send live data to cloud-based servers. Edge computing is integrated for low-latency response in critical intersections.
4. **Performance Evaluation Metrics:**
   Key Performance Indicators (KPIs) such as average waiting time, vehicle throughput, congestion index, and accident response time are analyzed. Comparative analysis is performed against traditional fixed-time traffic light systems. Real-world traffic simulation using SUMO (Simulation of Urban Mobility) validates the system's effectiveness.

Facilities required for proposed work

The system architecture of the proposed smart traffic control system consists of multiple interconnected layers, ensuring seamless data flow, processing, and decision-making.

System Components:

1. **Traffic Data Acquisition Layer:**
   IoT sensors, CCTV cameras, and GPS trackers collect live traffic data. Vehicle detection, lane occupancy, and speed monitoring are performed.
2. **Data Processing and Storage Layer:**
   The collected data is transmitted to cloud servers for preprocessing. Data cleansing, feature extraction, and predictive model updates occur in this stage.
3. **Traffic Prediction and Decision-Making Layer:**
   Machine learning models predict congestion levels and traffic density. Adaptive traffic light control algorithms adjust signals dynamically.
4. **Communication and Actuation Layer:**
   The processed data is sent to traffic signal controllers for real-time adjustments. Alerts are generated for emergency vehicles, congestion zones, and accident-prone areas.
5. **User Interface and Monitoring Layer:**
   Traffic authorities monitor the system via a web or mobile dashboard. Citizens receive live traffic updates through mobile applications.

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