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Intelligent Traffic Signal Control Network for Optimizing Traffic Flow

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ABSTRACT

The increasing use of vehicles, combined with advancements in sensor technology and data analytics, presents new opportunities to enhance the efficiency and safety of transportation systems. This paper proposes a framework for implementing intelligent traffic signal control networks that leverage real-time data from vehicle-to-infrastructure (V2I) communications and adaptive algorithms to dynamically optimize traffic signal timing, particularly at four-way intersection, which consist of a main road and a secondary road. By integrating vehicle position and speed, the system can adjust signal phases and timings in response to real-time conditions, thereby reducing congestion, idling, and intersection-related collisions. The simulation will explore the core components of smart traffic signal control architecture, including sensor integration, data analysis, and adaptive algorithms. Results from simulation studies demonstrate improvements in traffic flow, reduced emissions, and enhanced safety. This highlights the importance of smart traffic management technologies in building safer and more sustainable urban environments.

شبكة متحكم إشارات المرور الذكية لتحسين تدفق المرور

سناء عبدالله فضل [1] ، ناصر منصور ابوهمود [2]

الملخص

تقدم الزيادة في استخدام المركبات، جنبًا إلى جنب مع التقدم في تكنولوجيا الحساسات وتحليل البيانات، فرصًا جديدة لتعزيز كفاءة وسلامة أنظمة النقل. تقترح هذه الورقة إطارًا لتنفيذ شبكات التحكم في إشارات المرور الذكية التي تستفيد من البيانات الزمنية الحقيقية من الاتصالات بين المركبات والبنية التحتية (V2I) والخوارزميات التكيفية لتحسين توقيت إشارات المرور ديناميكيًا. من خلال دمج موقع المركبات وسرعتها، يمكن للنظام ضبط مراحل الإشارات وتوقيتها استجابةً للظروف الزمنية الحقيقية، مما يقلل من الازدحام والانتظار والحوادث المرتبطة بالتقاطعات. ستستكشف الدراسة المكونات الأساسية لهندسة التحكم في إشارات المرور الذكية، بما في ذلك تكامل الحساسات، وتحليل البيانات، والخوارزميات التكيفية. يتم التحكم في تقاطع رباعي يتكون من أربعة اتجاهات، مما يسهل تدفق الحركة بشكل أفضل. تظهر نتائج الدراسات المحاكاة تحسينات في تدفق المرور، وتقليل الانبعاثات، وزيادة السلامة. يبرز هذا أهمية تقنيات إدارة المرور الذكية في بناء بيئات حضرية أكثر أمانًا واستدامة.

الكلمات المفتاحية

التحكم بإشارات المرور
اتصالات المركبة بالبنية التحتية
تحليلات البيانات
سلامة المرور
إدارة المرور التكيفية

Introduction

In recent years, the rapid increase in vehicle usage has led to significant challenges in traffic management systems worldwide. Urban areas are experiencing heightened traffic congestion, increased travel times, and a rise in accidents, all of which have negative implications for public safety and environmental sustainability. As cities continue to grow and the number of vehicles on the roads increases, traditional traffic management methods are proving inadequate to address these issues effectively [1].

In Libya, cities like Tripoli and Benghazi face similar challenges due to rising vehicle numbers and inadequate infrastructure. Although precise statistics may be lacking, daily experiences indicate that residents spend significant time in traffic, negatively impacting quality of life and increasing stress levels. Reports suggest that urban congestion can lead to increased travel times and economic losses, highlighting the urgent need for innovative solutions to improve traffic management [2].

To combat these challenges, advancements in technology offer promising solutions. Modern sensing technologies and data analytics provide new opportunities to enhance the efficiency and safety of transportation networks. One of the most transformative innovations in this context is Vehicle-to-Infrastructure (V2I) communication. This technology enables vehicles to communicate with roadside infrastructure—such as traffic signals and signs—allowing for real-time adjustments to traffic management practices. The integration of smart traffic management systems, particularly smart traffic lights, is emerging as a vital component in creating safer and more efficient urban transportation environments. These systems leverage data from V2I communications to optimize traffic flow and improve safety for all road users, including vehicles and pedestrians. This paper aims to explore the framework for implementing smart traffic signal control networks that utilize real-time data and advanced algorithms to dynamically optimize traffic signal timing. By analyzing the core components of this architecture, we will

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highlight the potential benefits of adaptive traffic management technologies in reducing congestion, minimizing emissions, and enhancing overall road safety [3].

Modern Sensing Technologies and Vehicle-to-Infrastructure (V2I) Communication

Modern sensing technologies and Vehicle-to-Infrastructure (V2I) communication are pivotal elements in enhancing traffic management systems. V2I enables vehicles to communicate with roadside infrastructure, such as traffic signals, to optimize traffic flow and improve safety. This technology collects data on traffic conditions, weather advisories, and congestion, which can be transmitted to vehicles in real-time, allowing for informed decision-making by drivers and automated systems [4].

Smart Traffic Lights: Definition and Applications

Smart traffic lights are defined as signals equipped with sensors and communication technologies that adapt to real-time traffic conditions. These signals utilize data from V2I systems to dynamically adjust their timing, ensuring a smooth and efficient flow of traffic. Key applications include [5]:

- Adaptive Signal Control: Adjusting the timing of traffic lights based on current traffic volumes and patterns.
- Emergency Vehicle Preemption: Allowing emergency vehicles to pass through intersections without delay by changing signal phases.
- Pedestrian Safety Enhancements: Modifying signals to prioritize pedestrian crossings when needed.

Benefits of Adaptive Control:

In Table 1 Adaptive traffic signal control offers several benefits, including [6].

Table 1: Benefits of Adaptive Traffic Signals

Benefit	Description
Reduced Waiting Time	Signals adjust in real-time to minimize delays for vehicles and pedestrians
Improved Traffic Flow	Optimizes the timing of lights to reduce congestion and enhance overall traffic movement
Reduced Emissions	By minimizing stop-and-go traffic, adaptive signals contribute to lower vehicle emissions

Methodology

This study utilizes a simulation framework to model real-world traffic conditions using simulated scenarios that represent varying vehicle densities, positions, and speeds. Key parameters such as vehicle count, speed, and green-light timing are dynamically adjusted based on the simulated conditions**.**

1. Data Collection: Vehicle data is generated through a simulation model that tracks positions, speeds, and densities over time. The number of vehicles within a 1000-meter range is recorded to classify traffic levels as low, medium, high, or very high, enabling real-time adjustments to signal timings.

Sensors Used in Real-Life Traffic Data Collection

To apply the simulation to a real-world scenario, several types of sensors can be employed to collect the necessary data. These sensors can provide the same type of information generated in the simulation, such as vehicle positions, speeds, and traffic density. Here are the main sensor types:

A. Radar Sensors

Location: Mounted on traffic lights or streetlight poles at intersections.

Function: Radar sensors detect the distance and speed of vehicles by emitting radio waves and analyzing their reflections, providing precise data on traffic flow and vehicle speed.

B. CCTV Cameras

Location: Installed on traffic lights or high poles along the roads.

Function: These cameras capture real-time video footage, which can be processed using computer vision techniques to extract information about vehicle counts, speeds, and pedestrian movements.

C. Infrared Sensors

Location: Typically installed on traffic signals or pedestrian crossings.

Function: Infrared sensors detect vehicles and pedestrians by sensing their heat signatures, providing data on movement even in low-visibility conditions like night or fog.

D. Inductive Loop Sensors

Location: Buried underneath the road surface at intersections.

Function: These sensors detect the presence of vehicles above them by sensing changes in the electromagnetic field caused by metallic objects, such as cars. They are commonly used to count vehicles and measure waiting times.

Data Collection Unit

All the data collected from these sensors are transmitted to a Traffic Signal Controller Unit or a Central Traffic Management System (CTMS).

Location: Typically housed in cabinets near traffic intersections or centralized traffic control centers.

Function: Collects, processes, and analyzes the real-time data from sensors. Based on the incoming data, it adjusts traffic signals dynamically to optimize traffic flow.

2. Simulation Scenarios: Various scenarios are tested, including normal traffic and increased vehicle counts. The system dynamically adjusts green light durations to reduce waiting times and improve average speeds.
3. Adaptive Control Algorithms: An adaptive control algorithm responds to real-time traffic conditions by adjusting signal timings based on vehicle counts and average speeds. Emergency vehicles are prioritized by changing signal phases for unobstructed passage.

The operation of the smart traffic signal control system, which incorporates Vehicle-to-Infrastructure (V2I) communications, is illustrated in Figure 1. The system simulates traffic conditions and regulates intersection lights using simulated data, counting vehicles within a specified range at each time step. Traffic conditions are classified dynamically, allowing timely adjustments to signal timings. The system's performance is evaluated by calculating average speeds and total wait times, demonstrating its effectiveness in managing traffic flow.

In this study, the simulation model controls a four-way intersection consisting of a main road and several secondary roads, as shown in figure (2) in the accompanying figure. The simulation focuses on multiple traffic signals that are interconnected within the network to ensure coordinated traffic management. It monitors traffic flow in all directions, and when the sensors detect congestion in any direction, the signal timings are adjusted to improve overall traffic movement and reduce delays.

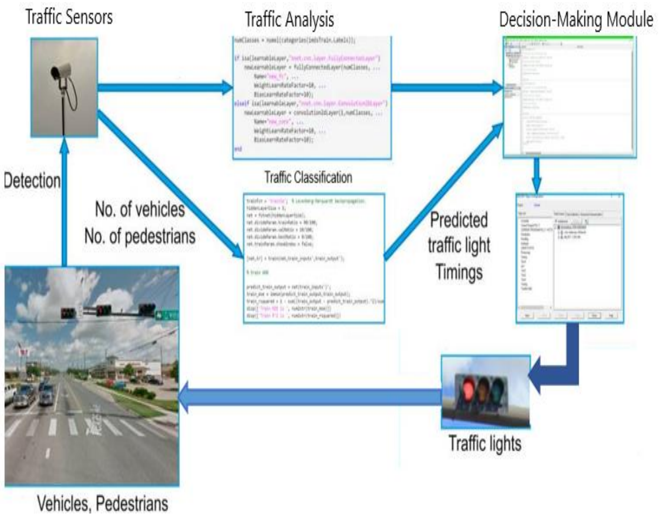

Fig.1: Flowchart of Traffic Analysis and Control Mechanism

Fig.2: Smart traffic intersection

Data Collection

Motion sensors and cameras used to collect accurate data about:

- Number of Vehicles: Measuring the total number of vehicles within a specified range.
- Vehicle Speeds: Monitoring the speeds of different vehicles to determine the flow of traffic.
- V2I Information: Collecting data related to emergency vehicles, such as ambulances or fire trucks, to facilitate their response in emergency situations.

The data can be simulated using the provided code, which generates random initial positions and speeds for the vehicles. This simulation includes models of traffic at different times of the day. As shown in the Figure 3 below, the simulation steps are defined.

Data Analysis

- Advanced algorithms are used to analyse the data collected from the sensors and vehicles. These algorithms include:
- Temporal Data Analysis: To understand traffic patterns during different times.
- Traffic is classified into categories (low, medium, high, and very high) based on the number of vehicles, which helps determine when to adjust signal timings.

Control Model

An algorithm is developed to control traffic signals based on traffic classification. This algorithm includes:

- Signal Timing Determination: Based on traffic density.
- Priority for Emergency Vehicles: Using V2I data to identify emergency situations, such as the passage of an ambulance, which leads to immediate changes in signal timings to facilitate their passage.

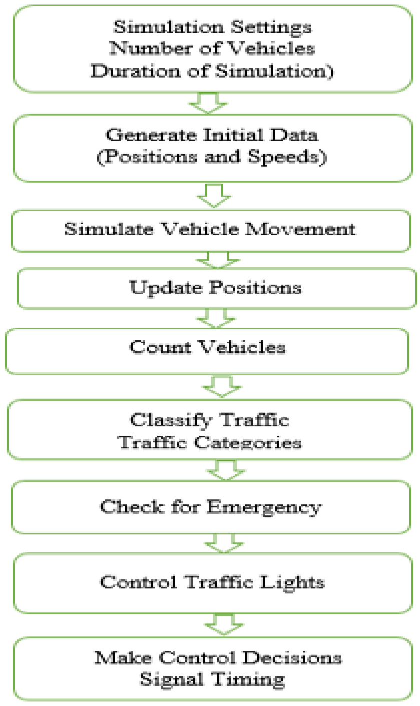

Fig.3: Flowchart of Traffic Analysis and Control Mechanism

Intersection Monitoring

- The system can control multiple streets at a single intersection. Data is used to determine traffic priority in each direction based on current conditions.
- Vehicle positions are updated in the code, and signal timings are determined based on the number of vehicles present in each range.

Emergency Response

In the event of an emergency vehicle, the system can adjust signal timings to deactivate signals in other directions and allocate a green signal for the emergency vehicle, reducing wait times and increasing traffic safety.

Assumptions of the Simulation Model

In this simulation model is based on assumptions regarding vehicle distribution and road type. Vehicles are randomly distributed across a virtual road network with a length of 1000 meters, assuming two lanes in each direction. Traffic densities vary between low, medium, high, and very high. The initial speeds of the vehicles are uniformly distributed between 0 and 20 m/s, simulating real-world conditions. It is also assumed that the roads are straight and without complex intersections, focusing purely on signal control at standard intersections.

Code Implementation Overview

The MATLAB code simulates traffic flow and a basic intelligent traffic signal control system. It consists of three main parts:

1. Data Generation Function: This function creates random initial positions and speeds for a set number of vehicles.
2. Main Simulation Loop: The simulation loop controls traffic signals by adjusting light durations based on the number of vehicles, allowing for more adaptive control.
3. Data Analysis: Metrics such as average speed and total waiting time are calculated to evaluate the system's performance

Results and Discussion

The performance of the smart traffic signal control system at the four-way intersection, featuring four interconnected traffic signals, has been extensively analysed through various simulations. The results demonstrate significant improvements in traffic flow and reductions in waiting times.

Impact on Traffic Flow and Waiting Times

Traffic Mobility Improvement: The proposed intelligent traffic control systems have shown the ability to enhance traffic mobility compared to traditional traffic signal control strategies. As indicated in Figure 8, these systems effectively manage traffic, leading to reduced congestion at intersections and improved average speed.

Emergency Vehicle Prioritization: Recent models prioritize emergency vehicles, such as ambulances, significantly reducing their waiting times at traffic signals. This prioritization not only benefits emergency response times but also optimizes overall traffic flow by minimizing disruptions. Figure (4) illustrates a significant decrease in the number of vehicles waiting, supporting the system's effectiveness in reducing waiting times [7].

Performance Metrics: Various performance metrics have been defined to measure the effectiveness of these systems, including traffic flow efficiency and delay reduction. The smart traffic signal controller has demonstrated marked improvements in traffic flow and congestion reduction, showcasing adaptability to dynamic traffic conditions.

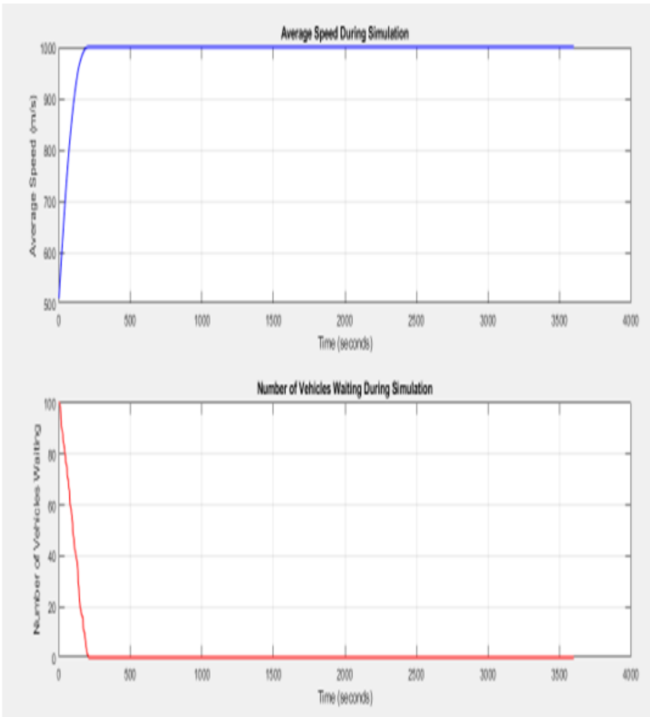

Fig.4: Traffic Simulation Analysis: Speed and Waiting Vehicles

The analysis reveals that an increase in the number of vehicles leads to longer waiting times and decreased average speeds. The effects on traffic were evaluated in different scenarios as shown in Table 2.

Normal Scenario: With 100 vehicles, an average speed of 10.444 m/s, and a total wait time of 1400 seconds with green light duration of 20 seconds.

Increased Vehicles: When the number of vehicles increased to 200, the average speed decreased to 9.8131 m/s and the total wait time increased to 6000 seconds, while the green light duration remained at 20 seconds.

Higher Speeds Scenario: The average speed rose to 15.131 m/s, but the total wait time was 4100 seconds, with a green light duration of 30 seconds.

Longer Red Light Scenario: The average speed dropped to 9.9416 m/s, and the total wait time increased to 6100 seconds, with a green light duration of 20 seconds..

Low Vehicle Count Scenario: The impact of a low vehicle count (20 vehicles) on traffic was analyzed. The scenario recorded an average speed of 11.59 m/s, short wait time indicates the absence of congestion.

short wait time indicates the absence of congestion. with a total wait time of 0 seconds and a green signal duration of 10 seconds.

The proposed smart traffic signal control system aims to improve traffic flow by reducing waiting times and increasing vehicle speeds, particularly in scenarios with high vehicle numbers. The system dynamically adjusts signal timing based on traffic density by:

1. Counting Vehicles: The number of vehicles(V) in a specific area is measured during each time interval.
2. Classifying Traffic: Traffic is categorized based on vehicle count (low, medium, high, very high).
3. Adjusting Signal Timing: Green signal timing is adjusted according to traffic category, increasing green time with higher density.
4. Improving Traffic Flow: This adjustment aims to enhance vehicle flow and reduce waiting times.

Table 1: Traffic Flow Analysis Under Different Scenarios

Scenario	Average Speed (m/s)	Wait Time (s)	Number of V	Green Time (s)
Normal	10.444	1400	100	20
Increased N.V	9.8131	6000	200	20
Higher Speeds	15.131	4100	200	30
Longer Red Light	9.9416	6100	200	20
Low N.V Count Scenario	11.59	0	20	10

Comparison of Traditional and Proposed Smart Traffic Lights in the Intelligent Control System

The results show that smart traffic signal systems provide significant improvements compared to traditional signals, as summarized in Table(3) . While traditional signals rely on fixed timing and do not respond to changes in traffic flow, smart systems use advanced technologies such as sensors and real-time data to dynamically adjust signal timing. This adaptability helps reduce congestion and improve traffic efficiency. Furthermore, smart systems have the capability to prioritize emergency vehicles, which aids in reducing wait times and enhancing overall traffic safety.

Practical Challenges and Benefits

The comparison between traditional and smart traffic signals shows clear benefits in reducing congestion and waiting times, but there are practical challenges in implementation. Traditional systems, while less efficient, are easier and cheaper to maintain. In contrast, smart systems require significant upfront investment in sensors and the infrastructure needed for vehicle-to-infrastructure (V2I) communication. However, the long-term benefits of smart traffic systems outweigh the initial costs, as they can improve traffic flow, reduce vehicle emissions, and enhance public safety. Successful deployment requires addressing technical

Table 3: Comparison of Traditional and Smart Traffic Signals

Feature	Traditional Traffic Signals **[8]**	Smart Traffic Signals
Technology Used	Relies on fixed timing systems, preset without changes based on traffic conditions	Utilizes advanced technologies such as sensors, cameras, and Vehicle-to-Infrastructure (V2I) data to dynamically adjust signal timing based on current traffic
Interaction with Traffic	Operates independently, not responding to changing traffic conditions	Adapts to traffic density, helping to improve flow and reduce congestion
Traffic Priority Control	Provides fixed priority to all vehicles without considering emergency situations	Can prioritize emergency vehicles like ambulances and fire trucks, aiding in faster response times
Data Collection and Analysis	Does not effectively collect traffic data	Gathers and analyzes real-time data, enabling decisions based on accurate information
Efficiency and Safety	May lead to increased congestion and delays	Aims to improve efficiency and reduce wait times, enhancing overall traffic safety

challenges such as data privacy and sensor accuracy, as well as ensuring that the infrastructure is adaptable to future advancements, including the integration of autonomous vehicles.

Environmental Impact Analysis

One significant advantage of the proposed smart traffic signal system is its potential to reduce vehicle emissions by minimizing idling time and stop-and-go traffic. In traditional systems, vehicles frequently stop at red lights, increasing fuel consumption and producing higher levels of emissions. By dynamically adjusting the green light timing based on real-time traffic data, the smart system can significantly reduce idle times.

Conclusion

This research paper emphasizes the significance of smart traffic signal systems in enhancing traffic management in urban environments. By utilizing Vehicle-to-Infrastructure (V2I) communication and real-time data, improvements in traffic flow, reduced waiting times, and increased road safety can be achieved. Simulation results show that smart systems adapt to dynamic traffic conditions, reducing congestion and emissions. Advanced data collection techniques, including motion sensors, enable precise adjustments to signal timings. Prioritizing emergency vehicles further enhances public safety. Future work could focus on integrating real-world data from Libyan cities to further validate the system's performance in diverse conditions. As technology evolves, smart traffic systems will play a crucial role in tackling future traffic challenges.

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