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Adaptive Traffic Signal Control System Based on Future Traffic Environment

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Abstract: Traffic congestion is a major challenge in urban environments due to increasing vehicle density and inefficient fixed-time traffic signal systems. Traditional traffic lights operate on predefined timers that do not consider real-time traffic conditions, resulting in unnecessary delays, increased fuel consumption, and higher carbon emissions. This paper proposes an Adaptive Traffic Signal Timer system using realtime computer vision and deep learning techniques to dynamically adjust traffic signal timings based on lane-wise vehicle density. The system employs the YOLO (You Only Look Once) object detection algorithm integrated with OpenCV to detect and count vehicles from live video streams. Based on calculated density metrics, optimal green signal durations are assigned dynamically. The proposed system improves traffic flow efficiency, reduces waiting time, and supports intelligent transportation and smart city infrastructure development.

Keywords: Intelligent Transportation System, Computer Vision, YOLO, Traffic Density Estimation, Adaptive Signal Control, Deep Learning.

I. INTRODUCTION

The amount of motor vehicles and correspondent travel demand are continuously increasing with economic and social development. The frequent occurrence of traffic congestion in urban road network has negative impacts on economy and environment. Due to the limited land resources of large cities and restrictions to transportation infrastructure construction from socioeconomic factors, to apply traffic management and control measures in a reasonable and effective way, improve the efficiency of existing transportation facilities, and accommodate the growing traffic demand in big cities have become significant research contents for counteracting urban traffic congestion. Traffic control is one of the most important technical means to regulate traffic flow, improve the congestion, and even reduce emissions. Its progress and development has always been accompanied by the development of information technology, computer technology, and system science. The selfadaptive control system can adjust the signal timing parameters in real time according to the control target of the manager (such as the minimum delay of the intersection) and the arrival characteristics of the traffic flow at the intersection. Compared with timing control and actuated control, the self-adaptive control system can make better use of the overall traffic capacity of the road network and effectively improve the efficiency of road network traffic. The traffic data collected by the current traffic control system using induction loop detector and other existing sensors is limited. With the advancement of the wireless communication technologies and the development of the vehicle-to-vehicle (V2V) and vehicle to infrastructure (V2I) systems, called Connected Vehicle or V2X, there is an opportunity to optimize the operation of urban traffic network by cooperation between traffic signal control and driving behaviors. This dissertation proposed a series of cooperative optimization methods for urban streets traffic control and driving assistant under the V2X concept. In addition to the existing induction loop detector technology, the video, infrared, radar, floating cars, and other acquisition technologies and equipment provide urban traffic control system with a network of dynamic acquisition traffic flow status data and controller state data, which greatly enriched the information environment and provides more possibilities for the informationalized and intelligent application research. Urban traffic control is entering the data-rich period of multisource holographic network traffic data from the period with only data of cross-section traffic flow. Recent advances in traffic control methods have ledto flexible control strategies for use in an adaptive traffic control system. [1]. Metropolitan road traffic digitized and informationalized infrastructure and related system construction has been developed rapidly in the past decade.

Recent advancements in artificial intelligence and mobile data analysis have enabled the development of systems capable of learning user behaviour patterns through passive sensing techniques. By analysing smartphone interaction data—such as screen usage duration, session frequency, application switching behaviour, and time-based usage trends—it becomes possible to infer behavioural states associated with low attention span and compulsive usage. These insights can be leveraged to predict the likelihood of a user entering a doomscrolling state.

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In this paper, we propose an AI-based system designed to detect and mitigate doomscrolling behaviour through personalized behavioural analysis. The system initially observes user interaction patterns over a learning period to establish an individual behavioural baseline. Based on this data, a machine learning model predicts potential doomscrolling states in near real time. When such a state is detected, the system provides gentle and timely interventions aimed at encouraging healthier usage habits rather than enforcing strict restrictions.

The primary objective of this work is to assist users— particularly students—in maintaining better focus, reducing unnecessary screen time, and developing mindful smartphone usage habits. By shifting from reactive control mechanisms to predictive and adaptive intervention strategies, the proposed approach aims to address the limitations of existing digital wellbeing solutions while preserving user privacy and usability.

II. SYSTEM OVERVIEW

The proposed system is designed to dynamically regulate traffic signals by analysing real-time vehicle density using computer vision techniques in a non-intrusive and automated manner. Unlike traditional fixed-time traffic lights, the system adapts signal durations based on actual road conditions, ensuring improved traffic efficiency and reduced congestion. At a high level, the system operates in three major phases: a data acquisition phase, a traffic analysis phase, and an adaptive control phase. During the acquisition phase, live video feeds from traffic cameras are processed to capture continuous information about vehicle movement across multiple lanes. This phase enables the system to monitor traffic conditions in real time. Once the video data is obtained, the system analyses each frame using a deep learning-based object detection model to identify and count vehicles. Lane-wise vehicle counts are computed and processed to estimate traffic density levels. Based on this analysis, the system determines the optimal signal timing for each lane. When high congestion is detected in a particular lane, the system allocates longer green signal duration, while lanes with lower traffic density receive shorter intervals. The objective is not only to automate signal control but also to enhance traffic flow efficiency and minimize unnecessary waiting time. The overall architecture emphasizes real-time responsiveness, adaptability, and scalability. By replacing static timers with predictive density-based control, the system aims to provide a more efficient and intelligent traffic management solution suitable for smart city environments.

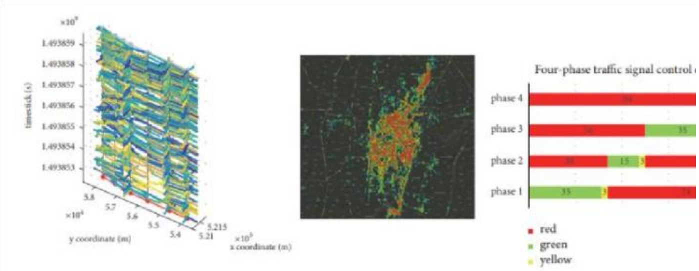

FIGURE 1: New traffic data environment.

III. METHODOLOGY

The proposed methodology focuses on dynamically optimizing traffic signal timings through real-time video analysis and density-based adaptive control. The system is designed to be automated, scalable, and suitable for real-world urban intersections. The methodology consists of three main stages: data acquisition, traffic density estimation, and adaptive signal control.

A. Data Collection

During the initial phase, the system captures live video feeds from surveillance cameras installed at road intersections. This phase enables continuous monitoring of vehicle movement across multiple lanes without requiring manual input or physical road sensors. The collected data consists only of visual traffic information and does not involve personal or identifiable vehicle details. Key data elements include the number of vehicles per frame, vehicle type classification (car, bus, truck, motorcycle), and their spatial position within predefined lane regions. To ensure efficiency, only the Region of Interest (ROI) corresponding to road lanes is processed. Frames are extracted at regular intervals to maintain real-time responsiveness while reducing computational load.

B. Feature Extraction

Once video frames are captured, relevant traffic features are extracted using a deep learning-based object detection model. The system identifies vehicles in each frame and calculates lane-wise vehicle counts. Extracted features include

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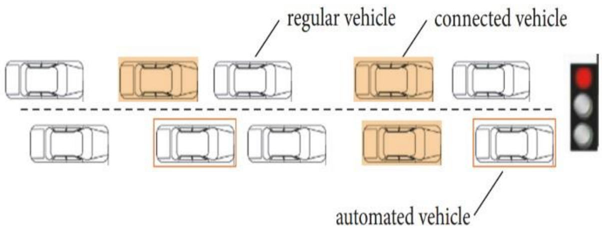
total vehicles per lane, vehicle occupancy ratio, and relative congestion levels across lanes. These values are normalized based on lane capacity to maintain consistency under varying traffic conditions. Density levels are categorized into low, medium, and high ranges to simplify decision making. This stage converts raw visual input into structured traffic metrics that represent real-time congestion conditions.

C. Prediction and Intervention Strategy

The computed density values are provided as input to an adaptive control algorithm that determines optimal green signal duration for each lane. The algorithm proportionally allocates signal time based on congestion levels, ensuring that lanes with higher vehicle density receive longer green intervals.

When the density of a particular lane exceeds a predefined threshold, the system dynamically increases its signal duration within permissible limits. Conversely, lanes with lower traffic density are assigned shorter green times. Signal timing updates occur periodically to avoid abrupt changes and ensure smooth traffic flow.

This adaptive approach enables the system to act proactively rather than relying on static fixed-time schedules, thereby reducing congestion, minimizing waiting time, and improving overall traffic efficiency.



IV. RESULTS AND EXPECTED OUTCOMES

The primary objective of the proposed Adaptive Traffic Signal Timer system is to accurately estimate real-time traffic density and dynamically optimize signal timings to improve traffic flow efficiency. Since the focus of this work is on system design, computer vision integration, and adaptive control modelling, the results discussed in this section represent the expected performance and practical outcomes of the proposed approach.

The system is expected to successfully detect and classify vehicles across multiple lanes under varying traffic conditions. By analysing features such as vehicle count per lane, occupancy ratio, and congestion distribution, the model can effectively differentiate between low, medium, and high traffic density levels. Real-time processing capability ensures that traffic conditions are continuously updated, enabling responsive signal adjustments.

One of the key expected outcomes is a measurable reduction in vehicle waiting time at intersections, particularly during peak traffic hours. By allocating green signal duration proportionally to lane-wise congestion levels, the system is expected to reduce unnecessary idle time, improve road throughput, and enhance overall traffic efficiency. Additionally, optimized signal timing may contribute to reduced fuel consumption and lower vehicular emissions.

The effectiveness of the system can be evaluated using standard performance metrics such as vehicle detection accuracy, frame processing rate (FPS), average waiting time reduction, and traffic throughput improvement. Comparative analysis with traditional fixed-time signal systems can further demonstrate efficiency gains. Simulation-based testing and real-time scenario evaluation can provide both quantitative and qualitative validation of system performance.

Overall, the proposed approach is expected to demonstrate the feasibility of integrating real-time computer vision and adaptive control algorithms for intelligent traffic management. The system highlights the potential of data-driven automation in improving urban mobility and supporting smart city infrastructure development.

V. DISCUSSION

The proposed Adaptive Traffic Signal Timer system demonstrates a practical and intelligent approach to managing traffic congestion using real-time computer vision and adaptive control techniques. Unlike traditional fixed-time traffic signal systems that operate independently of actual road conditions, the proposed system continuously monitors lane-wise vehicle density and dynamically adjusts signal durations. This real-time responsiveness makes the system particularly suitable for urban intersections where traffic patterns frequently fluctuate due to peak hours, events, or irregular vehicle flow.

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One of the key strengths of the proposed approach is its automated and non-intrusive design. By relying on camerabased visual analysis rather than embedded road sensors or manual traffic control, the system reduces infrastructure complexity and maintenance costs. The use of deep learning models enables accurate vehicle detection while maintaining scalability for multi-lane intersections. Additionally, proportional signal allocation ensures fair and efficient distribution of green time based on actual congestion levels.

Despite these advantages, certain limitations must be acknowledged. The performance of the system is highly dependent on camera quality, lighting conditions, and weather factors such as rain or fog, which may affect detection accuracy. Heavy occlusion in densely packed traffic scenarios can also reduce precision in vehicle counting. Furthermore, real-time processing requires sufficient computational resources, particularly when deployed across multiple intersections.

From an implementation perspective, the system is designed to be modular and adaptable, allowing integration with existing traffic infrastructure. However, calibration of lane boundaries and signal timing parameters must be carefully configured to ensure stable operation. Maintaining a balance between responsiveness and signal stability is critical, as overly frequent timing adjustments may lead to confusion or unsafe driving conditions.

Overall, while the proposed system offers a promising solution for intelligent traffic management, further large-scale testing and optimization are necessary. Future improvements may include incorporating weather-robust detection models, emergency vehicle prioritization, and reinforcement learningbased timing optimization. Real-world deployment studies will be essential to validate performance across diverse traffic environments and ensure long-term reliability.

VI. CONCLUSION AND FUTURE WORK

The multimode traffic flow consisting of conventional vehicles, intelligent connected vehicles, and automated vehicles is gradually becoming the norm throughout the world. There-fore, it is imperative to build a new generation of traffic control systems to meet its development and application needs. Most of the existing traffic control systems adopt "prior" feed-forward control method or delay-based limited information control method. The control effect depends on the accuracy of the model describing the actual traffic environment, and it cannot learn and adjust the control knowledge online based on the feedback of the control effect. Obviously, the large-scale development and application of new technologies such as floating vehicles, vehicle-to-vehicle communication(V2V), Internet of vehicles (V2I), V2X, and automatic driving will greatly promote the development of the technical route of urban traffic control systems from the data-poor era to the data-rich era. The real-time detection of the spatiotemporal data based on urban road network traffic status can provide rich and highquality basic data and fine-grained assessment of control effects for traffic control. In the face of the main defects encountered in the existing self-adaptive traffic control system, relying on abundant traffic control data and using the data-driven approach to delve a closed-loop feedback self-adaptive control system with better uncertainty response capability and higher intelligent decision-making level are inevitable result of the objective needs of the development and application of traffic control and advanced infrastructure technologies. Also, it can provide support for the interaction and reduced attention span due to frequent smartphone interaction between the traffic control system and the multimode traffic flow. Therefore, facing the limitations and major short comings of existing traffic signal control systems, relying on a wealth of traffic control interaction conditions and data, and developing a collaborative control system with a high degree of refinement, precision, and better responsiveness and intelligence are the objective need and development direction of traffic control technology. Although the outcome of this paper is multiintersection coordination control theory under the oriented future traffic environment, it can provide scientific support for the development of future road network traffic control systems and can be widely used in new generation traffic control systems. Also, it can improve road network efficiency to a

greater extent, reduce traffic operation costs, prevent and mitigate traffic congestion at intersections, and reduce energy consumption and emissions. Traffic signal control based on reinforcement learning is a true sense of closed-loop feedback self-adaptive control and the instantaneity, accuracy, and selflearning can be guaranteed, which will be one of the future research trends. Besides, it will also provide an entry point and technical support for the development of V2X systems, Internet of vehicles, and autonomous driving industries. Therefore, the related achievements of the adaptive control system for the future traffic environment have extremely broad application prospects.

VII. ACKNOWLEDGMENT

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